A Reorbiter for GEO Large Space Debris Using Ion Beam Irradiation

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Abstract: In recent years, space debris problems have become very serious for space development. The worst case occurs in low earth orbits (LEO). The situation in and near geosynchronous earth orbit (GEO) is not as bad as in LEO. The debris problem in the GEO region, however, should not be left as it is because GEO is unique and has few debris-cleaning modes. Thus, we have proposed a new concept for a reorbiter to reorbit large space debris (dead spacecraft left in orbit after end of mission). The concept is based on the idea of thrusting a debris object by irradiating it with an ion beam. After the reorbiter, equipped with two ion engines, approaches a debris object, the ion beam exhausted from one of them irradiates and thrusts it and changes its orbit. The other ion engine, with a higher thrust, installed on the opposite side is operated so that the reorbiter follows the debris object within a certain distance range. In application to a GEO debris object, its orbit is raised by about 300 km according to debris mitigation guidelines. A preliminary system study was conducted assuming debris objects weighing 1,000 to 2,000 kg, a reorbiter weighing 1,000 kg, and ion engines with 40- to 100-mN thrust levels. It was found that the reorbiter would take 6 to 25 days to reorbit and a much shorter time to return. Issues that must be addressed to develop this system were identified, and preliminary discussions were conducted. The ion engine for debris irradiation is required to have sharp ion beam. Ion trajectory analyses were conducted to determine grid dimensions appropriate for this requirement.

Nomenclature

d_a	=	accelerator-grid hole diameter
d_s	=	screen-grid hole diameter
J_{all}	=	all beam current
J_{debris}	=	beam current irradiating debris
j_b	=	beamlet current
l_{cc}	=	grid-hole center-to-center distance
l_g	=	screen-to-accelerator-grid separation
N	=	discharge chamber ion number density
t_a	=	accelerator grid thickness
t_s	=	screen grid thickness
V_a	=	accelerator grid voltage
α	=	acceleration
α_x	=	beam divergence half angle including x (in percent) of all beam current

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I. Introduction

The population of space debris is increasing year by year, and debris mitigation has become essential to sustaining space activities in the future. The United Nations Space Debris Mitigation Guidelines established in 2007 recommend that spacecraft in the LEO region should be deorbited within 25 years after the ends of their missions and that spacecraft in the GEO region should be reorbited to the graveyard orbit about 300 km higher than GEO after the ends of their missions.

However, it has been widely recognized that these mitigation measures alone are not sufficient because in these orbit regions there is already a very large population of spacecraft left after the end of their missions. In particular, recent numerical simulations of the evolution of the space debris population indicate that the population in the crowded LEO region has reached the point where the environment is unstable and population growth is inevitable due to mutual collisions between debris objects. This result suggests that debris remediation measures should be taken urgently, and thus studies of active debris removal have been widely begun.

In the GEO region, the debris population increase due to collisional cascading has not been predicted yet, though accidental break-ups from stored energy have been reported. In this region, however, unique features and problems exist as follows.

a) GEO is one single limited resource that the whole world utilizes. Thus, if the debris population is excessively increased by collisions or explosions, its influence will be extremely large.

b) The debris in the GEO region will stay there permanently because we cannot expect any decrease in the debris population due to atmospheric drag.

c) Though the sizes of the catalogued objects in the GEO region are about 50 cm or larger, there may be a lot of debris objects of smaller sizes (20 cm to 30 cm class) there whose exact orbits are not known.

d) So far, not all geosynchronous satellites have been reorbited after the end of their missions in compliance with the Inter-Agency Space Debris Coordination Committee (IADC) guidelines. Thus, the number of large objects in this region is increasing.

For these reasons, it is becoming more and more important to protect the GEO region from debris generation.

The situation of space objects in the GEO region is as follows[1, 2]. More than 1,200 objects are catalogued in and near GEO. Though reorbiting compliant with the IADC reorbiting guidelines has been conducted to a certain extent, technical difficulties remain in conducting orbit raising at the end of a mission, and there are some cases where reorbiting cannot be conducted due to failures of the satellites. The end-of-life reorbiting rates of geosynchronous satellites have not been high even in recent years. During 2009, 21 spacecraft reached end of life, and only 11 of them were reorbited more than 250 km above GEO. During 2010, at least 16 spacecraft reached end of life, and only 11 of them were reorbited following the IADC recommendations. These facts show that there are still too many satellites that were not or could not be properly reorbited.

Recently, in these situations, proposals have been actively made for reorbiting the satellites left as space debris after end of life. In Europe, development of a debris removal system called ROGER has begun, which will capture GEO debris using a net and transport it to the graveyard orbit[3]. In the US, a GEO debris reorbiter called GLiDeR has been proposed, which would generate electrostatic force to tug large debris objects for reorbiting[4].

In Japan, we have proposed a new concept for a reorbiter that reorbits large GEO debris objects to the graveyard orbit using the thrust of ion beam irradiation[5]. In this paper, the features of this concept are described, and the results of a preliminary study of this reorbiter system are given. In particular, thruster grids suitable to this system were designed based on a numerical model of ion optics system.

II. Concept of the Reorbiter

Figure 1 shows a schematic drawing of the reorbiter concept. The reorbiter is equipped with two (or more) ion engines (Ion engines A and B) whose thrust directions are opposite. Ion engine A is installed on the side of the reorbiter that faces the debris, and Ion engine B on the opposite side of the reorbiter. The reorbiter approaches a large debris object assumed to be a dead satellite within a certain distance. The ion beam exhausted continuously from Ion engine A irradiates it and applies thrust to it. This thrust raises the orbit of the debris object gradually. The thrust is so small that the orbit is raised in a spiral way. Ion engine B is operated so that the reorbiter follows the debris object by its thrust. The thrusts of the ion engines are adjusted so that the distance between the debris and the reorbiter is kept within a certain range. After they reach the graveyard orbit, the reorbiter returns to the GEO region to reorbit another debris object, and this round trip is repeated to reorbit a number of debris objects.

This reorbiter features the following.

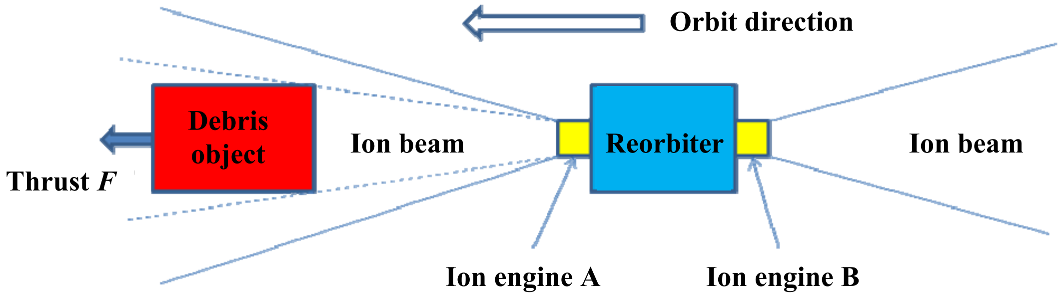


Figure 1. Concept of a reorbiter using ion beam irradiation.

a) It is not necessary to reduce rotation or tumbling of debris objects.
b) Technologies for capturing debris objects are not required.
c) The proposed method of reorbiting does not depend on the detailed shapes of debris objects such as grappled parts. Thus, similar procedures can be used for different debris objects.

The velocity increment is about 11 m/s for reorbiting a GEO debris object to the graveyard orbit about 300 km higher than GEO. This velocity increment is much smaller than the velocity increment of 90 m/s to 140 m/s required for deorbiting a LEO debris object to the lower orbit that complies with the "25-year rule" in the debris mitigation guidelines. The velocity increment of 11 m/s is small enough for ion beam irradiation to provide. Using this measure, we can avoid applying some of the difficult technologies required for active debris removal in LEO. Specifically, we can avoid reducing tumbling, or angular momentum, of the debris object, synchronous flying around it, confirming what to grapple, and capturing the debris object. The proposed reorbiter relies on a rendezvous with an uncollaborative debris target, which is also required for various methods of active debris removal, and ion engine technology, which is mature.

However, some technical issues that should be addressed to realize this reorbiter system are as follows.
a) Approach to an uncollaborative object by low thrust (chemical thrusters could be used, but propellant mass would be increased).
b) Orbit transfer by low thrust, for which a short relative distance must be kept to an uncollaborative object.
c) Improvement in the convergence of the ion beam exhausted from an ion engine.
d) Evaluation of the effects of ion beam irradiation on debris objects and on the reorbiter, and countermeasures if necessary.

In particular, issue b above is the key technology of this proposal and seems very challenging. However, in reorbiting, we only have to raise the orbit by about 300 km, and the target orbit does not have to be exact. This simplifies the problems with issue b.

III. Preliminary System Study

A. Target Debris and Reorbiter System

We assumed the following conditions in conducting a preliminary study of the proposed system.
a) The target debris object is a geosynchronous satellite still in orbit after the end of its mission or due to a failure and having a mass of 1,000 to 2,000 kg.
b) The mass of the reorbiter is 1,000 kg.
c) The ion engine on the reorbiter for irradiating the debris object has a thrust of 40 mN to 80 mN.
d) The distance between the debris object and the reorbiter is about 20 m.
e) The debris object has a sectional area of 3 m^2 to 4 m^2 that is irradiated by the ion beam.

It should be noted that the debris object is not irradiated by the whole ion beam but only by a fraction of the ion beam, which we call the debris irradiating efficiency. Under the above conditions, the thrust acting on the debris object is 10 mN to 20 mN, which is about 25% of the ion engine thrust.

The direction and magnitude of the thrust of ion beam irradiation do not depend on the shapes of debris objects, or the dependence is negligibly small, if they are irradiated by the same amount of ion beam. This is because the ions in the ion beam lose almost all their kinetic energy when they hit a debris object, and thus almost all the momentum of the ions is transferred to the debris object.

Table 1. Reorbiting time, returning time and propellant mass versus debris mass and ion engine thrust.

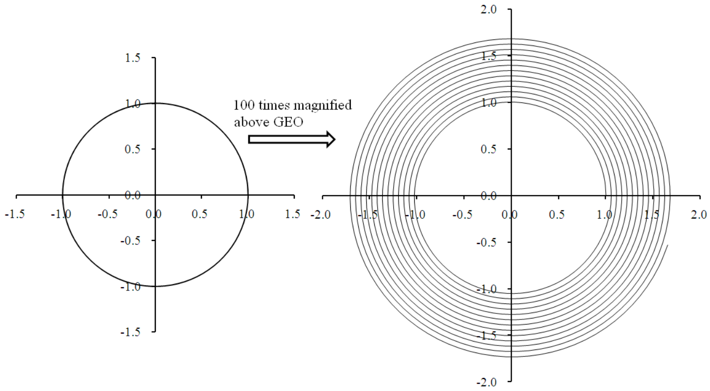
Case	Debris mass (kg)	Debris thrust (mN)	Acceleration (m/s^2)	Thrust of ion engine A (mN)	Thrust of ion engine B (mN)	Time of debris reorbiting (d)	Time of returning to GEO (h)	Propellant mass (kg)
A	2,000	10	0.5×10^{-5}	40	45	25.2	75.6	66.2
B	2,000	20	1.0×10^{-5}	80	90	12.6	37.8	66.2
C	1,000	10	1.0×10^{-5}	40	50	12.6	75.6	36.7
D	1,000	20	2.0×10^{-5}	80	100	6.3	37.8	36.7

Debris irradiating efficiency of 25% and reorbiter mass of 1,000 kg are assumed.

B. Orbit Transfer

The velocity increment of 11 m/s is required for the orbit transfer from GEO to the graveyard orbit. This velocity increment is the difference between the circular orbiting speeds of 3,075 m/s at GOE and 3,064 m/s at the graveyard orbit. Ion engine B generates a thrust such that the debris object and the reorbiter have the same magnitude of acceleration.

With the above assumptions, we calculated the thrust of the ion engines, the time to reorbit, and the time to return to GEO after debris disposal and present them in Table 1. For the cases considered, it takes 6 to 25 days to reorbit and 38 to 76 hours to return to GEO.



(a) In uniform scale. (b) In magnified scale above GEO.

Figure 2. Orbit from GEO to the graveyard orbit. The unit for the coordinates is the radius of GEO.

Figure 2 shows the orbit from GEO to the graveyard orbit. It was calculated for the case of a constant azimuthal acceleration of 1.0×10^{-5} m/s^2 from a two-dimensional equation of motion in polar coordinates. In Fig. 2(b), the raised height above GEO is shown on the 100-times-magnified scale because the height of 300 km is much smaller than the orbit radius of GEO. Figure 3 shows the raised height above GEO versus the azimuthal angle relative to the starting point in GEO. For the beginning of the orbit transfer, the increase in this angle is small, but it increases with the orbit rising because of the increase in the orbiting period. Even in the least acceleration case, orbit raising in visible areas from Japan will be possible, and it will ease the reorbiting operation.

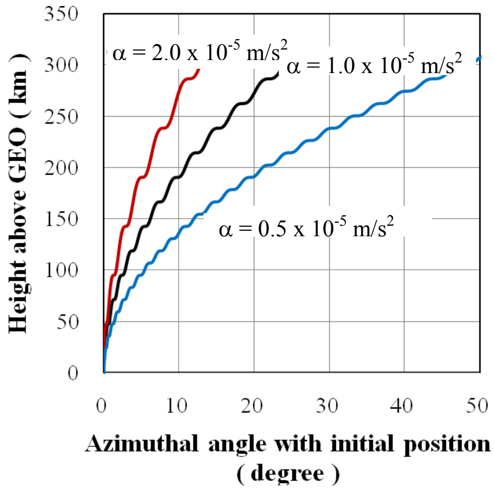


Figure 3. Raised height above GEO versus the azimuthal angle relative to the starting point for three cases of acceleration α.

C. Navigation

Because of the small gravity field in GEO and the small acceleration of the reorbiter and debris object, the reorbiting trajectories are almost the same as in inertial space within small time ranges. This suggests that it will be possible to keep the relative distance between the reorbiter and the debris object by simple control methods. Increasing the acceleration of the debris object can increase the separation distance, and increasing the acceleration of the reorbiter can decrease it.

Keeping the distance between the reorbiter and the debris object within a certain range is one of the key issues of this system. Thus, we made a simple simulation of distance control based on the analytic solution of Hill's equation for constant acceleration. The reorbiter was assumed to have a constant acceleration, and the acceleration of the debris object was adjusted depending on the distance between the reorbiter and the debris object. The direction of the acceleration was set along the line connecting the reorbiter and the debris. Because the ion beam is divergent, it is reasonable to assume the larger acceleration for the smaller distance and the smaller acceleration for the longer distance. If this control logic works well, we can have a very simple control system because of the divergent property of the ion beam. However, results of the simulation showed that the change in the distance gradually increases with time. This suggests that more complicated procedures are necessary for stable control.

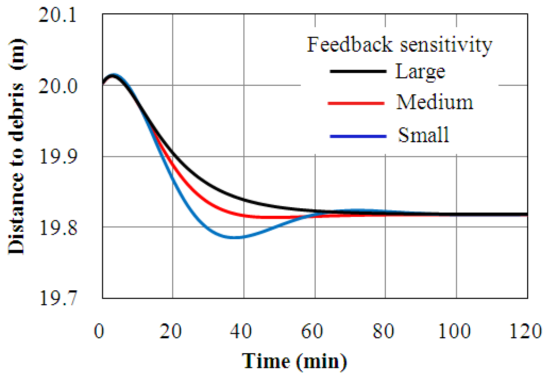


Figure 4. Changes in the distance between the reorbiter and the debris object with time. The black, red, and blue curves indicate the cases of large, medium, and small feedback sensitivities, respectively.

Thus, the simulation was improved by considering the relative velocity between the debris object and the reorbiter. In addition to the control based on the distance between the debris object and the reorbiter, the acceleration of the debris object was increased for approach and decreased for recession. The results of the improved simulation are shown in Fig. 4, indicating that good convergence in the distance control can be obtained.

The navigation system is another key issue of this reorbiter. However, the study of it has not begun yet. Rendezvous with uncollaborative objects is being studied in other research being conducted at JAXA on active removal of space debris in LEO[6]. Studies of optical sensors and passive radars are also being conducted. The results of these studies are expected to be of great help in developing this reorbiter system.

IV. Ion Engines

A. Requirements for the Ion Engines

As shown in Fig. 1, the reorbiter needs two (or more) ion engines (Ion engines A and B). Ion engine B is for thrusting the reorbiter to change its orbit, and so it is not special. The required thrust is 45 to 100 mN. In Japan, we are conducting research of an ion engine with thrust levels as high as 100 mN[7]. On the basis of this technology, Ion engine B can be developed with no critical issues. Or, if we use four ion engines in place of a single ion engine, the thrust required for each thruster is less than 25 mN. This thrust level can be achieved by the existent 20-mN-class ion engine that was developed for Japanese geosynchronous satellites[8]. Endurance requirements for Ion engines A and B are not severe because the velocity increment necessary to this orbit transfer is not so large compared with other missions using ion engines.

However, we have a concern over Ion engine A about its beam divergence requirement. The 20-mN-class ion engine has a beam divergence angle of about 10 degrees, and the large ion engine has one of about 13 degrees[9, 10]. Here, the beam divergence angle is defined as the 95% half-cone angle, within which 95% of the whole ion beam is contained. In Section III.A, we assumed the distance between the debris object and the reorbiter is about 20 m. This is the distance for which 25% of the whole ion beam hits the debris object under the condition that the debris object is spherical and 2 m in diameter and is irradiated by the ion beam from an ion engine with a 95% half-cone angle of 10 degrees.

If we can improve the ion beam convergence of ion engines, we gain the following advantages.

a) Smaller reorbiter systems can be made by using smaller ion engines because the efficiency of debris irradiation can be increased.

b) Longer distances between the debris and the reorbiter can be kept, and thus safer orbit transfer can be conducted and the effects of back-sputtering on the reorbiter can be reduced.

Table 2. Distance from the reorbiter to the debris object for three cases of ion beam divergence and two cases of debris irradiating efficiency J_{debris}/J_{all}.

J_{debris}/J_{all}	Beam divergence angle α_{95}* (deg)		
	5	7.5	10
25%	36 m	27 m	18 m
50%	24 m	18 m	12 m

* α_{95}: Half-cone angle including 95% of the ion beam

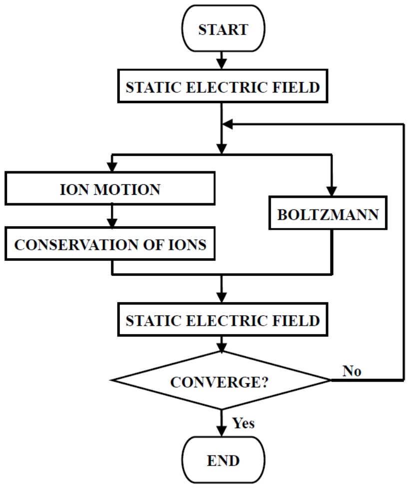


Figure 5. Flowchart of the code.

To obtain a target for improving the ion beam convergence, we calculated the distance from the reorbiter to the debris object for three cases of ion beam divergence and two cases of debris irradiating efficiency. The ion beam density profile was approximated by a Gauss distribution with axial symmetry. The results are shown in Table 2, and they indicate how much longer the distance between the debris object and the reorbiter can be made by improving the efficiency of ion beam irradiation.

B. Evaluation of Beamlet Divergence

To determine suitable values of the grid dimensions and operating conditions of Ion engine A, we conducted computations of the trajectories of ions extracted through ion optics systems using a computer code that had been developed by one of the authors[11]. Although this code can be used for extensive conditions of grid systems, we applied it to simple configurations of symmetrical two-grid systems without grid offsets assuming flat grids.

The flowchart of the code is shown in Fig. 5. First, the electric field is obtained by solving Poisson equation, and the ion trajectories in this field are calculated using the equation of ion motion. Then, the ion number density is obtained using conservation of ions. The electron number density is determined by Boltzmann equation. With these results, the electric field is obtained again. This sequence is repeated until convergence is achieved. Figure 6 shows the analyzed region and grid dimensions. Periodic boundary conditions are applied on the upper and lower boundaries of the analyzed region, and the potential of 0 V on the downstream boundary.

In the ion trajectory computations, we devised the following guidelines to obtain trajectories with smaller divergence angles.

a) To reduce ion number density in the discharge chamber. This would bring smaller repulsive force among ions in the ion beamlet to decrease beamlet divergence.

b) To increase the separation between screen and accelerator grids. This would make equipotential contours flatter between the grids to decrease beamlet divergence.

The beamlet current itself can be decreased by applying these guidelines. However, we expect that the beamlet current within a certain small divergence angle would be increased.

We conducted trajectory computations for a large number of cases, and could confirm that the guidelines above gave as good results as was expected. Figure 7 shows some of the representative results of the beam divergence changes. In this figure, the beam divergence half angle α_x is defined as a vertical angle of the circular cone in which X (in percent) of the all beamlet current is contained. The grid dimensions used in these computations are shown in Table 3. The operating conditions are shown in Table 4, and the ion number density N in

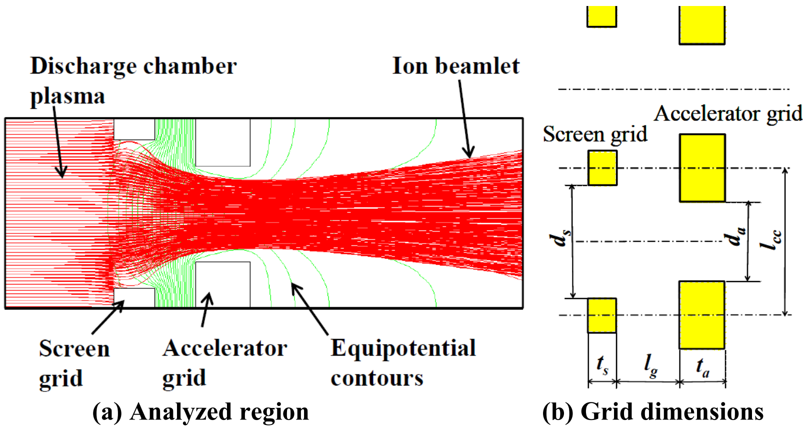


Figure 6. Analyzed region and grid dimensions.

Table 3. Grid dimensions used in the computations.

	Screen grid	Accelerator grid
Hole diameter (mm)	2.3	1.45
Thickness (mm)	0.5	0.8
Open area fraction	0.68	0.27
Grid separation (mm)	0.8 to 2.4	
Hole center-to-center distance (mm)	2.65	

Table 4. Operating conditions used in the computations.

Beam voltage	1,000 V
Accelerator grid voltage	-200 V
Discharge voltage	30 V
Electron temperature	
in upstream	3.0 eV
in downstream	3.0 eV
Initial ion velocity	300 m/s
Propellant	Xenon

the discharge chamber was assumed to be 3 x 10^{17} /m^3 and 5 x 10^{17} /m^3. Figure 7 indicates that we can have smaller beam divergence angles for larger grid separations, and α_{95} was about 4 degrees in the minimum case. We found that α_{50} and α_{25} are also decreased with the increase in the grid separation.

To conduct more quantitative evaluation of beamlet convergence effects on debris objects, we calculated the beamlet current within certain divergence angles. Results are shown in Fig. 8 for the divergence angles of 3 and 6 degrees. The beamlet current within a divergence angle of 3 degrees irradiates a circular debris object in 2-m diameter located 19.1 m apart from the ion engine. This configuration is almost the same as we assumed in the preliminary system study, and thus it is a reasonable measure for determining grid dimensions and operating conditions.

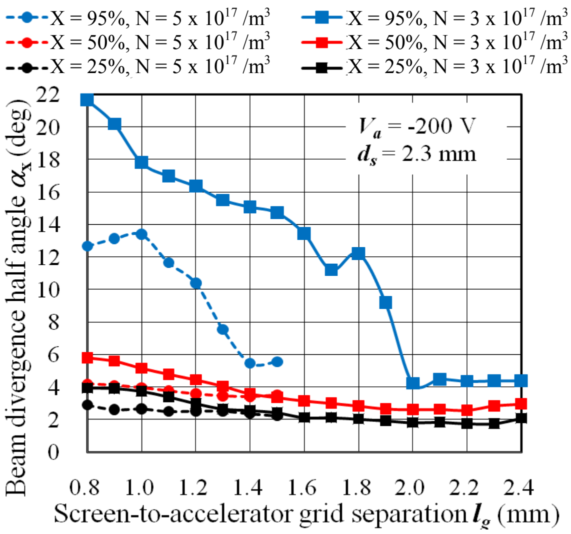


Figure 7. Representative results of the beam divergence changes.

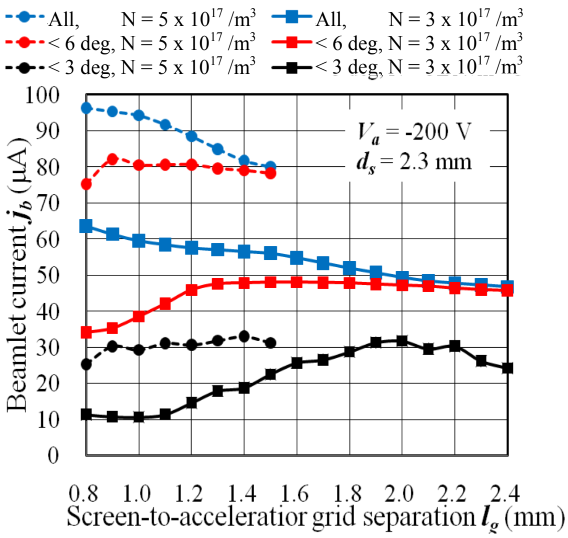


Figure 8. Beamlet current versus grid separation.

For the ion number density of 3 x 10^{17} /m^3, though the whole beamlet current itself is decreased, the beamlet current j_b within 3 degrees is increased with the increase in the grid separation, and reached about 30 μA for the grid separation of 1.6 to 2.4 mm. For the ion number density of 5 x 10^{17} /m^3, the situation is almost the same although ion extraction became impossible for the grid separation larger than 1.5 mm.

Usually, the ion density in the discharge chamber of an ion engine is not uniform but has some radial distribution, which we have to accept when designing ion engine grids. To evaluate the effects of this non-uniformity, we calculated changes in the beamlet currents for a certain range of discharge chamber ion number density. Results are shown in Fig. 9 for a grid separation of 1.4 mm. This value of the grid separation was chosen from the results of Fig. 8. Ion extraction was possible at l_g = 1.4 mm even for N = 5 x 10^{17} /m^3, and also the beamlet current within 3-degree divergence was moderate for N = 3 x 10^{17} /m^3. The broken curve in Fig. 9 indicates 25% of the whole beamlet current. It is found from this figure that for the ion-number-density range from 2.7 x 10^{17} /m^3 to 5.5 10^{17} /m^3 the

Table 5. Conditions for estimating grid diameters.

	Case A	Case B
Ion number density ($10^{17}/m^3$)	3.0	5.0
All beamlet current (μA)	56.5	70.9
Beamlet current within 3 deg (μA)	18.8	29.4
Grid separation (mm)	1.4	

beamlet current within 3-degree divergence is larger than this 25% curve. This means that if we design an ion engine that can produce ions with this density range in the discharge chamber, a debris object in 2-m diameter located 19 m apart is irradiated by more than 25% of the ion beam of the ion engine.

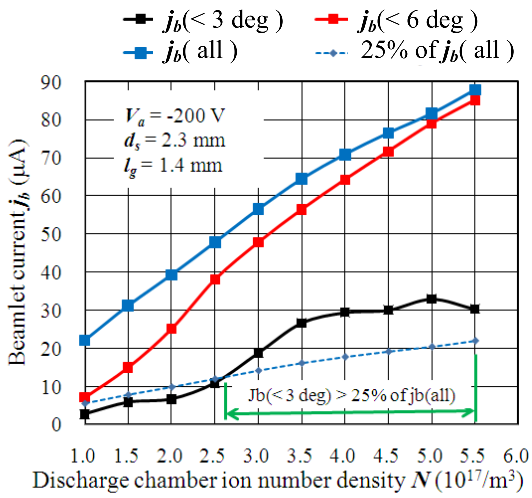


Figure 9. Beamlet current versus ion number density.

C. Grid Design

Grid diameters were estimated for two cases on the basis of the results above. The result of beamlet current for N = 3 x 10^{17} /m^3 was used as Cases A (conservative case) and that for N = 5 x 10^{17} /m^3 as Case B. Table 5 shows values of the beamlet current for these cases. The thrust irradiating debris objects was assumed to be 10 mN or 20 mN. Number of the ion engines producing each thrust value was assumed to be one or four.

For these cases, numbers of the grid holes and diameters of the grids were obtained, and are shown in Table 6. Here, we used the screen-grid hole-diameter of 2.3 mm and the screen-grid open-area-fraction of 68.2%. We suppose to make the grids with carbon/carbon composite because it can make the grids thermally stable, resulting in ion beamlet stability[12]. In Table 6, there are some cases where the grid diameters may be too large if we make them with carbon/carbon composite. However, no problems will happen if we use four ion engines in such cases.

Table 6. Grid diameter estimation.

Case A				
Thrust to debris	Number of thrusters	Trust per thruster	Number of grid holes	Grid diameter
10 mN	1	30.0 mN	10,197	281 mm
	4	7.5 mN	2,549	140 mm
20 mN	1	60.1 mN	20,394	397 mm
	4	15.0 mN	5,099	199 mm
Case B				
Thrust to debris	Number of thrusters	Trust per thruster	Number of grid holes	Grid diameter
10 mN	1	24.1 mN	6,520	205 mm
	4	6.0 mN	1,630	102 mm
20 mN	1	48.2 mN	13,040	288 mm
	4	12.1 mN	3,260	144 mm

V. Ion-Beam Irradiation Effects

A. Effects on Debris Objects

Ion sputtering and thermal inputs are considered as the main effects of ion beam irradiation on debris objects.

Ion Sputtering

To evaluate effects of ion sputtering, it is essential to obtain data on sputtering rates, but we could not obtain them yet. Thus, this section is only for describing some preliminary considerations.

Once the mass of a debris object is known, the momentum required for reorbiting is determined. Thus, for a given species and energy of ions and surface material of the debris object, the sputtered mass or volume can be calculated, and it does not depend on the thrust applied to the debris object. If we assume that a debris object weighing 2,000 kg is irradiated by xenon ions with energies of 1 kV, then it must be hit by 2.6 x 10^{24} ions in total to achieve a velocity increment of 11 m/s.

How large a mass or volume is sputtered depends on the material of the debris surface. Though various materials are used for satellite body surfaces, most of them are usually covered with thermal-control materials such as multilayer insulations, typically polyimide films, and with cover glass of solar cells, particularly in spin-stabilized satellites.

We evaluated the sputtering of aluminum in place of polyimide and glass; sputtering yield data for these materials were difficult to obtain. For the condition of 2.6 x 10^{24} xenon ions hitting the debris object, a mass of 140 g, or a volume of 52 cm^3, of aluminum is sputtered, assuming a sputtering yield of 1.2[13]. For a sputtered area of 4 m^2, the surface is etched to a depth of 13 μm. For a rotating debris object, the etched area is spread, and the depth is reduced to 4 μm to 5 μm. We expect that no problems will occur with this degree of sputtering, which is smaller than the outermost thickness of the multilayer insulation and the thickness of cover glass.

*Thermal Effec*t

The thermal input to the debris object is determined by the product of the energy per ion and the number flux of ions. For an ion acceleration voltage of 1 kV, an ion beam current of 0.38 A is required to generate a thrust of 20 mN, and thus the thermal input is 380 W. For a thermal input area of 4 m^2, the heat flux density is 96 W/m^2. This value is 7% of a solar power incidence density of 1,370 W/m^2, and thus no serious effects are expected.

B. Effects on Reorbiter and Remedies

Back-Sputtering

Also to evaluate effects of back-sputtering, it is essential to examine the effects experimentally, but we could not obtain such experimental data so far. Thus, this section is also only for describing some preliminary considerations.

In Section V.A, we showed that a certain amount of the debris surface material is sputtered. This means that some of the sputtered material may fly to the reorbiter and may be deposited on it. This sputtered material can affect the solar cells, thermal control surfaces, optical sensors, and other parts of the reorbiter. A preliminary estimate of the back-sputtering was made on the same assumptions as in Section V.A. Aluminum is sputtered by xenon ions with 1 kV, and the distance from the debris object is 20 m. In addition, we assumed a uniform distribution of the sputtered material over a hemisphere whose center is at the debris object. Then, we estimated that the deposition thickness on the reorbiter is 0.025 μm per reorbiting and thus 0.25 μm for reorbiting 10 debris objects.

Effects on Solar Cells

In estimating the effects on solar cells, we considered the angle of the solar array face relative to the debris object. The reorbiter follows the debris object and thus is always located behind it. The solar array is rotated to point toward the sun. Accordingly, the back-sputtered material is deposited on the back side of the solar array for one half of the orbit, and the incident angle is varied from zero to 90 degrees for the other half. As a result, the sputtered material deposited on the solar cells is reduced to $1/\pi$ of the above value (0.08 μm for reorbiting 10 debris objects).

A simple remedy for solar cell contamination is to carry extra cells to compensate for the performance degradation. By keeping the distance to the debris object longer, the deposition is reduced in inverse proportion to the distance squared, but the thrust to the debris object is also reduced.

The heaviest deposition occurs when the solar array faces normally to the debris object. If the ion beam irradiation is stopped for the 90-degree arc of the orbit to avoid heavy back-sputtering, the deposition is reduced to about 29% of its value without the stoppage. Coasting for this period causes a 1.33 times longer reorbiting time.

Effects on Other Parts

Optical sensors, particularly their lenses, will be affected by the deposition of sputtered material. Installing shutters on the sensors can be a remedy for this issue. Synchronous operation of the ion beam irradiation and the shutter can prevent contamination. By opening the shutter only when the beam exhaustion is stopped, we can prevent contamination of the lenses. The ion beam exhaustion can be easily intermitted repeatedly, and the shutters can be mirrors rotating synchronously with the on and off operation of the ion beam exhaustion.

VI. Future Work

The main objective of this paper is to present a new concept for reorbiting GEO debris objects by ion beam irradiation. These results are preliminary. Thus, future work must deal with each point of this paper in greater depth. In particular, the navigation, experimental evaluation of ion beam convergence, and experimental evaluation of the back-sputtering effects on the reorbiter are of great importance.

VII. Conclusion

We have proposed a new concept for a reorbiter to reorbit large GEO space debris. The concept is based on the idea of thrusting a debris object by irradiating it with an ion beam. Thus, reorbiting can be conducted without catching debris objects and therefore without the various sophisticated technologies required to catch them. A preliminary system study was conducted, which showed that the system is feasible but has several issues that must be addressed in future work. Ion trajectory analyses were conducted to determine grid dimensions and diameters appropriate for the ion engine irradiating debris objects.

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