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Orbital Debris Environment Model in the Geosynchronous Region

Toshiya Hanada* and Tetsuo Yasaka†
Kyushu University, Fukuoka 812-8581, Japan

The Kyushu University orbital debris environment model in the geosynchronous region has been updated to provide a better and more accurate description and understanding of orbital debris environment than the previous model. The main advantage of the present model over the previous model is to introduce more realistic breakup dispersion to estimate collision hazards to other spacecraft caused by breakup fragments. The results from the new model indicate that all aged satellites should move into a disposal orbit at the end of mission to reduce potential hazards to operational satellites. However, boosting up all aged satellites cannot preserve the current orbital environment sufficiently because debris fragments from explosions are still hazardous to operational satellites. The results also indicate that safekeeping procedures for all rocket bodies and spacecraft that remain in the geosynchronous region after completion of their mission are required as well as in low Earth orbit.

Nomenclature

A	=	cross-sectional area, m^2
A_i	=	cross-sectional area of objects in the category i, m^2
a	=	semimajor axis of the orbit, km
$C_{ij}(t)$	=	collision number between sets of objects in the categories i and j in the year t
C_o	=	collision probability of object o with the other objects, 1/year
D_{ki}	=	number density of object i in the annulus k, 1/km^3
e	=	eccentricity of the orbit
L	=	mission lifetime, year
$\ell(t)$	=	launch rate for geostationary satellites in the year t
m_e	=	ejecta mass, g
n	=	number of fragments produced by a breakup
P_{ko}	=	probability that object o will be in the cell k
$p(\theta)$	=	normalized probability that a given object will be at a given true anomaly θ
r	=	radius of the orbit, km
U_{oi}	=	relative velocity between objects o and i, km/s
V_k	=	volume of the cell k, km^3
$X_i(t)$	=	number of objects in the category i in the year t
x	=	fragment mass, g
$Y_i(t)$	=	number of breakup-damaged objects in the category i in the year t
$y(x)$	=	cumulative number of fragments mass x and greater
$\alpha_{ij}(t)$	=	normalized collision rate, defined as averaged collision probability between an object in the category i and another object in the category j, each having a unit cross-sectional area, 1/m^2/year
$\gamma_i(t)$	=	explosion probability for the category i in the year t, 1/year
Δt_k	=	time spent by a given object in the annulus k
$\Delta X_i(t)$	=	yearly increment of growth for the category i in the year t
$\delta(t)$	=	disposal fraction in the year t
δ_{ij}	=	Kronecker delta, which returns unity if $i = j$ but otherwise returns zero
θ	=	true anomaly, rad
μ	=	migration ratio, defined as a ratio of fragments that cross geostationary altitude to all fragments produced by a breakup of an object in a given category
$\rho(t)$	=	number of rocket bodies remaining in drift orbit in the year t

Introduction

SINCE the Space Age began, human beings have continued to extend their activities into space. Human beings have launched many rockets and inserted many satellites into many orbits. Such space activities have provided human beings with conveniences, new knowledge, and technologies. Space is limited in spatial extent, however. Now space debris represents a significant hazard to future space operations, with over 95% of the more than 8000 cataloged objects in orbit being debris.[1] Spent rocket bodies and inactive payloads occupy the most on-orbit population in weight and number. Particles from centimeters through millimeters in size, which are difficult to detect from ground facilities, are hazardous and can destroy space structures not sufficiently protected. The number of such particles is estimated to be on the order of millions. Such particles have been generated by on-orbit breakup events, including explosions and collisions. One breakup in space can create several hundred or more fragments that are potentially hazards to other spacecraft. The spatial density of such fragments can be predicted if mass and dispersion velocity distributions of fragments are given. Because a collision is a statistical phenomenon, a suitable breakup model enables us to simulate the future orbital debris environment. This simulation helps us to understand how objects accumulate in space so that we can perform mitigation studies to preserve the future orbital environment.

The orbital debris environment in low Earth orbit (LEO) has been investigated carefully by utilizing ground observation facilities, inspecting a variety of hardware retrieved from space and investigating hypervelocity impact test data. These collected data are available as a database and used to build LEO orbital debris environment models such as NASA Johnson Space Center Evolution Model (EVOLVE) and Orbital Debris Engineering Model and the ESA Meteoroid and Space Debris Terrestrial Environment Reference Model. Engineers engaged in space programs such as International Space Station can evaluate their protection design and determine the mitigation standards based on the database and the LEO orbital debris environment model. The orbital debris environment in geostationary Earth orbit (GEO), on the other hand, has not been investigated carefully because of technical limitations of ground observation facilities and the near impossibility of retrieving

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*Associate Professor, Department of Aeronautics and Astronautics, 10-1 Hakozaki 6-chome, Higashi-ku; toshi@aero.kyushu-u.ac.jp. Member AIAA.

†Professor, Department of Aeronautics and Astronautics, 10-1 Hakozaki 6-chome, Higashi-ku; yasaka@aero.kyushu-u.ac.jp. Member AIAA.

hardware from the geosynchronous region. To date, however, two explosions were reported officially. There is no atmospheric drag in GEO so that newly created fragments can stay in GEO without orbital decay. GEO orbital debris population grows continuously, and more satellites are to be expected to operate in GEO in the near future. Therefore, a GEO orbital debris environment model is needed to understand how objects accumulate in GEO and to analyze not only the present but also future GEO orbital debris environment.

To provide a better and more accurate description and understanding of the GEO orbital debris environment, including the physics and modes of GEO orbital debris production and the estimated future state of the environment under various assumptions and usage scenarios, a new orbital debris environment model named GEODEEM (GEO Orbital Debris Environment Evolution Model) has been developed based on the GEO_EVOL model,[2] the first model that forecasts the long-term on-orbit population growth in the geosynchronous region. The advantages of the GEODEEM model over the GEO_EVOL model include 1) introducing more realistic fragment dispersion to estimate the collision hazard of fragments to operational satellites, 2) adopting a new technique and three-dimensional spatial density bins to estimate the collision probability among objects, and 3) providing spatial density in the geosynchronous region. To describe how many fragments out of all breakup fragments reach the GEO altitude, the GEO_EVOL model defined a constant migration ratio. However, the migration ratio should be given in terms of breakup altitude and energy level. The new model describes the on-orbit population growth with respect to the associated energy level, assuming numbers of breakups at respective altitude bins based on the population in respective bins. To estimate the collision probability, the GEO_EVOL model used simple two-dimensional (radial and latitudinal) spatial density bins based on an assumption that object distribution along longitude is uniform. The details about the new technique are described in this paper.

The simulations have been conducted for two typical cases using the present model. One is the "no mitigation" case where all aged satellites will be left in original altitude without maneuvers to move into disposal orbits. The other is the "postmission disposal" case where all satellites will perform maneuvers to move into disposal orbits in accordance with the International Telecommunications Union (ITU) recommendation. The comparison between two cases will show that the postmission disposal practice will reduce collisions but that object population and flux on operational satellites still grow because of explosions. This paper will indicate not only the importance of postmission disposal but also the necessity of safekeeping procedures for all rocket bodies and spacecraft that remain in the geosynchronous region after completion of their mission as well as in LEO to mitigate the orbital debris population in the geosynchronous region.

Model Description

Object Categories

In the model presented, objects in the geosynchronous region are placed in several categories according to their orbital properties, mainly their orbital period and inclination,[2,3] as shown in Table 1. The first category is operational satellites. Operational satellites are controlled to stay within a narrow geostationary altitude bin. The second category is abandoned satellites. Abandoned satellites are normally aged satellites left in original altitude without maneuvers to move into disposal orbits. Their orbital inclination changes up to 15 deg with a period of 54 years, but their orbital period still maintains Earth revolution period. Therefore, abandoned satellites intersect the geostationary altitude bin where most operational satellites are controlled to stay twice a day. The third category is disposed satellites. Disposed satellites performed maneuvers to move into disposal orbits so that disposed satellites do not intersect the narrow geostationary altitude bin. Upper stages and apogee kick motors used to insert the payload into orbit are all placed in the fourth category, rocket bodies, without grouping according to their orbital properties as in satellites. This category is not assigned in the GEO_EVOL model.

Normally fragmentation debris is not geosynchronous, but some of these debris pass the narrow geostationary altitude bin where operational satellites are controlled to stay. All fragments created by a breakup among satellites in the categories operational satellites and abandoned satellites can pass geostationary orbit during each revolution. These fragments are placed in the fifth category. On the other hand, if the energy imparted at a breakup is small enough or ejection velocity vector is away from GEO fragments created by a breakup among satellites in the categories disposed satellites and/or rocket bodies do not reach geostationary altitude and then are grouped in the sixth category. Otherwise, those that reach geostationary altitude are grouped in the fifth category.

According to Ref. 4, produced with the ESA Database and Information System Characterizing Objects in Space (DISCOS), an object is considered as geostationary or near geostationary if it meets the following criteria: 1) eccentricity smaller than 0.1, 2) mean motion between 0.9 and 1.1 revolution per sidereal day, 3) inclination lower than 20 deg. As of 1 January 2000, 731 objects met these criteria. Sixty-five more objects are also known to be in this orbital region although no orbital elements are available in DISCOS. Thus the total number of objects in geosynchronous region is 796, including 174 rocket bodies placed in the fourth category and six debris (either operational debris or fragmentation debris) placed in the fifth or the sixth category depending on whether they cross GEO. Among 616 satellites, 547 satellites with recently updated orbital elements are categorized according to their orbital properties as defined in Table 1. Forty-one satellites, which are in a drift orbit with lower altitude, do not meet the definition shown in Table 1 but are included in disposed satellites. Among 69 satellites for which there were no orbital elements available during last six months, 24 satellites launched after 1990 are categorized as operational satellites, whereas other 45 satellites launched before 1990 are included in abandoned satellites.

Model Equations

Figure 1 illustrates the relationship among the just-mentioned six categories considering launch, postmission disposal, explosions, and collisions. Assuming that the mission lifetime of all operational satellites are the same and taking a year interval for the incremental time step, yearly increments of growth for the six categories can be expressed in simple equations as

$$\Delta X_1(t) = \ell(t) - \ell(t-L) - Y_1(t) \tag{1a}$$

$$\Delta X_2(t) = [1-\delta(t)]\ell(t-L) - Y_2(t) \tag{1b}$$

$$\Delta X_3(t) = \delta(t)\ell(t-L) - Y_3(t) \tag{1c}$$

$$\Delta X_4(t) = \rho(t) - Y_4(t) \tag{1d}$$

$$\Delta X_5(t) = \sum_{i=1}^{6}\left[\sum_{j=i}^{6}\mu_{ij}n_{ij}C_{ij}(t) + \mu_i n_i \gamma_i X_i(t)\right] \tag{1e}$$

$$\Delta X_6(t) = \sum_{i=1}^{6}\left[\sum_{j=i}^{6}(1-\mu_{ij})n_{ij}C_{ij}(t) + (1-\mu_i)n_i\gamma_i X_i(t)\right] \tag{1f}$$

Table 1 Object categories in GEODEEM and their definitions

Category	Object description	Period, min	Inclination, deg	GEO crossing?	Initial
1	Operational satellites	1434–1438	– 1	Yes	195
2	Abandoned satellites	1434–1438	1 –	Yes	225
3	Disposed satellites	1438–	——	No	197
4	Rocket bodies	——	——	No	174
5	Fragments crossing GEO altitude	——	——	Yes	2
6	Fragments staying above GEO	——	——	No	4

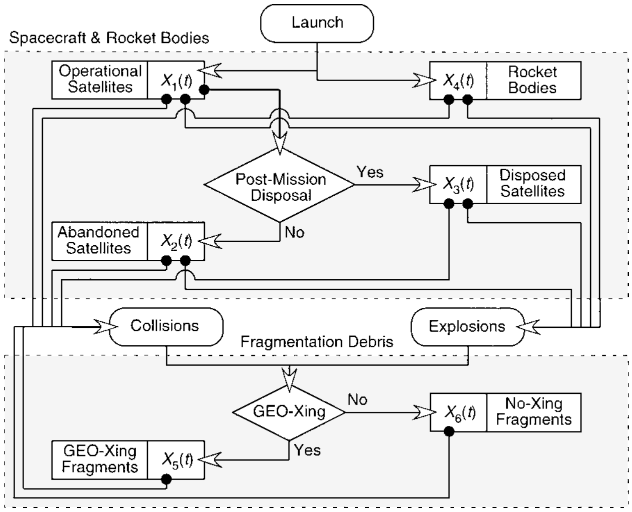


Fig. 1 Accumulation mechanism of objects in the geosynchronous region.

where

$$Y_i(t) = \sum_{j=1}^{6}(1 + \delta_{ij})C_{ij}(t) + \gamma_i X_i(t) \tag{2}$$

$$C_{ij}(t) = \begin{cases} \alpha_{ij} X_i(t) X_j(t)(A_i + A_j) & \text{if} \quad i \neq j \\ \alpha_{ij} X_i(t)[X_i(t) - 1]A_i & \text{if} \quad i = j \end{cases} \tag{3}$$

Breakup Model

Estimating collision probability between satellites and fragmentation debris requires a breakup model that can describe a breakup process quantitatively. The necessary quantities are number, mass, and velocity distributions of breakup fragments. These properties of fragments created by an on-orbit breakup have been predicted by using those acquired from the laboratory tests and the on-orbit breakup events, but they include some uncertainties. In the present model, according to the Yasaka and Oda breakup model,[2] the incremental velocities of fragments are statistically adjusted to satisfy momentum and energy conservation laws, whereas the fragment mass distribution is separately given by an empirical exponential form. To describe a collision in GEO that would be characterized by relatively low energy compared to that in LEO, we use the equation

$$y(x) = 0.78(x/m_e)^{-0.68} \tag{4a}$$

obtained by low-velocity impact experiments.[5,6] For an explosion we use the equation

$$y(x) = 0.45(x/m_e)^{-0.75} \tag{4b}$$

as well as Yasaka and Oda. The mass and cross-sectional area of the fragment debris are related through the relationship

$$m = \begin{cases} 62.013A^{1.13}, & A \geq 8.04 \times 10^{-5} \\ 2030.33A^{1.5}, & A < 8.04 \times 10^{-5} \end{cases} \tag{5}$$

provided by Reynolds.[7] From all cataloged objects in the geosynchronous region, an average mass of spacecraft is 1200 kg and that of rocket bodies is 2000 kg. We estimate the number of fragments greater than 10 cm in size, which would be potentially hazards to other spacecraft, by combining Eqs. (4) and (5) and then provide Table 2.

Figure 2 demonstrates debris fragment flux from a near-synchronous US TITAN 3C TRANSTAGE explosion. The solid line represents the result from the NASA EVOLVE 4.0 model, and the broken lines represent the results from the present model with the associated breakup energies of 1 and 10 J/g. The EVOLVE model is based on actual observed on-orbit breakup data in LEO and creates a thousand or more fragments greater than 1 mm in size. For both models, however, largest 500 fragments are sorted out to estimate the flux. As Fig. 2 illustrates, the flux of fragments peaks at the breakup altitude, and it is on the order of 10^{-9}/m^2/year at that altitude. The flux decreases away from the breakup altitude. However, debris fragments can reach as much as a thousand kilometers above or below the breakup altitude. Figure 2 indicates that the present model would obtain a complete agreement with the EVOLVE model for a breakup energy between 1 and 10 J/g.

Table 2 Number of 10-cm-or-greater fragments created by a breakup

Breakup type	Spacecraft	Rocket body
Explosion	252	370
Collision with spacecraft	388	472
Collision with rocket body	472	549
Collision with fragment	242	343

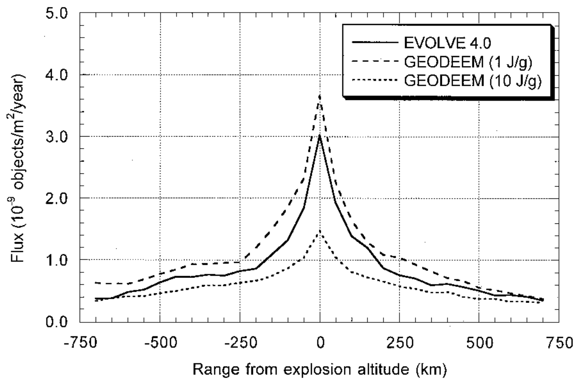


Fig. 2 Debris fragment flux from a near-synchronous US TITAN TRANSTAGE explosion.

Disposal Fraction

ITU and the international community recommend boosting spacecraft above geostationary altitude at the end of mission. According to Loftus and Johnson,[8] more than 160 geostationary satellites had been placed in the disposal orbits to date. The disposal perigee altitude, recommended by Inter-Agency Space Debris Coordination Committee, is 235 km + [1000 × reflectivity coefficient × average cross-sectional area (m^2)/mass (kg)] above nominal geostationary altitude.[9] A recent study of geostationary spacecraft retired during 1997–1998 found that only about one-fourth of the spacecraft were placed in disposal orbits satisfying the recommendation.[10]

In this paper disposal fraction is assumed 0%, meaning that none of satellites performs maneuvers to move into disposal orbits at the end of mission, or 100%, meaning that all satellites do. The disposal orbits is assumed a circular orbit with 300 km above nominal geostationary altitude.

Explosion Probability

Summing up the time that each spacecraft spent in orbit since its launch gives 8200 years, while a geostationary spacecraft EKRAN 2 (International Designator 1977-092A) exploded on 25 June 1978. Dividing an explosion by the sum makes an annual rate of explosion of 1.2×10^{-4} per spacecraft. Applying the same method to rocket bodies with a near-synchronous US TITAN 3C TRANSTAGE (1968-081E) explosion on 21 February 1992 provides an annual explosion rate of 4.1×10^{-4} per rocket body.

Collision Probability

According to Chobotov[11] or Reynolds et al.,[12] collision probability of an object with other objects is the product of cross-sectional area, spatial density, time, and relative velocity between the colliding objects. Based on this relationship and an assumption that object distribution along longitude is uniform, Yasaka and Ishii[13] considered an annulus (see Fig. 3), whose cross-sectional area is rectangle

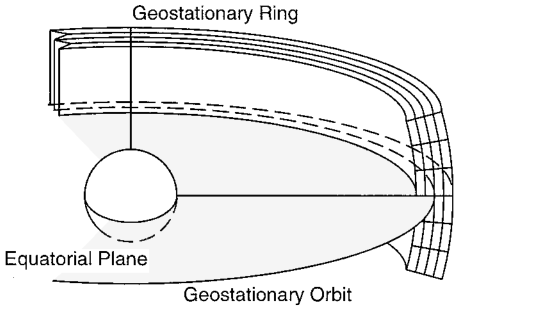


Fig. 3 Geostationary ring to estimate collision probability.

with some lengths in latitude and radial directions, and they adopted the equation

$$C_o = \sum_k \Delta t_k \sum_{i=1}^{N} AU_{\mathrm{oi}} D_{\mathrm{ki}} \tag{6}$$

to estimate the collision probability. The normalized collision rates in the previous model were evaluated by the preceding technique. However, real objects in and near GEO are not uniformly distributed along longitude. The annuli are divided into cells to consider this fact in the present model. The new method considers a cell and estimates the probabilities that colliding objects will be in the cell with the equation

$$p(\theta)\,\mathrm{d}\theta = \frac{r^2}{2\pi a^2\sqrt{1-e^2}}\,\mathrm{d}\theta \tag{7}$$

Replacing Δt_k in Eq. (6) by P_{ko} and evaluating D_{ki} from P_{ki} and V_k, then we can obtain the equation

$$C_o = \sum_k P_{\mathrm{ko}} \sum_{i=1}^{N} AU_{\mathrm{oi}} \frac{P_{\mathrm{ki}}}{V_k} \tag{8}$$

The normalized collision rates in the present model are evaluated by Eq. (8). The cell has a volume with a length of 50 km in radial direction and angles of 1 deg each in the latitudinal and longitudinal directions.

The collision probability among satellites and/or rocket bodies of which current orbital elements are available can be estimated by the just-mentioned technique. Carrying out evaluations of the collision probability between combinations of any two categories, we can obtain Table 3. Table 3 indicates higher collision probabilities than those evaluated by Yasaka and Ishii[13] because the number of objects in the geosynchronous region increased by a factor of three.

Although operational satellites must be controlled by periodic station-keeping maneuvers to stay within a narrow geostationary altitude bin, the collision probability among the operational satellites is not zero. The operational satellites can drift under the effects of perturbing forces until they perform station-keeping maneuvers so that finite values of relative velocities do exist among them. In addition to the preceding reason, the classification defined in Table 1 allows the operational satellites a longitudinal drift with a rate of 0.5 deg per day and an orbital inclination less than 1.0 deg. Therefore, the collision probability among the operational satellites is not zero.

Normalized collision rates for $\alpha_{ij} (i = 1, \ldots, 4, j = i, \ldots, 4)$ in Eq. (3) are set as shown in Table 4 by averaging the collision probability shown in Table 3 with the objects numbers. Some of them are smaller, but some of them are larger compared with those evaluated by Yasaka and Ishii.[13] However, most of them are on the same order magnitude as those in the previous model.

The collision probability of breakup fragments with each group can be estimated from the debris fragment flux shown in Fig. 2 and each group's spatial density shown in Fig. 4. It can be expected from these figures that the collision rate of breakup fragments with operational or abandoned satellites always peak at the nominal geostationary altitude without regards to the breakup altitude. It can be also expected that the peak level decreases as the breakup altitude gets away from the nominal geostationary altitude. However, it is

Table 3 Collision probability between combinations of any two object categories

Categories	1	2	3	4
1	4.361×10^{-7}	——	——	——
2	1.160×10^{-6}	4.592×10^{-7}	——	——
3	8.980×10^{-9}	2.651×10^{-8}	4.015×10^{-8}	——
4	9.691×10^{-8}	9.561×10^{-8}	3.389×10^{-8}	2.643×10^{-8}

Table 4 Normalized collision rates set in GEODEEM ($\times 10^{-11}$/m^2 per year)

Category	1	2	3	4
1	3.000	——	——	——
2	3.769	2.850	——	——
3	0.027	0.075	0.208	——
4	0.361	0.338	0.125	0.216
5	0.040	0.708	0.105	0.233
6	——	——	0.057	0.150

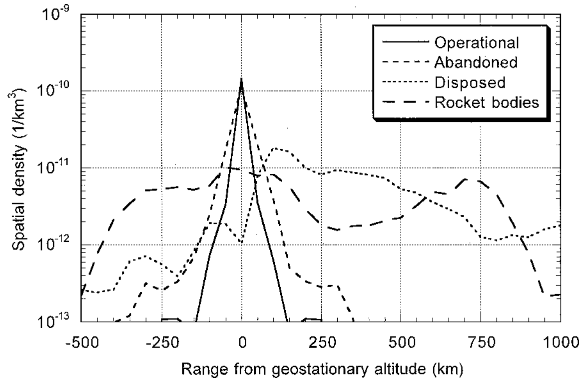


Fig. 4 Spatial density in the geosynchronous region.

difficult to figure out the results regarding disposed satellites and rocket bodies as well. This difficulty is because, as Fig. 4 illustrates, disposed satellites and rocket bodies are distributed within a wider altitude range than operational or abandoned satellites are.

As just mentioned, the collision probability with breakup fragments varies with breakup conditions. Therefore, it is difficult to keep each normalized collision rate a single value over the projection period as in the previous model. In addition, the migration ratio cannot be kept in constant. This difficulty is because we cannot assume how many breakups occur, when and where they occur, and how much energy they release. A possible assumption is that breakup number at each altitude bin is proportional to on-orbit population. Therefore, breakup altitude for each breakup event can be estimated randomly, under the constraint of this assumption. Fragments are being created according to the Yasaka and Oda model with an associated energy level and the chosen breakup altitude and then are added to the fifth or the sixth category depending on whether they reach GEO or not to update the normalized collision rates in the next time interval. The normalized collision rates of breakup fragments with each group shown in Table 4 are initial values estimated from the known population. However, the collision probability among debris fragments is neglected because their cross-sectional areas are assumed two orders magnitude lower than those of satellites are or rocket bodies are.

Annual Launch Rate

Figure 5 shows annual rate of launch into geostationary altitude in the past. Future launch traffic in the current version of the NASA EVOLVE model recycles that of the last 8 years. The authors applied the same rules as in the EVOLVE model to the present model. The launch traffic in the present model is assumed that of 1992 through 1999 cycled over the projection period beginning in the year 2000.

Simulations

Because the GEODEEM model is a Monte Carlo simulation model, the following results have been derived from the average of 10 Monte Carlo iterations in order to obtain reasonable statistics. The most important data derived from these simulations are the following: 1) number of objects passing the nominal geostationary altitude, 2) cross-sectional area flux on an operational satellite, and 3) number of breakups including both of explosions and collisions. In the following, the just-mentioned data will be presented for two typical cases: the "no mitigation" case and the "postmission disposal (PMD)" case. Each satellite is assumed to have a mission lifetime of 10 years, and for the postmission disposal case if end of life is reached after the 10th year in the projection period the satellite is moved to within 10 km of a circular orbit with 300 km above GEO. It is assumed that an explosion will release energy of 1 J/g, whereas impact energy will be estimated from the flux and spatial density. The projection period is 100 years.

Figure 6 demonstrates population growth of objects greater than 10 cm over 100 years with details of contributions of each category to the population after 100 years. There is no difference between the two cases in the population growth because few collisions occurred over 100 years, as will be mentioned later. However, we can observe the difference in the details of contributions of each category. The fragments created by breakups are highest in number for both cases, but the ratio of fragments crossing geostationary altitude (referred as X_5) to the total number of fragments ($X_5 + X_6$) is quite different. The ratio is 70% for the no mitigation case and 60% for the postmission disposal case. The reason is because all fragments released from abandoned satellites pass the geostationary altitude, whereas many fragments released from disposed satellites do not reach the geostationary altitude as shown in Fig. 2.

Figure 7 demonstrates cross-sectional area flux on an operational satellite over 100 years with details of contributions of each category to the flux after 100 years. The flux for the PMD case is less than that for the no mitigation case by a factor of three. As illustrated in the details of contributions of each category in Fig. 7, the contribution of satellites to the flux for the PMD case is much less than that for the no mitigation case. For the PMD case all aged satellites performed maneuvers to move into a circular orbit with 300 km above geostationary altitude so that the satellites do not interfere with any operational satellites. Besides, even if the disposed satellite breaks up for any reason the chances of operational satellites being hit by fragment debris are moderately reduced, compared to the chances if the breakup occurs at nominal geostationary altitude.

Table 5 provides the debris fragment productions over 10 Monte Carlo runs over 100 years and indicates that that debris fragments were mainly created by explosions. Over 40 satellites and rocket bodies exploded over 100 years, whereas few collisions occurred. However, even if over 40 explosions occurred Table 5 indicates that PMD reduced collisions in the geosynchronous region. The no mitigation case got 14 collisions over 10 Monte Carlo runs, whereas the PMD case got only two collisions. The main difference in the collision activity between two cases is that no collisions among abandoned satellites are observed as shown in Fig. 8. Besides, Fig. 8

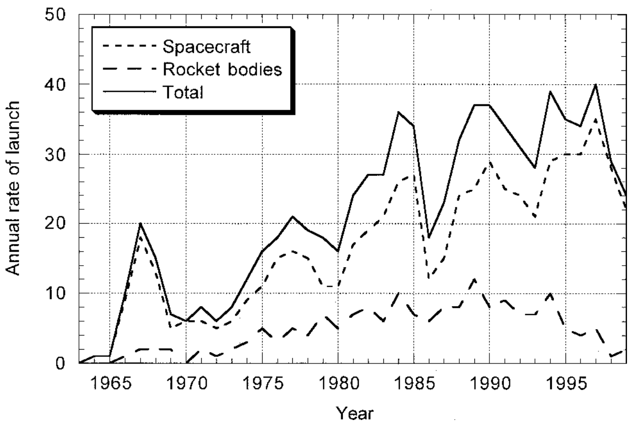


Fig. 5 Annual rate of launch into geosynchronous region.

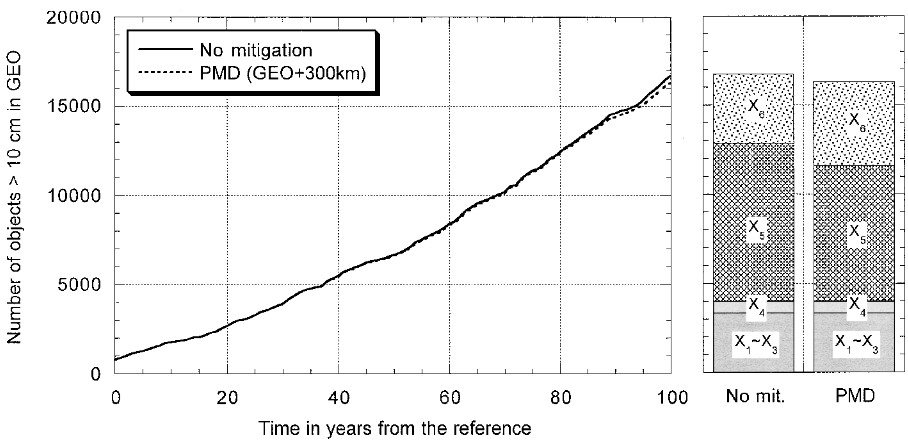


Fig. 6 Population growth of objects greater than 10 cm in size.

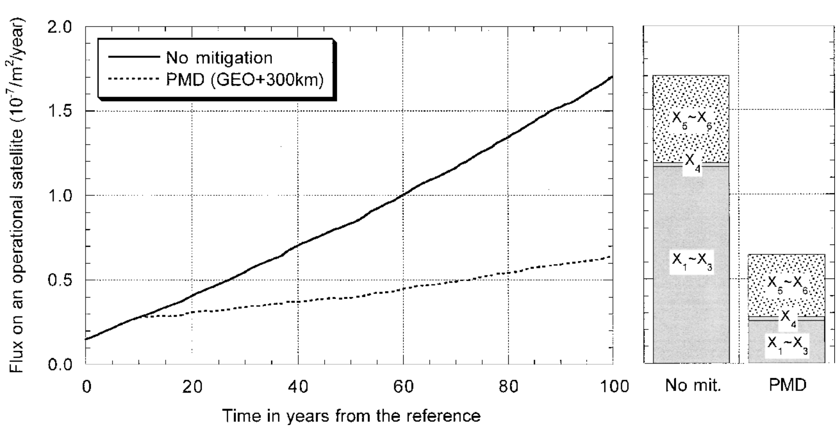
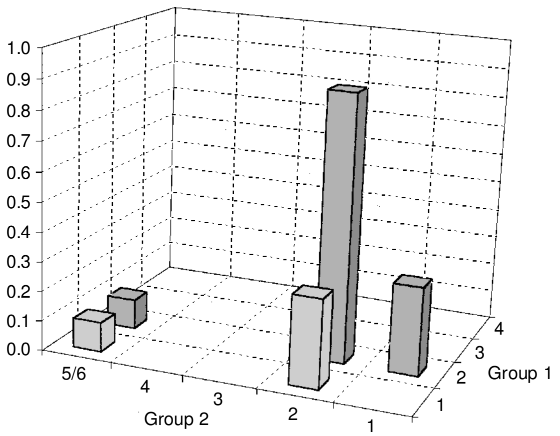


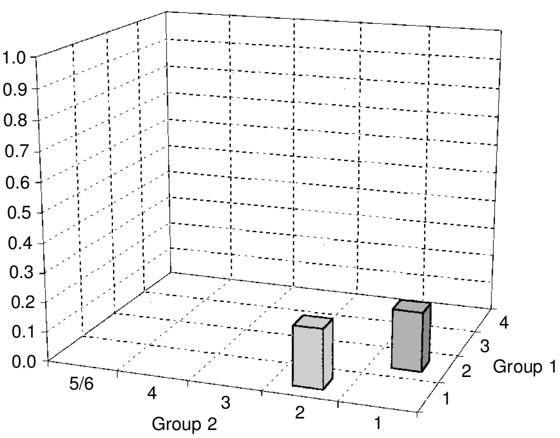
Fig. 7 Cross-sectional area flux on an operational satellite.

Table 5 Fragmentation debris productions over 10 Monte Carlo runs after 100 years (standard deviation in parentheses)

Breakup type	No mitigation	Postmission disposal
Explosion (spacecraft)	24.9 (5.7)	24.9 (5.7)
Explosion (rocket bodies)	16.0 (3.3)	16.1 (3.0)
Collision	1.4 (1.4)	0.2 (0.4)



No mitigation



Postmission disposal

Fig. 8 Collision activities within 100 years.

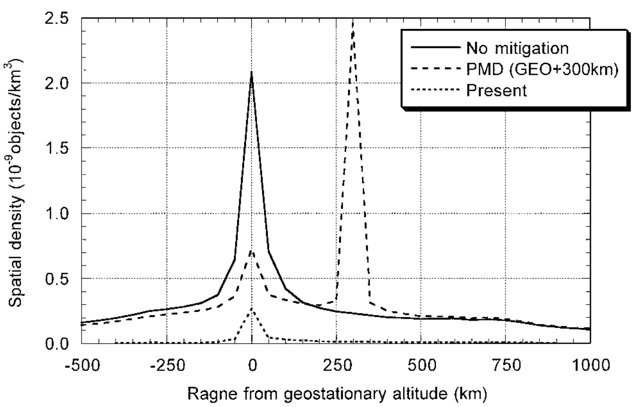


Fig. 9 Spatial density after 100 years.

shows that the no mitigation case got four operational satellites damaged by collisions, whereas the PMD case got two damaged operational satellites.

Figure 9 illustrates the spatial density in the geosynchronous region after 100 years for both cases with the current spatial density level represented by a dotted line. For the no mitigation case the spatial density at the nominal geostationary altitude increases by a factor of eight, compared to the preset level. In addition, the altitude range whose spatial density is greater than the present level broadens from −250 to +200 km after 100 years. Although all aged satellites performed maneuvers to move into disposal orbits for the PMD case, the spatial density at the nominal geostationary altitude increases by a factor of three. This increase in spatial density is because many fragments can reach the nominal geostationary altitude even if a satellite breaks up at higher or lower altitude range. We should consider the orbital debris environment in the disposal region. Spatial density at the disposal altitude bin increases and becomes greater than that at the nominal geostationary altitude. However, the disposal altitudes in actual procedure will differ substantially, and the peak will be much leveled off than that shown in Fig. 9, where all disposal altitude are assumed identical.

Conclusions

A new orbital debris environment model GEODEEM has been developed based on the GEO_EVOL model for forecasting on-orbit population growth in the geosynchronous region. The results from the new model indicate the direction of our efforts for preserving geostationary orbital environment. One thing must be postmission disposal as ITU and the international communities have recommended. Postmission disposal greatly reduces the cross-sectional area flux on operational satellites by elimination of aged satellites. At the same time the cross-sectional area flux of debris fragments on operational satellites is also effectively reduced because substantial portion of fragments will stay outside of GEO without interactions to operational satellites, after their creation by an accidental breakup in a disposal altitude. However, the cross-sectional area flux of debris fragments on operational satellites is still increasing, and we cannot ignore this. We should consider how we could reduce the debris fragments themselves to reduce their flux. From suspected causes of historical breakups, we could do something to reduce it. For example, explosions considered herein are battery-related events and residual propellants. Safekeeping procedures for all rocket bodies and spacecraft that remain in the geosynchronous region after completion of their mission, as well as in LEO, are required.

The present model as well as the GEO_EVOL model depends strongly on a given breakup model. The authors have adopted the Yasaka and Oda breakup model that satisfies the basic physical and energy and momentum conservation laws. Although this model is easy to be applied to any simulations, without dependence on elaborate observation data, it has not been validated against actual breakup phenomena in GEO. Consequences of actual breakup in space include many uncertainties. At the present various mathematical models have been built to describe breakup processes in space. The authors plan to investigate how these breakup model effects on the orbital debris environment model.

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D. L. Cooke
Associate Editor