JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 29, No. 1, January-February 1992

Catalog Growth Rate Study (Hazard Analyzed in Geosynchronous Transfer Orbits)

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Ninety-eight satellite breakup events have resulted in 7458 trackable objects being cataloged by the Space Surveillance Network (SSN), of which 2940 are still in orbit. The vast majority (96%) of this debris resides in altitudes with orbital periods below 127 min. The remnants from these fragmentations now account for 44% of the total cataloged population (6567) and 57% of the low-Earth-orbit (LEO) population. The accurate assessment of the effects of breakups can only be performed by looking at all aspects of on-orbit population growth. The total population is divided into lower LEO (LEO1), upper LEO (LEO2), high-Earth-orbit (HEO), and geosynchronous orbit (GEO) regimes. Most of these subsets of the total population have individually exhibited linear growth rates combining to result in a catalog population increase of 240/yr. The debris generated by satellite breakups is the most variable portion of the population due to the randomly spaced large additions by these events and cyclic cleansing by solar activity. Cessation of fragmentations can significantly improve our LEO environment as it already has in the 1000-2000 km (LEO2) region. An analysis of objects in geosynchronous transfer orbits (GTO) shows that there is a great dependence on the inclination and argument of perigee of a GTO satellite to the hazard it poses to GEO satellites. (All data are current as of December 8, 1989.)

Introduction

THE effects of the 98 known satellite breakups[1] has been substantial. Yet, the true accounting of their impact on space operations can only be accurately appraised by examining fragmentation debris with respect to other sources contributing to the growth of the catalog population. Figure 1 shows the breakdown of the total trackable on-orbit population. Fragmentation debris accounts for 44% while inactive payloads (20%), rocket bodies (16%), operational debris (14%), and active payloads (6%) constitute the remaining population. The historical growth of each of these components will be presented for a variety of orbital regimes.

The orbital categories used in this paper are listed in Table 1. Figure 2 depicts the breakdown of the components of the on-orbit population in each regime with the number of on-orbit cataloged objects listed on each bar. The low-Earth-orbit (LEO) population contains 75% of all cataloged objects in similar proportions to the total catalog. The high-Earth-orbit (HEO) and geosynchronous-Earth-orbit (GEO) regions show a larger percentage of payloads and rocket bodies and a smaller amount of fragmentation debris. This trend may be more the result of an inability to sense and track fragmentation debris than an actual characteristic of the population.

All Altitudes

Figure 3 depicts the historical growth of the total on-orbit population. This plot was created by excluding interplanetary probes and by adding fragmentation debris to the catalog in the year it was created not necessarily when it was first detected.[2] Over 200 probes have officially been launched with well over 100 still "in orbit." Yet none of these pose a collision hazard to any Earth-orbiting satellites. The linear growth rate of 240/yr since 1959 provides a good approximation to

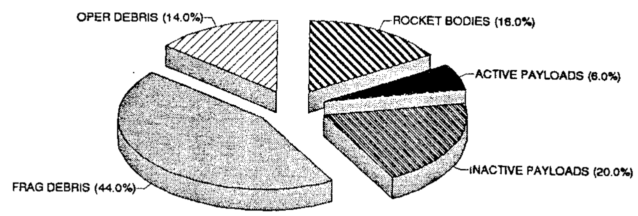

Fig. 1 On-orbit population (December 8, 1989).

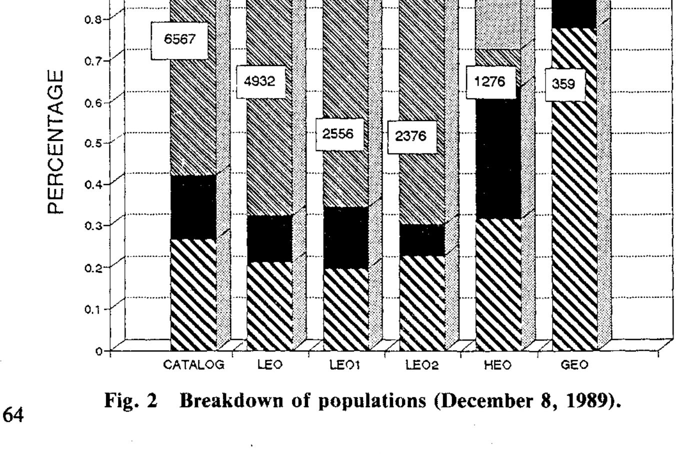

Fig. 2 Breakdown of populations (December 8, 1989).

Presented as Paper 90-1358 at the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Baltimore, MD, April 16-19, 1990; received May 14, 1990; revision received Oct. 7, 1990; accepted for publication Oct. 15, 1990.

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Table 1 Orbital categories

All altitudes (catalog)	Total cataloged population minus interplanetary probes
LEO	<127-min orbital period
LEO1	>105-min orbital period
LEO2	105–127-min orbital period
GEO	1436.2 ± 16-min orbital period
HEO	Not LEO or GEO (includes circular semisynchronous, "Molniya," and GTO satellites)
GTO	Geosynchronous transfer orbit, perigee in LEO and apogee near 35,787 km

Table 2 Orbital regime of breakups

	HEO	LEO1	LEO2	Total
	1960–1977			
Breakups	4	24	16	44
Breakups with >10 objects in orbit	1	5	15	21
	1978–present			
Breakups	17	35	3	55
Breakups with >10 objects in orbit	0	9	2	11

the actual growth. The fluctuations in the curve are primarily due to satellite breakups and cyclic solar activity. The debris produced by breakups is greatly affected by solar activity as evidenced in the fragmentation debris curve. Solar maxima in 1979–80 and 1989–90 have had the greatest impact on the environment. The last few solar maximums and minimums are marked on the linear growth line.

Figure 4 shows the contributions of payloads and rocket bodies to be very constant and linear with a combined effect of 90/yr. The operational debris has increased very little over time with the initial deposition due mainly to the Westford Needles experiment. Over the years, fragmentation debris has averaged about half of the total population, as it does now.

LEO Population

The LEO population growth is shown in Fig. 5 with a 190/yr growth plotted against the actual growth. Nearly all of the cataloged fragmentation debris (2940) are in LEO (2835). By dividing LEO into lower LEO (LEO1) and upper LEO (LEO2) regions a better understanding of debris growth rates is attained. Most objects in the 1000–2000 km band (LEO2) probably will not have any effect on systems such as the space station and the Space Shuttle for decades since atmospheric drag has a negligible impact at these altitudes. Figures 6 and 7 show the population growth in LEO1 and LEO2, respectively. The growth of fragmentation debris in LEO1 is very erratic but still fluctuates about an annual linear increase of about 120. The plot of growth in LEO2, Fig. 7, shows a leveling off of fragmentation debris which led to a flattening of the total growth curve. The drastic change may be explained by examining the location and severity of satellite breakups over time. Table 2 depicts the number of satellite breakups in each orbital regime (data from Ref. 1).

Data in Table 2 show that only about a third of all satellite breakups have 10 or more objects still in orbit (substantial). Through 1977, about 70% of the "substantial" breakups occurred in LEO2 whereas only 18% have occurred since 1977. Five breakups over an eight-year period (1969–1977) produced 1121 cataloged fragments of which 884 are still in orbit. These events produced a substantial rise in the LEO2 population.

Although the fragmentation debris and rocket bodies have shown little growth in LEO2 since 1977, the number of payloads has grown steadily. Figure 8 highlights the fact that fragmentation debris deposited in LEO2 before 1977 still dominates the population despite a leveling off of its growth over the last decade.

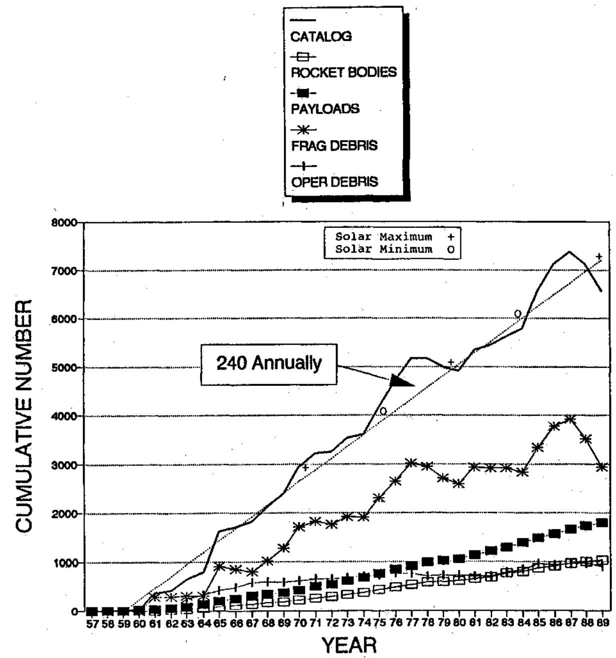

Fig. 3 On-orbit population growth (line).

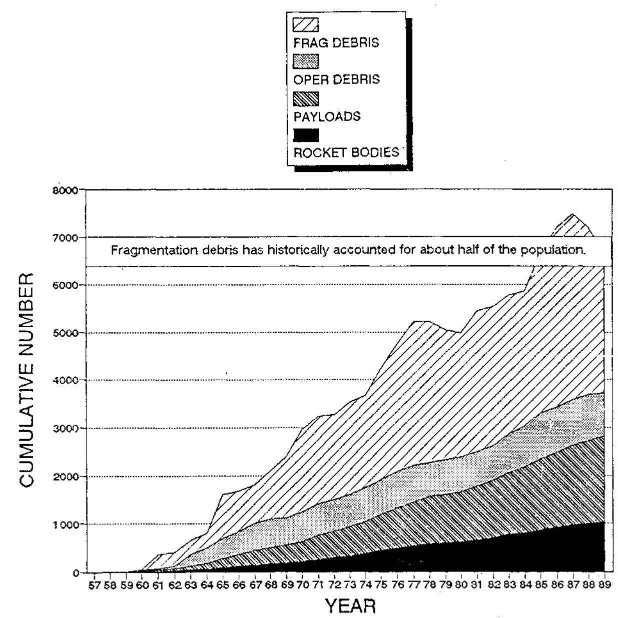

Fig. 4 On-orbit population growth (area).

Geosynchronous Orbit

The GEO regime is defined in this paper as 1436.2 ± 16 min orbital period which provides an altitude buffer of ±300 km about the GEO altitude of 35,787 km. Figure 9 shows that operational and fragmentation debris has little effect on GEO growth. As a matter of fact, there is no fragmentation debris in the catalog. This may be largely the result of limited resolution of objects in GEO. The deployment of payloads in GEO is the major source of GEO catalog growth while the rocket-body population has also steadily increased. Of the nearly 400 objects shown as being in GEO orbit, at least 10% have outdated element sets ("lost") or have been moved to supersynchronous disposal orbits. In the present analysis objects that have been moved to supersynchronous orbits (>16 min above GEO) are included in the HEO count.

The growth rate in GEO exhibited two stages. From 1963–1973 the population grew at a rate of about 4–5/yr, whereas from 1973 to present the number of GEO objects has increased

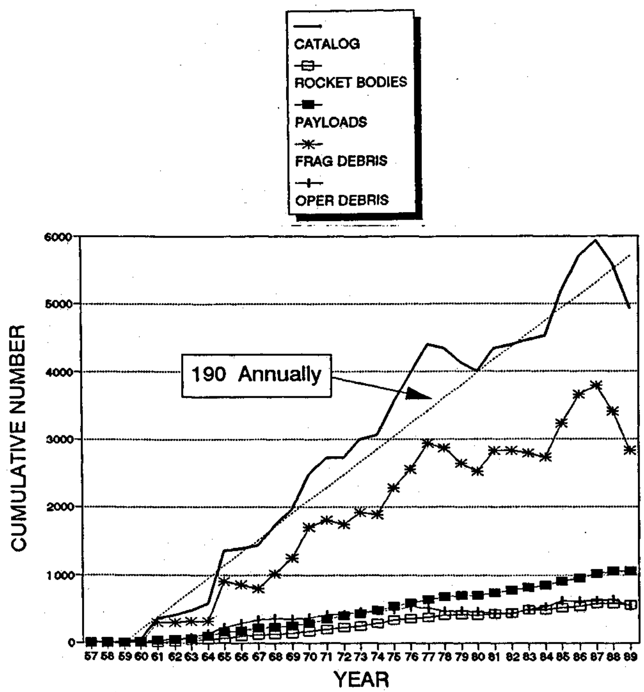

Fig. 5 LEO population growth.

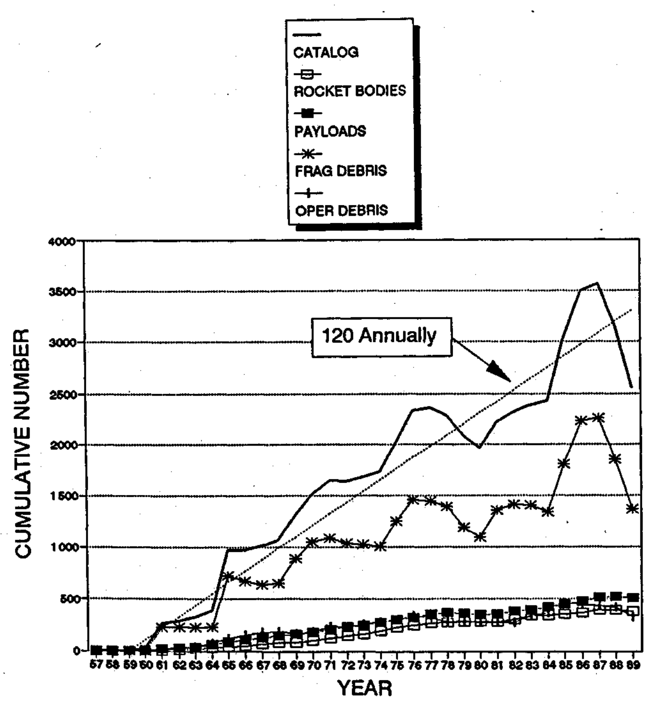

Fig. 6 LEO1 population growth.

at about 22/yr. The use of linear rates to describe the historical growth of GEO oversimplifies the complex series of technical, operational, and political constraints that affect this orbital regime. Thus, analysts should be careful in predicting the future of GEO simply from this limited database.

High Earth Orbit

A HEO satellite is defined as any satellite not in LEO or GEO. Figure 10 depicts the growth of objects in HEO showing nearly equal contributions by payloads, rocket bodies, and operational debris. The operational debris is mainly the result of the Westford Needles experiment. The limited amount of fragmentation debris in the HEO catalog may be largely the result of our inability to sense and track objects at high altitudes, especially when they are in highly elliptical orbits. HEO objects contain three major classes of satellite orbits: semisynchronous, Molniya-type, and geosynchronous transfer orbits (GTO).

Semisynchronous

Semisynchronous orbits are being used at an increasing rate as the NAVSTAR and GLONASS systems are being deployed. Rocket bodies used to launch these systems remain in semisynchronous transfer orbits (SSTO) with perigees in LEO and apogees around 19,000 km.

Molniya

"Molniya"-type satellites have large inclinations with apogees around 40,000 km and perigees in LEO. The third major type of HEO orbit is GTO which results from the placing of

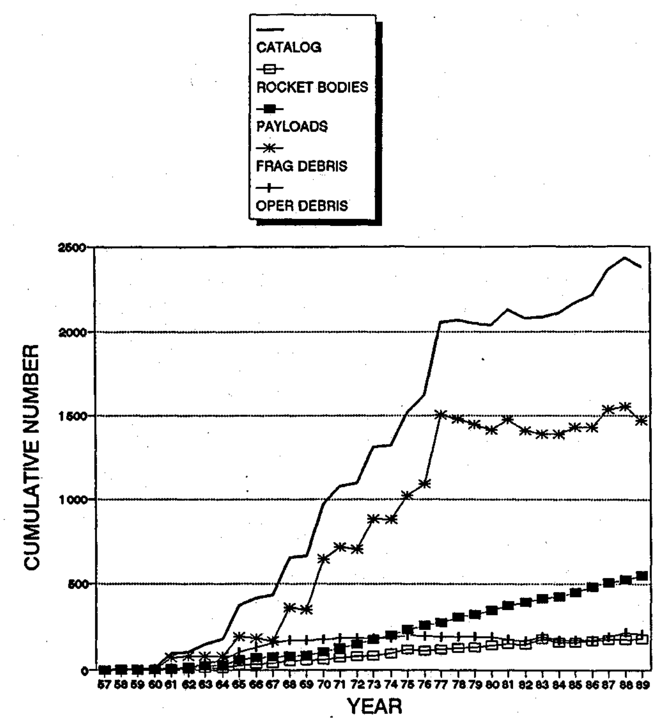

Fig. 7 LEO2 population growth.

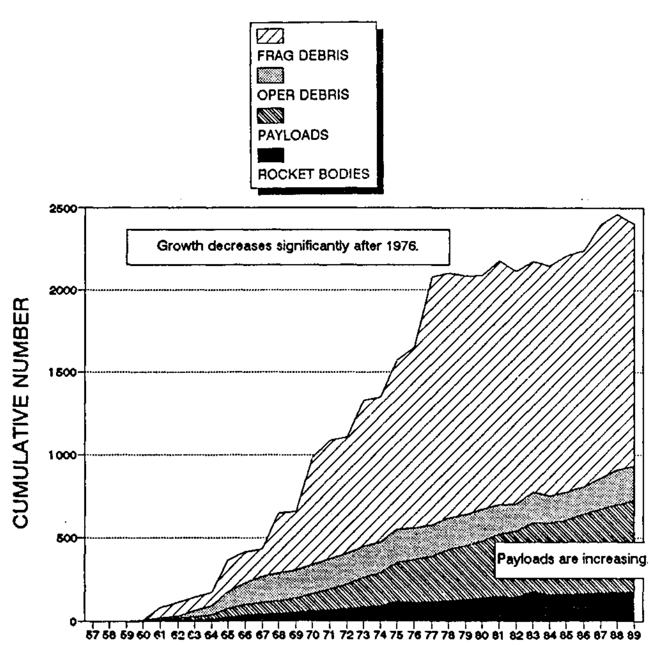

Fig. 8 LEO2 population growth (area).

satellites into GEO. The HEO objects of most concern are those that intercept the LEO environment. Figure 11 shows the log of the number of objects that have perigees below 500 km (y axis) vs their apogee (x axis). The numbers are tabulated in 100-km increments of the apogee height. Sixty-five percent of all cataloged satellites with perigees below 500 km have apogees below 2250 km, and other families of orbits are readily observable in the plot.

Geosynchronous Transfer

The objects in GTO require a closer look due to their transit between LEO and GEO regions. The number of cataloged objects in GTO is small, accounting for less than 1% of the total catalog population. Yet, closer examination of other data (three-card element sets) supplied by the SSN shows that only half of these objects are probably still in orbit. It is possible, however, that there are also other objects that cannot be tracked in this regime. Presently, the GTO population is half rocket bodies and half operational debris. These objects are roughly grouped into three inclination bands of 7 (ESA), 27 (US/PRC/Japan), and 47 (USSR) deg. The on-orbit GTO population now accounts for only about one-tenth of the total ever placed into GTO.

The concern about GTO objects is that they encounter both LEO and GEO, thus, possibly, creating a unique cross-contamination hazard.[3] To assess this hazard three attributes must be studied: 1) orbital lifetime, 2) time spent in LEO, and 3) time spent in GEO. First, the orbital lifetime of an object in GTO is affected by its inclination and right ascension. A lower-inclination satellite is fairly stable while any inclination above 36 deg will result in a much shorter lifetime due to solar-lunar perturbations that will depress the perigee altitude.[4] Analysis has shown that the GTO objects placed in orbit by the USSR do not usually remain in orbit for more than 6 months since they select a right ascension value that causes solar-lunar perturbations to force the object to re-enter. Reference 5 outlines reasons why the Soviet GTO objects decay so quickly. Other spacefaring countries could easily employ similar procedures to eliminate the need for the present analysis by insuring that very few objects would be added to the GTO regime.

Second, time in LEO is an important measure of a GTO object's hazard. Let us take for example a satellite with a perigee of 350 km and an apogee of 35,787 km (GEO). This object would spend only 2.2 and 1.5% of its period (about 10 min) per orbit below 1000- and 500-km altitude, respectively. The

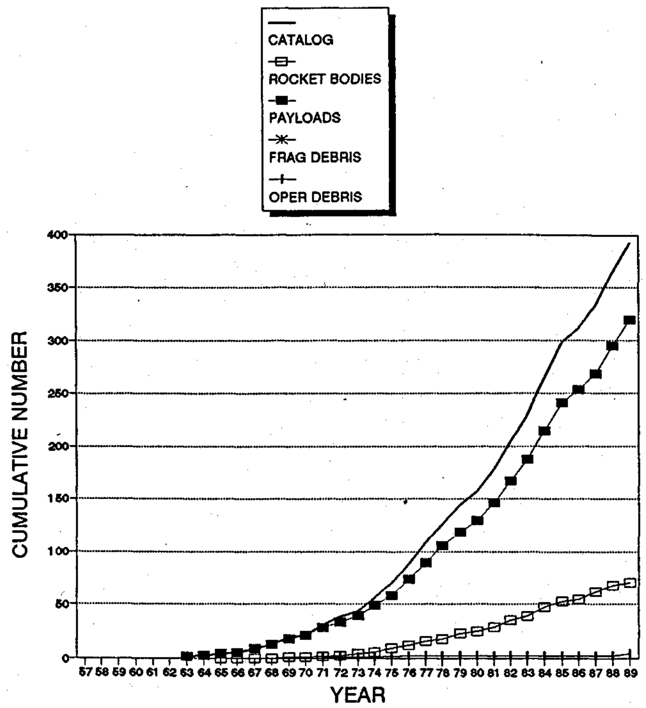

Fig. 9 GEO population growth.

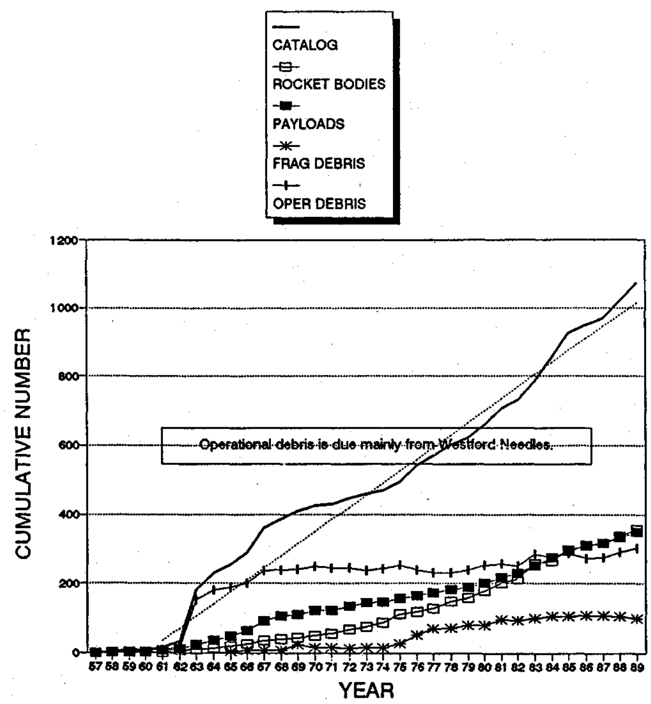

Fig. 10 HEO population growth.

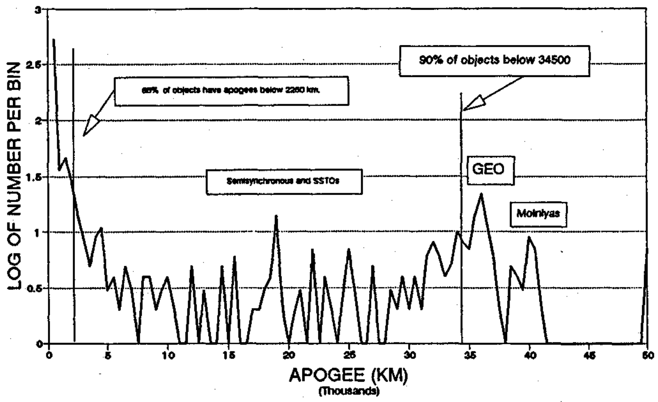

Fig. 11 Highly eccentric orbits.

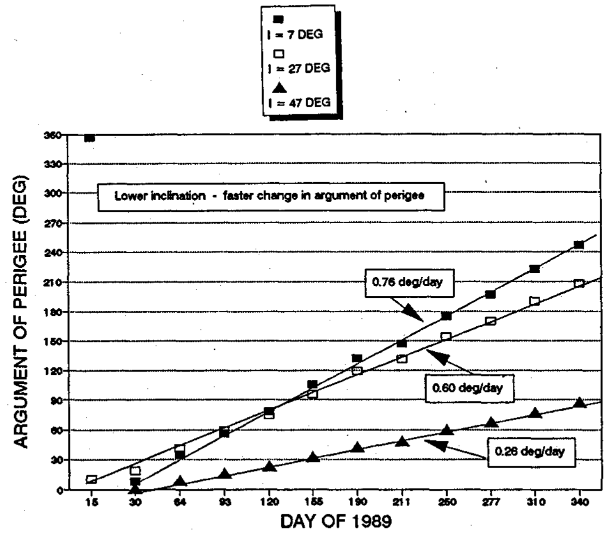

Fig. 12 Argument of perigee vs time.

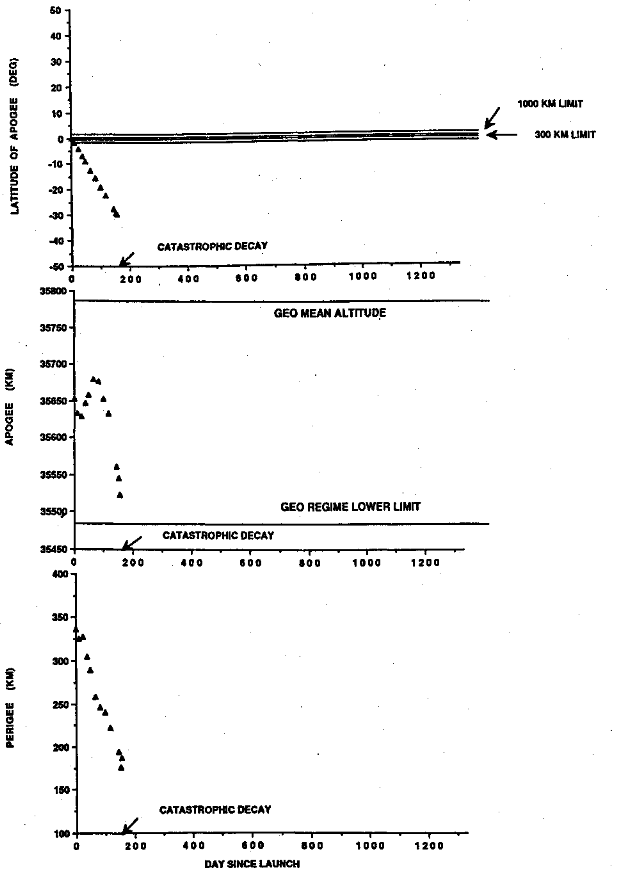

Fig. 13 GTO—Soviet operational debris (orbital history).

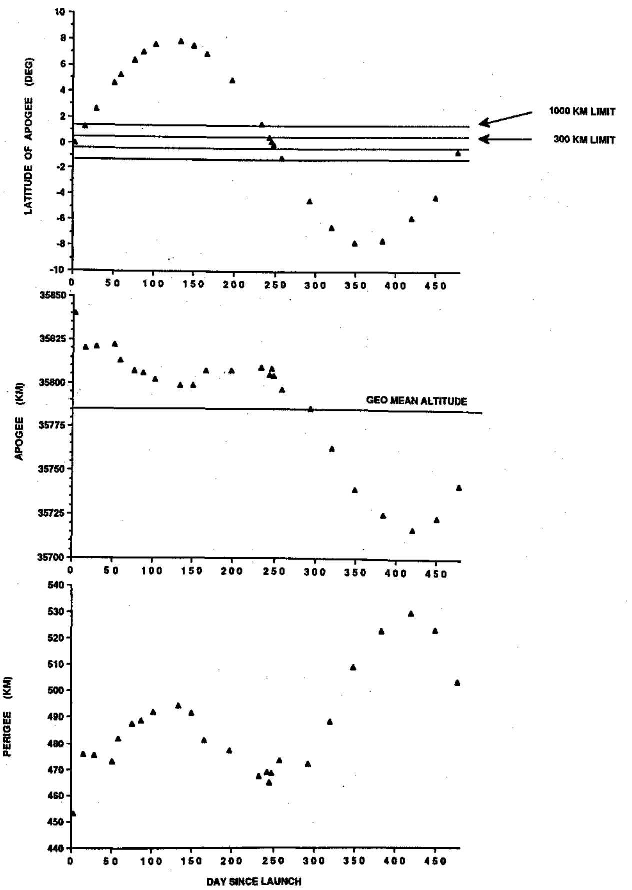

Fig. 14 GTO—ESA-launched rocket body (orbital history).

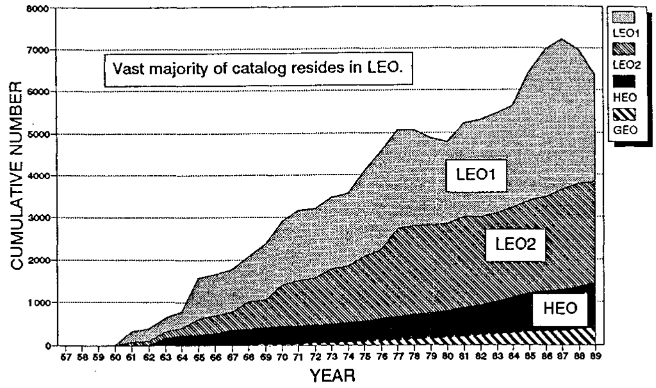

Fig. 15 On-orbit population growth by orbital regime.

orbital velocity is, however, greater than other objects residing at these altitudes by about 30%. For example, at 1000 km the circular orbital velocity is 7.35 km/s whereas it is 9.58 km/s for the example case. Since probability of collision is a function of relative velocity multiplied by time, the effective time in LEO would be comparable to 13 min per orbit. Our example GTO object, however, has a period about seven times longer than LEO orbits. As a result, over 50 GTO objects in our example orbit would be needed to produce a comparable hazard as one object in LEO.

Last, the time a GTO satellite spends in the vicinity of the geostationary belt is of great interest. This paper defines 300 km to be the buffer zone within which a GTO object will pose a hazard to geostationary satellites. The example satellite, 350/35,787 km, remains in the vicinity of GEO altitude for 58 min. This equates to 9.1% of its orbital period. The north-south (normal to GEO plane) 300-km component equates to 0.41 deg in latitude. Thus, for GTO objects to encounter the GEO region where operational satellites reside, they must also reach apogee at a very low latitude. The latitude of apogee LA is found by

$$LA = -\sin^{-1}(\sin i \sin w) \tag{1}$$

where w is the argument of perigee and i is the inclination.

The argument of latitude is close to zero only when $i = 0$ deg or $w = 0$ or 180 degrees. For the three inclination values of 7, 27, and 47 the argument of perigee must be within 3.4, 0.9, and 0.6 deg of 0 or 180 deg, respectively, to compromise the 300-km buffer zone established. The Satellite Catalog (December 8, 1989) lists 23 objects on-orbit that have perigees below 500 km and apogees within 300 km of GEO. Upon further scrutiny, it was discovered that only 12 of these were actually still in the prescribed GTO orbit while the other 11 have probably re-entered. Of the 12 objects, none of their latitudes of apogee were within the 0.41 deg on December 8, 1989. The closest object was within about 1400 km of the GEO belt in the North-South direction at apogee. It should also be noted that rocket bodies left in GTO are characteristically smaller than those abandoned in LEO.

At the beginning of each GTO object's life, it will have an argument of perigee of 0 or 180 deg but over time will vary. Figure 12 plots the argument of perigee values vs time for an object in each inclination (7, 27, and 47 deg). The higher inclination orbit has its argument of perigee move slowest (0.26 deg/day) while the 7-deg orbit's argument of perigee changes 0.76 deg/day. Because of this change, on the average a GTO object will spend only 4-13 days per year (1-4%) in the vicinity of GEO (north-south direction). Combining this with the fact that a GTO object spends only about 9% of its orbital period within 300-km altitude of GEO, the example GTO object spends about 0.3% of its lifetime near enough to GEO to pose a hazard (as defined in this paper). This amounts to about 1 day out of each full year. By increasing the buffer zone to 1000 km, the total time at risk to GEO increases to about 5 days out of each year.

It is illustrative to review the process outlined for assessing the hazard from a GTO object by examining two typical cases. Both objects were deposited in GTO within 2 weeks of each other. Figure 13 contains a series of plots showing the perigee, apogee, and latitude of apogee over time for a piece of Soviet operational debris with a 47-deg inclination. As discussed earlier, prudent selection of the right ascension causes the object to re-enter within 6 months. Figure 14 depicts the orbital dynamics of an ESA-launched rocket body. Over time the perigee fluctuates about 500 km whereas its apogee is continually within the 300-km buffer zone. Yet, the uppermost plot again shows that the latitude of apogee spends a very small amount of time within 300 km north-south of the GEO belt. This object is only a "hazard" to GEO when it is within 300 km radially and normal to the orbital plane.

Summary

Figure 15 shows the contributions of each orbital regime to the overall catalog growth. There are six major conclusions from this study.

1) A linear growth rate holds for most individual orbital regimes.

2) It is important to specify an orbital regime when stating a growth rate.

3) Fragmentation debris has contributed significantly to the catalog population. It has been especially important in LEO even though solar activity acts to cleanse much of it from orbit.

4) Reductions in the number of breakups have significantly altered the debris environment of the LEO2 region.

5) Objects in GTO pose a negligible hazard to both LEO and GEO due to their small number and orbital geometries.

6) Analysts must be careful in using the satellite catalog due to complexities in the cataloging and updating process.

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