REORBITING OF SATELLITES IN HIGH ALTITUDES

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ABSTRACT

The Inter-Agency Space Debris Coordination Committee (IADC) and UNCOPUOS request that GEO spacecraft at their end-of-life are raised to a graveyard orbit with sufficient altitude clearance to operational satellites. Based on orbital data in ESA's DISCOS database the situation near the geostationary ring (GEO) is assessed for a reference epoch in December 2008. An analysis of the orbital evolution histories of 970 objects showed that 335 of the GEO objects were controlled inside their longitude slots, 476 were drifting above, below or through GEO, 154 were captured at one of the two stable libration points, and 5 objects had an ill-defined orbit status (e.g. due to insufficient orbit data). Furthermore, there were 46 controlled satellites and 170 uncontrolled objects with no TLE information at all. Thus, the total number of known objects in the geostationary region was 1186, out of which 381 were controlled, 800 were uncontrolled and 5 could not be classified.

During the year 2008, 12 GEO spacecraft reached their end of life. Seven of them were re-orbited following the IADC guidelines, two were re-orbited with an insufficient GEO clearance and three spacecraft were abandoned without any re-orbiting manoeuvre. The re-orbiting statistics of the years from 1997 to 2008 show that the adherence to the IADC space debris mitigation guidelines is slowly improving over time.

Also the re-orbiting practice of GPS satellites is analysed. For 22 of the 56 launched GPS satellites a disposal manoeuvre was identified from the DISCOS TLE data. Since the year 2000, the orbits of the GPS satellites are usually raised by about 1000 km at end-of-life.

Finally the re-orbiting options of Galileo satellites are compared. An alternative to the currently proposed orbit raising after end-of-life is the re-orbiting into a lower orbit with the highest achievable eccentricity. It will take more than 100 years until a satellite will finally decay. But the average risk that the satellite will encounter a collision during its long journey towards its final decay is about 10^{-7} which can be considered low enough to make it an attractive re-orbiting alternative.

1. INTRODUCTION

The geostationary ring is a valuable resource currently populated by 335 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 proposed that spacecraft should be systematically removed from GEO at their end-of-mission [11]. In the same year, for the first time in space history, INTELSAT sent an aging satellite into a GEO graveyard orbit. Since then a number of guidelines and recommendations for GEO end-of-mission disposal by national and international institutions was following as described in [9] and [2]. In the early 1980s, the disposal orbit guideline of NOAA (US National Oceanic and Atmospheric Administration) was 300 km above GEO.

Also during the 1980s, the International Telecommunications Union (ITU) began addressing the issue of end-of-mission disposal and super-synchronous graveyard orbits. Although the ITU did not explicitly recommend a specific super-synchronous graveyard orbit, its definition of GSO "as a mean radius of 42,164 ± 300 km and extending to 15º north and south latitude" indirectly dictated a minimum perigee altitude of the disposal orbit of 300 km above GEO.

In 1989 ESA adopted a resolution on space debris, including as a risk reduction measure "the re-orbiting of geostationary satellites at the end of their life into a disposal orbit". Subsequently 10 ESA-controlled geostationary satellites (all except for the failed Olympus-1 satellite) were re-orbited by at least 300 km above GEO after completion of their mission.

In 1995 the International Academy of Astronautics recommended to re-orbit "geostationary satellites at end-of-life to disposal orbits with a minimum altitude increase of 300 km to 400 km above GEO depending on spacecraft characteristics" [1]. At the same time,

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national space agencies like NASA, NASDA, RKA (later ROSCOSMOS), CNES and ESA developed their own guidelines. All of these 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). The recommended minimum altitude increase (in km) was given as

$$H = 235\text{km} + 1000\text{km} \times c_R \times (A/m)/(1\ \text{kg/m}^2) \quad (1)$$

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

In view of such guidelines and recommendations one would expect that the geostationary ring is a well protected and unlittered space. However, only about 40% of all retired GEO satellites follow the internationally agreed recommendations. About 60% so far are re-boosted into a too low orbit that will sooner or later return to the GEO altitude, or they are completely abandoned in the GEO ring without any end-of-life disposal manoeuvre.

In this paper an updated survey of the GEO population, and a summary of GEO re-orbiting practices is provided for the past 12 years (1997-2008).

2. ANALYSIS OF GEO ORBITAL DATA

The basic source of information for the analysis presented here are the Two-Line Elements (TLE) generated by the US Space Surveillance Network. Updates of these TLE data are automatically downloaded and processed by ESA's DISCOS Database (Database and Information System Characterizing Objects in Space) on a daily basis. For the GEO environment characterization one TLE per week and object is considered. The GEO 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 revolutions per sidereal day, corresponding to a radius of 42,164 -2,500/ +3,150 km
- inclination lower than 30°

970 objects met these criteria as of 31 December 2008. Their orbital histories were analyzed in order to classify the objects according to six different categories:

- C_1: 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 0.3º,
- C_2: objects under longitude control (only E-W control) - the longitude is nearly constant but the inclination is larger than 0.3º,
- D: objects in a drift orbit,
- L_1: objects in a libration orbit around the Eastern stable point (longitude 75ºE),
- L_2: objects in a libration orbit around the Western stable point (longitude 105ºW),
- L_{1+2}: objects in a libration orbit around both stable points.

3. THE CURRENT STATUS OF GEO

Next to the 970 objects which fulfilled the orbital criteria by 31 Dec 2008, there are 216 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 1186. They were classified as follows:

- 381 are controlled (251 under longitude and inclination control),
- 476 are in a drift orbit,
- 154 are in a libration orbit,
- 103 are uncontrolled with no orbital elements available,
- 5 could not be classified (4 of them were recently launched and are en route to their longitude slot).
- 67 were uncatalogued but can be correlated with a launch event

Fig. 1 illustrates the fractional contributions of the different GEO categories. In ESA’s annual report "Classification of Geosynchronous Objects" [8] the status of all individual objects can be traced. In this paper we confine ourselves to some statistical data.

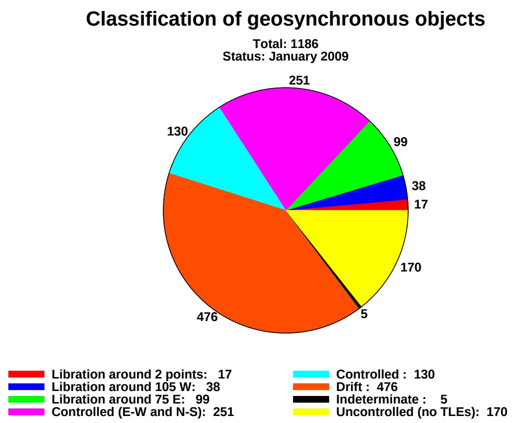

Figure 1. Number of objects in each category in Jan 2009. The 130 controlled objects consist of objects in class C_2 (only East-West station keeping) and objects where no TLEs are available.

Fig. 2 shows the number of objects under control (bottom bars), in drift orbit (intermediate bars), and in libration orbit (top bars) as a function of 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 per year were abandoned in such libration orbits (see Table 1), with a decrease in recent years to 3 or less.

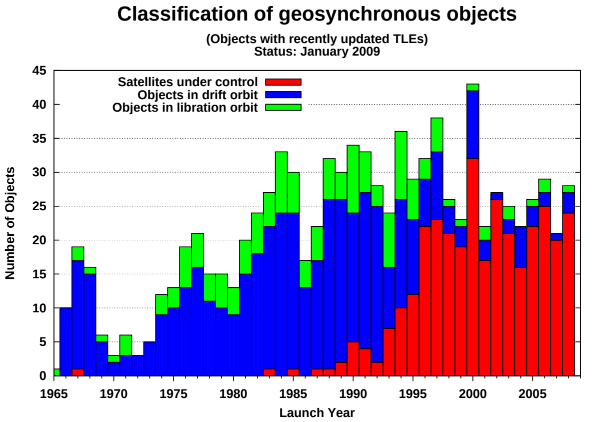

Figure 2. Number of objects in each of the defined GEO categories versus launch year. Status: Jan 2009.

Fig. 3 shows the distribution of the longitude of the 335 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 unoccupied area around 200°E, the congestion of the geostationary ring becomes evident.

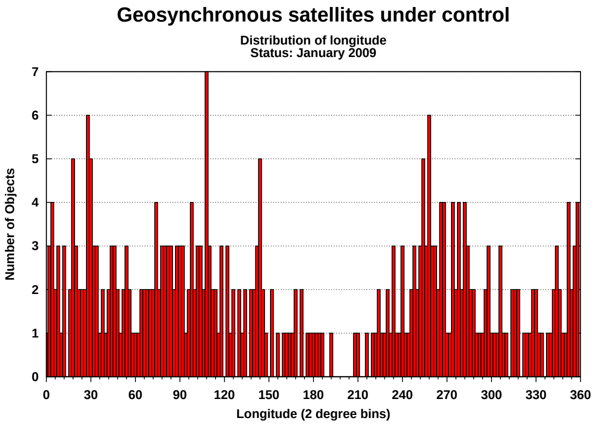

Figure 3. Distribution of the longitude of the 335 satellites under control (with updated TLEs) in 2-degree bins. Status: Jan 2009.

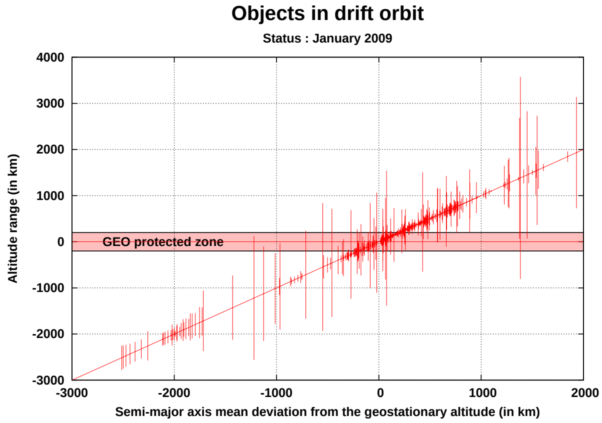

Figure 4. Distribution and altitude range of objects in a drift orbit. Status: Jan 2009.

Fig. 4 illustrates the distribution of near-GEO objects in a drift orbit. Each vertical line represents one orbit. The horizontal axis gives the mean deviation of the semi-major axis from the geostationary altitude. It is inversely proportional to the mean drift rate of the object. The vertical axis indicates the mean deviation of the perigee and apogee from the geostationary altitude. The actual orbital altitude varies between these two values. According to IADC recommendations, a satellite should be re-orbited at its end-of-life to a graveyard orbit with a perigee altitude which is approximately 300 km above the GEO ring (see Eq. 1). All lines which cross the shaded area represent satellites which were not reorbited according to the IADC guidelines. They daily intersect the 200 km protected zone around the geo-stationary ring.

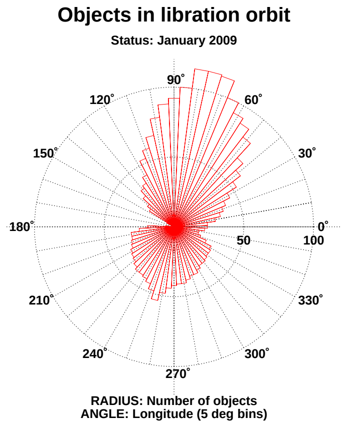

Figure 5. Distribution of the objects in libration orbit in 5° bins of geographic longitude (objects with updated TLEs only, for full explanation see description in the text). Status: Jan 2009.

Fig. 5 illustrates the distribution of near-GEO objects in a libration orbit. For every 5º longitude interval, the number of objects librating through this angular interval is given. For instance, an object librating between 64°E and 86°E is counted in the 5 intervals 62.5° to 67.5°, 67.5° to 72.5°, 72.5° to 77.5°, 77.5° to 82.5° and 82.5° to 87.5°. For the same reason, all objects classified as librating around the Eastern stable point (L_1) or around the 2 stable points (L_{1+2}) are counted in the interval 72.5°E to 77.5°E, because they all go through the longitude 75°E. Thus, the number of objects at 75°E shown in this figure is equal to the sum of the objects in the L_1 and L_{1+2} categories.

4. RECENT GEO REORBITING STATISTICS

Apart from reviewing the current situation in GEO, it is also interesting to analyze trends in disposal practices of retired GEO spacecraft over the past 12 years. Two-Line-Element sets, in weekly time intervals, as stored in ESA's DISCOS database, were processed to detect the last orbit manoeuvres of de-commissioned GEO satellites. This was considered to be the disposal date, if such a manoeuvre was performed. If a satellite was abandoned, with no end-of-life manoeuvre, then the longitude history was analyzed to determine the date when the satellite left its allocated orbital slot.

In total 179 GEO satellites reached their end-of-life during the last 12 years. According to their TLE orbital data histories, 46 of these (i.e. 26%) were abandoned with no attempt of re-orbiting. 29 satellites were abandoned in the eastern hemisphere (mainly Russian spacecraft) and are now librating around the eastern libration point L_1 at 75ºE over India. The libration period is between 2 years (e.g. Elektro 1) and nearly 5 years (e.g. Cosmos 2224). 14 spacecraft were abandoned in the western hemisphere and are now librating around the western libration point L_2 at 105ºW. Four spacecraft were abandoned in orbits librating around L_1 and L_2 crossing nearly all longitudes during a libration period of nearly 10 years.

In total, 56 GEO spacecraft (31 %) performed an end-of-life disposal manoeuvre which left the spacecraft in an orbit too close to GEO. Some spacecraft operators reserve only a minimum amount of propellant to free their own orbital slot. The insufficiently re-orbited satellites will then drift at an altitude slightly above the geostationary ring, well within the GEO protected area of ±200 km. This is an altitude shell reserved for station acquisition and re-location manoeuvres of GEO satellites.

Table 1: Summary of GEO re-orbiting practices (IADC/too low: complies/does not comply with IADC re-orbiting requirement).

	libration orbits			disposal orbits		
	L_1	L_2	L_{1+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
2005	-	1	1	5	11	18
2006	2	1	-	7	9	19
2007	1	-	-	1	11	13
2008	1	1	1	2	7	12
total	28	14	4	56	77	**179**

In the past 12 years only 77 retired GEO spacecraft (i.e. 43%) were disposed of in accordance with the IADC recommendations, either by complying with Eq. 1, or by disposal with a Sun-oriented eccentricity-vector and an initial perigee clearance, which guarantees no revisit of the GEO protected area within at least 200 years. Long-term analyses indicate that the associated disposal eccentricity may not exceed 0.003. It can be noticed that there is a trend towards "cleaner" GEO disposal operations over time. In the last 6 years, 51 out of 92 GEO spacecraft (55 %) were properly reorbited (see Table 1).

In 2008 a total of 29 GEO new spacecraft were deployed, and 12 spacecraft were retired. 7 of these were re-orbited complying with the IADC guidelines:

- Marisat 3 (76101A, US, 330 x 1205 km)
- Optus A3 (87078A, Australia, 350 x 425 km)
- Optus B1 (92054A, Australia, 275 x 330 km)
- Superbird A1 (92084A, Japan, 290 x 365 km)
- Orion 1 (94079A, US, 390 x 570 km)
- Skynet 4D (98002A, Great Britain, 305 x 330 km)
- PAS 6B (98075A, US, 241 x 393 km)

2 satellites were not properly disposed:

- Gorizont 28 (93069A, Russia, 43 x 310 km)
- Galaxy 10R (0002A, US, 170 x 190 km)

3 satellites were left in libration orbits:

- Echostar 2 (96055A, US) around L_2
- Gorizont 33 (00029A, Russia) around L_1 and L_2
- Xinnuo 2 (06048A, China) around L_1

Probably also Nigcomsat 1 (07018A, Nigeria) got stranded in a libration orbit around L_1, but this remains to be confirmed.

5. REORBITING OF GPS SATELLITES

By the end of the year 2008, 57 satellites were launched to form the Global Positioning System (GPS) of the United States. One launch failed. The remaining satellites include 10 Block-I satellites, all are no longer in service ([3], [4]), and 46 Block-II/IIA/IIR/IIR-M satellites, of which 15 are no longer in service (REF USNO1, USNO3), and hence there are currently 31 active GPS satellites. For the 25 GPS satellites that are indicated as "no longer in service" ([4], [5]), we used DISCOS TLE data to search for any disposal manoeuvres. We analysed the history of apogee and perigee altitude and tried to detect significant changes that might indicate manoeuvres. As in DISCOS historical TLEs are available with an inhomogeneous spacing in time the estimated epoch range of a disposal manoeuvre might be several weeks. During our analysis we searched for changes of the apogee and perigee height between subsequent TLE sets larger than 100 km.

According to the available DISCOS data and the selected analysis approach three no longer servicing GPS satellites have not performed a disposal manoeuvre: the Block-I satellite 1980-011A and the Block-IIA satellites 1992-079A and 1993-032A. Fig. 6 shows that for those three satellites the evolution of the perigee over time is as expected for a satellite placed in a near-circular orbit at nominal GPS altitude. The satellite 1993-032A has performed a small manoeuvre increasing the perigee, but this took place more than 20 months prior the published decommissioning date [5], which makes it unlikely that this was a disposal manoeuvre. While satellites that were manoeuvred into a disposal orbit by raising the perigee show a stable perigee height, Fig. 6 shows the decreasing perigee height of satellites not being manoeuvred. This is due to the growth of the eccentricity that may reach 0.7 within 150 years due to a resonance between the geopotential and the luni-solar perturbations ([6], [7]). As decommissioned GPS satellites may not necessarily be expected in near-circular orbits only, the growth in eccentricity has to be taken into account while defining MEO survey strategies [9]. It is worth noting that the satellite 1980-011A already has an eccentricity of 0.031 at the end of 2008, which corresponds to a difference between perigee and apogee of about 1650 km.

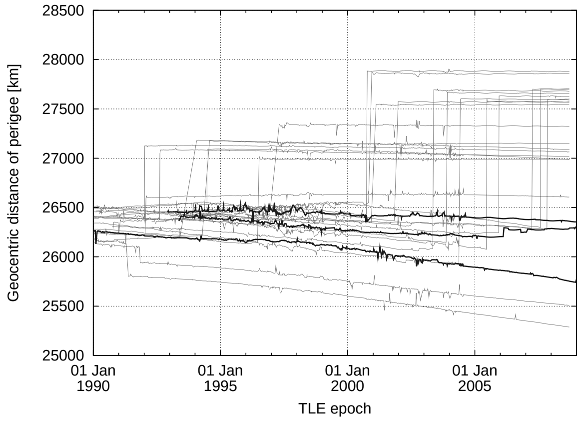

Figure 6. Evolution of the geocentric distance of the perigee for all GPS satellites labelled as "no longer in service". Three apparently not manoeuvred satellites are indicated by bold black lines. The orbital data was taken from DISCOS.

Fig. 7 gives the geocentric distance of the perigee and apogee after the detected disposal manoeuvre as a function of time, and also indicates the nominal altitude of the GPS satellites. The first nine disposal manoeuvres are those detected for the Block-I satellites followed by the 13 detected for the Block-II satellites. Apparently for the Block-II satellites the disposal manoeuvre aims to raise the perigee by about 1000 km (to above 27,500 km), as well as seeks to circularise the orbit. The analysis further indicates that two early disposal manoeuvres in 1991 did not raise the perigee, but in fact lowered the perigee below the nominal radius of about 26,600 km (satellites 1978-047A and 1980-032A), which will also lead to a growing eccentricity.

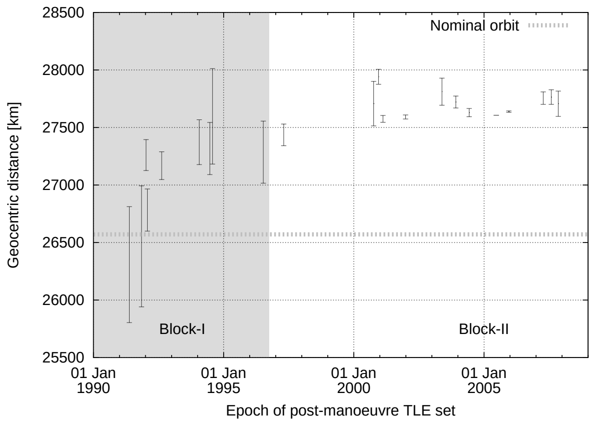

Figure 7. Geocentric distance of perigee and apogee for the first TLE-set after a detected disposal manoeuvre. The orbital data is provided by DISCOS for all GPS satellites labelled as "no longer in service".

6. REORBITING OF GALILEO SATELLITES

Galileo is a Global Navigation System composed of 30 navigation satellites and a ground infrastructure with the main control centres in Europe and a network of dedicated stations deployed around the world. The Galileo constellation is defined as a Walker 27/3/1 and is composed of 3 equally-spaced orbital planes with a nominal inclination of 56 degrees and a semi-major axis of 29,600 km. Each plane will contain nine equally-spaced satellites plus a spare satellite. The first launches are foreseen in 2010 with the full constellation deployed by the end of 2013.

The reorbiting policy for Galileo satellites consists of raising the orbital altitude by 300 km at the end-of-life. A very low initial eccentricity and the right argument of perigee shall guarantee a stable orbit that does not cross the Galileo altitude for many decades. However, the eccentricity will grow and sometime in the next century the satellites will drift through the altitude region of the navigation constellations. An alternative is the re-orbiting into an orbit with the highest achievable eccentricity (e = 0.01 if the same ΔV of 19 m/s is applied which lowers the perigee by 600 km). The eccentricity will grow until the spacecraft is entering the atmosphere. However, even when selecting the most favourable initial right ascension and argument of perigee, it will take more than 200 years until a satellite will finally decay. To achieve shorter lifetimes of 120 – 150 years, ΔVs of 60 to 100 m/s are required [12],[13].

During most of the residual lifetime, the perigee of the orbit will stay above LEO and even when the perigee drops below 2000 km, the spacecraft spend only a short fraction of their orbital period in LEO. This explains the very low collision probability for these orbits which is on the order of 10^{-7} for the entire duration of the decay.

Only 4 out of the 10 simulated disposal orbits cross some debris orbits in their LEO lifetime. A complete set of Monte Carlo runs would be needed to have a more reliable estimate of the collision risk. Nonetheless it gives a clear idea that the additional collision risk related to the transit of HEO objects in LEO does not increase in any significant way the overall LEO collision risk (and therefore has no influence on a possible collisional cascade).

Given these numbers, the reorbiting into a lower maximum-eccentricity orbit is an alternative option to dispose Galileo satellites after end-of-life.

7. CONCLUSIONS

Satellites in Low-Earth Orbit can and shall be reorbited into orbits with a residual lifetime of less than 25 years. Long-Term simulations have shown that this is a very efficient measure to stop the accumulation of space debris in LEO. However, this is economically not feasible in high-altitude orbits. The best solution for GEO spacecraft as of today is to dispose them in a graveyard orbit about 300 km above the nominal GEO altitude. The corresponding IADC and UN guidelines are followed more and more, but still about half of all satellites are not reorbited properly.

For Galileo satellites an alternative to a reorbiting to higher orbits was presented. If the perigee is lowered and oriented in an optimum direction, the satellite will finally reenter in the atmosphere of the Earth within 120 to 250 years.

ACKNOWLEDGEMENTS

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