

# Disposal of Spacecraft at End of Life in Geosynchronous Orbit

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A number of national and international organizations have adopted a policy of removing spacecraft at the end of life from the geosynchronous ring. However, a resolution of several technical issues still remains before an international policy can be developed and implemented by all users of geosynchronous orbits. The present study reviews the cataloged population of objects in the geosynchronous ring. The probability of collision is computed as a function of range and orbital inclination of an object. Long-term stability of supersynchronous disposal orbits and of the geopotential stable points is examined. Several disposal options are considered. The results of the study show that the use of the supersynchronous orbits for disposal purposes is economical and effective in significantly reducing the collision hazard. The use of the geopotential stable points for disposal of spacecraft at the end of life, on the other hand, was found to be impractical.

## I. Introduction

**B**ECAUSE of the uniqueness and usefulness of the geosynchronous equatorial orbit (GEO), the population of objects in this orbit has increased continuously. Reference 1 shows, for example, that at the beginning of 1988, there were 286 cataloged satellites residing in this orbit, not including spent upper stages. Of these, 110 to 130 operating satellites were on station along with 150 that are nonfunctional or abandoned.

Reference 2, on the other hand, shows that of the approximately 453 cataloged objects traversing GEO altitudes, only about 150 are geostationary. The others are either geosynchronous or in highly elliptical ("Molniya") semisynchronous orbits. There are also a number of military spacecraft, the orbits of which are not generally available in published form.

To reduce the collision hazard within GEO, approximately 30 to 35 satellites have been removed from GEO at the end of life. Several strategies are available for disposing of GEO satellites, such as moving them to stable longitudes or raising them to orbits above geostationary altitude.

The benefits of removing old spacecraft from GEO are a) the freeing of desirable longitudinal positions for replacement spacecraft and b) the reduction of collision damage potential, which can become high for collocated satellites.<sup>3</sup> The primary issues involved are a) the protection of GEO as a unique natural resource and b) operational considerations such as cost effectiveness of the maneuver, risks of explosion, structural breakup, or other malfunctions in carrying out the maneuver and national and international policy considerations. Other issues include the potential impact on future traffic to GEO and the perturbative effects on disposal orbits (e.g., solar radiation and the sun/moon gravitational perturbations). In other words, abandoned rocket stages or satellites should not be a hazard to future missions, and their orbits should not intersect GEO over long periods of time.

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The purpose of the present study is to review the population environment in GEO, examine average probabilities of collision as a function of altitude, and consider the feasibility of removing spacecraft to supersynchronous (higher altitude) orbits or to the geopotential stable points. Distributions of the GEO population are described, average spatial density and collision probability are computed, and the rationale for removing spacecraft from GEO is reviewed.

## II. Geosynchronous Ring

Orbits in the geosynchronous ring may be classified as a) low or high inclination, and b) sub- or supersynchronous altitude drifting orbits. The ideal geostationary orbit has an altitude of 35,787 km and a period of 1436.2 min. A satellite whose period of revolution is equal to the period of rotation of the earth about its axis is called a geosynchronous satellite. A geostationary satellite is a geosynchronous satellite in a circular orbit, which lies in the plane of the Earth's equator and rotates about the Earth's polar axis in the same direction. Consequently, it remains "fixed" over a point on the equator.

Table 1 1988 geosynchronous catalog

Owner	Spacecraft	Rocket bodies
Australia	3	—
Brazil	2	—
Canada	10	—
European Space Agency	8	—
France	4	—
Great Britain	1	—
India	3	—
Indonesia	4	—
Intelsat	20	—
Italy	1	—
International Telecommunications Satellite Organization	4	—
Japan	12	—
Mexico	2	—
North Atlantic Treaty Organization	7	—
People's Republic of China	2	—
Saudia Arabia	2	—
United States	91	24
Soviet Union	64	65
Unknown	50	—
Total	290	89

The owners of the 379 GEO objects in the *United States Space Command Catalog* of February 1988 are identified in Table 1. An illustration of the GEO objects in the equatorial plane is shown in Fig. 1, where the objects located at or near the same longitude are shown displaced radially inward. The distribution in right ascension of the ascending node (RAAN) is given in Figs. 2 and 3, which illustrate the clustering (bunching) of orbits in the 60 deg and 100 deg range. A view of the GEO population is also shown in Fig. 4, where the apparent sinusoidal distribution in latitude is the result of the orbital bunching of orbit nodes of aging spacecraft and rocket bodies.

Distributions of the GEO objects with orbital inclination and eccentricity (apogee-perigee difference) are shown in Figs. 5 and 6, respectively, for the February 1988 and October 1979 catalogs.

A significant increase in the number of objects is apparent in the time interval considered. The drift rate distribution for the 1988 catalog is also shown in Fig. 7. It can be seen that only about 70 objects have drift rates of less than 0.01 deg/day and fewer than 180 objects less than 0.1 deg/day. These are "fixed" or active satellites, and the remaining objects are probably uncontrolled or abandoned debris.

### III. Spatial Density and Collision Hazard

#### A. Spatial Density

The spatial density as a function of radius  $r$  and latitude  $L$  of the  $N$  objects in the geosynchronous ring, defined by toroidal volume, can be expressed approximately as

$$\rho(r, L) \approx \sum_{k=1}^N \rho_k \quad (1)$$

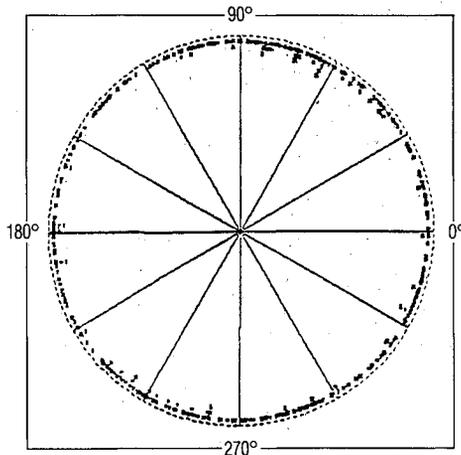


Fig. 1 Longitudinal distribution of object in the geosynchronous ring (March 1989).

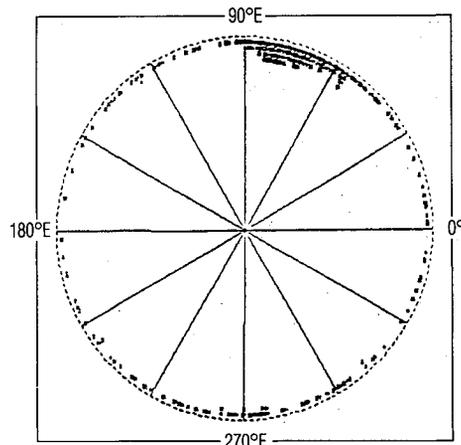


Fig. 2 RAAN distribution of objects in the geosynchronous ring (March 1989).

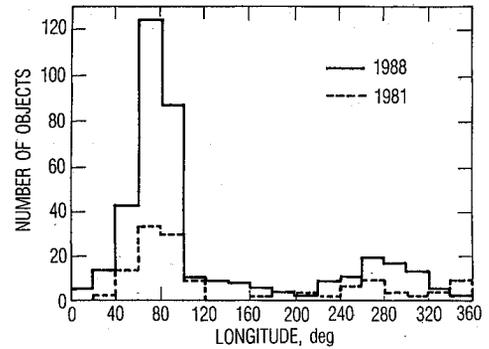


Fig. 3 Right ascension of ascending node (deg).

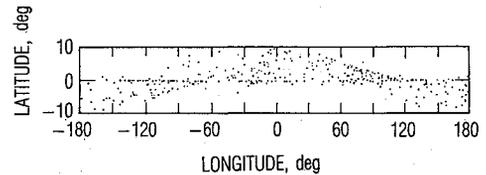


Fig. 4 View of geosynchronous objects.

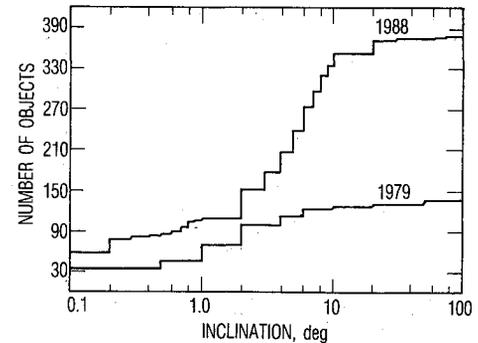


Fig. 5 Geosynchronous orbit inclination distribution.

where

$$\rho_k = \frac{P_k(r_1, r_2) P_k(-L, L)}{\Delta V_k} \quad (2)$$

with the probability of the  $k$ th object being within the toroidal volume

$$\Delta V_k = \frac{4\pi}{3} (r_2^3 - r_1^3) \sin L \quad (3)$$

defined by the arbitrary orbital radii  $r_1, r_2$ , and latitude  $L$  as shown in Figs. 8. Here  $P_k(r_1, r_2)$  = probability that the  $k$ th object is within the radial range  $\Delta r = r_2 - r_1$  and  $P_k(-L, L)$  = probability that the  $k$ th object is between the latitudes  $-L$  and  $L$ . For example, if  $r_a \geq r_2 > r_1 \geq r_p$  where  $r_a$  and  $r_p$  are the orbit apogee and perigee, respectively, and if  $i > L$  where  $i$  is the orbit-plane inclination of the object

$$P_k(r_1, r_2) = P_k(r_p, r_2) - P_k(r_p, r_1) \quad (4)$$

where the probability that the object lies between perigee ( $r_p$ ) and some radius ( $r$ ) is derived in Ref. 4 as

$$P(r_p, r) = \frac{1}{2} + \frac{1}{\pi} \sin^{-1} \left[ \frac{2(r-a)}{(r_a - r_p)} \right] - \frac{1}{a\pi} \sqrt{(r_a - r)(r - r_p)} \quad (5)$$

and the probability that the object is between the latitudes  $-L$  and  $L$  is

$$P(-L, L) = \frac{2}{\pi} \sin^{-1} \left( \frac{\sin L}{\sin i} \right) \quad (6)$$

where  $a$  and  $i$  are the object orbit semimajor axis and inclination, respectively.

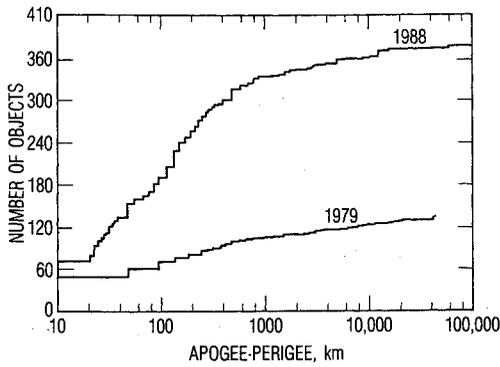


Fig. 6 Geosynchronous eccentricity distribution.

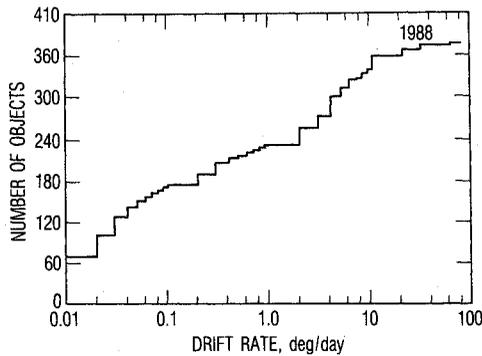


Fig. 7 Geosynchronous drift rate distribution.

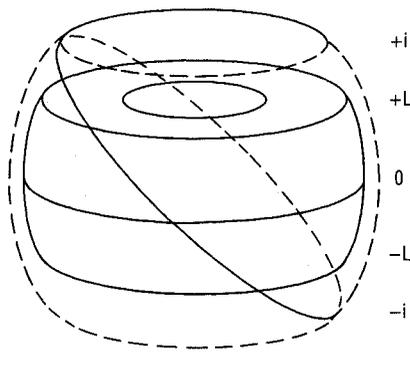


Fig. 8a Toroidal volume.

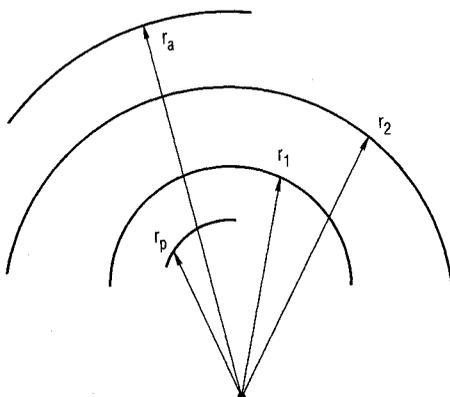


Fig. 8b Radial parameters.

Equation (1) is plotted in Fig. 9 for the 379 objects of the GEO catalog considered. The results show that the spatial density is maximum (about  $10^{-8}$  sats/km<sup>3</sup>) in a narrow range of the geosynchronous altitude and a latitude band of  $\pm 1$  deg. The density increases as latitude decreases. It decreases by about two orders of magnitude at  $\pm 100$  km above or below GEO. The subsequent decrease with altitude is not as high as in the first 100 km range; it is about three orders of magnitude at  $\pm 600$  km range.

**B. Probability of Collision**

The probability per revolution that a satellite in a circular orbit will collide with an object can be computed from the relation<sup>5</sup>

$$P(\text{col/rev}) = A \bar{V}_r T \int_{r_1}^{r_2} \int_{-L}^L \rho(r,L) f(L) dL dr \quad (7)$$

where

- $\rho(r,L)$  = object density function
- $f(L)$  = weighting function to indicate the time fraction spent by a satellite in a latitude band,  $-L, L$
- $\frac{T}{V_r}$  = satellite period
- $\bar{V}_r$  = mean relative velocity between the satellite and the objects in GEO
- $A$  = satellite projected area normal to  $\bar{V}_r$

The probability of collision for a spacecraft in a circular orbit with inclination  $i$ , for a given range above or below GEO, has been computed and plotted in Fig. 10. The results show that the probability of collision is greatest for GEO satellites and decreases as a function of range above or below

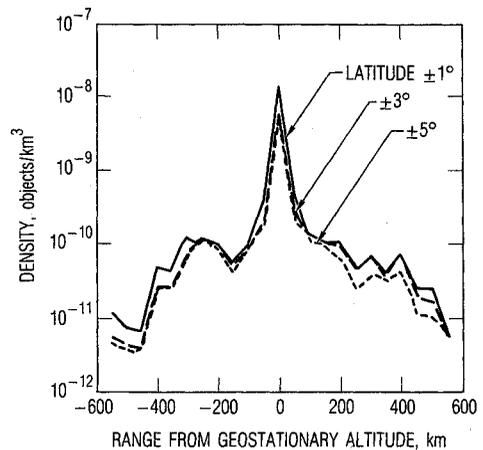


Fig. 9 Population density as a function of range and latitude from GEO.

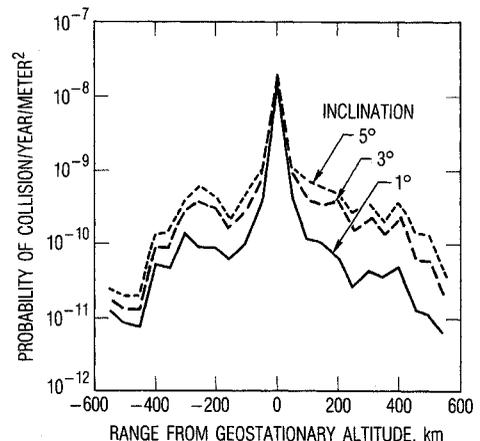


Fig. 10 Probability of collision for circular orbit as a function of inclination and range from GEO.

GEO. It also increases with inclination due to higher relative velocities between the satellite and the objects in GEO. For example, a decrease of two orders of magnitude is apparent for a spacecraft in an orbit with an inclination of 1 deg at  $\pm 100$  km above or below GEO.

#### IV. Disposal Options

Some of the satellites launched into the geosynchronous orbit have been removed at the end of life to either higher or lower altitudes. The primary benefits for removing old spacecraft from the geosynchronous orbit are 1) freeing of desirable longitudinal positions for replacement spacecraft to avoid interference from old spacecraft and 2) reduction of collision damage potential for other spacecraft.

The removal of inactive satellites has evidently become a practice at Intelsat and the European Space Agency (ESA). The first case of end-of-life removal occurred in May 1977, when three Intelsat 3 satellites F2, F3, and F4 were moved to disposal orbits at 3580-, 3700-, and 400-km altitudes beyond the altitude of the geosynchronous orbit.<sup>6</sup> The ATS 6, Raduga 5, Anik 1, SMS 1, SMS 2, and Intelsat 4 F2 and F4 were removed later to disposal orbits at 3580-, 3700-, and 4000-km altitudes beyond the altitude of the geosynchronous orbit.<sup>6</sup> The ATS 6, Raduga 5, Anik 1, SMS 1, SMS 2, and Intelsat 4 F2 and F4 were removed later to disposal orbits. Similarly, in January 1984, GEOS 2 was placed 269 km above GEO by ESA using 2 kg of propellant in three impulses.

Similar requirements are placed on future spacecraft by the U.S. Navy UHF Follow-On, DSCS-III, and so forth, which require removal of satellites to supersynchronous orbits by at least 370 km from GEO. Also, AUSSAT, the Australian Agency, requires removal capability of up to 1110 km above GEO at the end of life.

The practice of removing satellites from GEO is not without some risk and cost to the spacecraft operator. The risk is the probability of failure during the maneuver, which may result in an orbit with higher relative velocities or even a collisional breakup. The cost is the slightly reduced life and the potential loss of the satellite as a spare or a decoy. (The latter may sometimes be of benefit to military spacecraft.)

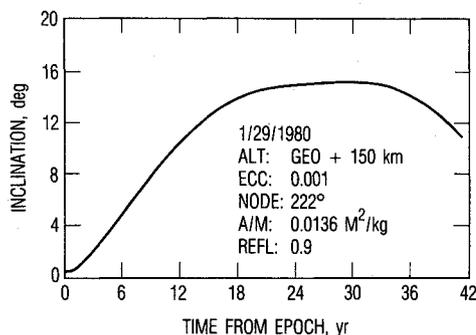


Fig. 11 Inclination drift in supersynchronous orbit.

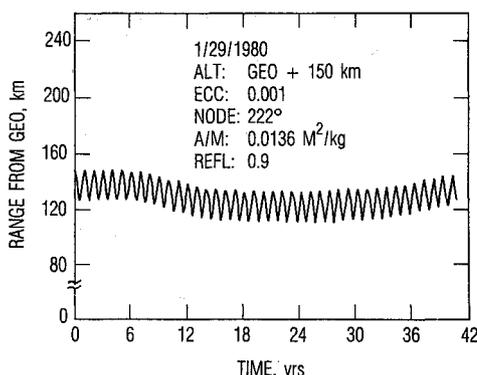


Fig. 12 Perigee drift in supersynchronous orbit.

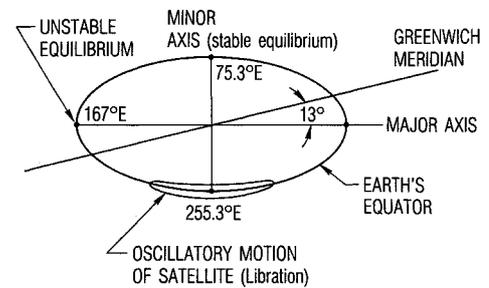


Fig. 13 Geopotential stable points.

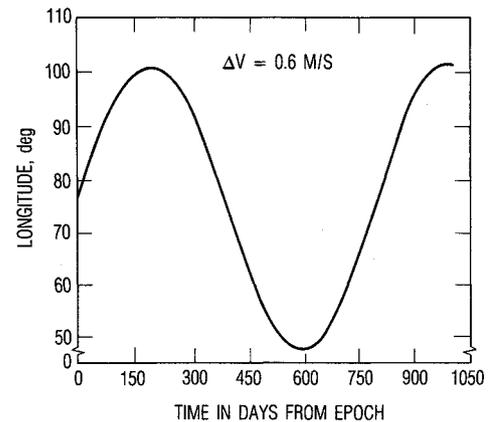


Fig. 14 Longitude time history near stable point.

In view of this, decisions concerning removal of a spacecraft at the end of life should be made only after careful analysis of all factors. To minimize the explosion hazard from fuel decomposition, a burn to depletion of propellants should also be considered.

#### A. Supersynchronous Orbit Disposal

The potential for reduction of the probability of collision is illustrated in Fig. 10, which shows that a two- or three-order-of-magnitude decrease in the collision hazard results by placing a spacecraft about 300 km above the geosynchronous orbit. The velocity impulse for such a maneuver is only 10.8 m/s requiring, for example, only 5 to 10 kg of propellant for a typical spacecraft. This translates to a month or two of life reduction and can be accomplished by a two-impulse maneuver.

The technique of initially deploying satellites to a supersynchronous orbit can also be used to ensure that the apogee-injection stage remains above geosynchronous. This procedure is attractive in that it effectively removes the threat posed by the apogee-injection stage to objects in the geosynchronous corridor.

The long-term stability of supersynchronous orbits has been examined numerically using program ELEMENT<sup>7</sup> and found to be satisfactory. For example, the first order, nearly resonant perturbation for circular orbits displaced in an altitude  $\pm 150$  km from a typical synchronous, nearly equatorial orbit results in the maximum radial excursion on the order of only  $\pm 2.31$  km almost entirely due to the lowest order tesseral harmonic  $J_{2,2}$ .

The effects on the sun/moon perturbation, however, will cause an orbital inclination growth from zero to nearly 15 deg in 27.4 years, as illustrated in Fig. 11. The in-plane motion, on the other hand, is caused mostly by solar radiation pressure. For example, for an object with an area-to-mass ratio of 0.014 m<sup>2</sup>/kg and a coefficient of reflection of 0.9, the maximum cyclical perigee altitude variation is only about 24 km/yr. A longer-term perigee variation of about 20 km is also apparent in Fig. 12, which illustrates the perigee drift due to solar radiation pressure. For a detailed description of the general inclination history, see Ref. 8.

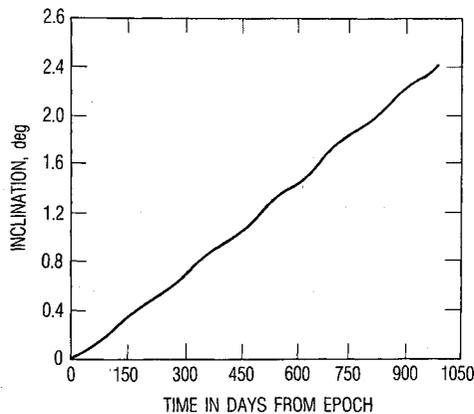


Fig. 15 Inclination time history near stable point.

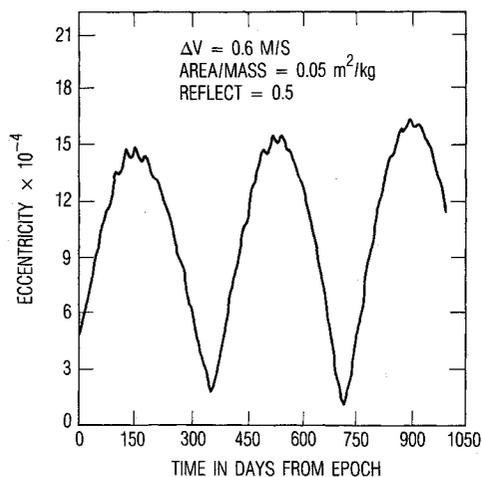


Fig. 16 Eccentricity time history near stable point.

### B. Geopotential Stable Point Deployment

Another possibility exists, at least in theory, of placing spent satellites and rocket stages at the geopotential stable points. There are two such points located in the equatorial plane at  $75.3^\circ\text{E}$  and  $255.3^\circ\text{E}$  longitude, as illustrated in Fig. 13. Objects placed a given distance away will oscillate about the stable point (on the Earth's minor axis) with a period of several years. Therefore, if objects can be placed at such points with negligible position and velocity errors, they will tend to remain in the longitudinal vicinity of such points. However, they will still be subject to the perturbative effects of the solar/lunar gravitation and radiation pressure. A velocity error (between nominal geosynchronous velocity and true orbital velocity) of only a fraction of 1 m/s can cause large oscillations of an object about the stable point.

Figures 14, 15, and 16 illustrate the longitudinal displacement, inclination, and eccentricity changes in 1000 days for an object initially at  $75.3^\circ\text{E}$  longitude with a velocity error of 0.6 m/s and an area-to-mass ratio of  $0.05\text{ m}^2/\text{kg}$  obtained using program GEOSYN.<sup>9</sup> The coefficient of reflectivity is 0.5. The results show the extreme sensitivity of the longitudinal position of an object to an initial velocity error. It is also clear that the sun/moon gravitational perturbation is present. The placement of spent satellites and rocket stages at the geopotential

stable points would therefore be ineffective in reducing the collision hazard. The resultant oscillations of the objects would continue to pose a collision threat to each other, to active spacecraft, and to drifting bodies in the vicinity or passing near such points.

### V. Summary and Conclusions

The tracked satellite population in the geosynchronous orbit has been examined and its spatial density evaluated. The probability that a spacecraft will collide with an object in the ring has been computed and found to be on the order of  $10^{-8}/\text{m}^2$  of spacecraft area per year, not including the effects of longitudinal bunching of objects (e.g., collocation of satellites) or of smaller debris that cannot be tracked. The maximum probability of collision for spacecraft in circular, inclined orbits was found to be at geosynchronous altitude, decreasing rapidly with distance from this altitude. Thus, the removal of spacecraft at the end of life to supersynchronous orbits 300 to 600 km above geosynchronous would free longitudinal locations for future satellites (avoiding bunching effects) and would decrease the collision hazard significantly (up to three orders of magnitude) with the current population of objects. The velocity impulse for such maneuvers is modest (on the order of 10 m/s) with a typical propellant requirement of less than 10 kg. The long-term stability of supersynchronous orbits was found to be adequate.

The feasibility of using the geopotential stable points for end-of-life disposal was also examined. However, the high sensitivity to initial velocity errors at deployment and the sun/moon and the solar radiation pressure perturbation effects would make this approach impractical.

### VI. Acknowledgment

The author wishes to thank M. R. Rakoczy for her assistance in the evaluation of the collision hazard in the geosynchronous orbit.

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