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BREAKUP, COLLISION AND POPULATIN GROWTH IN GEOSTATIONARY ORBIT

Tetsuo Yasaka and Shun'ichi Oda

NTT Radio Communication Systems Laboratory
1-2356 Take, Yokosuka

1. Introduction

Interactions among orbiting objects in Low Earth Orbit was investigated in Europe by Eichler, et al 1)and in the United States by Kessler 2), revealing that uncontrolled growth of space debris will come upon reaching a certain level of spatial density even at the absence of further launch. The critical density is the situation at which debris creation balances with elimination by the effect of thin atmosphere. Therefore, the critical density is a function of altitude.

Due to lack of effective natural forces to decelerate orbital objects from the geostationary altitude, the number of objects in this region will not decrease, but will accumulate at a rate no less than the launch rate. Recent accumulation rate is about 25 pieces per year and is increasing roughly linearly each year. Controlled satellites are located within a very narrow ring on the equatorial plane at the geostationary altitude. Spatial density within the ring is very high and if local clustering at several busy longitudes is considered, the peak density is found to be higher by orders of magnitude. Defunct satellites abandoned in this ring do not remain in the ring any more, while maintaining the altitude and thus the orbital period. These abandoned objects travel along north-south direction, traversing through the dense ring twice a day. The maximum speed of the traverse is 800m/s. Possibility of collision between active satellites and abandoned objects has been an issue being investigated by many scientists.

We have a knowledge that at least two explosional breakups have taken place in the vicinity of the geostationary orbit. One is a communication satellite launched by former Soviet Union, and the other is a separated final stage launched by US. Since there are many uncontrollable objects at the geostationary altitude with various kinds of energy resources, the possibility of further explosions cannot be ignored.

Breakup occurred in this region, either collisional or explosional, will produce numerous smaller fragments, which will also interact with other operational or defunct satellites. It has been reported earlier that those fragments cross the breakup altitude at least once during a revolution, and that this effect is very long lasting even with the presence of solar pressure perturbation.

A program "GEO-Evol" was developed to simulate population growth. Annual launch rate, rate of satellite re-orbiting, collision and explosion rates are considered to determine object population in this altitude.

2. Debris Environment Evolution Model

In dealing with debris environment modeling in the geostationary region, several software packages have been developed in NTT Radio Communication Systems Laboratory. As an direct extension to the existing software systems, "GEO-Evol" was developed to simulate a long term evolution of the environment, as shown in Fig. 1. "OrbGen" generates orbits of objects contained in the "Orbit Data" file, in the format of either Two-Line-Element or Satellite Situation Report. "V-File" is a general

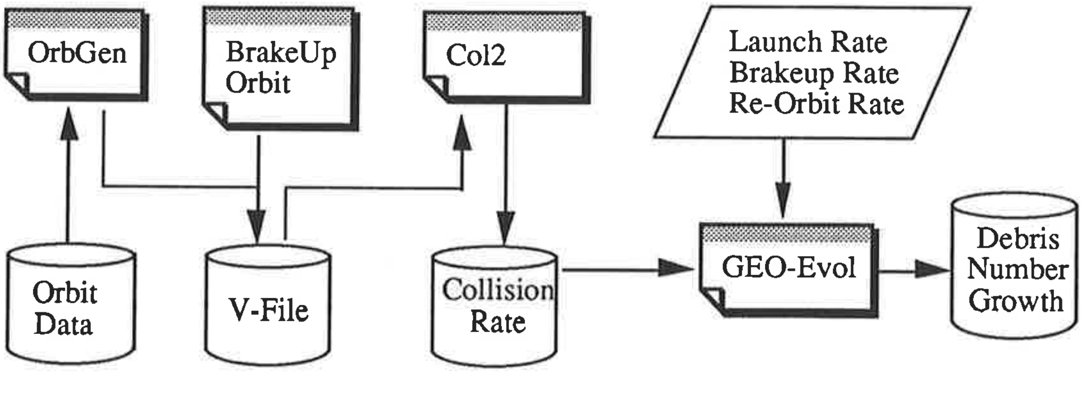

Fig. 1. Software Package System for GEO Debris Environment Simulation

purpose file. It contains information on position and velocity vector of each object at prescribed time interval which generally is 1/100 or 1/300 of a period. "BrakeUpOrbit" simulates breakups, either collisional or explosional, generates orbit elements of all fragments and outputs a "V-File". Collision rate between any two sets of objects are analyzed by "Col2", with a reference to V-File data. "V-File" is also referred to by a separate package to calculate spatial density distribution. All packages, including "GEO-Evol", are coded in Pascal language and run on standard Macintosh personal computers.

The purpose and function of "GEO-Evol" is to estimate population in geostationary orbit and its vicinity in the future, based on the present situation and projected space activities. Objects are classified according to their orbit properties, mainly altitude/period and inclination. The variable $X_1(t)$ is the number of operational satellites which are controlled within the narrow geostationary ring. $X_2(t)$ is the number of objects in inclined geosynchronous orbits. Each of them has a circular orbit of geostationary altitude, with an inclination in excess of common operational angle of one degree. These objects represent dead satellites which are abandoned in its operational orbit after its useful life. $X_3(t)$ represents the number of objects in higher orbits which do not interfere with the geostationary orbit. Fragments produced by breakups are normally in elliptical orbits. $X_4(t)$ is the number of those fragments that cross the geostationary orbit, and $X_5(t)$ is the number that do not.

The increment of these variables are expressed as:

$$\Delta X_1(t) = R(t) - R(t\text{-}L) - Y_1$$
$$\Delta X_2(t) = (1\text{-}p)R(t\text{-}L) - Y_2$$
$$\Delta X_3(t) = pR(t\text{-}L) - Y_3$$
$$\Delta X_4(t) = n_1 Y_1 + n_2 Y_2 + \beta n_3 Y_3$$
$$\Delta X_5(t) = (1\text{-}\beta) n_3 Y_3$$

where $R(t)$ is the launch rate at time t, L is the length of operational life, p is the rate of re-orbit maneuver at satellite's end of life, β is the rate of fragments which cross the geostationary altitude, n_1,n_2 and n_3 are the numbers of fragments produced by a breakup in geostationary, inclined synchronous and higher orbits, respectively, Y_1, Y_2 and Y_3 are breakup rates of objects in each of three classes of orbits.

A breakup rate is a sum of collisional and explosional rates as:

$$Y_i = \sum_{j=1}^{5} C_{ij} + \gamma X_i(t)$$

$$C_{ij} = \alpha_{ij} X_i X_j (A_i + A_j)$$

where C_{ij} is a collision rate between sets of objects in orbit class i and j, γ is an explosion rate of orbiting objects, A_i, A_j are cross-sectional areas of objects and α_{ij} is a normalized collision rate between one object in orbit i and another in j.

In actual calculation, Y_i's should take integer values. Monte Carlo technique is introduced to identify whether either collisional breakup or explosional breakup occur at each instance depending upon the values of C_{ij} and γX_i which are generally very small numbers compared to unity.

Table 1. Normalized Collision Rates
col/m2/year

	X1	X2	X3	X4
X1	4.0E-11	4.8E-11	-	3.2E-11
X2	4.8E-11	4.1E-12	-	5.0E-12
X3	-	-	7.3E-13	-
X4	3.2E-11	5.0E-12	-	-
X5	-	-	-	-

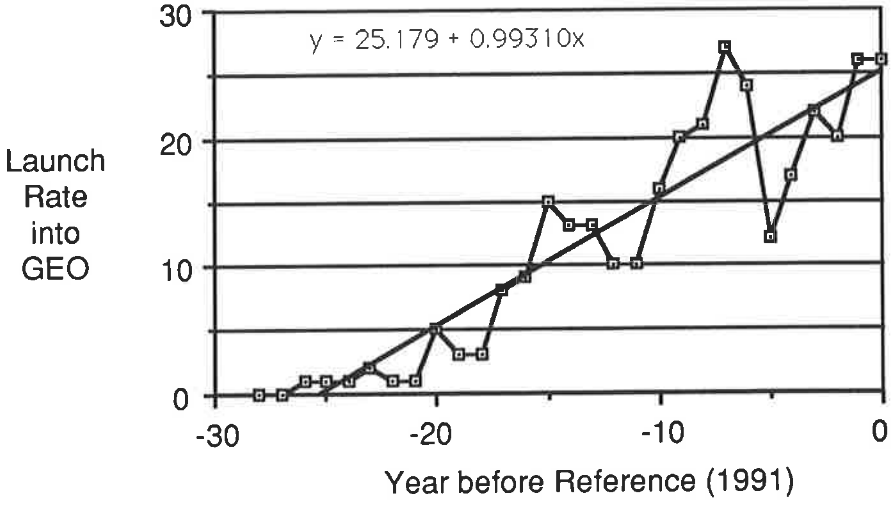

Fig. 2. Launch Rate Record

Launch Rate

The launch rate $R(t)$ in the future is an important parameter for long term prediction. Fig. 2 shows a plot of past launches. This includes 112 controlled stationary satellites, 146 objects in inclined geosynchronous orbits and 69 objects which have been re-otbited into higher orbits. This does not include 45 satellites whose orbit elements are not any more available. The launch rate increases almost linearly, with an annual increment of one. In the present simulation $R(t)$ starts from 25 until it reaches the maximum launch rate which is assumed to be 100.

Normalized Collision Rates

Collision rates are given in various reference. Reference 3 provides normalized rates among controlled GEO satellites (X_1), objects in inclined geosynchronous orbits (X_2), objects in higher orbits (X_3) and fragments created by a collision in GEO (X_4). Although the reference gives finite collision rates between the objects in higher orbits and geosynchronous objects, these interferences are neglected in this simulation because of the definition here and rather small number by magnitudes. Another reference 4 gives interaction between fragments created in higher orbit and geosynchronous objects. This effect is taken care of by the factor β, which is assumed as 0.5. Table 1. shows the values of these coefficients α_{ij} used in the present simulation.

3. Simulated Results

Simulation is conducted to find out GEO debris environment evolution for 200 years. Typical results obtained are shown in Fig. 3, in which re-orbit ratio and explosion ratio are main parameters. Number of fragments produced by a breakup, either collisional or explosion is assumed 300, and cross sectional areas of satellites or objects before and after are 50 m^2 and 0.1m^2, respectively.

If the re-orbit ratio is zero, which means that all satellites are abandoned in the geostationary altitude after its mission end, the number of objects left in inclined geosynchronous orbit (X_2) increases very rapidly. In fact, the rate of increase is the same as the launch rate whose maximum is assumed 100. However, it is rather clear that the explosion rate (γ) has a dominant effect on the growth of fragment number and the re-orbit ratio has a secondary effect. At the rate of 1e-4 explosions per year per object, the fragment number will become far greater than intact object number. By the end of the 21st century, the fragment number exceeds 10,000. However, if the explosion rate γ is below 1e-5 per year per piece, the re-orbit ratio has a strong influence on the fragment number.

What happens if the launch rate drops down to zero after some time? Fig. 4 is an example assuming $R(t) = 0$ for $t > 50$. At a high explosion rate, the fragment number keeps growing, while, the number is kept moderate at lower explosion rate. In these examples, moderate satellite size (50m^2) and rather small fragment size (0.1m^2) are assumed. Fig. 5 shows the growth with larger satellites and fragments. The growth is simply proportional to these sizes.

To have a numerical idea, breakup numbers and numbers of satellites damaged during operation are listed in Table 2. The third and fourth columns show breakups of intact objects colliding with another satellite and fragment. The numbers on the left of "/" show the number in the first 100 years, and the

Table 2. Breakup Numbers in 100 / 200 Years

Exp. Rate	Re-Orb. Rate	Col. Sat-Sat	Col. Frag	Explosions	Op. Sat. Damaged
0	1	0 / 1	0 / 0	0 / 0	0 / 1
	0.5	1 / 7	0 / 1	0 / 0	0 / 4
	0	1 / 9	0 / 0	0 / 0	0 / 4
1e-6	1	0 / 1	0 / 0	1 / 2	0 / 1
	0.5	0 / 7	0 / 1	1 / 3	0 / 4
	0	1 / 9	0 / 1	0 / 2	0 / 4
1e-5	1	0 / 2	0 / 0	2 / 17	0 / 1
	0.5	1 / 7	0 / 1	3 / 11	0 / 4
	0	1 / 9	0 / 2	4 / 15	0 / 4
1e-4	1	0 / 2	0 / 3	30 /140	5 / 15
	0.5	1 / 7	0 / 6	30 /145	5 / 18
	0	1 / 9	0 / 10	27 /140	5 / 18

$A_i = 50$ (i=1,2,3), = 0.1 (i=4,5)   Launch Rate: 100 Maximum ones on the right show the numbers during 200 years.

4. Conclusions and Discussions

Model Refinement

The content of "GEO-Evol" is rather too simple to handle actual environment dynamics. The first requirement is to model more appropriately the effect of fragments created in elevated altitude bands. Since many fragments have orbits which come as low as a few thousand km from the original altitude at which the breakup takes place, and since all fragments are sensitive to solar radiation pressure which alters eccentricity of the orbit, the interaction of these with other intact objects will go through very complicated procedures. In the present model, this interaction is taken care of only by a constant migration factor β.

The second refinement required is the evaluation of interaction of objects in higher orbits, both among themselves and with other objects in normal GEO altitude. At present many objects have elliptical orbits whose perigee altitudes are below GEO. Some objects may end up with a rather low perigee after re-orbiting maneuver, and subsequent orbit perturbation may cause interaction with operational satellites. In the present model, all these possible interactions are not considered.

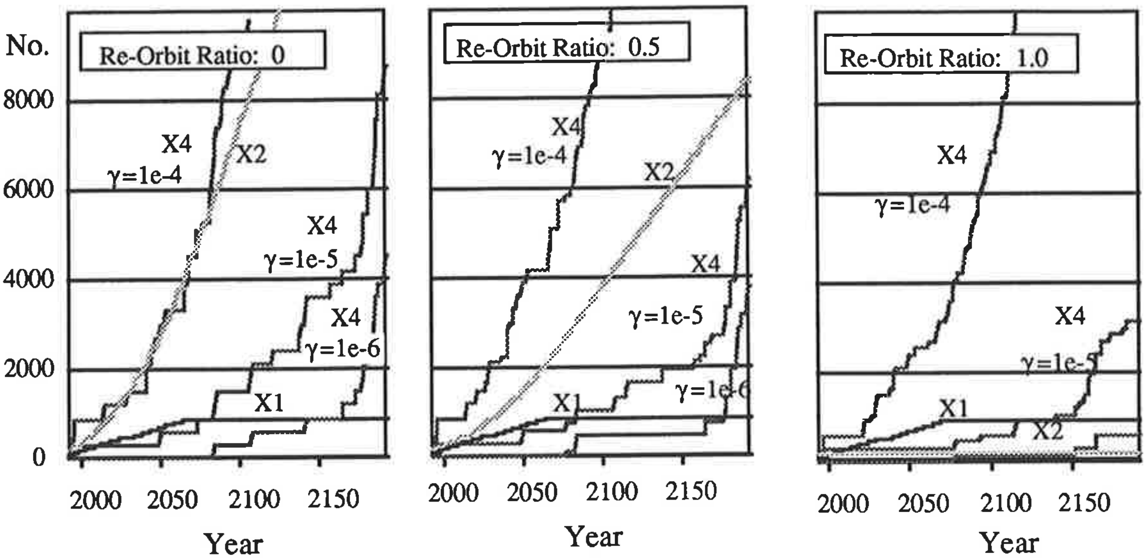

Fig. 3. Object Number Evolution in GEO
ni = 300, Ai = 50 (i=1,2,3), =0.1 (i=4,5)

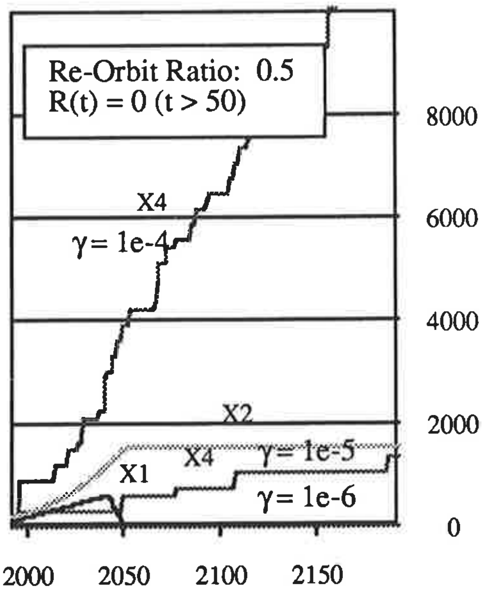

Fig. 4. Effect of Launch Rate Decrease

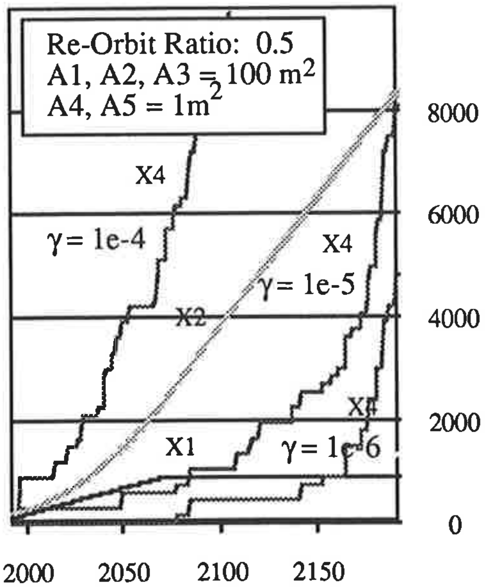

Fig. 5. Effect of Satellite Size Increase.

Number of fragments created by a breakup will differ considerably, depending on the nature of the breakup. Size distribution of the fragments and satellite size which will grow larger in the future will have to be considered more carefully.

With all these refinements needed in more realistic simulation, however, the basic concluding results obtained by the present simple model will be kept valid. The degrees of influence by the above factors on the environment are smaller by one to two orders of magnitudes than the factors considered here.

Fragment Creation

Explosion rate in GEO is the most important factor in controlling debris environment. Among 500 pieces of object launched and accumulated during past 29 years in the vicinity of GEO, at least 2 pieces have exploded. Accumulated stay time of these objects is 5000 year-piece, or the average stay time of 500 pieces of object is 10 years. A simple estimate of explosion rate, therefore, is 2/5000, or 4 x 10-4 per piece per year. An urgent technical issue which has become evident is reduction of the explosion possibility, by perhaps two orders of magnitude. It is perhaps not valid to assume a same explosion rate of an object for nearly 200 years. For instance, a propulsion related explosion will become rare after a few tens of years, during which residual propellant perhaps is exhausted by slow leaks caused by degradation of seal materials. Material degradation in space will in turn release components and flakes and then cause disintegration of the satellite in gradual manner. It is not clear at all now about the rate of the gradual disintegration. The explosion rate in the present model is understood partially to represent this disintegration possibility.

Environment Protection

The most important conclusion of this work is that the explosion rate must be reduced at lease two orders of magnitude, and then the re-orbit maneuver must be conducted at full effort. The explosion rate reduction can be attained by dis-energizing any spent satellites and propulsion modules. Residual propellant venting is the most commonly conducted measure in low earth orbit rocket bodies. The similar procedures should be similarly effective to objects in geostationary altitude. Careful examination of battery design will reduce accidental explosion of batteries inside spacecrafts. By way of these two dis-energizing methods combined, the explosion rate is expected, rather easily, to be reduced by a few orders of magnitudes.

Once the explosions are controlled, re-orbiting maneuvers will be the controlling factor to the environment evolution. A concern will remain as to the excessive accumulation of objects and accidental collisions in the higher "graveyard" orbit. Because the collision rate in this region is about two orders of magnitude less than that in the nominal geostationary altitude, the possibility of the environment contamination by fragments is small at least in next 200 years. However, higher orbit raising than present practice of about 300 km is desired. This will relax spatial density in the "graveyard" orbit, and eliminates the rate of fragment migration into geostationary altitude in case of accidental explosion or debris release due to material degradation. The re-orbiting maneuver generally signifies propellant exhaustion, as well.

References

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