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ACTIVITIES ON SPACE DEBRIS IN JAPAN

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1. BACKGROUND

In the course of space development by mankind, space debris continued to increase. This brought forth a new issue that had not existed. Today, the space debris is considered as an issue that all space faring nations must react with coordination, in order to maintain safe and expanding space development tomorrow. It must be recognized that Japan, as one of the members of major space development nations, is naturally obliged to take a part of the activity to cope with the issue by making contributions and cooperations to the international community.

In the United States, President Regan requested to all space sectors, in the national space policy of February 1988 that they "will seek to minimize the creation of space debris." In ESA, Director General Professor R. Lust stated in the preface to ESA's "Space Debris Report" issued in Nov. 1988, "If we fail to take prevention measures (protecting space from artificial debris), future generations will inherit an ominous legacy." These clear guideline and statement are based upon discussions in the UN-COPUOS, IAF, COSPAR and ITU, and researches of individual academic societies and organizations including NASA and ESA. The issue which has been made clear at these venues is that artificial space debris has accumulated to a level that influences todays space activities, and if its growth is unchecked, continuation of the space activity itself will be in peril in near future.

In Japan, one of the world's earliest warning of this issue was made in 1971 by a paper from ISAS$^{1)}$, followed by independent researches in various organizations. However, quality and quantity of the researches are kept still low, far from significant international contributions. Also it should be pointed out that there is no guideline made by the nation toward this issue.

Considering these situations, the Space Debris Study Group was founded by Japan Society for Aeronautical and Space Sciences in September 1990. The objectives are to promote overall space debris related researches, to stimulate public awareness and to provide guidelines to cope with the issues in this field. Over 50 members from space related organizations and industries gathered to discuss technical and social matters. The members are subdivided into sub-groups to deal with respective areas of observation, cause, protection, modeling and social impacts. Summing up the activities, the group issued the interim report in January 1992 and the final report in March 1993.

2. SPACE DEBRIS ENVIRONMENT

Since the launch of Sputnik in 1957, 3508 launches were made by the end of 1992. The launch rates were kept rather constant for over 20 years around 120~130 per year, which dropped to slightly less than 100 after the end of the cold war. The number of objects in near earth space cataloged by USSPACECOM is 7120 at the end of 1992. The detection and tracking capability of the SPACECOM is limited to 10 cm in low altitude and 1m in altitude as high as geosynchronous orbit. Therefore, the number of trackable objects does not include that of smaller objects than 10 cm in diameter.

Among these trackable objects, functioning satellites constitute only 6%. Others are mission-ended satellites (21%), rocket bodies (16%), operational debris (12%) and fragment debris (45%) created by breakups in orbits. There are 112 breakups recorded by the end of 1992. They are believed to have created very many untrackable small debris. US estimates that the number of debris including untrackable ones of more than 1 mm diameter is 3,500,000. The total mass of objects in orbits is 3,000 tons.

Orbital velocity of objects in Low Earth Orbit (LEO) is about 7 km/s. The relative speed of debris at encounter depends on the angle of orbit crossing and the average is 10 km/s. Large kinetic energy causes large damage at collision. For instance, an aluminium sphere of 1 cm diameter has an equivalent energy as a family car running at 50 km/h. Environment in the vicinity of 500 km altitude is relatively well known through investigations of surfaces of returned materials by space shuttles. Here, a facility with a projected area of 1,000 square meters encounters with a debris of more than 1 cm size at a rate of 10 % in ten years. The space station requires ten year's survivability of more than 0.9955. This means that the space station must overcome collisions up to a few centimeter size debris.

Breakups that created a large amount of debris mostly took place in LEO. This region is characterized by cleaning effect by atmospheric drag and increase or decrease of debris population is determined by the rate of creation and cleaning. Recent studies pointed out a danger of further debris creation as a result of debris impact to other objects. Investigations of dynamic relation between creation and cleaning showed an existence of critical density, above which chain reaction of collisions makes the number of debris increase even though no further launch takes place. This was found out independently by US and German. US calculation shows that at altitudes of 1000 km and 1500 km, the present spatial density already exceeds the critical density.

It was once considered that in Geostationary Orbit (GEO), the immediate danger is less severe because the number of debris is not large and relative velocity is small. Functioning geostationary satellites are controlled within a narrow ring and the density at the center part of the ring is very high. On the other hand, spent satellites without orbit control pass through the narrow ring twice in a day in North-South direction. The average relative speed at the time of GEO passing is 300 m/s, which is equivalent to the speed of passenger jet planes. The maximum speed is 800m/s.

Present data shows that a satellite of 100 square meters, life span of ten years, will collide with another object at a rate of 0.001%, which might be considered small enough. However, considering more than 500 objects in this region including all satellites and upper stage rocket motors, the rate of collision increases by two orders of magnitude. Assuming 20 annual launches and no orbit raising maneuvers, a collision will take place with a probability of 5% within next 20 years. Debris created in this region, due to lack of atmospheric drag, will eternally pose hazard to other geostationary satellites. Two breakups in the vicinity of GEO have been reported. In spite of this fact, there is no data on smaller debris available. Existing data include only the main bodies of satellites and motors and they do not reflect fragment population which dominates in LEO. Although it could be safely recognized that the amount of small debris in GEO is not as significant as that in LEO, actual situation remains unknown.

3. ACTIVITIES

Observation

Radar observation has been conducted at Kyoto University utilizing MU radar whose main purpose is middle and upper atmosphere research2). It is a powerful monostatic Doppler radar operating in VHF band with 475 Yagi antenna elements, providing a very fast beam steering capability. The peak power is 1 MW, and the beam width is 2.6 degrees. Debris detection capability is shown in Fig. 1 which compares the height distribution of observed objects with that calculated from US SPACECOM data. The major advantage of the MU radar in debris observation is its fast beam steerability. The beam can be pointed to any desired direction within the coverage of 30 degrees from the zenith in 10 μsec. By switching the beam toward various directions, creating multiple beams which overlap each other, a passage of an object can be observed. Because of low frequency band in which this radar operates, it is not possible to obtain detailed information on the complexity in the shape of the object. However, this characteristic is suitable in determining the basic shape of the object from RCS variation. An example of RCS variation is shown in Fig. 2, which was obtained from observation of COSMOS 1023 rocket booster. The maximum RCS value agrees well with geometrical cross section of 7.4m x 2.4m. The dominant component of RCS variation spectrum gives the spin rate and the magnitude gives the axial ratio of the object.

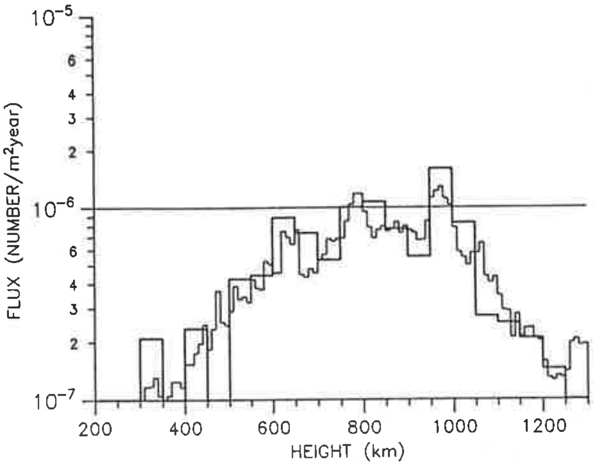

Fig.1 Height distribution of the debris flux derived from the MU radar observations(thick line) and from the US SPACECOM catalog

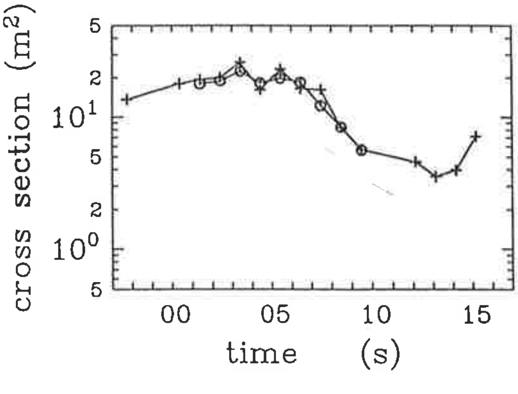

Fig.2 RCS variation of KOSMOS 1023 rocket booster

Geostationary objects are observed by Communication Research Laboratory, using 1.5m aperture optical telescope, located in Koganei, Tokyo. It was build for the purpose of space laser communication experiment. Choosing an appropriate CCD detectors, objects as small as 20 cm at geostationary altitude are theoretically observable. Up to the present, only known geostationary satellites were detected and no smaller unknown objects were found. Although this is a good news from the standpoint of debris hazard, it must be noted that the observation time has been quite limited by the primary mission of the telescope and therefore the results may not prevail over the whole arc nor time. Based on the knowledge accumulated during this experiment, a system which will be suitable for debris observation was proposed by the group.

The importance of Japanese contribution to international community in the field of observation has been recognized. Kyoto University is in process of setting up a plan with a cooperation of Indonesian government to build a larger MU type radar in Sumatra. Although the debris observation is not the primary mission, this is expected to increase our knowledge on debris situation.

Causes of space debris

Orbital objects consist of operational satellites, no-more functioning satellites, rocket bodies and various fragments. Among orbital objects, debris created by explosions are largest in number. Causes are rocket upper stage explosion, intentional destruction and other unknowns. Other unknowns are believed to include those caused by hypervelocity collision with another object.

Objects launched by US, USSR, ESA and PRC experienced at least one major breakup. Among major space development groups, Japan is the only country which is free from significant debris creation. Perhaps it is most important to avoid significant accidental debris creation in the future and to maintain the clean record of Japan. For this purpose, intensive study was undertaken to investigate debris creation possibilities in the present space development activity elements, in respective phases of launch and satellite operations, both normal and non-normal procedures.

During normal operations, debris creations are found out to be (1) alumina particles, nozzle closures and igniters associated with solid motors, (2) yo-yo despiners, clamp wires, optical instrument covers and some sort of thermal blankets, associated with satellite deployment. As an example, X ray observatory, "Ginga", was designed to release 12 objects in the satellite orbit including 4 small metal pieces of 1 cm size. Fig. 3 shows altitude and inclination of related objects in US catalogue. They are identified to be the satellite, final stage motor, 2 yo-yo despiners, 2 clamp wires, a yo tumbler and one of mass holders. In the foreseeable future, satellite recovery missions will be conducted, and generally they contribute minimizing debris. However, there are possibilities of additional debris release at the time of recovery. For instance, in case of SFU missions, a sun-shield of an infrared telescope will be separated at the mission end, and experimental deployment structure, in case of retraction failure, will be also discarded.

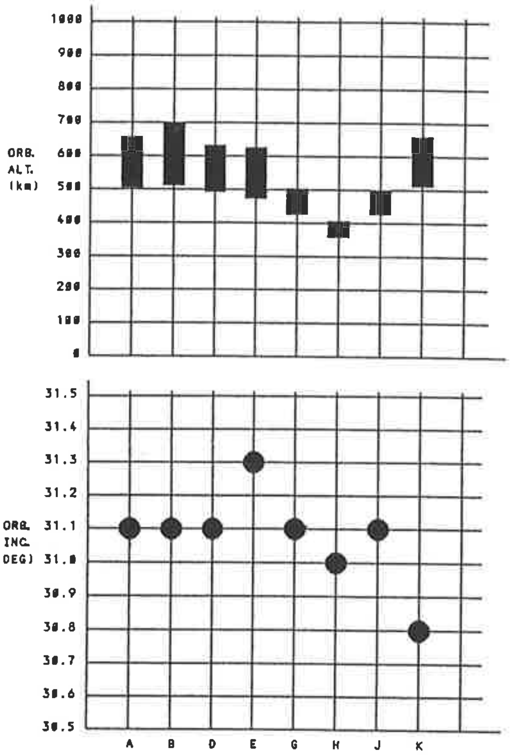

Fig.3 Orbital objects Associated with Ginga

There is a possibility of debris creation at the time of ECS-b (Ayame-2) launch. This was launched by N-I in February 1980, and 8 seconds after the solid apogee motor ignition, the satellite stopped transmitting signals. The satellite is believed to have been damaged by the apogee motor when it experienced non-normal combustion. Although no fragments were observed, a number of debris could have been created if the motor exploded during the operation.

Debris creation causes in other countries were also investigated somewhat in detail. Knowledge obtained in this course will help future debris creation. Therefore, international cooperation is considered important, particularly in identifying causes of breakups whose causes are now unknown, through exchange of information and experiences.

Protection Technology

Experiments utilizing hyper-velocity accelerators are most fundamental at present state of technologies. They are vital not only to time limited space station protection system design but also to development of basic impact phenomena science and of understanding of debris creation and dispersion phenomena. Considering existence of various types of accelerators in universities and national laboratories, effective utilization of those systems under a coordination is important. Table 2 illustrates various facilities now available in the country. Not included in the table is a facility utilizing shaped charge device, which is under development, the capability of which is over 10 km/s. National Aerospace Laboratory is carrying on collaborated work with various institutions to accumulate impact data under various impact conditions.

Table 1. Hyper-Velocity Accelerators in Japan

Bore Size (mm)	Projectile Mass (g)	Projectile Velocity (km/s)	Organization
Power Gun			
25	20	2.0	Tohoku Univ.
27	25	2.5	Kyusyu Univ.
30	40	2.1	Inorganic Material Lab
30	90	1.7	Inorganic Material Lab
Two-Stage Light Gas Gun			
20	10	4.5	Tohoku Univ.
14	4	4.0	Tohoku Univ.
14	2	5.5	Tohoku Univ.
10	1.7	4.9	NASDA
Rail Gun			
13	1	7.5	ISAS
10	2	3	KHI
15	4	3	MHI
10-35	0.02	6/4	JSW

Hypervelocity impact analysis is very important in view of the fact that any experimental means are not sufficient to simulate actual impact phenomena in space because of inability to attain velocity over 10 km/s. Various software systems are in progress. Fig 4 shows an example, in which Lagrange coordination system is employed in stead of conventional Euler coordination system[3]. Interactive re-zoning technique is employed after impact on the first sheet until the debris cloud reaches the second sheet. The whole numerical computation takes about one day utilizing 10 MIPS class engineering work station, including manual manipulations.

In actual design area, data concerning impact damage needs to be accumulated in more systematic manner. In particular, data on rather low impact velocity around 3 km/s must be obtained, because the damage is sometime most critical in this velocity area. Analyses will be important in simulating impacts at velocity range of over 10 km/s. However, any analytical tool must be verified by experimental results and areas of usefulness must be clearly defined so that users may be always aware of the limitation of the tool.

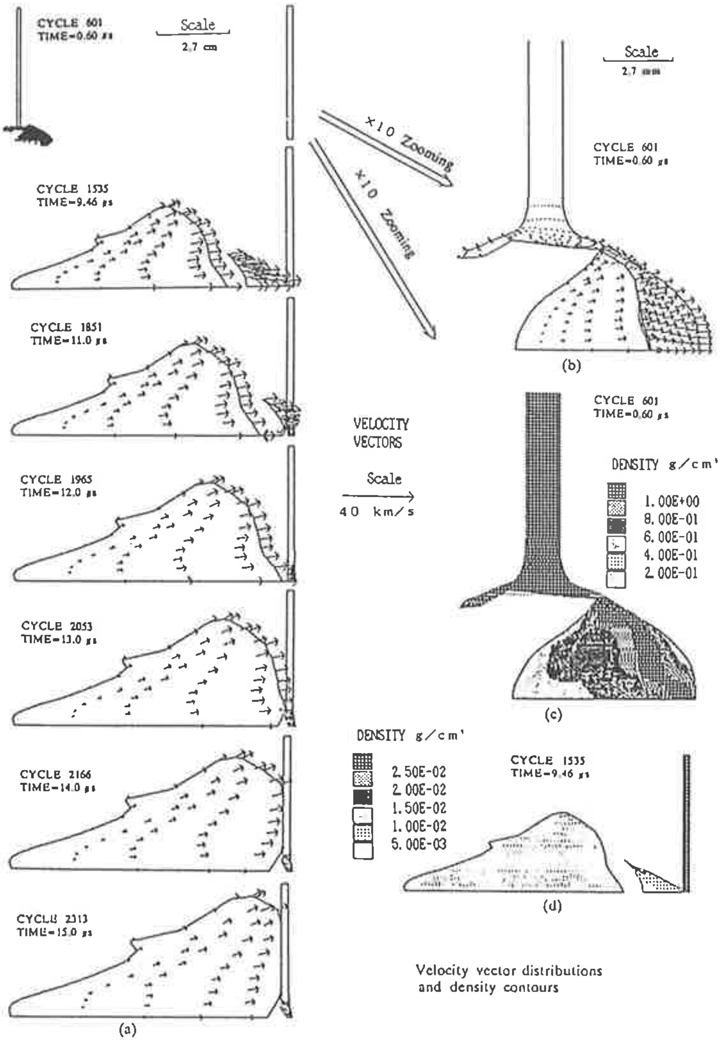

Fig.4 Hypervelocity Impact Analysis by Lagrange Coordinate

Modeling Technology

Modeling purposes are twofold: modeling debris environment and modeling of collision/explosion phenomena. US, Europe and Japan have developed environment modeling technologies, enabling estimation of collisional environment including in those areas of space that are not described by observation data. It is also becoming capable to estimate future environmental evolution. US developed various collision/explosion models based on orbital collision/explosion observations and hyper-velocity impact tests. Characteristics of debris released as a result of fragmentation can be estimated by these models and the results may be applicable for estimation of eventual environment change.

Modeling efforts have been more or less concentrated to geostationary orbit application in Japan. A progress of practical interest is being made by CCIR, which is in a authorization process of recommendation on geostationary orbit environment protection. Re-orbiting into higher orbit will be required to all satellites at their end of life. However, the height requirement is not clearly stated, and the recommendation merely suggests "to increase the perigee altitude by, for example, 300 km or more" and "Definition of an effective minimum altitude is a topic of further study". Toward this end, a long term orbit perturbation analysis and fragment dispersion after collisional and explosional breakup have been conducted. Through the long term orbit analyses, orbit parameter variations were calculated as shown in Fig. 5a, and the range of motion in Fig. 5b. An object will stay in a ring of 50 km in altitude band, 10,000 km in north-south direction band, when the effect of solar radiation pressure is ignored[4]. Fragments are sensitive to the solar radiation pressure. In this case, the eccentricity of the fragment orbit increases with time after creation at the geostationary orbit. The time during which the fragment passes through the dense geostationary ring decreases as the eccentricity increases, but the velocity of the fragment going through the ring increases proportionally to the ring. Since the rate of collision of the fragment with other geostaionary satellites is proportional to the product of time and velocity, the rate will remain the same for a long time. The fragment cloud created at elevated altitude is shown in Fig. 6a. The altitude rage in which the fragments disperge is a function of the energy associated as shown in fig. 6b[5]

Japanese contributions in other area of modeling is rather limited. It is proposed that spacecraft SFU which will be launched by H-II and retrieved by the Shuttle should be investigated with intense effort to obtain orbital debris environment data in low earth orbit. The surface examination process is also proposed to associated organizations.

Social, Economic and Legal Impacts

An impact of a satellite loss due to debris impact can be serious, and the loss will be equivalent to 36 billion yen for replacement, and additional 11 million yen per day in revenue, taking a communication satellite as an example. The loss will be usually covered by insurance. The impact and penetration rate of a satellite in LEO is calculated as 0.072 and 0.24 each year in 1987 and 2005 projected environment, respectively. However, a rate of catastrophic damage is estimated to be at least two orders of magnitude less. Compared with the present rate of loss due to malfunction of spacecrafts and launch, the loss probability due to debris impact will be very small, and the insurance rate will not be influenced by the debris environment, at least until the beginning of the next century.

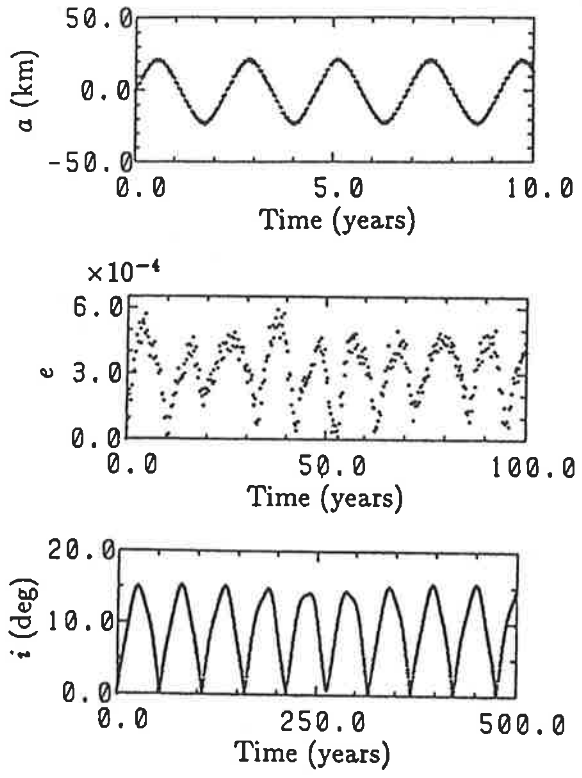

Fig.5(a) Variations of semimajor axis(a), essentricity(e), and inclination(i) of an object at GEO

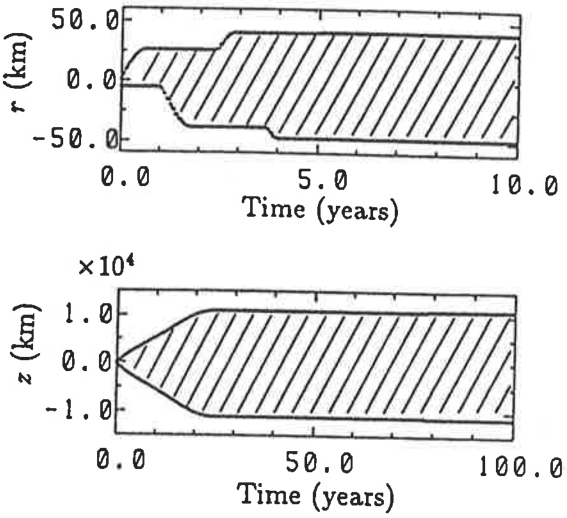

Fig.5(b) Range of motion of an object at GEO

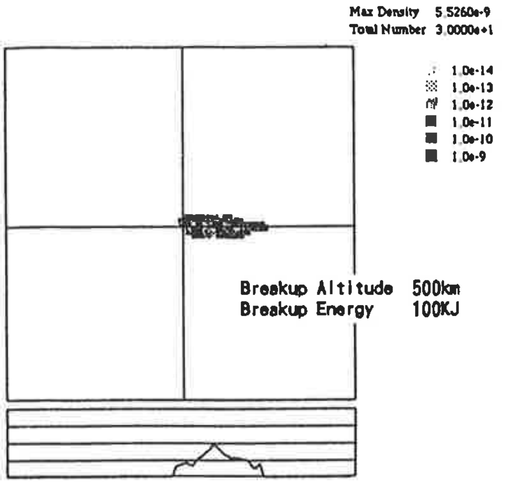

Fig.6(a) Fragment Distribution after Break up

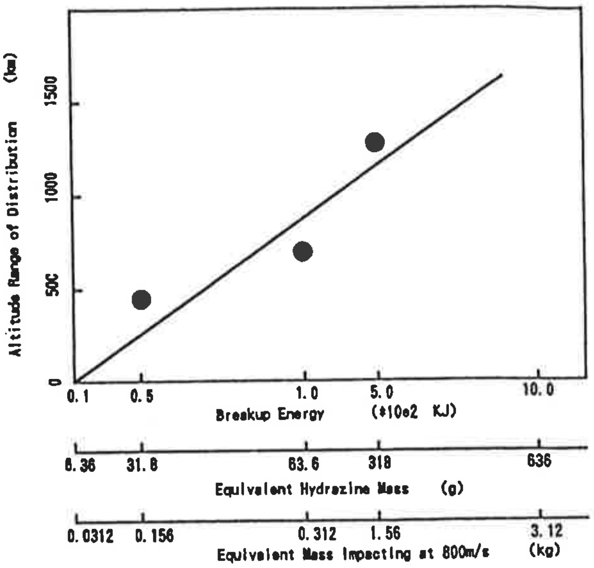

Fig.6(b) Energy and Altitude Range

An economical impact of various debris mitigation practices were estimated both in technology development and in flight hardware cost. Table 3 shows the cost impacts of three options: launch vehicle upper stage passivation, upper stage propulsive de-orbit and geostationary satellite disposal into 300 km higher orbit. Geostationary satellite disposal has a largest impact of 26 million dollars, because of the operational life shortening. In case of the propulsive de-orbit, taking Titan 34D as an example, payload capacity is decreased by 40 kg by installation of de-orbit device, and the launch cost of 120 million dollar is increased by 7.8 million dollars.

Legal problems associated with space debris have been investigated in detail. Discussions in this field are quite diversified and are not included in this paper. The discussion, however, highlited the need for international agreement of various levels, leading to a recommendation of an organization jointly supported by space development agencies and companies, in order to deal with policy, supervision and coordination associated with space environment.

Table 2. Cost Impact of Debris Mitigation Practices

Cost Items	Development	Flight H/W
Upper Stage Passivation		
Hardware Change	$450,000	$140,000
Integration	-	$95,000
Payload Weight Reduction	-	-
Inquiry and Fees	$320,000	$50,000
Total	$770,000	$285,000
Upper Stage Propulsive De-Orbit		
Propulsion System	$1,200,000	$400,000
Attitude Control System	$11,000,000	$3,200,000
Integration	$13,100,000	$1,900,000
Payload Weight Reduction	-	$1,700,000
Fees	$2,300,000	$600,000
Total	$27,600,000	$7,800,000
GEO Satellite Disposal into 300 km Higher Orbit		
Hardware Change	$1,530,000	$840,000
Integration	-	$260,000
Lifetime Reduction	-	$24,000,000
Related Costs	$520,000	$800,000
Total	$2,050,000	$25,900,000

4. ORBIT ENVIRONMENT PROTECTION

To cope with rapid accumulation of orbital debris, many nations and organizations have adopted various policies, which are summarized as abandonment or careful execution of ASAT, residual fuel/pressurant venting from rocket upper stages and de-orbiting of geostationary satellites at their end of life. However, these policies are not sufficient to suppress further debris creation and growth.

Orbit environment conservation with respect to space debris is necessary for insuring long lasting and expanding space activities. For this, various organizations and scientists have proposed various technical measures. The most recently, ad hoc expert group of Committee on Safety, Rescue and Quality in IAA compiled a report[6)] containing methods of debris control proposed in three levels. JSASS Debris Study Group is basically in support of this document.

There are various technological proposals already made to cope with debris and orbit environment protection. The next steps to be taken are practical measures toward adoption of those methods. The Group identified the following actions as appropriate to be taken in Japan and to be proposed to world community as well.

Adoption of Technical Standards
(Needs and Methodologies already Established)

1) Space hardware and their operation standards for minimizing operational debris.

2) Energy passivation technical standards for mission ended hardware.

Technical Investigations for Standard Adoption

(Technical Choices Existing)

1) Orbit selection techniques for early entry of orbiting objects after mission.

2) Geostationary satellite energy passivation and minimum re-orbit altitude.

Policy and Organizational Structure Selection

(Technology and Effectiveness Evaluation Needed)

1) Technology definition and cost to effectiveness evaluation of orbiting object removal methods.

2) Investigation on organization structure for implementing orbiting object removal.

Considering all technical capabilities and potentials thus defined, considering debris population growth history and predictions, and commemorating the 50-th year of the first man-made space object, it is proposed that the year 2007 be the target for orbit environment protection.

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