END-OF-LIFE DISPOSAL OF GEOSTATIONARY SATELLITES

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ABSTRACT

For more than 25 years, the practice of reorbiting of a geostationary satellite at the end of its mission in order to protect the GEO environment has been recommended and performed by a number of operators. In recent years, an internationally recognised re-orbiting altitude has been defined by the Inter-Agency Space Debris Coordination Committee (IADC). Based on orbital data contained in the DISCOS database, the situation on the geostationary ring is analysed. In January 2005, from 1124 known objects passing through the geostationary region, 346 are controlled within their allocated longitude slots, 416 are drifting above, below or through GEO, and 143 are in a libration orbit. For 153 objects there is no orbital information available and for 60 uncatalogued objects orbital elements are derived from European measurements. In the eight years from 1997 to 2004, 117 spacecraft reached their end of life; 39 were reorbited in compliance with the IADC recommendation, 41 were reorbited below the minimum recommended altitude, and 37 were abandoned without any end-of-life disposal manoeuvre. Apart from these catalogued objects, the ESA 1-m telescope has observed many smaller debris (down to 10-15 cm) in this orbital region representing a collision risk for GEO spacecraft which is difficult to quantify.

1. INTRODUCTION

The geostationary ring is a valuable resource currently populated by more than 340 operational satellites. Unlike in low Earth orbit there is no atmospheric drag which will remove abandoned objects over time. Therefore, it is the responsibility of the spacecraft operators to keep this unique orbital region clean. Already in 1977, Perek (1977) proposed that spacecraft should be systematically removed from their geostationary orbit (GEO) at end-of-mission. In the same year INTELSAT sent for the first time in space history an aging satellite into a GEO graveyard orbit.

Since then a number of guidelines and recommendations for end-of-mission disposal were issued by national and international institutions as described by Johnson (1999) and in a United Nations Committee for the Peaceful Use of Outer Space report (1999). In 1995 the International Academy of Astronautics (IAA, 1995) recommended to reorbit "geostationary satellites at end-of-life to disposal orbits with a minimum altitude increase 300-400 km above GEO depending on spacecraft characteristics". At the same time, space agencies like NASA, JAXA, Roskosmos and ESA developed national guidelines. All recommended an altitude increase of more than 200 km above GEO. Finally in 1997, an international consensus was found within the Inter-Agency Space Debris Coordination Committee (IADC, 1997). The recommended minimum altitude increase (in km) is given as

$$\Delta H = 235 + 1000 \cdot C_R \cdot A/m \quad (1)$$

where C_R is the solar radiation pressure coefficient (usually with a value between 1 and 2), A is the average cross-sectional area and m is the mass of the satellite.

In view of these guidelines and recommendations one would expect that the geostationary ring is a well protected and unlittered space. However only about one third of all satellites follow the internationally agreed recommendations. Two out of three satellites are reboosted into an orbit so low above GEO that they will sooner or later interfere with geostationary satellites or they are completely abandoned without any end-of-life disposal manoeuvre.

In this paper an updated survey of the reorbiting practices in the geostationary ring during the last eight years (1997-2004) is given. Also the significant population of uncatalogued objects as small as 10-15 cm, which was detected by ESA's 1 meter telescope at Teneriffe (Flury et al., 2000, Schildknecht et al., 2004) is shortly discussed. The large number of other objects (mostly upper stages in geostationary transfer orbits) that pass through GEO and also represent a hazard are not considered in this analysis.

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2. ORBITAL DATA ANALYSIS

The basic source of information are the NASA Two-Line Elements (TLE). They are copied into ESA's DISCOS Database (Database and Information System Characterising Objects in Space) every day except Saturday and Sunday by ESOC's Mission Analysis Section. Geostationary objects are selected from the DISCOS Database according to the following criteria:

- eccentricity smaller than 0.1,
- mean motion between 0.9 and 1.1 revolution per sidereal day, corresponding approximatively to a radius of 42164 $\pm$ 2800 km,
- inclination lower than 20 degrees.

869 objects met these criteria as of 31 December 2004. Their orbital histories were analysed in order to classify them according to different categories. Six different types of categories are defined:

- C1: objects under longitude and inclination control (E-W as well as N-S control) - the longitude is nearly constant and the inclination is smaller than 0.3 degrees,
- C2: objects under longitude control (only E-W control) - the longitude is nearly constant but the inclination is higher than 0.3 degrees,
- D: objects in a drift orbit,
- L1: objects in a libration orbit around the Eastern stable point (longitude 75 degrees East),
- L2: objects in a libration orbit around the Western stable point (longitude 105 degrees West),
- L3: objects in a libration orbit around both stable points.

The algorithm to classify the objects is described by Samson (1999).

3. CURRENT SITUATION IN GEO

Next to the 869 objects which fulfill the orbital criteria above, there are 255 more objects also known to be in this orbital region although no orbital elements are available in DISCOS. Thus, the total number of objects in the geostationary region is 1124. They were classified as follows:

- 346 are controlled (221 under longitude and inclination control),
- 416 are in a drift orbit,
- 143 are in a libration orbit,
- 153 are uncontrolled with no orbital elements available,
- 60 are unidentified objects detected by European telescopes and
- 6 could not be classified (they were recently launched and are en route to their longitude slot or they had a recent manoeuvre).

Figure 1 illustrates the percentage of the various categories. In the annual report "Classification of Geosynchronous Objects" by Serraller and Jehn (2005) the status of all the individual objects can be found. In this paper we confine ourselves to some statistical data.

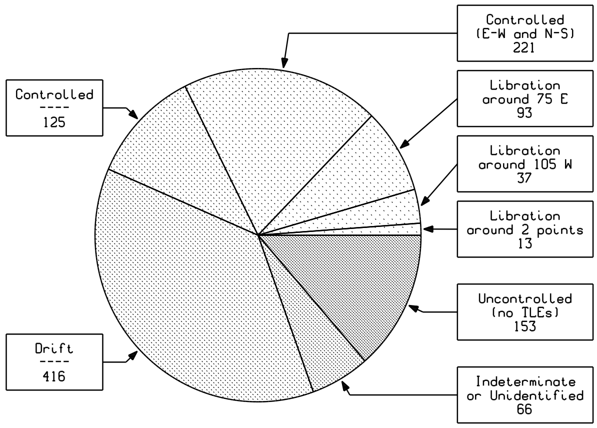

Figure 1. Number of objects in each category. The 125 controlled objects consist of the 83 objects in class C2 (only East-West station keeping) and 42 objects which TLEs are not available.

Figure 2 shows the number of objects under control (bottom bars), in drift orbit or in libration orbit (top bars) according to the launch year. Most of the satellites launched before 1990 are meanwhile either in a drift orbit or in a libration orbit. Up to 10 objects were abandoned in such libration orbits every year.

Figure 3 shows the distribution of the longitude of the 290 satellites under control for which the orbital position is known. A concentration of satellites over Europe and also over the United States can be observed. Except for a small "hole" around 200° East, the congestion of the geostationary ring becomes evident.

Figure 4 illustrates the distribution of the objects in drift orbit. Each vertical line represents one object. The horizontal axis gives the semi-major axis mean deviation from the geostationary altitude, which is inversely proportional to the mean drift rate of the object. The vertical axis gives the perigee and apogee mean deviation from the geostationary altitude. The altitude of the object varies between these two values. It can be seen that

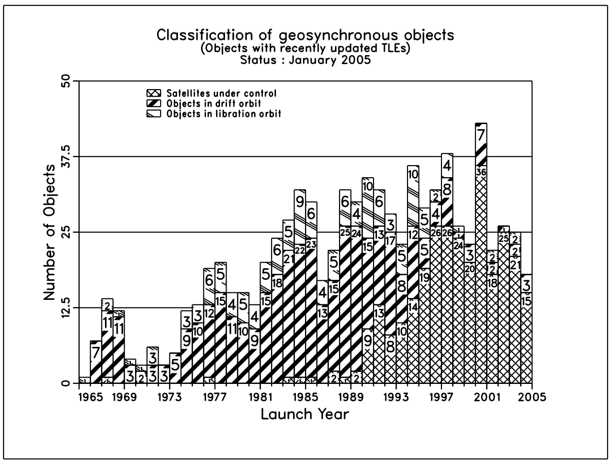

Figure 2. Number of objects in each category according to the launch year.

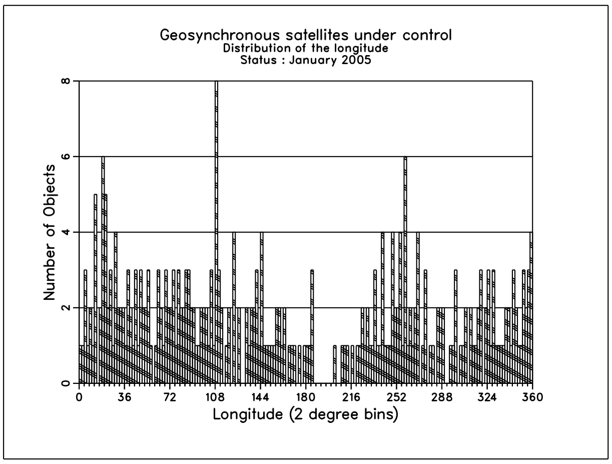

Figure 3. Distribution of the longitude of the 294 satellites under control (with updated TLEs) in 2-degree bins.

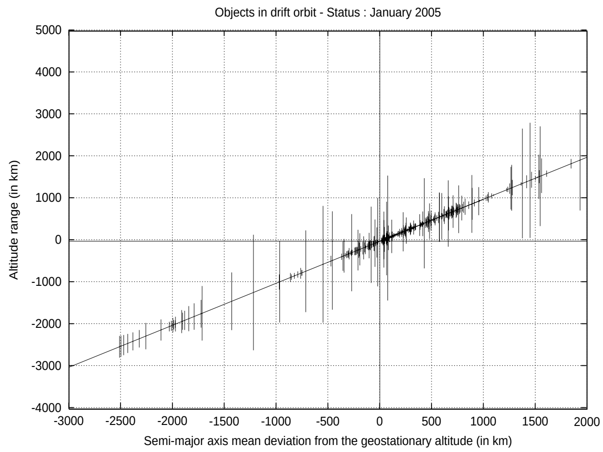

Figure 4. Distribution and altitude range of objects in drift orbit.

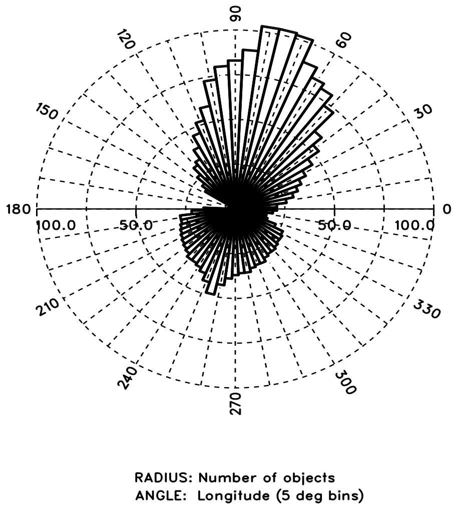

Figure 5. Number of objects in libration orbit in 5-deg bins of geographic longitude (objects with updated TLEs only).

if the eccentricity is large, the object will go through the geostationary altitude. According to the IADC recommendation, a satellite should be reorbited at its end-of-life to a graveyard orbit with a perigee altitude which is about 300 km above the GEO ring (see Eq. 1). All lines which are either totally or partly below the horizontal line at 300 km above GEO represent objects entering into the protected zone around GEO.

Figure 5 illustrates the number of objects in a libration orbit that pass through a given longitude. The 105 objects classified as librating around the Eastern stable point (category L1) or around both stable points (category L3) are counted in the interval 72.5-77.5, because they all go through 75° E longitude. 49 objects (35 in category L2 and 14 in category L3) librate through the Western stable point at 105° W, whereas only a few librating satellites pass through 0 or 180° E.

4. LONG-TERM PROPAGATION OF LOW GRAVEYARD ORBITS

In the year 2004 there were 5 satellites reorbited below the altitude recommended by IADC. Table 1 lists the names, countries and the initial disposal altitudes of these 5 satellites.

A long-term orbit propagation of these 5 satellites was performed. An orbit propagator based on averaging techniques developed by Van der Ha (1980) is used taking into account perturbations due to the geopotential, Sun and Moon gravity and solar radiation pressure:

- In the treatment of the geopotential, the potential is developed into zonal and tesseral terms. For the zonal terms, the development extends to the fourth order. For the tesseral terms, it includes the contribution of J_{22}, J_{31}, J_{32}, J_{33}, J_{41} and J_{42}. Second-

Table 1. Satellites reorbited in 2004 below the IADC recommended altitude

COSPAR ID	Name	Country	km above GEO
1985 109 B	Morelos 2	Mexico	180 x 220
1986 026 B	Brazilsat 2	Brazil	170 x 190
1992 021 A	Telecom 2B	France	195 x 225
1993 048 B	Insat IIB	India	9 x 160
1997 078 A	Galaxy 8-i	US	145 x 180

order terms in eccentricity and normalized deviation in semi-major axis ($\frac{a-r_s}{r_s}$ where r_s = 42164 km) are ignored.

- For the third body perturbation, the influences of the Moon and the Sun are implemented. The position of the Sun in the geocentric reference frame is described by non-singular elements and is estimated at each integration step with the hypothesis of a constant rotation rate for the Sun mean longitude in this frame. The position of the Moon in the geocentric reference frame is described by Keplerian elements where the anomaly is replaced by the mean longitude. The position of the Moon is estimated at each integration step with the hypotheses of a constant motion of mean longitude, constant motion of nodes and constant motion of apsides.
- The solar radiation pressure is taken into account as a force along the Sun-Earth line which is inversely proportional to the square of the distance to the Sun. No shadow effects are considered.

A conservative value of 0.02 m^2/kg was used for the area-to-mass ratio (AMR) of the five satellites and the reflectivity coefficient C_R was set to 1.5 (see Eq. 1). Figure 6 to 10 show the perigee and apogee evolution over 200 years of these 5 satellites. It can be seen that especially Insat IIB will constitute a nearly permanent risk for active geostationary satellites. The other 4 spacecraft stay at least 100 km above GEO throughout the next 200 years. These figures also reveal an oscillation of the eccentricity with a periodicity of about 10.5 years (Sun and Moon perturbations alone cause a period of 8 to 9 years) which was observed already by Chao (1998).

Eight other spacecraft were retired in 2004. In five cases a proper reorbit manoeuvre was performed putting the spacecraft at least 300 km above GEO. The 5 satellites are: Astra 1A (88109B), GSTAR 4 (90100B, US), Insat II R (92010B, India, previously Arabsat 1C), GOES 8 (94022A, US) and PAS 6 (97040A, US). However, three satellites were abandoned at the geostationary altitude without performing any end-of-life manoeuvre. Comstar 4 (81018A, Tonga) and Zhongxing 6 (97021A, China) are now librating around the Eastern stable point. ACTS (93058B, US) was moved to 105° W already in August 2000 after it was realised that the propellant reserves revealed a much lower amount than expected. However, it was only decommisioned on 28 April 2004.

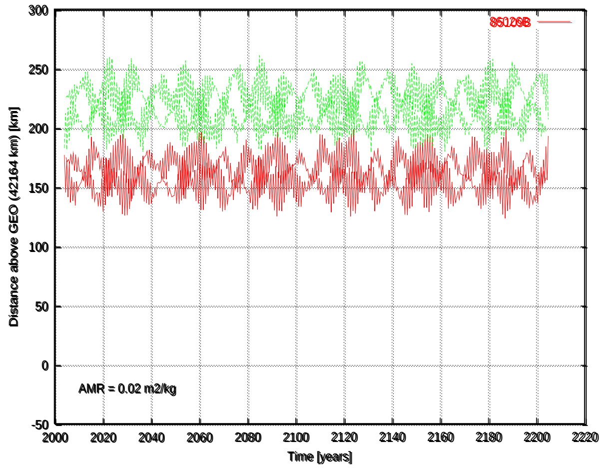

Figure 6. Evolution of perigee and apogee altitude above GEO of 1985 109 B (Morelos 2).

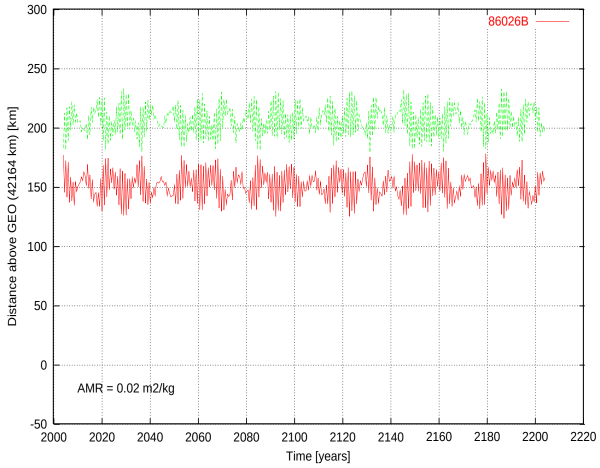

Figure 7. Evolution of perigee and apogee altitude above GEO of 1986 026 B (Brazilsat 2).

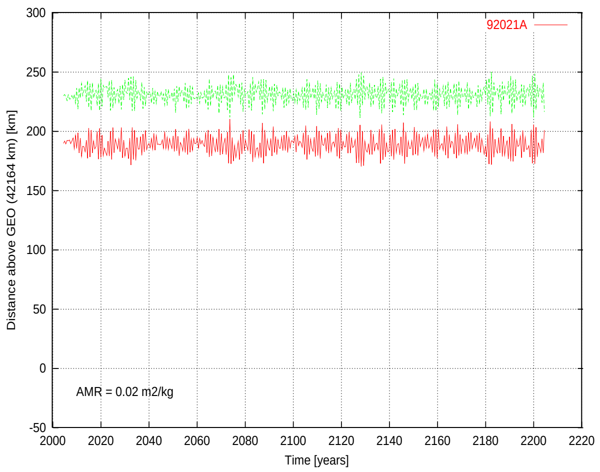

Figure 8. Evolution of perigee and apogee altitude above GEO of 1992 021 A (Telecom 2B).

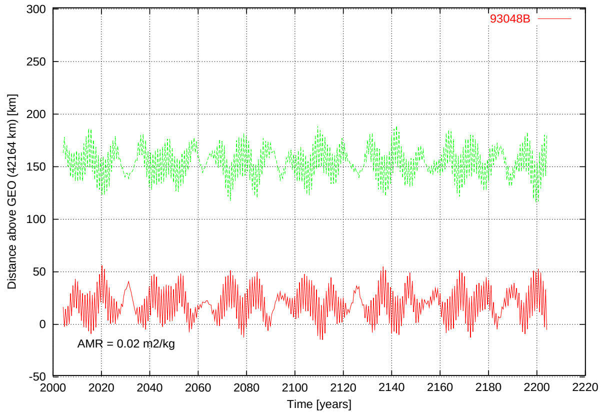

Figure 9. Evolution of perigee and apogee altitude above GEO of 1993 048 B (Insat IIB).

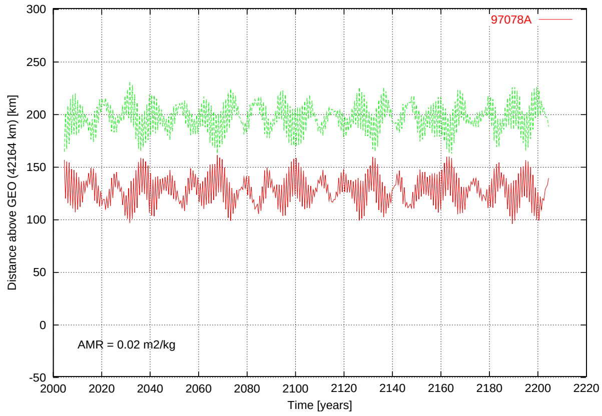

Figure 10. Evolution of perigee and apogee altitude above GEO of 1997 078 A (Galaxy 8-i).

5. REORBITING STATISTICS IN THE YEARS 1997 TO 2004

In total 117 satellites reached their end-of-life during the last eight years. According to the orbital data in the DISCOS database, 37 of these (i.e. one third) were abandoned without any reorbiting manoeuvre. 24 were abandoned in the Eastern hemisphere (mainly Russian spacecraft) and are now librating around the Eastern libration point L_1 at 75° E over India. The libration period is between 2 years (Elektro 1) and nearly 5 years (Kosmos 2224). 11 were abandoned in the Western hemisphere and are now librating around the Western libration point L_2 at 105° W. Two spacecraft were abandoned in orbits librating around L_1 and L_2 crossing nearly all longitudes during a libration period of nearly 10 years.

41 GEO spacecraft performed an end-of-life manoeuvre where the perigee was not raised above GEO + 250 km, which is the approximate reorbiting altitude calculated with Eq. 1 for typical GEO spacecraft. Some spacecraft operators reserve only a minimum amount of propellant to free their own orbital slot. The reorbited satellites will then drift slightly above the geostationary ring in a region which is declared ”protected” because it is the area where GEO satellites are drifting during station acquisition or during relocation manoeuvres.

Only 39 GEO spacecraft were reorbited in compliance with the IADC recommendations. 8 of them were Intelsat satellites, 6 Japanese, 3 Russian, 8 US American and 14 belonging to other countries, including three Eutelsat satellites. Table 2 summaries the reorbiting practices during the last eight years. Table 3 shows the owners of the spacecraft which reached end-of-life. There are some general trends to be seen: Whereas some countries like Japan or organisations like Intelsat and Eutelsat tend to comply with the general reorbit recommendations, other nations like China and Russia are more reluctant to take measures to preserve the geostationary ring.

Table 2. Reorbiting practices from 1997 to 2004

	Left around			Graveyard orbit		
	L_1	L_2	L_1/L_2	too low	IADC	Total
1997	1	2	-	6	6	15
1998	7	3	-	6	6	22
1999	5	1	-	4	5	15
2000	3	1	2	2	3	11
2001	5	1	-	6	2	14
2002	1	1	-	5	4	11
2003	-	1	-	7	8	16
2004	2	1	-	5	5	13
Total	24	11	2	41	39	117

Table 3. Reorbiting practices from 1997 to 2004 - distribution by country.

	Left around	Graveyard orbit	
	L_1 and/or L_2	too low	acc. to IADC
China	4	1	-
Intelsat	-	3	8
Japan	-	2	6
Russia	26	3	3
USA	5	13	8
Other	2	19	14
Total	37	41	39

6. UNCATALOGUED DEBRIS IN GEOSYNCHRONOUS ORBITS

The ESA 1-m telescope is used since 1999 to search for debris at geostationary altitude (36000 km above the Earth surface). The sensitivity of the telescope is limited to objects brighter than visual magnitude of 20 or 21 under good observation conditions (Flury et al. 2000). Visual magnitude of 20 corresponds to an object of about 10 cm assuming an albedo of 0.08. The observational data reveals that there are many more uncatalogued objects than catalogued ones. Since a complete scan of the geostationary region including a cross-correlation of the detections has not yet been made, it is difficult to make reliable estimates of the number of 10 cm objects in the GEO region. Nevertheless, it is expected that the number is larger than 2000. The MASTER 2001 model requires the simulation of 11 additional explosions in GEO to match the inclination and right ascension data observed in Tenerife and Zimmerwald during the last few years.

Assuming a constant increase in the number of objects in GEO from 0 satellites in 1964 to 1000 objects in 2004, the integrated product of time and number of satellites amounts to 20000 satellite-years. Assuming an explosion rate proportional to satellite-years this means there is about 1 explosion every 2000 satellite-years or in other words, currently there is a GEO explosion rate of one in two years!

Another hitherto unknown debris source was discovered by the ESA 1-m telescope (Schildknecht, 2004). Figure 11 shows a large number of objects with a mean motion of about 1 rev/day and eccentricities of up to 0.55. Liou and Weaver (2004) speculate that these objects may be similar to the thermal blankets or Multi-Layer Insulation which are known to rip off from LEO satellites and which may now have also been detected in GEO. Due to their very large area-to-mass ratios they can build up considerable eccentricities in a few months.

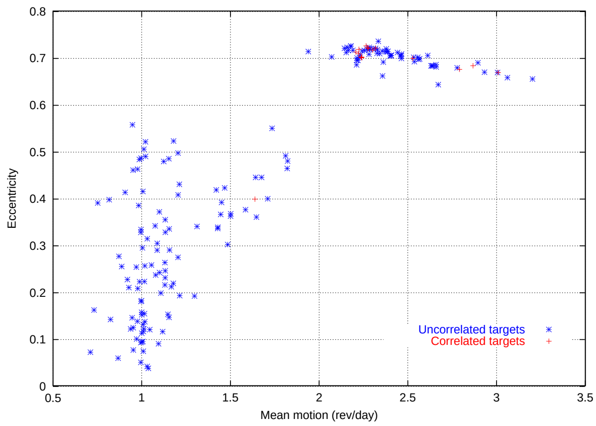

Figure 11. Eccentricity versus mean motion of objects detected with the ESA 1-m telescope between August 2002 and July 2003.

7. CONCLUSIONS

Analysis of orbital data of 869 objects in or near the geostationary orbit revealed that 143 satellites were abandoned in the past and are now librating through all longitudes of the geostationary ring. 416 objects are drifting, mostly above GEO, but many of them intrude into the protected GEO region daily. These abandoned objects pose a collision risk to the active GEO spacecraft. Therefore the reorbiting of GEO spacecraft at end-of-life is recommended since over 25 years.

In 1997 the Inter-Agency Space Debris Coordination Committee issued a world-wide accepted recommendation to reorbit GEO spacecraft by at least 235 km plus a term depending on the spacecraft characteristics (see Eq. 1). However, this recommendation is only followed in one out of three cases. During the last eight years, from 1997 to 2004, only 39 out of 117 spacecraft were properly reorbited. 41 were put in a disposal orbit with a perigee below the IADC recommended value. And 37 GEO spacecraft were completely abandoned without any end-of-life manoeuvre.

In order to preserve the unique resources which the geostationary orbit offers, a strict compliance with internationally agreed reorbiting procedures is required. As long as major space-faring nations ignore these recommendations, the collision risk will steadily increase in the geostationary ring.

The observations made with the ESA 1-m telescope reveal that the situation in the geostationary ring is even more critical than what analysis of the catalogued objects tell us. We are just about to discover the full scope of the debris problem in GEO, which was previously thought to be much less compelling than the debris problem in LEO.

ACKNOWLEDGEMENTS

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