ON THE EFFECTIVENESS OF END-OF-LIFE RE-ORBITING FOR DEBRIS MITIGATION IN GEOSTATIONARY ORBIT

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Abstract

The effect of satellite breakups over 72 yr, as a function of the end-of-life re-orbiting altitude (0-2000 km), was analyzed in terms of fragment contribution to the object density in the GEO ring, both short and long-term. On the short-term, the explosions in geostationary orbit are the most detrimental for the GEO ring environment, even though the average fragment density in the ring is never higher than 1/5 of the background, decreasing to less than 1/100 of the existing environment after 4 yr (apart for a density rebound five decades later, due to luni-solar perturbations). Spacecraft end-of-life re-orbiting is a possible mitigation solution. But the re-orbiting altitude is critical if explosions continue to occur. In order to reduce the post-event average density by an order of magnitude with respect to an explosion occurring in GEO, more than 500 km of re-orbiting are needed. Concerning the long-term environmental impact, the re-orbiting strategy supported by IADC seems adequate to guarantee, after 2-3 years, a long-term average density of fragments in the GEO ring at least two orders of magnitude below the existing background. But at least 1000 km of re-orbiting are needed to stay below that threshold also in the short-term. In conclusion, the re-orbiting strategy recommended by IADC is totally adequate in the long-term, but only if satellite passivation is quite extensively carried out.

Key Words

Debris mitigation
Geostationary ring
Long-term evolution
Orbital debris
Satellite breakups
Satellite re-orbiting

Abbreviations

ASAP	Artificial Satellite Analysis Program
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
CLDSIM	CLoud Debris SIMulator
cm	centimeter
CNUCE	former Centro Nazionale Universitario di Calcolo Elettronico
g	gram
GEO	GEostationary Orbit
IADC	Inter-Agency space Debris Coordination committee
JPL	Jet Propulsion Laboratory
km	kilometer
m	meter
mm	millimeter
yr	year

Introduction

Since the beginning of the space age, the geostationary orbit (GEO) has been regarded as a fundamental resource for the present and the future of the humankind. Today, a large fraction of space launches (30-40%) and satellites put in orbit are reserved for missions in GEO. As of 31 December 1999, 796 objects resulted present in the geosynchronous region, even though the operational spacecraft were just 30-35% of that figure (Hernandez and Jehn, 2000).

Due to the very rapid increase of spacecraft and apogee kick motors in the geosynchronous region, a growing concern matured in the 1980s regarding the possible overcrowding of GEO, jeopardizing the long-term exploitation of such irreplaceable orbit (Hechler and Van der Ha, 1981; Fusco and Buratti, 1984). The risk of collision between space objects in GEO was estimated, in particular to devise affordable and effective end-of-life disposal measures, such as satellite re-orbiting (Chobotov, 1990). In the following decade it became clear that also spacecraft and upper stage breakups contribute to the GEO debris environment. Extensive investigations of its long-term evolution, based on a simple object accumulation model, were carried out in Japan (Yasaka and Ishii, 1992; Yasaka, 1994; Yasaka, et al., 1999), while other authors studied the short (Kamprath and Jenkin, 1998) and medium-term (Anselmo and Pardini, 2000) collision risk represented by explosions affecting the geostationary ring.

In order to preserve the geostationary orbit for future use, the Inter-Agency Space Debris Coordination Committee (IADC) proposed and endorsed a re-orbiting strategy for end-of-life GEO satellites (IADC, 2000). They should be disposed to a region above GEO and passivated, in order to reduce the risk of inadvertent explosions. The recommended perigee of the disposal orbit should be higher of the geostationary altitude by an amount ΔH (km) given by

$$\Delta H = 235 + C_r \times 1000 \times A / M \qquad (1)$$

where A is the satellite average cross-sectional area (m^2), M is the satellite mass (kg) and C_r is a radiation pressure corrective coefficient, typically between 1 and 2, specifying the amount of solar radiation transmitted, absorbed and reflected by the spacecraft (IADC, 2000).

The aim of this paper is to apply a new modeling approach and specific software tools (Anselmo and Pardini, 2000) to investigate the effectiveness of end of life re-orbiting for long-term collision risk mitigation in GEO. Several low intensity satellite explosions, for $0 \leq \Delta H \leq 2000$ km, were simulated and accurately propagated for 72 years, including all the relevant perturbations. For each fragmentation, the additional contribution to the object density in GEO was computed as a function of time, debris size and right ascension (i.e. position along the ring). These results were therefore compared with the debris background, in order to assess the additional collision risk entailed by each specific fragmentation event and the long-term effectiveness of the IADC recommendations.

Simulated Explosions

A low intensity explosion (Su and Kessler, 1985; Reynolds, 1990) of a 2000 kg spacecraft was simulated at 8 different altitudes in between 0 and 2000 km above the geostationary altitude (Tables 1 and 2). The breakups were modeled using the CLDSIM software developed at CNUCE (Pardini, 1995), while the resulting debris clouds, consisting of 1734 fragments larger than 1 mm, were propagated for 72 years with a modified, multi-object version of the ASAP numerical integrator developed at JPL (Kwok, 1987). The perturbations included were the geopotential (8 x 8 gravity field), the luni-solar attraction and the radiation pressure with eclipses.

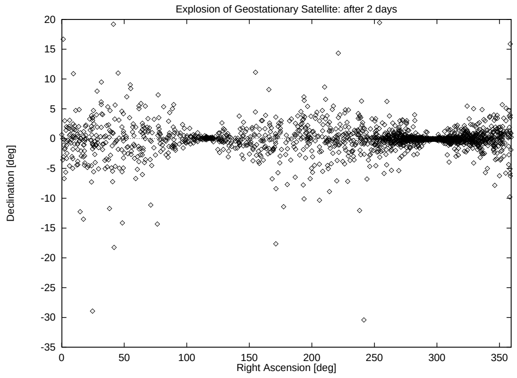
Table 1. Breakup altitudes above GEO

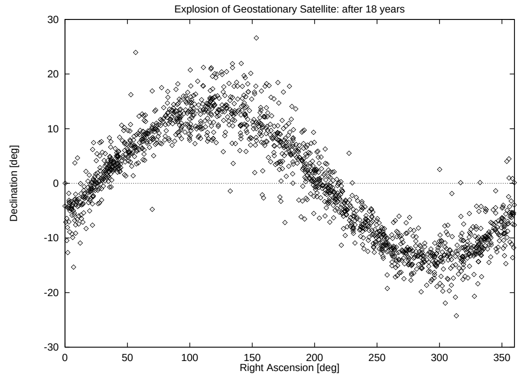
Simulation Number	Altitude above GEO (km)
1	0
2	100
3	200
4	300
5	400
6	500
7	1,000
8	2,000

Table 2. Characteristics of the simulated fragmentation events

Explosion epoch	11 May 1999
Explosion right ascension	298°
Explosion declination	0°
Fragments ≥ 1 mm	1734
Fragments ≥ 1 cm	1625
Fragments ≥ 10 cm	689
Maximum debris ΔV	1.8 km/s

The debris clouds produced by the simulated explosions were propagated for 72 years, saving the results at intermediate time steps (2 days, 1 year, 6, 12, 18, 24, 30, 36, 42, 48, 54, 60, 66 and 72 years). The following set of figures provides the time evolution of the debris orbital distribution (right ascension versus declination) for the explosions in geostationary orbit and 500, 1000 and 2000 km above the geostationary altitude.


Explosion of Geostationary Satellite: after 2 days
Declination [deg]
Right Ascension [deg]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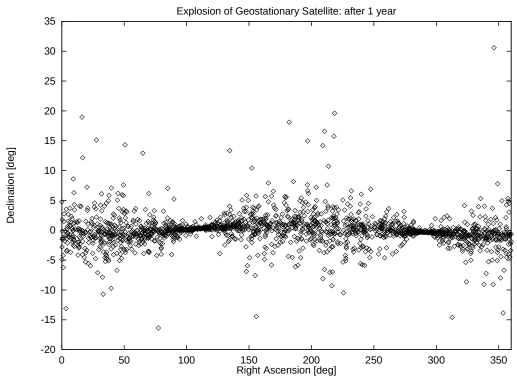
Right Ascension [deg]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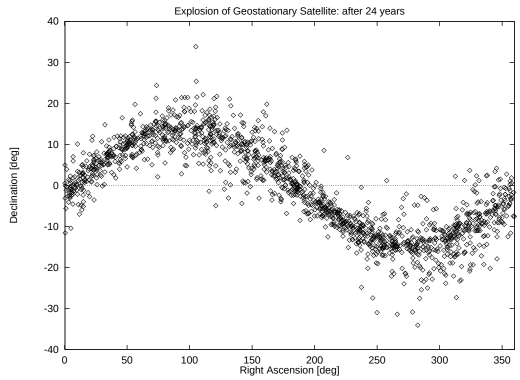
Right Ascension [deg]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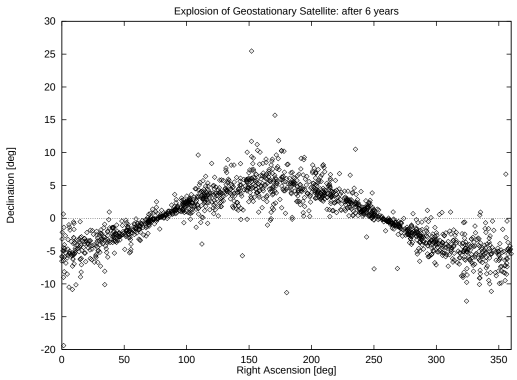
Declination [deg]
Right Ascension [deg]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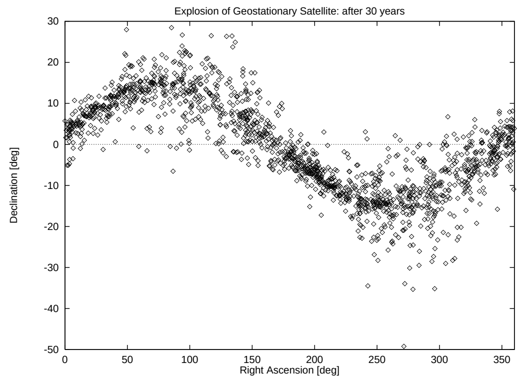
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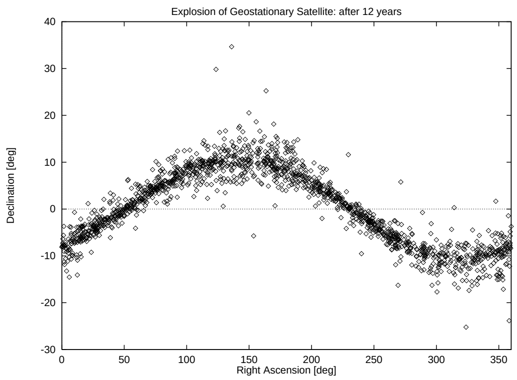
Right Ascension [deg]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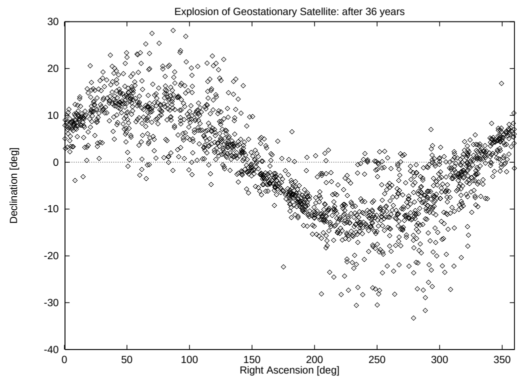
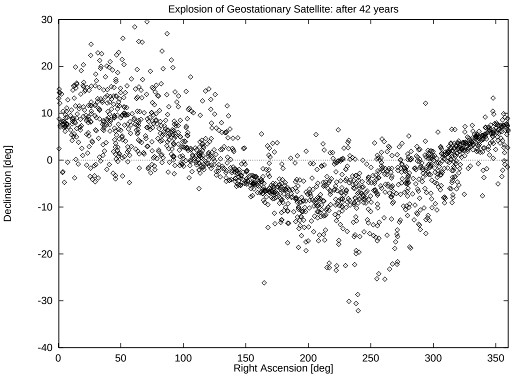

Explosion of Geostationary Satellite: after 36 years
Declination [deg]
Right Ascension [deg]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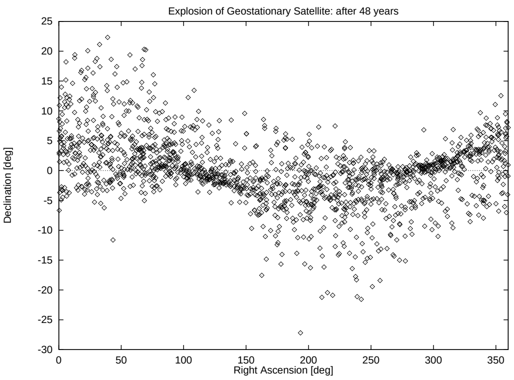
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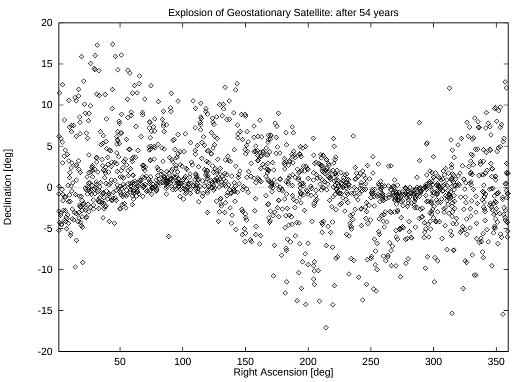
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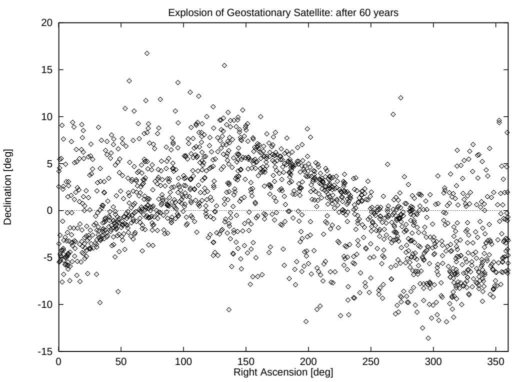
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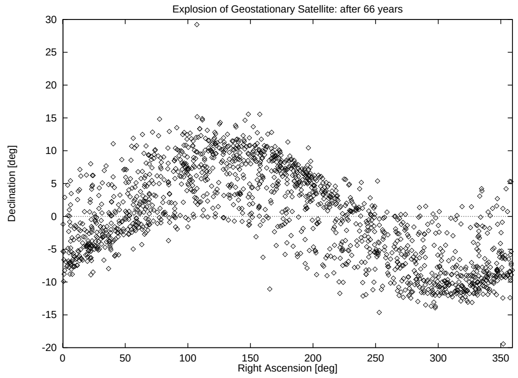
Right Ascension [deg]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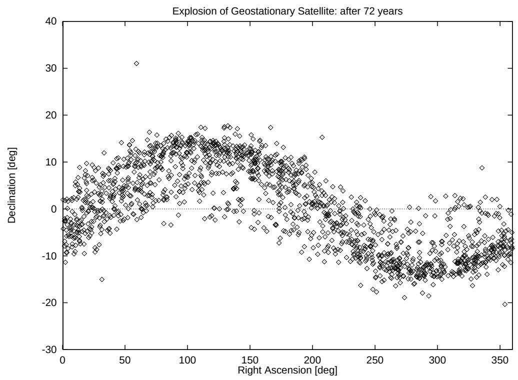
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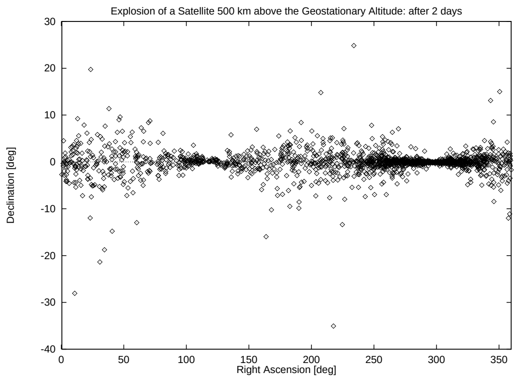
Right Ascension [deg]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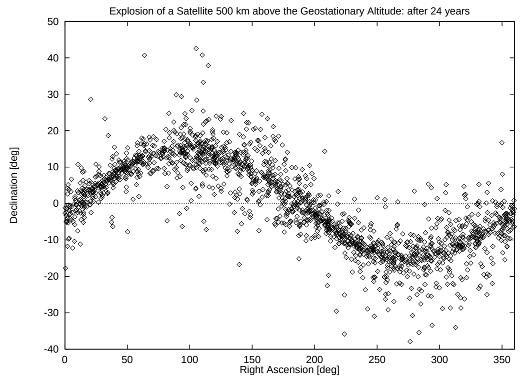
Right Ascension [deg]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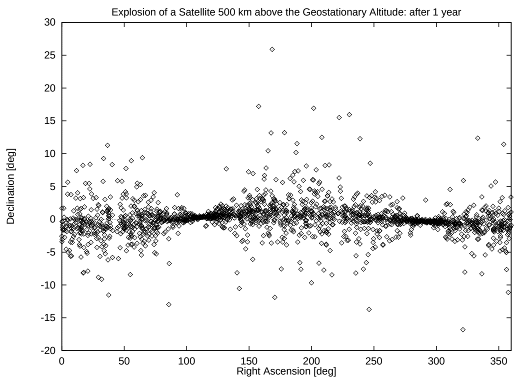
Right Ascension [deg]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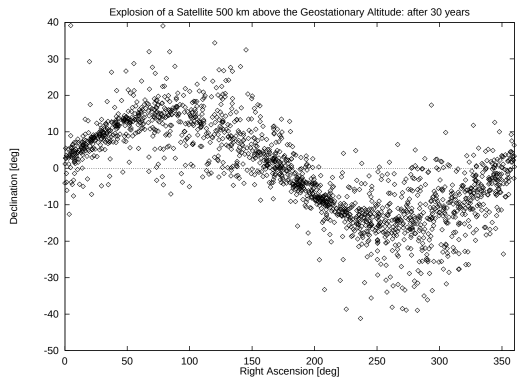
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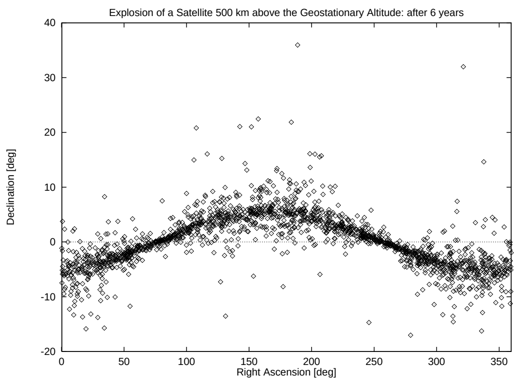
Right Ascension [deg]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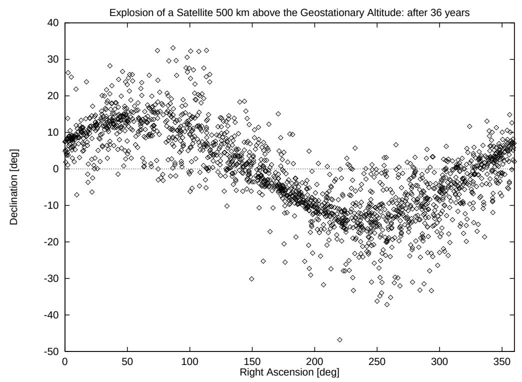
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Declination [deg]
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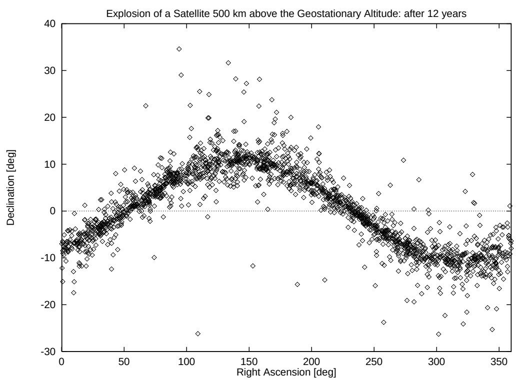
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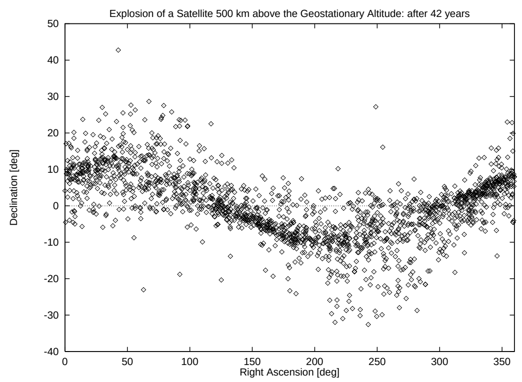
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Declination [deg]
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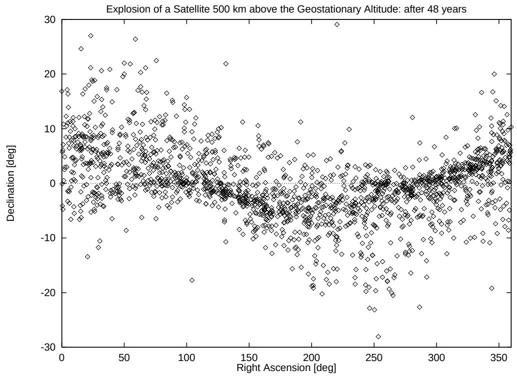
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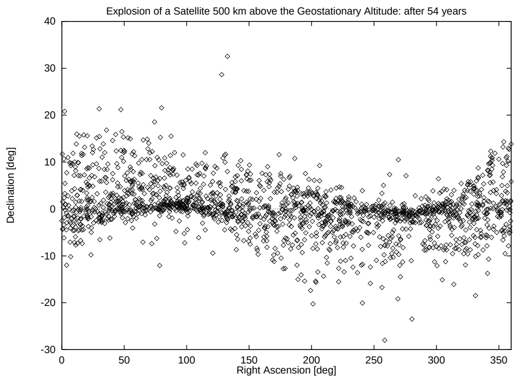
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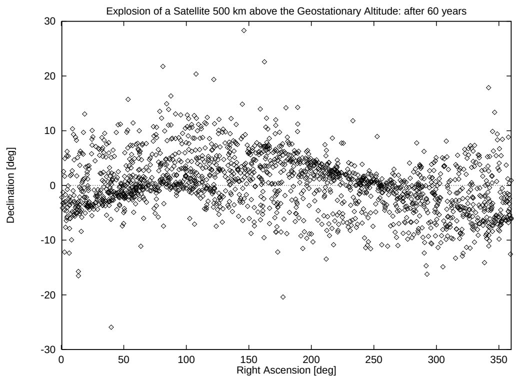
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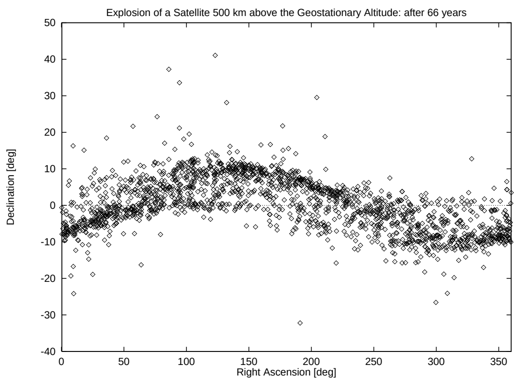
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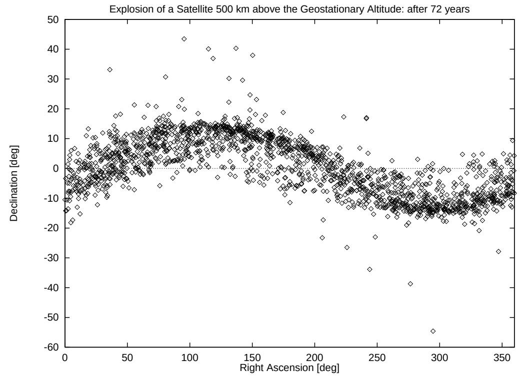
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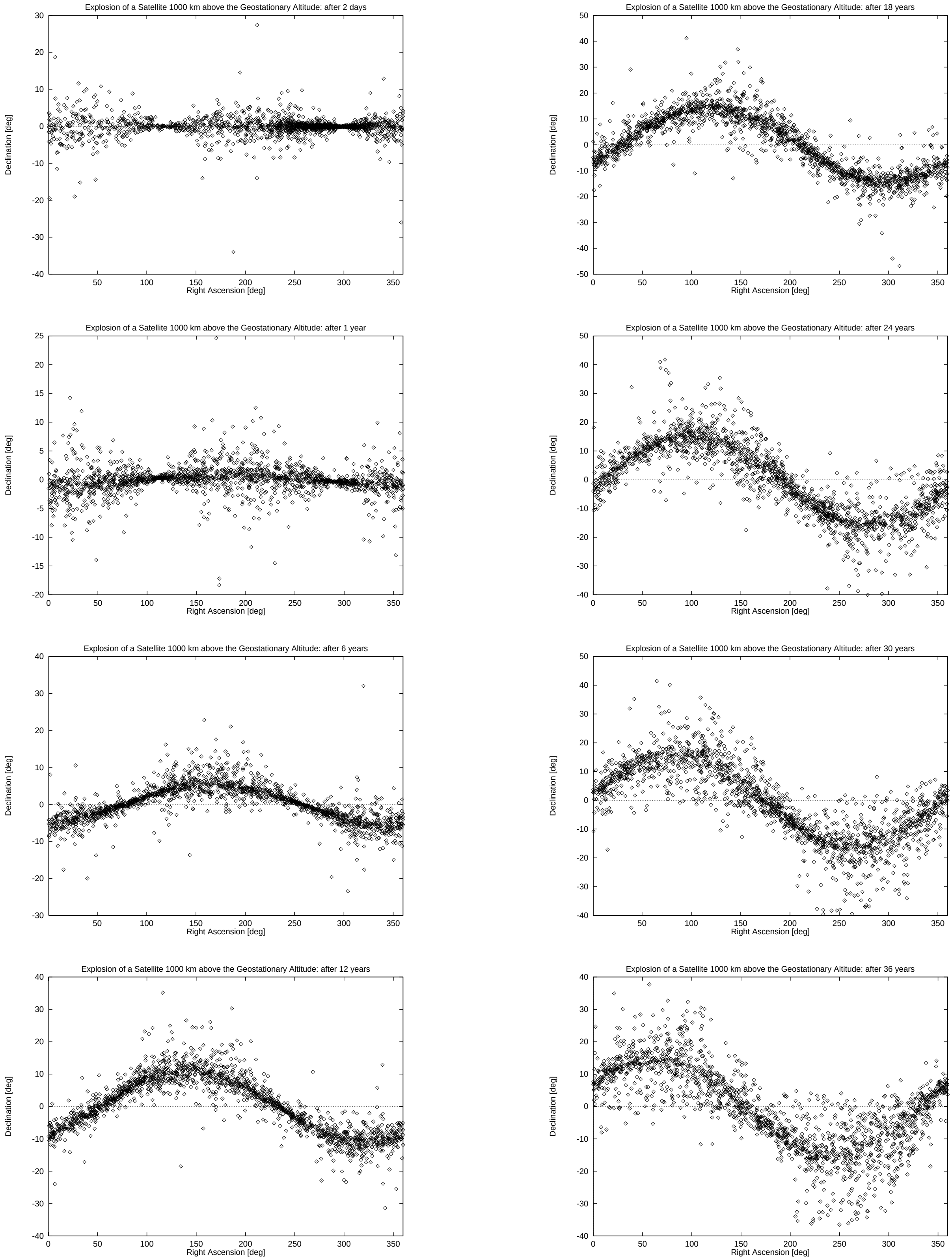
Explosion of a Satellite 1000 km above the Geostationary Altitude: after 2 days
Explosion of a Satellite 1000 km above the Geostationary Altitude: after 18 years
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Explosion of a Satellite 1000 km above the Geostationary Altitude: after 24 years
Explosion of a Satellite 1000 km above the Geostationary Altitude: after 6 years
Explosion of a Satellite 1000 km above the Geostationary Altitude: after 30 years
Explosion of a Satellite 1000 km above the Geostationary Altitude: after 12 years
Explosion of a Satellite 1000 km above the Geostationary Altitude: after 36 years
Declination [deg]
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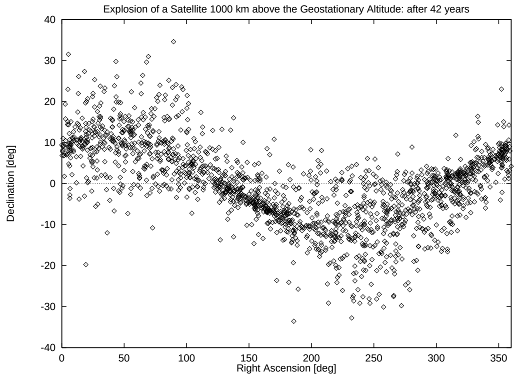
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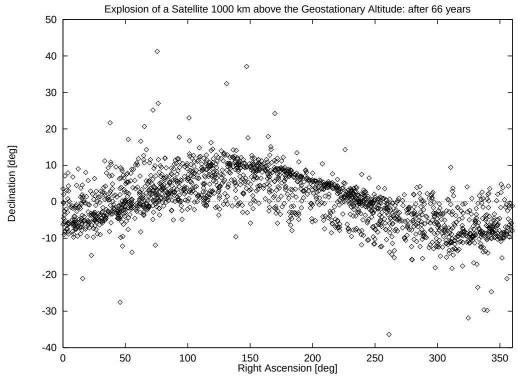
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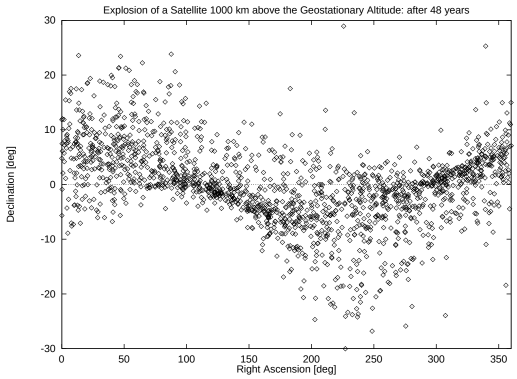
Explosion of a Satellite 1000 km above the Geostationary Altitude: after 48 years
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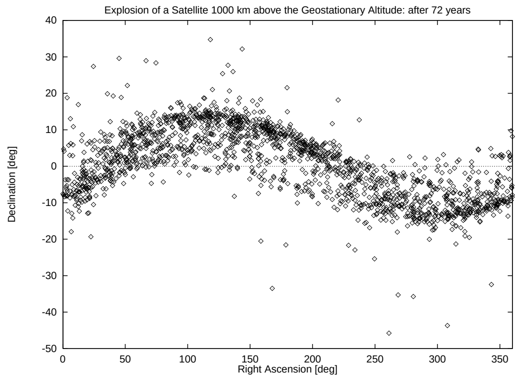
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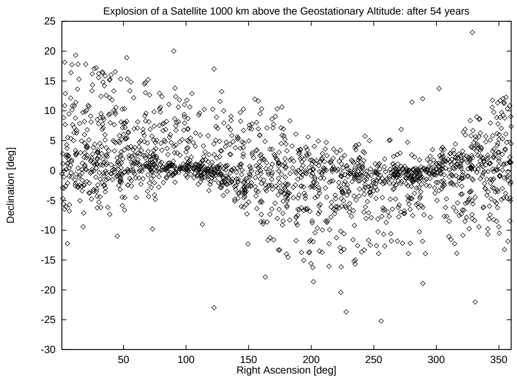
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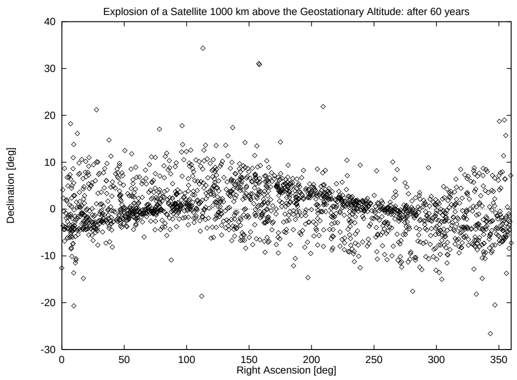
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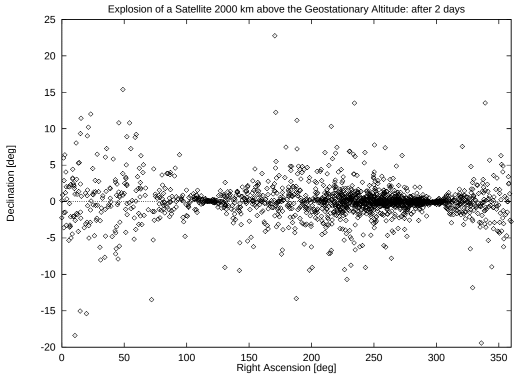
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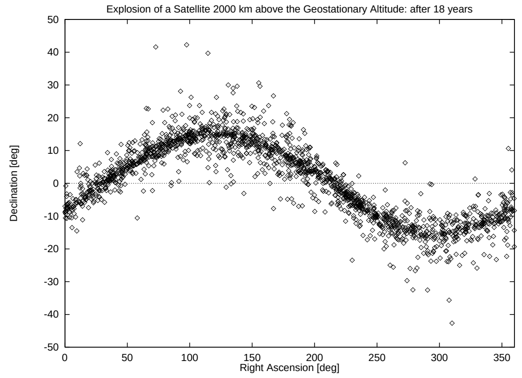
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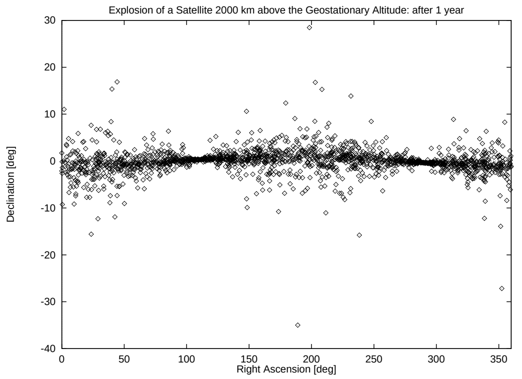
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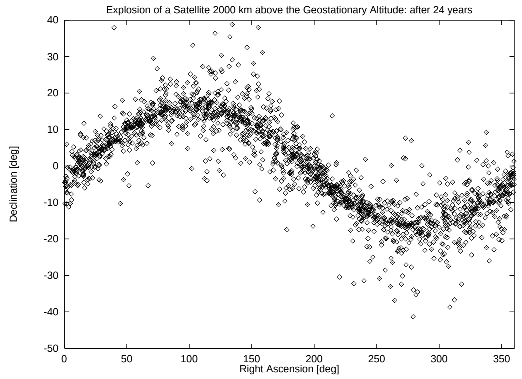
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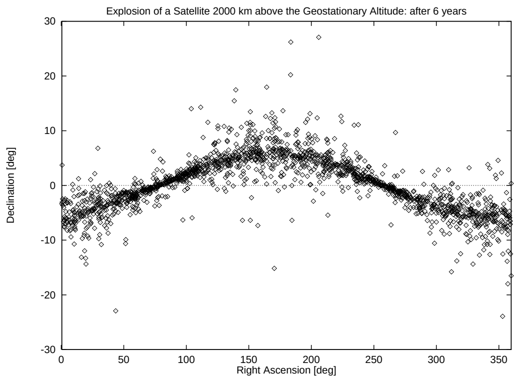
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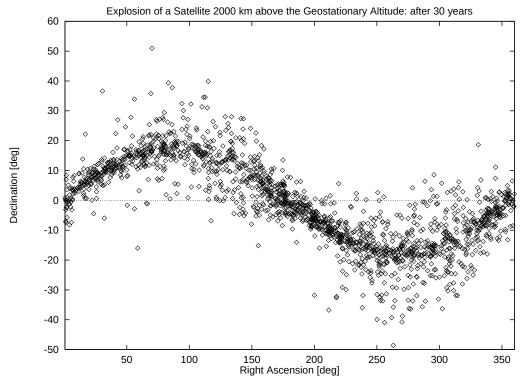
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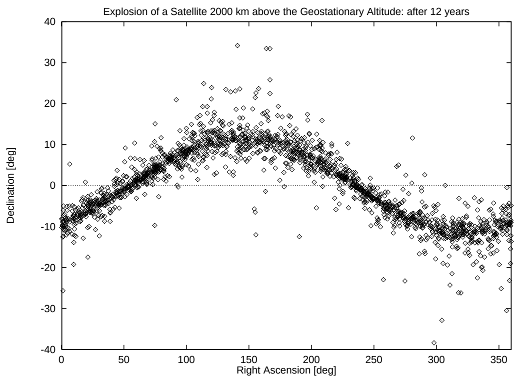
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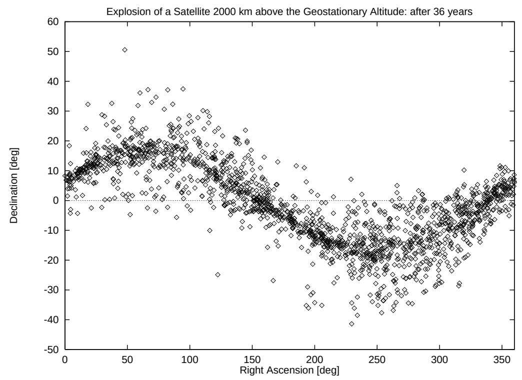
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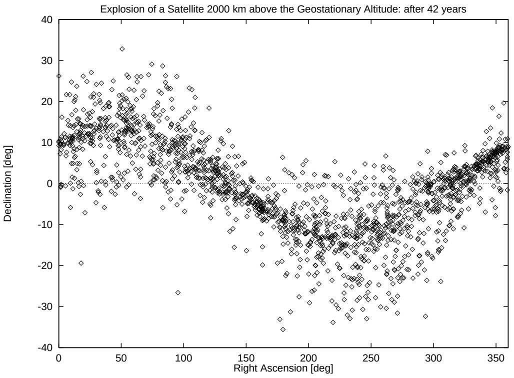
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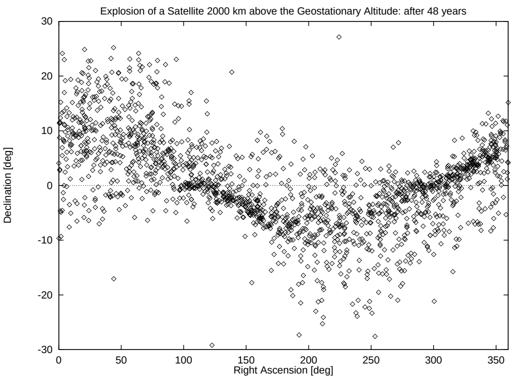
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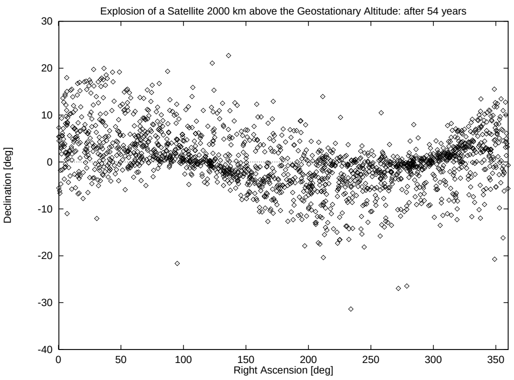
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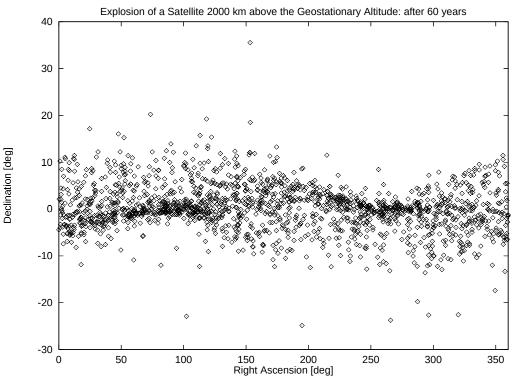
Declination [deg]
Right Ascension [deg]


Explosion of a Satellite 2000 km above the Geostationary Altitude: after 60 years
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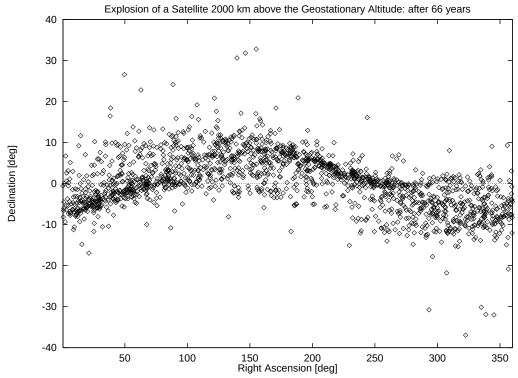
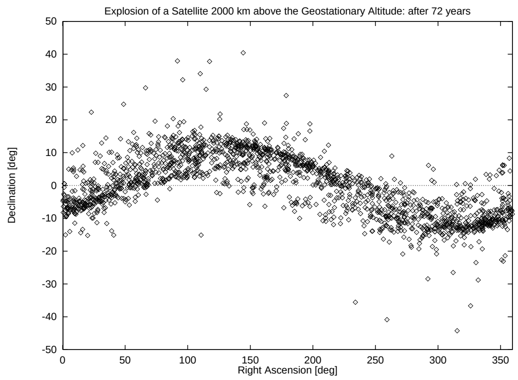
Right Ascension [deg]


Explosion of a Satellite 2000 km above the Geostationary Altitude: after 66 years
Declination [deg]
Right Ascension [deg]


Explosion of a Satellite 2000 km above the Geostationary Altitude: after 72 years
Declination [deg]
Right Ascension [deg]

Debris Density in the Geostationary Ring

The aim of the analysis presented in this paper was to evaluate the effectiveness of end of life re-orbiting to mitigate the effects of accidental explosions on the GEO ring, where most of the active synchronous satellites spend their operational life. The GEO ring was defined as the volume of space centered on the geostationary orbit (mean altitude of 35,786 km, zero inclination), ± 75 km in altitude and ± 0.1° in declination.

The object density in the GEO ring was obtained in the following way (Anselmo and Pardini, 2000):

1. The GEO ring was subdivided in right ascension sectors, or cells, of assigned amplitude;
2. At any given epoch after the simulated explosion, the mean anomaly intervals ΔM, corresponding to the orbital crossings of the right ascension cells in the GEO ring, were numerically computed for each debris produced by the simulated explosions;
3. Taking into account the i^{th} debris diameter d and fractional contribution per orbit $\Delta M_{ij} / 2\pi$, it was then easy to compute the average object density ρ_j in the j^{th} right ascension cell:

$$\rho_j(d) = \frac{\sum_i^N \frac{\Delta M_{ij}}{2\pi}}{V_j} \tag{2}$$

with the cell volume V_j given by:

$$V_j = \left(2R_0{}^2 + \frac{1}{6}\Delta R^2\right)\sin\frac{\Delta\delta}{2}\,\Delta R\cdot\Delta\alpha \tag{3}$$

where R_0 is the geostationary orbit mean radius vector, and ΔR, $\Delta\delta$ and $\Delta\alpha$ define the cell size in altitude, declination and right ascension, respectively.

Results

The debris clouds produced by the simulated explosions were propagated for 72 years, saving the results at intermediate time steps. Therefore, any saved file provided a snapshot of the debris orbital distribution at a particular explosion elapsed time. By using the mathematical approach described in the previous section, it was then possible to translate that orbital distribution into the corresponding debris density in the GEO ring, making possible a comparison with the actual background environment.

The background debris density in the GEO ring was estimated by using the CNUCE orbital debris reference model (Pardini et al., 1998), based on the simulation of past fragmentation events and updated to January 1, 1999. The average background density found was 3.76×10^{-8} km^{-3} for debris larger than 1 mm, 3.50×10^{-8} km^{-3} for debris larger than 1 cm, and 3.47×10^{-8} km^{-3} for debris larger than 10 cm. However, these values must be considered a lower limit, because the knowledge of the environment at GEO altitude is still quite incomplete, even for large objects (Talent et al., 1997).

Fragmentation in GEO

The low intensity explosion of an operational geostationary satellite produces a sizable amount of debris affecting the GEO ring. In the days following the event, the peak debris density close the explosion right ascension is about 5 and 3 times higher than the background, respectively for particles with diameter d larger than 1 and 10 cm. The corresponding average densities along the GEO ring – 6.94×10^{-9} km^{-3} ($d \geq 1$ cm) and 5.09×10^{-9} km^{-3} ($d \geq 10$ cm) – are approximately 1/5 and 1/7, respectively, of the debris background.

In less than 1 yr the peak density decreases below the background environment, while the average density is reduced by a further factor 5. The orbital plane evolution, due mainly to the luni-solar perturbations, reduces significantly, in a few years, the intervals of right ascension crossed by the fragments. But the debris orbital inclinations come back close to zero about 54 yr after the explosion, with a new increase of the density in the overall GEO ring. Nevertheless, the orbital perturbations, including the solar radiation pressure, have enough time to increase the eccentricities and spread the nodes, relieving the burden on the GEO ring, with peak debris densities lower by at least one order of magnitude with respect to the background. For $d \geq 1$ cm, the peak and average densities are, respectively, 3.75×10^{-9} km^{-3} and 7.04×10^{-10} km^{-3}, while for $d \geq 10$ cm they are 3.49 $\times 10^{-9}$ km^{-3} and 5.80×10^{-10} km^{-3}. After 72 yr, the average contribution of the explosion fragments to the GEO ring environment is reduced to at least 1/400 of the background.

Fragmentation above GEO

The set of figures and tables (Tables 3-10) presented in the following of this report show the immediate effect on the GEO ring of explosions occurring at varying altitudes above the geostationary altitude. For a typical exploding satellite, just 100 km above GEO are sufficient to reduce the peak debris density in the GEO ring at a level comparable to the existing background, and the average density one order of magnitude below. However, in order to guarantee peak densities at least one order of magnitude lower than the background, the explosion should occur 400 km above GEO, while to have average fragments densities two orders of magnitude lower than the existing environment, the explosion should occur 1000 km above the geostationary altitude.

Due to obvious kinematics, for explosions occurring above the geostationary orbit, the peak debris density in the GEO ring cannot lie exactly at the explosion right ascension. However, up to 300 km, the peak density soon after the explosion can still be found around the explosion right ascension. At 400 km, comparable density peaks can be observed both around the explosion right ascension and 180° apart. Above 400 km, the peak debris density is always observed 180° apart from the explosion right ascension. To this change of geometry it does not correspond a further strong decrease of the peak density at higher altitudes. For instance, soon after the event, the peak density in the GEO ring due to an explosion occurred 500 km above is slightly higher than that observed if the explosion had occurred 100 km below. Even for an explosion occurring 2000 km above GEO, the peak density remains 1/20 – 1/30 of the existing background.

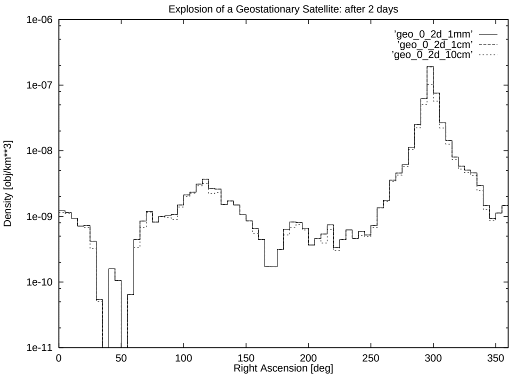
The long-term evolution of the debris clouds is quite complex. The figures and tables (Tables 3-10) given in the following of this report show the time evolution of the average fragment density as a function of debris size and explosion altitude. It is clear than even after several decades the contribution to the GEO ring environment can be small, but not always negligible. A 300 km re-orbiting altitude may by sufficient to maintain the long-term average density of fragments larger than 1 cm in the GEO ring below 1/100 of the existing background, but only a re-orbiting above 1000 km may guarantee the same also in the 2-4 yr following the explosion.

A first set of figures shows the debris density in the geostationary ring at various time steps and for each simulated explosion.

It follows a set of tables (3-10) and figures showing the time evolution of the average fragment density and peak density, in the geostationary ring, as a function of debris size (1 cm and 10 cm) and explosion altitude. The definitions adopted in the tables are the following:

- time: elapsed time from the explosion event, in years;
- 1cm_ave: average fragment density of debris larger than 1 cm, in number of objects per km^{-3};
- 1cm_max: peak fragment density of debris larger than 1 cm, in number of objects per km^{-3};
- ra_max: right ascension corresponding to the peak density of centimeter objects, in degrees;
- 10cm_ave: average fragment density of debris larger than 10 cm, in number of objects per km^{-3};
- 10cm_max: peak fragment density of debris larger than 10 cm, in number of objects per km^{-3};
- ra_max: right ascension corresponding to the peak density of decimeter objects, in degrees.

The last two figures illustrate the long term evolution of the average fragment density in the geostationary ring, as a function of debris size and explosion altitude.


Explosion of a Geostationary Satellite: after 2 days
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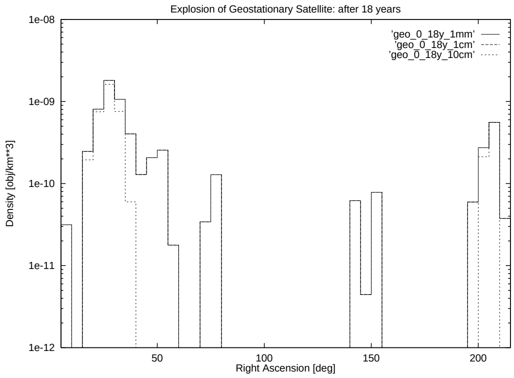
'geo_0_2d_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of Geostationary Satellite: after 18 years
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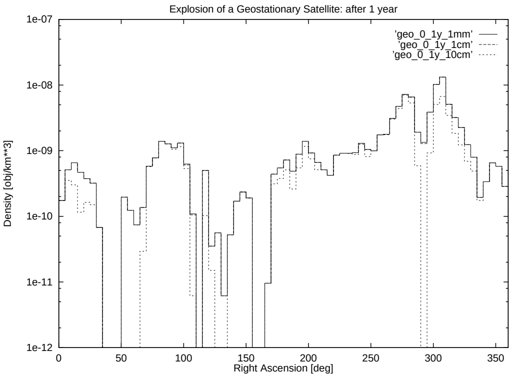
'geo_0_18y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Geostationary Satellite: after 1 year
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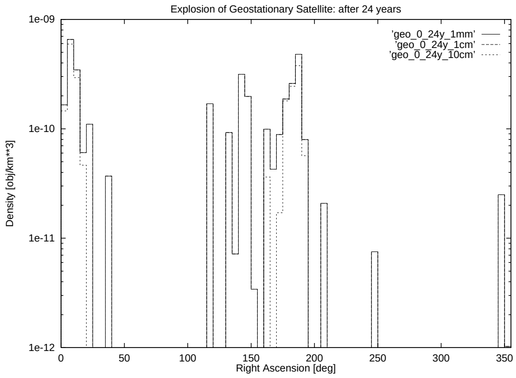
Density [obj/km**3]
Right Ascension [deg]


Explosion of Geostationary Satellite: after 24 years
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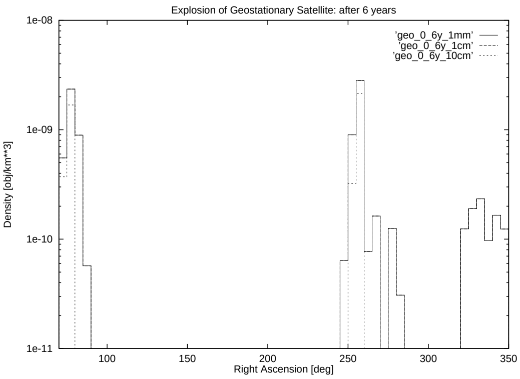
Density [obj/km**3]
Right Ascension [deg]


Explosion of Geostationary Satellite: after 6 years
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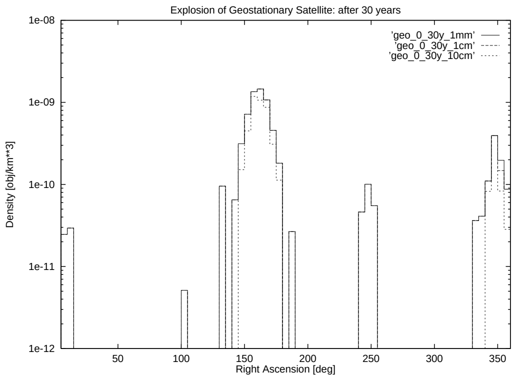
Density [obj/km**3]
Right Ascension [deg]


Explosion of Geostationary Satellite: after 30 years
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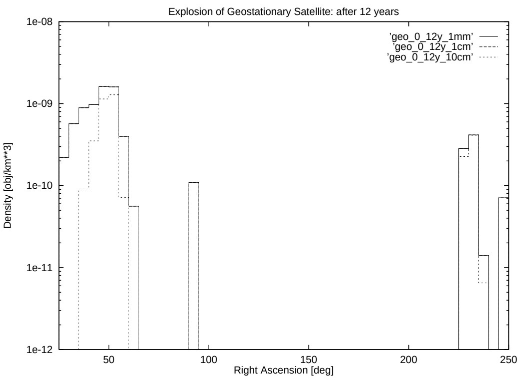
Right Ascension [deg]


Explosion of Geostationary Satellite: after 12 years
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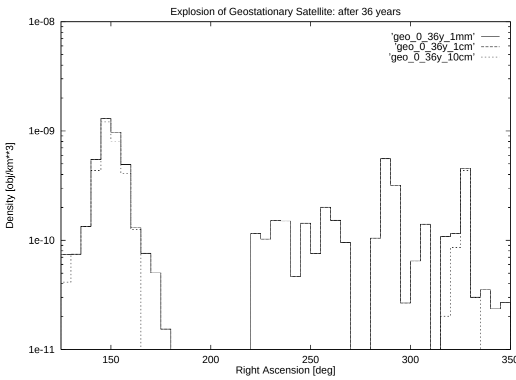
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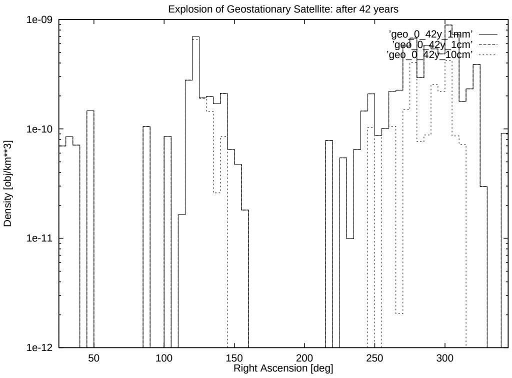
Right Ascension [deg]


Explosion of Geostationary Satellite: after 42 years
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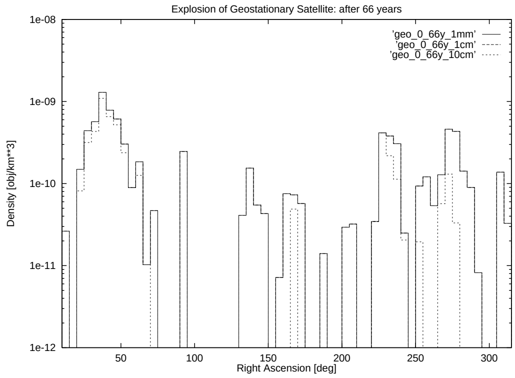
Right Ascension [deg]


Explosion of Geostationary Satellite: after 66 years
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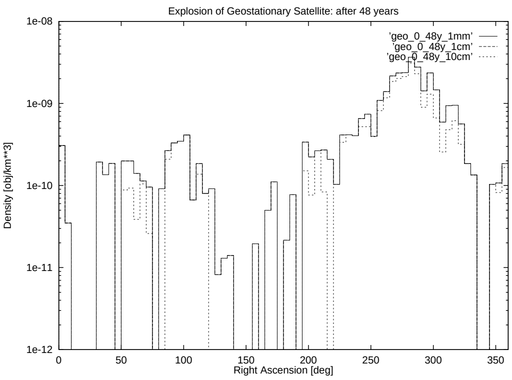
Right Ascension [deg]


Explosion of Geostationary Satellite: after 48 years
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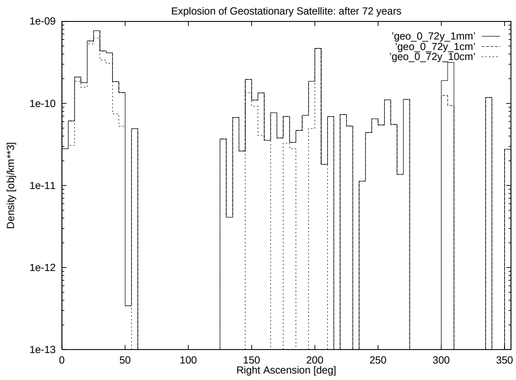
Explosion of Geostationary Satellite: after 72 years
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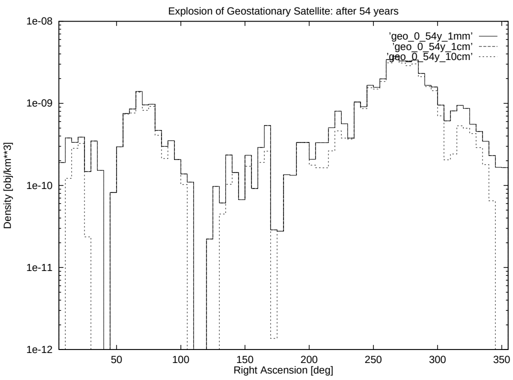
Explosion of Geostationary Satellite: after 54 years
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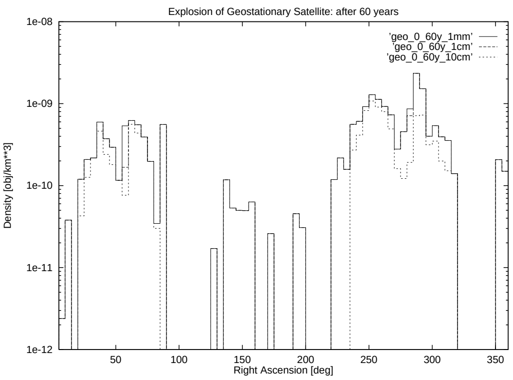
Right Ascension [deg]


Explosion of Geostationary Satellite: after 60 years
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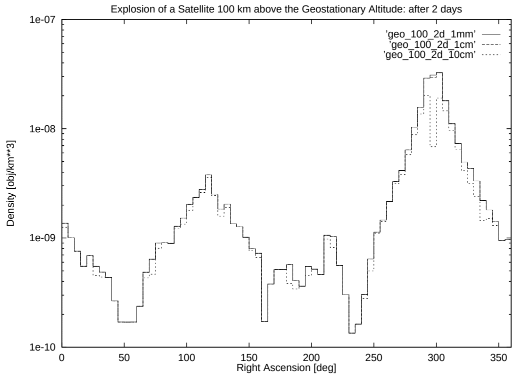
Right Ascension [deg]


Explosion of a Satellite 100 km above the Geostationary Altitude: after 2 days
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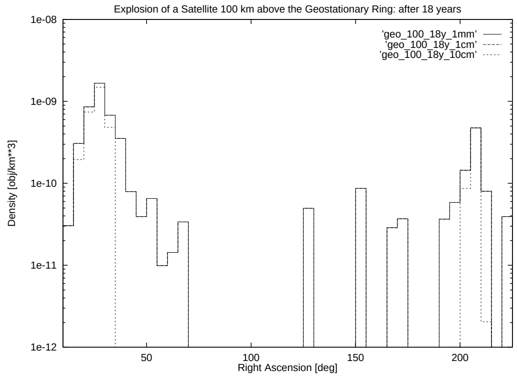
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 100 km above the Geostationary Ring: after 18 years
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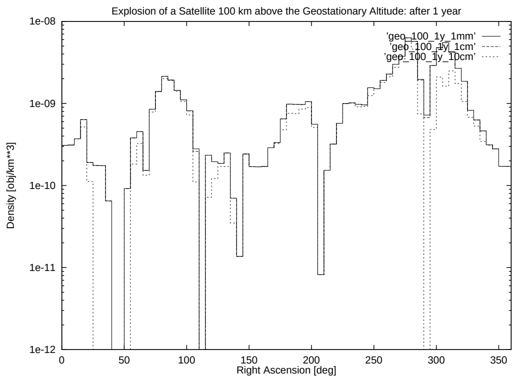
Right Ascension [deg]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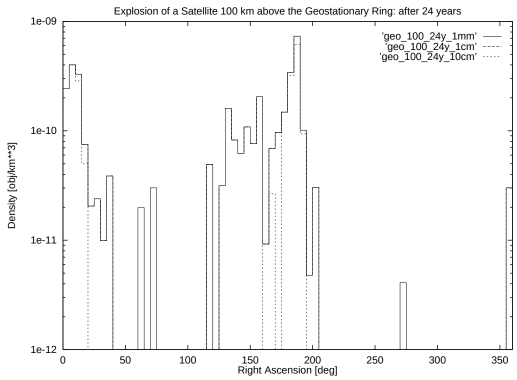
Right Ascension [deg]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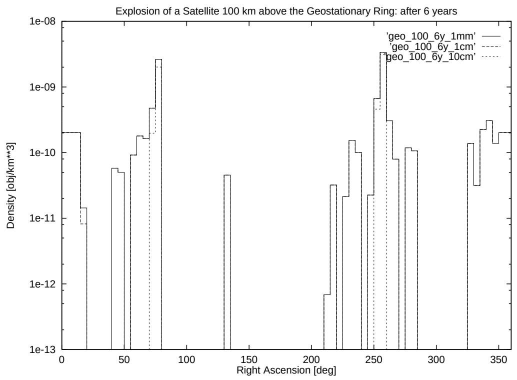
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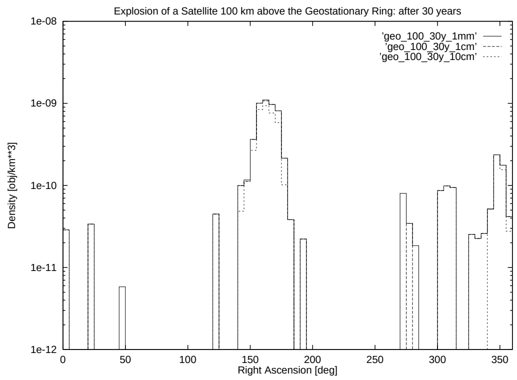
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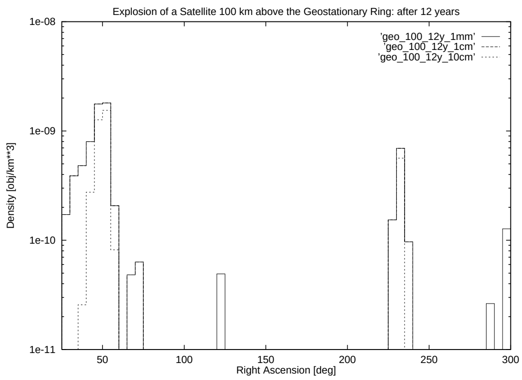
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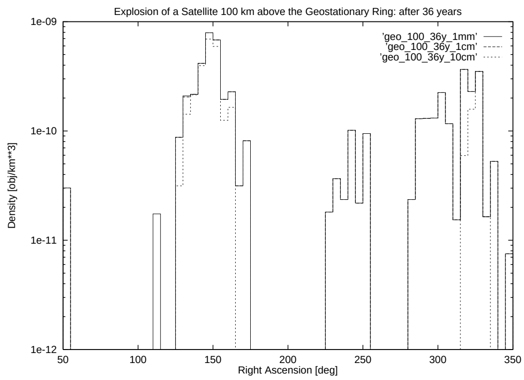
Right Ascension [deg]


Explosion of a Satellite 100 km above the Geostationary Ring: after 36 years
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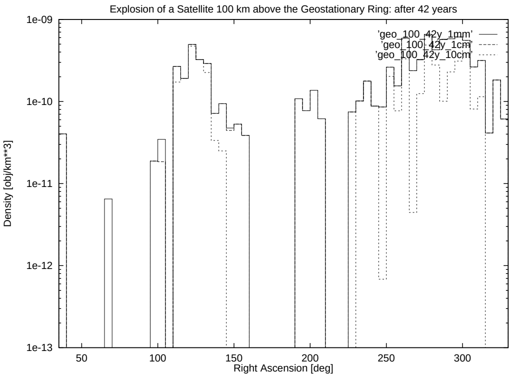
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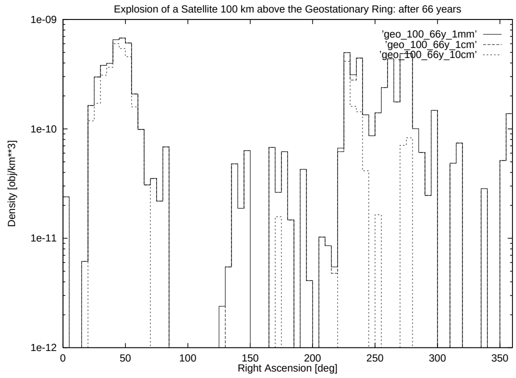
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 100 km above the Geostationary Ring: after 66 years
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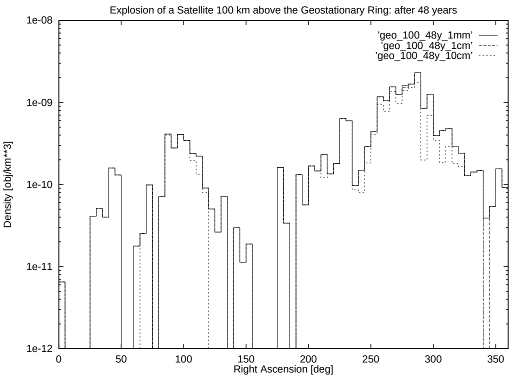
Explosion of a Satellite 100 km above the Geostationary Ring: after 48 years
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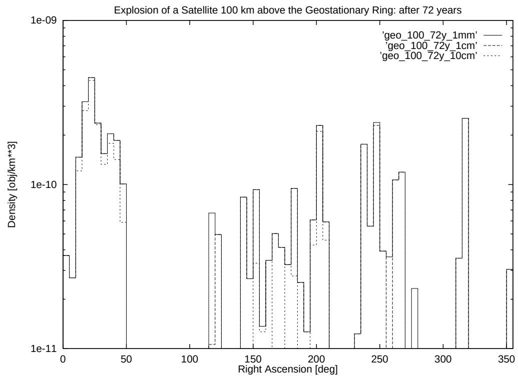
Right Ascension [deg]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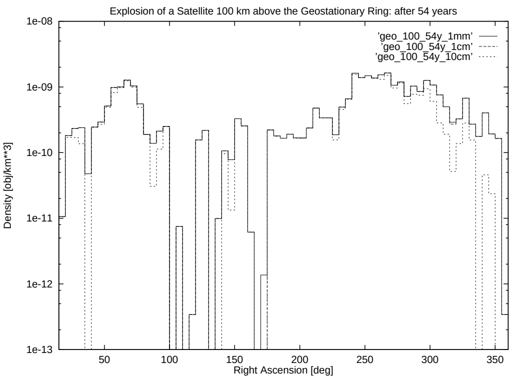
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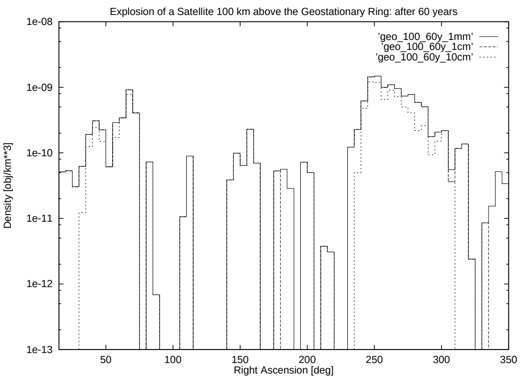
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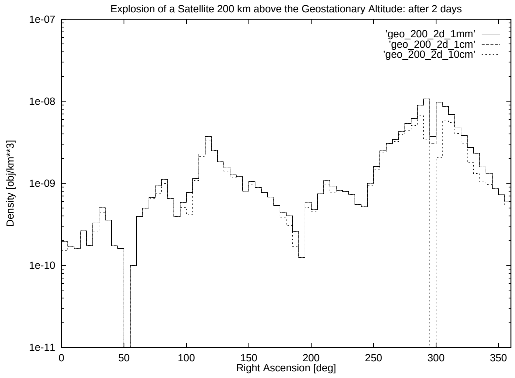
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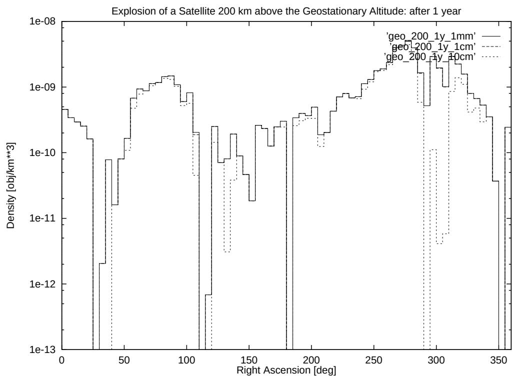
Density [obj/km**3]
Right Ascension [deg]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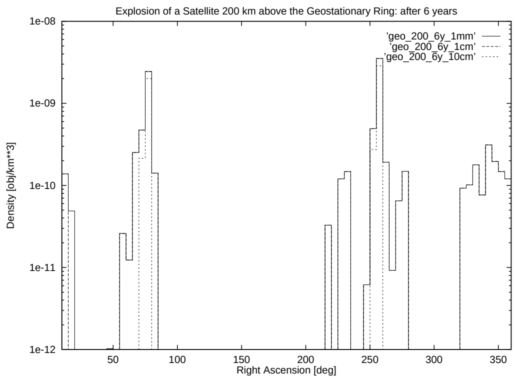
Density [obj/km**3]
Right Ascension [deg]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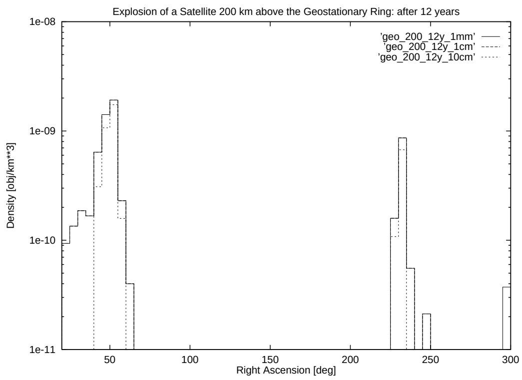
Density [obj/km**3]
Right Ascension [deg]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Density [obj/km**3]
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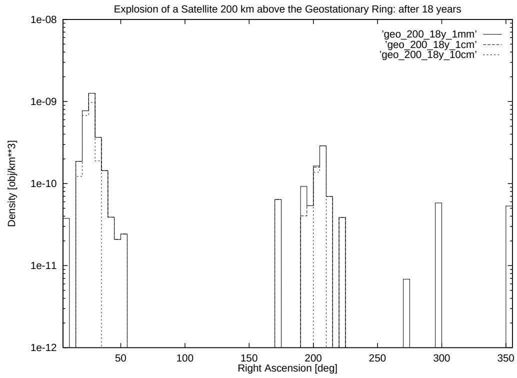
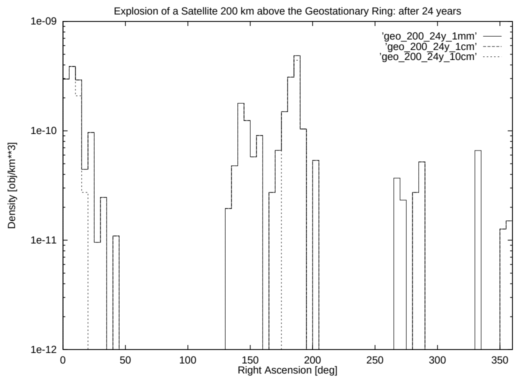
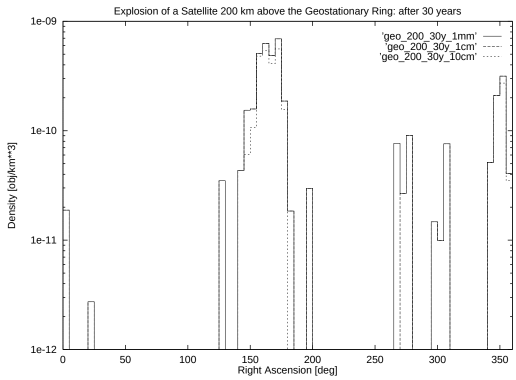

Explosion of a Satellite 200 km above the Geostationary Ring: after 18 years
'geo_200_18y_1mm'
'geo_200_18y_1cm'
'geo_200_18y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 24 years
'geo_200_24y_1mm'
'geo_200_24y_1cm'
'geo_200_24y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 30 years
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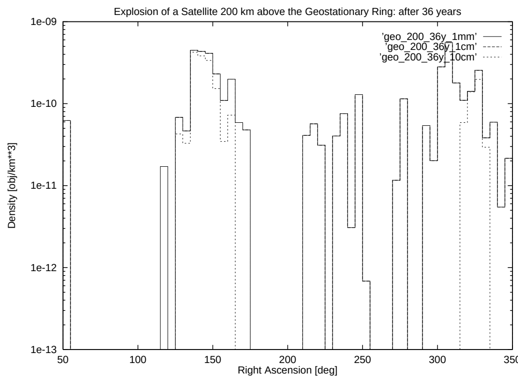
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 36 years
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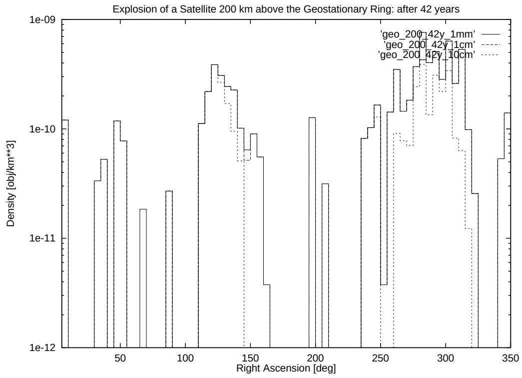
'geo_200_36y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 42 years
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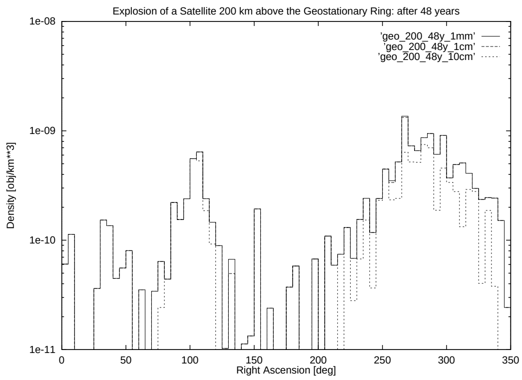
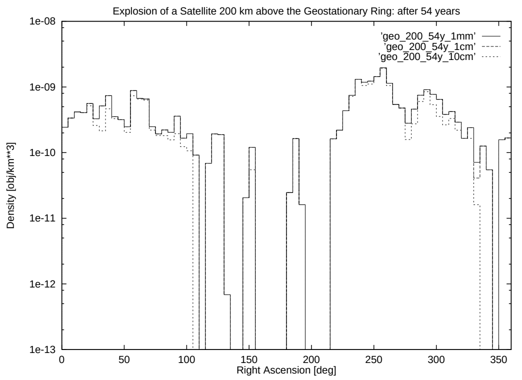
'geo_200_42y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 48 years
'geo_200_48y_1mm'
'geo_200_48y_1cm'
'geo_200_48y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 54 years
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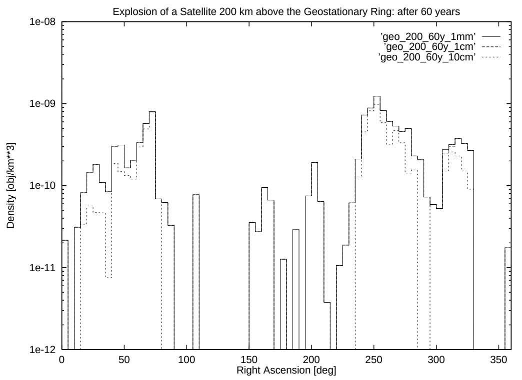
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 60 years
'geo_200_60y_1mm'
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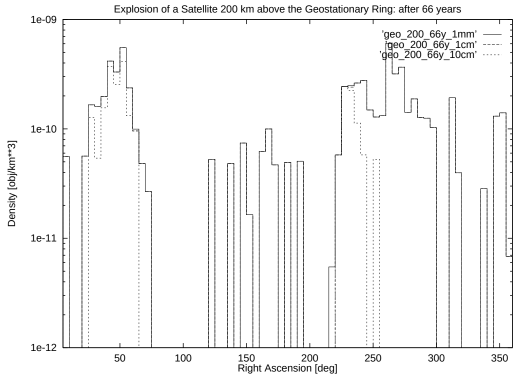
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 66 years
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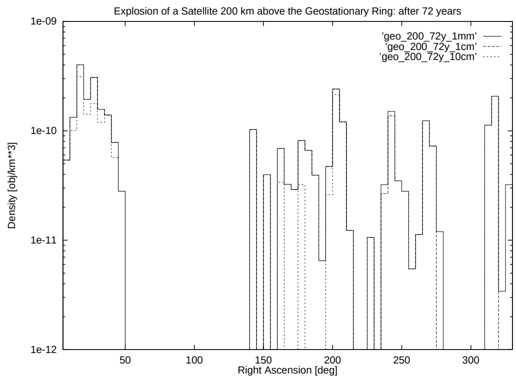
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 200 km above the Geostationary Ring: after 72 years
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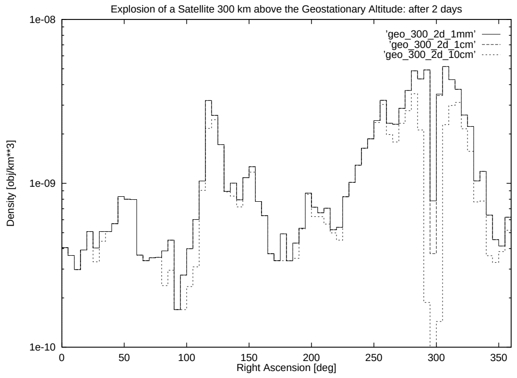
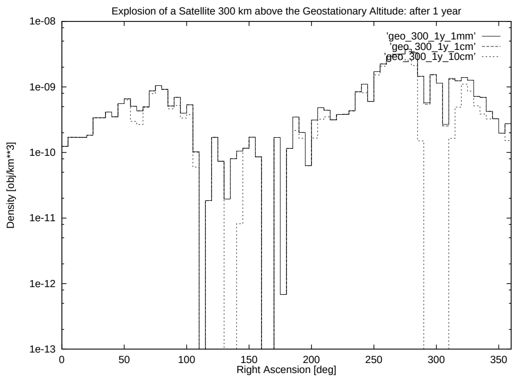
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Altitude: after 2 days
'geo_300_2d_1mm'
'geo_300_2d_1cm'
'geo_300_2d_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Altitude: after 1 year
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'geo_300_1y_1cm'
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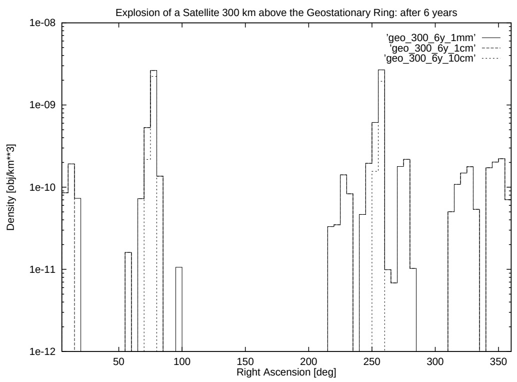
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 6 years
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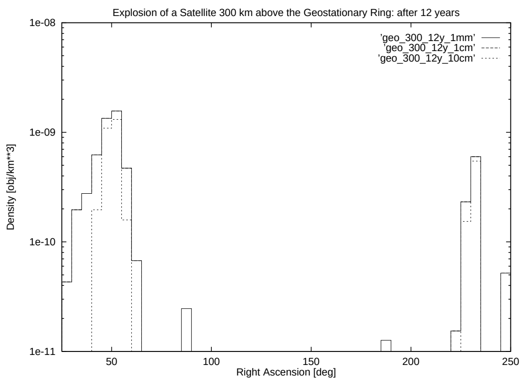
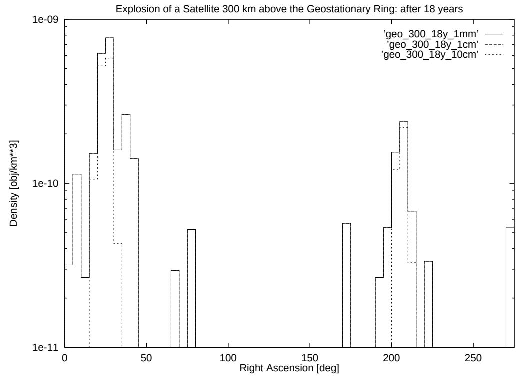
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 12 years
'geo_300_12y_1mm'
'geo_300_12y_1cm'
'geo_300_12y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 18 years
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'geo_300_18y_1cm'
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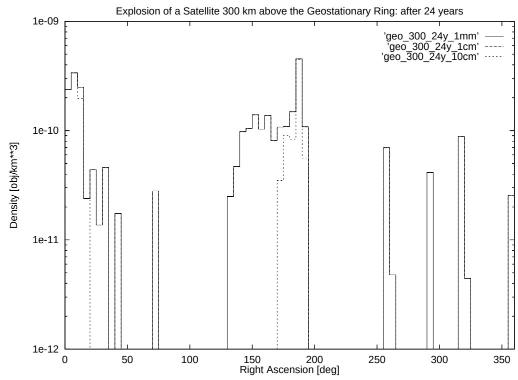
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 24 years
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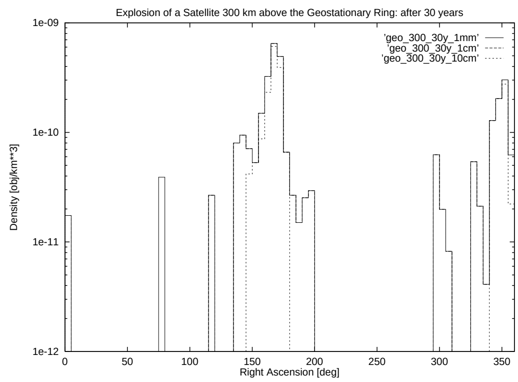
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 30 years
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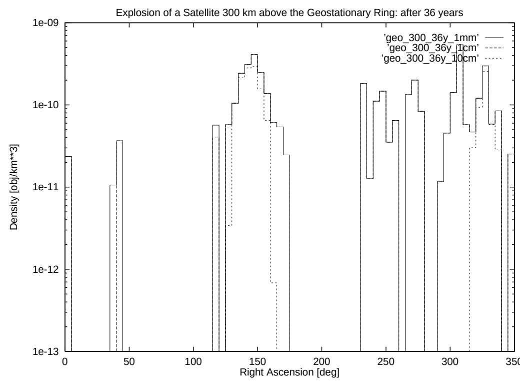
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 36 years
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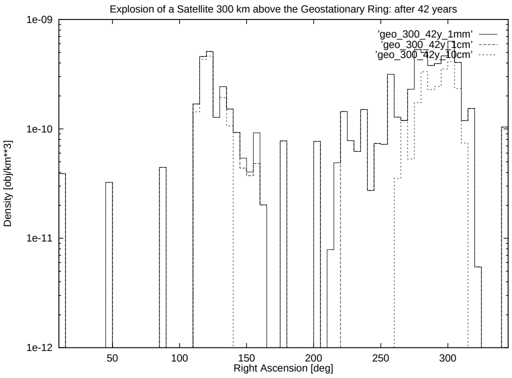
'geo_300_36y_1cm'
'geo_300_36y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 42 years
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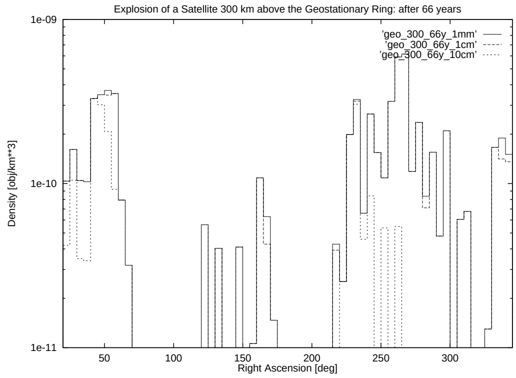
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 66 years
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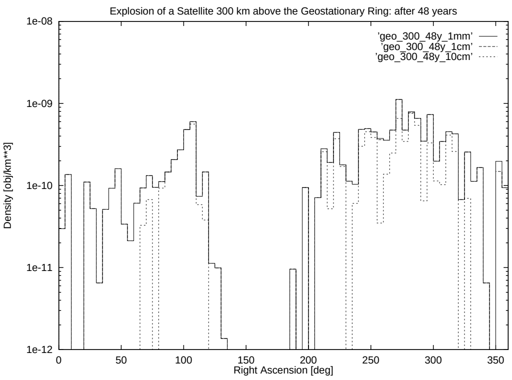
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 48 years
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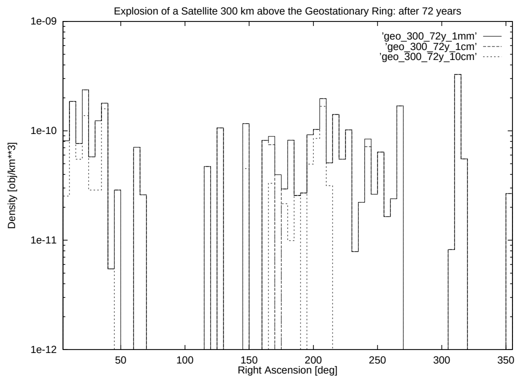
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 72 years
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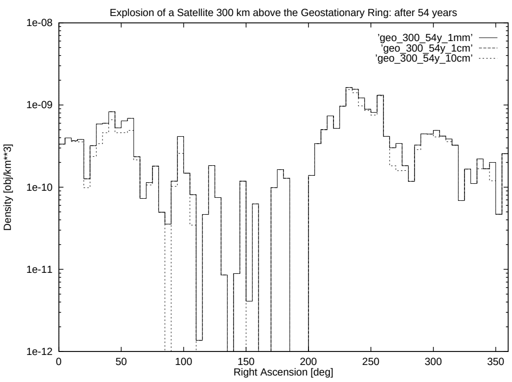
'geo_300_72y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 54 years
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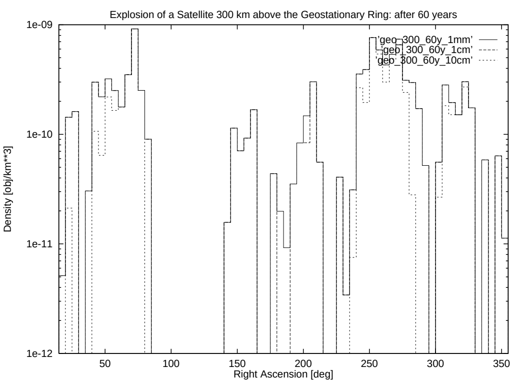
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 300 km above the Geostationary Ring: after 60 years
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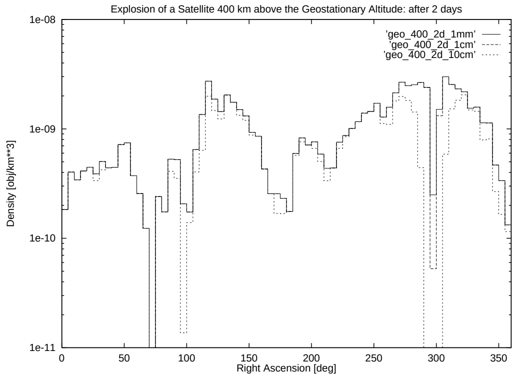
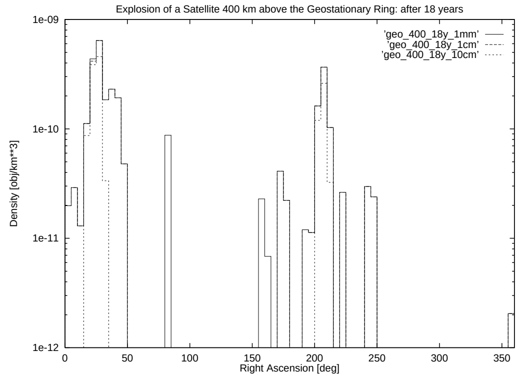
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 400 km above the Geostationary Altitude: after 2 days
'geo_400_2d_1mm'
'geo_400_2d_1cm'
'geo_400_2d_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 400 km above the Geostationary Ring: after 18 years
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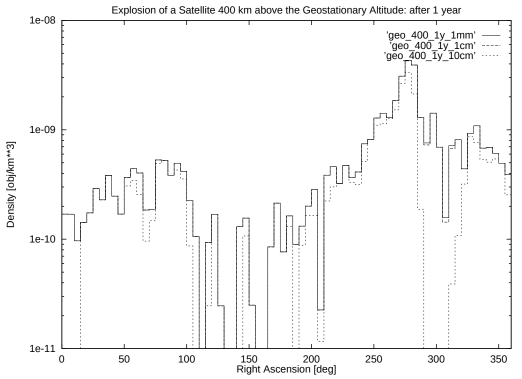
Right Ascension [deg]


Explosion of a Satellite 400 km above the Geostationary Altitude: after 1 year
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Density [obj/km**3]
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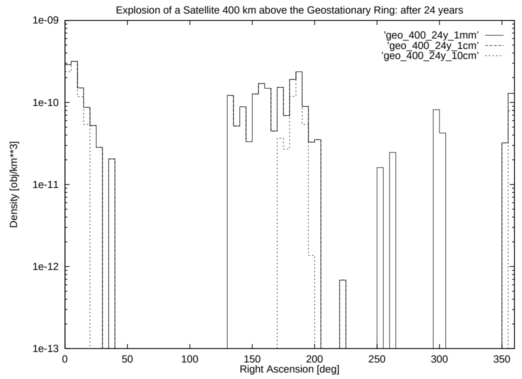
Explosion of a Satellite 400 km above the Geostationary Ring: after 24 years
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Density [obj/km**3]
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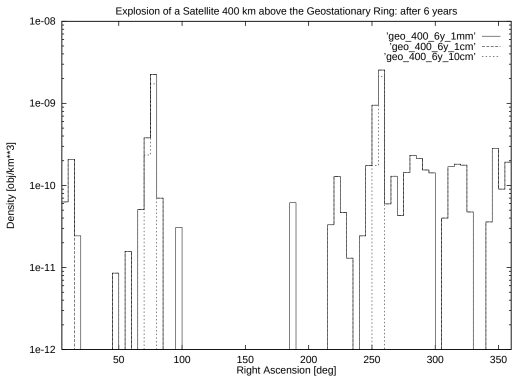
Explosion of a Satellite 400 km above the Geostationary Ring: after 6 years
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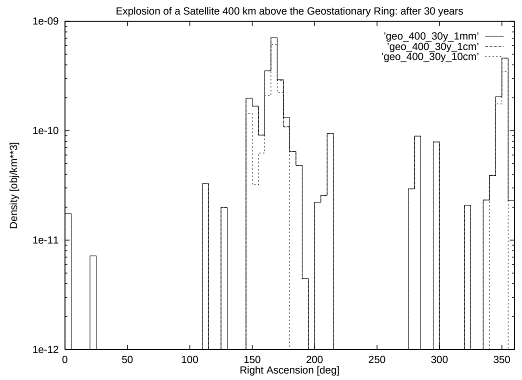
Right Ascension [deg]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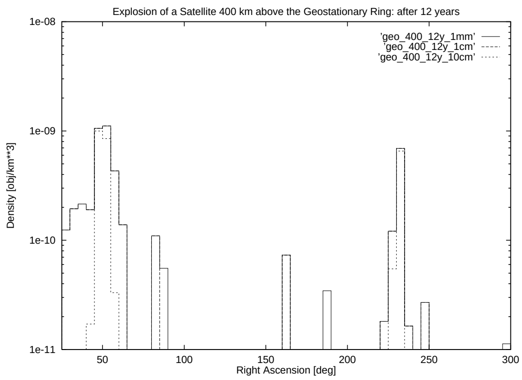
Explosion of a Satellite 400 km above the Geostationary Ring: after 12 years
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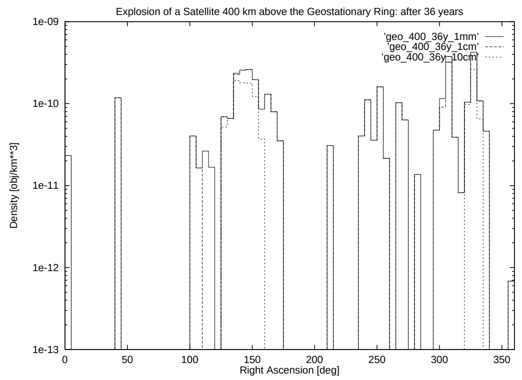
Right Ascension [deg]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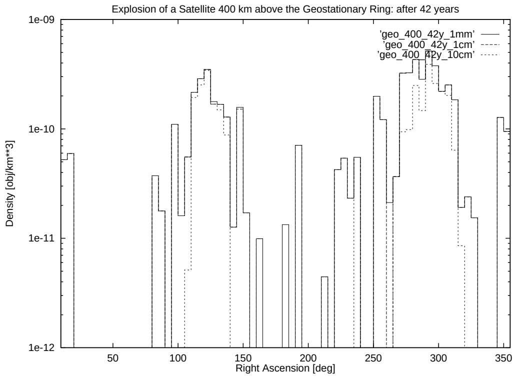
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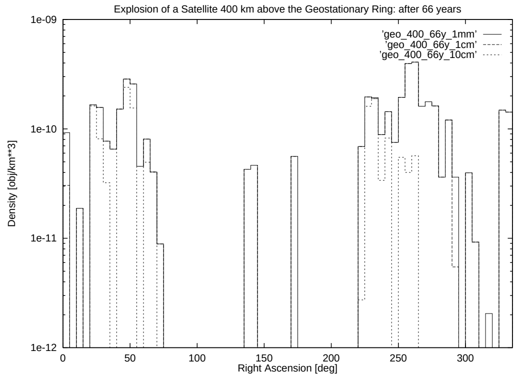
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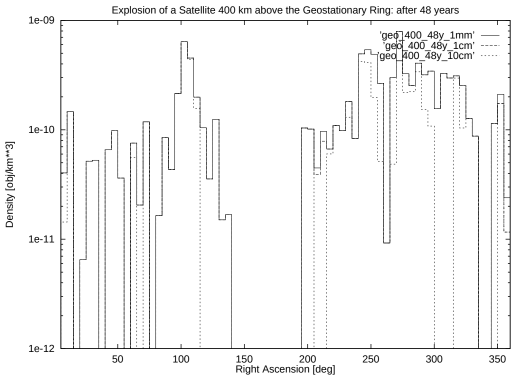
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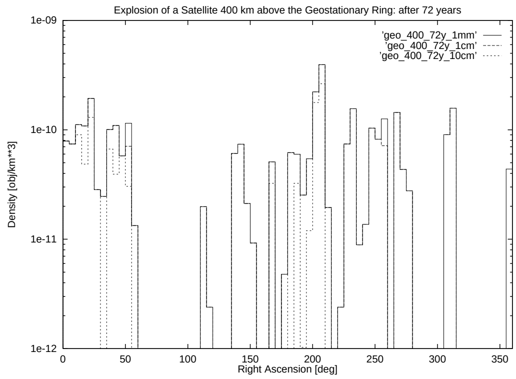
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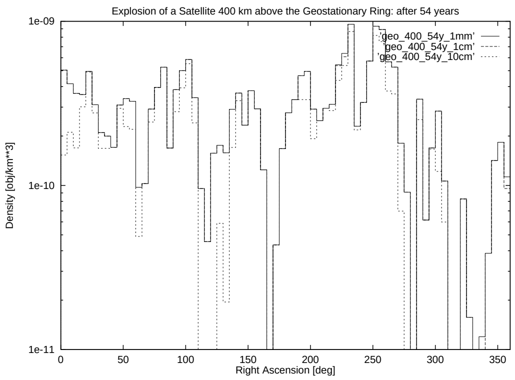
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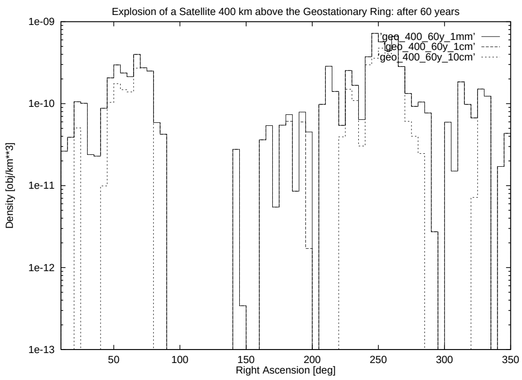
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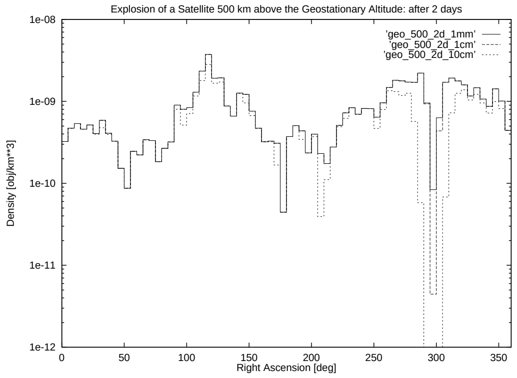
Explosion of a Satellite 500 km above the Geostationary Altitude: after 2 days
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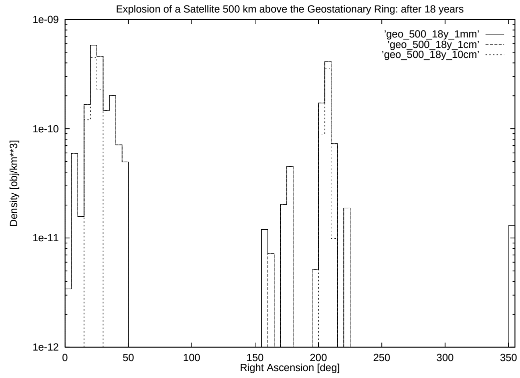
Density [obj/km**3]
Right Ascension [deg]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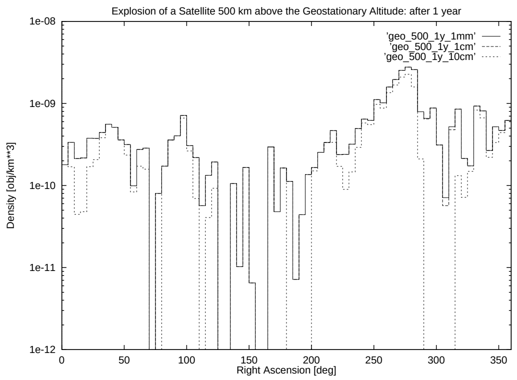
Explosion of a Satellite 500 km above the Geostationary Altitude: after 1 year
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'geo_500_1y_1cm'
'geo_500_1y_10cm'
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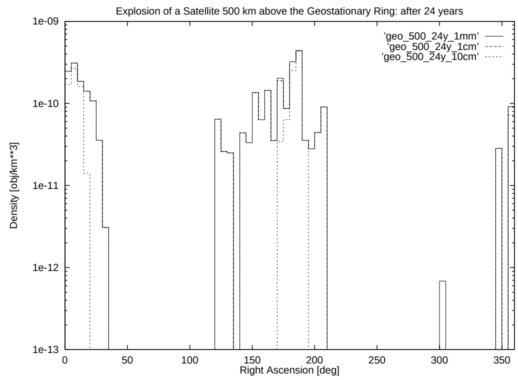
Right Ascension [deg]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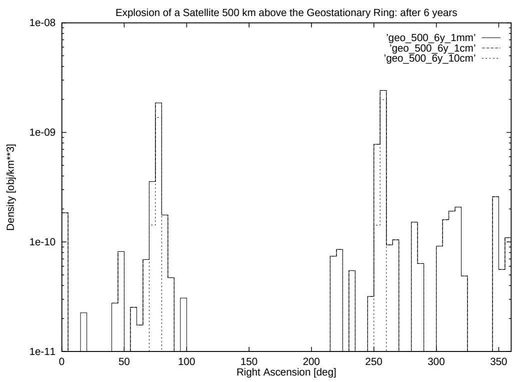
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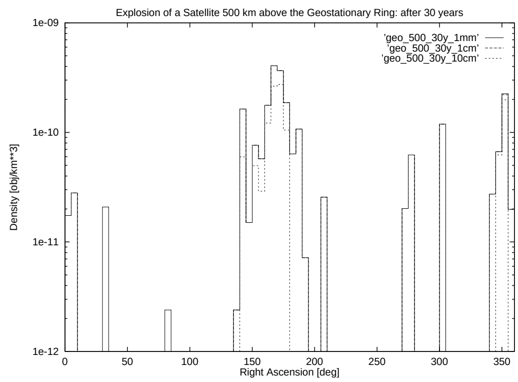
Right Ascension [deg]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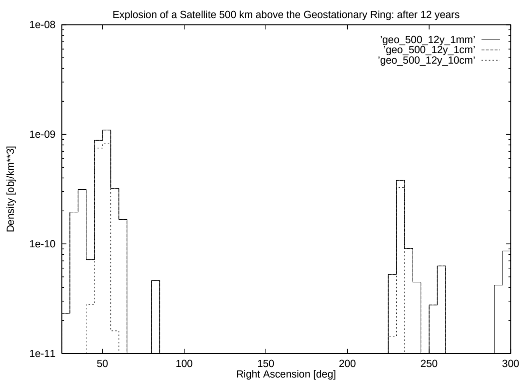
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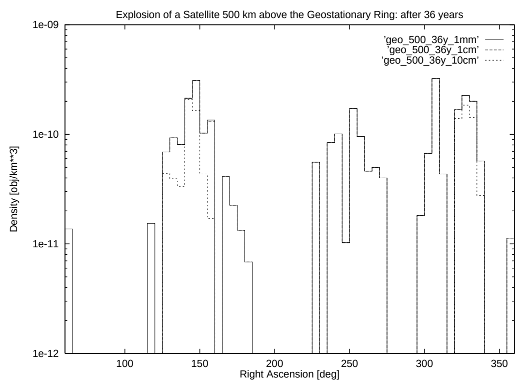
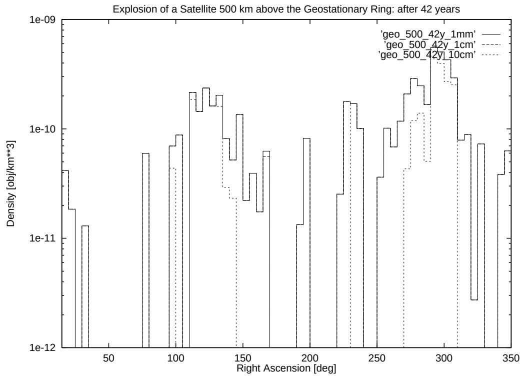
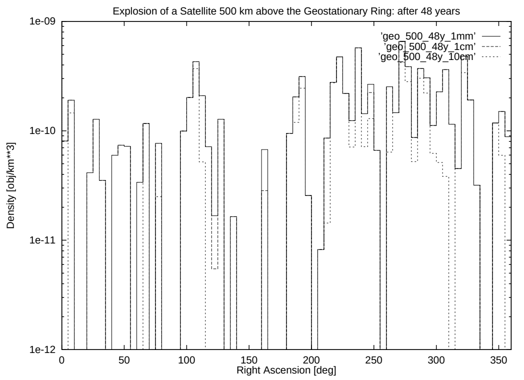
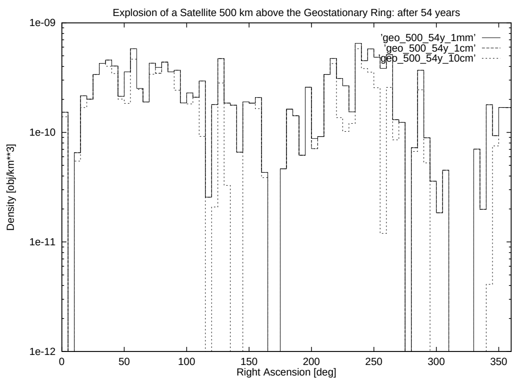
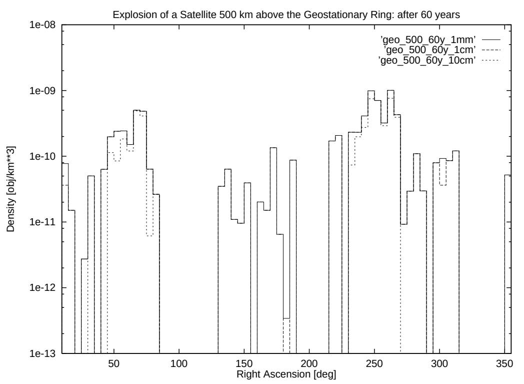
Density [obj/km**3]
Right Ascension [deg]

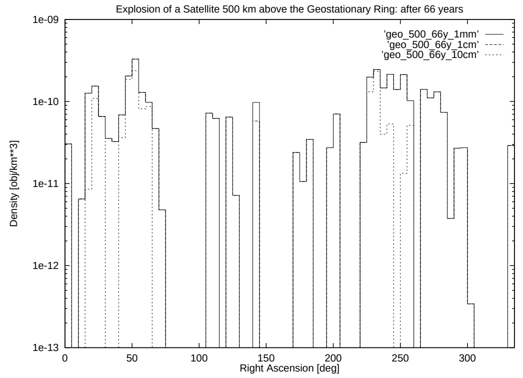

Explosion of a Satellite 500 km above the Geostationary Ring: after 36 years
'geo_500_36y_1mm'
'geo_500_36y_1cm'
'geo_500_36y_10cm'
Density [obj/km**3]
Right Ascension [deg]

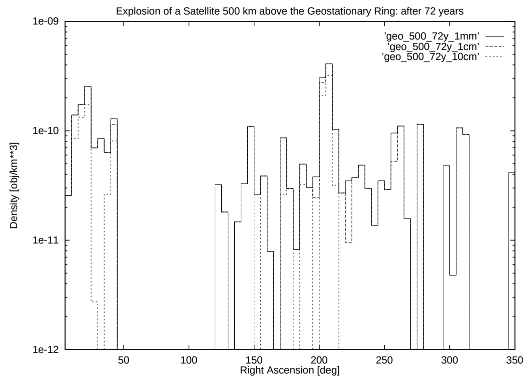

Explosion of a Satellite 500 km above the Geostationary Ring: after 42 years
'geo_500_42y_1mm'
'geo_500_42y_1cm'
'geo_500_42y_10cm'
Density [obj/km**3]
Right Ascension [deg]

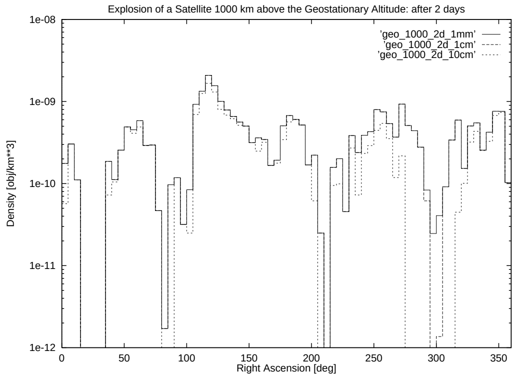

Explosion of a Satellite 500 km above the Geostationary Ring: after 48 years
'geo_500_48y_1mm'
'geo_500_48y_1cm'
'geo_500_48y_10cm'
Density [obj/km**3]
Right Ascension [deg]

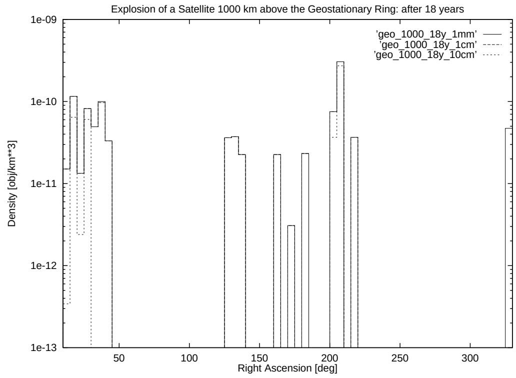

Explosion of a Satellite 500 km above the Geostationary Ring: after 54 years
'geo_500_54y_1mm'
'geo_500_54y_1cm'
'geo_500_54y_10cm'
Density [obj/km**3]
Right Ascension [deg]

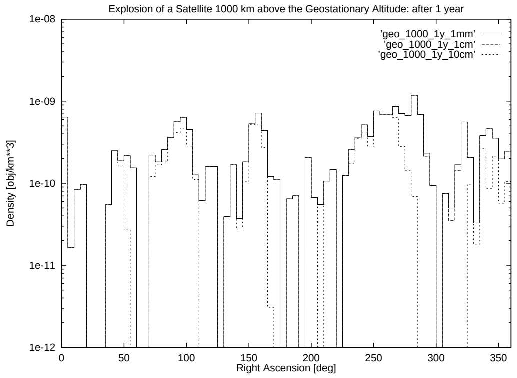

Explosion of a Satellite 500 km above the Geostationary Ring: after 60 years
'geo_500_60y_1mm'
'geo_500_60y_1cm'
'geo_500_60y_10cm'
Density [obj/km**3]
Right Ascension [deg]

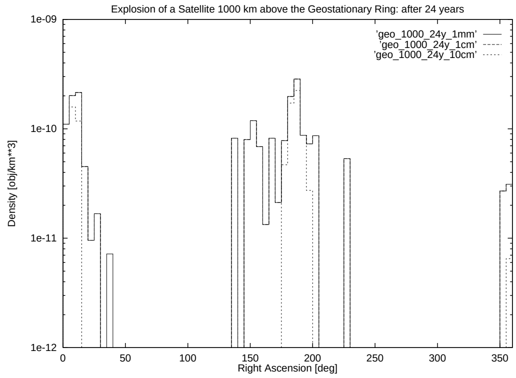

Explosion of a Satellite 500 km above the Geostationary Ring: after 66 years
'geo_500_66y_1mm'
'geo_500_66y_1cm'
'geo_500_66y_10cm'
Density [obj/km**3]
Right Ascension [deg]

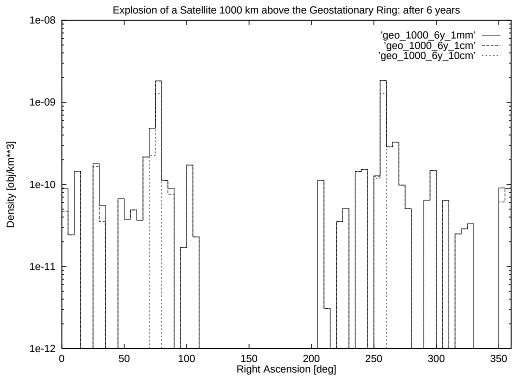

Explosion of a Satellite 500 km above the Geostationary Ring: after 72 years
'geo_500_72y_1mm'
'geo_500_72y_1cm'
'geo_500_72y_10cm'
Density [obj/km**3]
Right Ascension [deg]

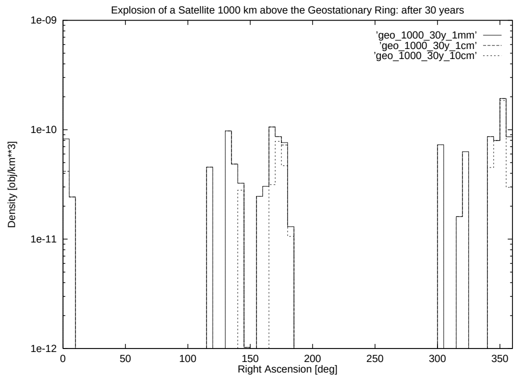

Explosion of a Satellite 1000 km above the Geostationary Altitude: after 2 days
'geo_1000_2d_1mm'
'geo_1000_2d_1cm'
'geo_1000_2d_10cm'
Density [obj/km**3]
Right Ascension [deg]

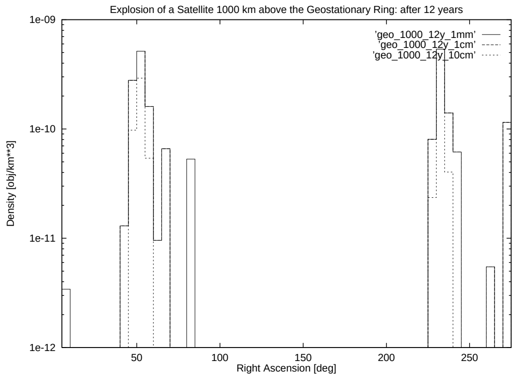

Explosion of a Satellite 1000 km above the Geostationary Ring: after 18 years
'geo_1000_18y_1mm'
'geo_1000_18y_1cm'
'geo_1000_18y_10cm'
Density [obj/km**3]
Right Ascension [deg]

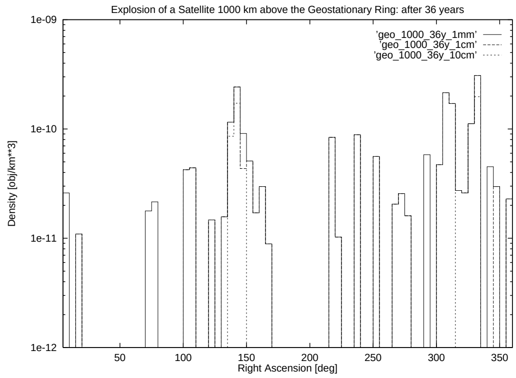

Explosion of a Satellite 1000 km above the Geostationary Altitude: after 1 year
'geo_1000_1y_1mm'
'geo_1000_1y_1cm'
'geo_1000_1y_10cm'
Density [obj/km**3]
Right Ascension [deg]

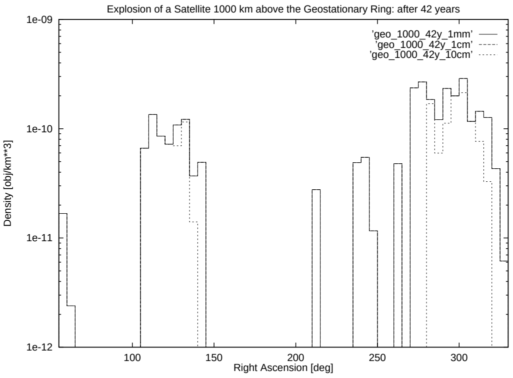

Explosion of a Satellite 1000 km above the Geostationary Ring: after 24 years
'geo_1000_24y_1mm'
'geo_1000_24y_1cm'
'geo_1000_24y_10cm'
Density [obj/km**3]
Right Ascension [deg]

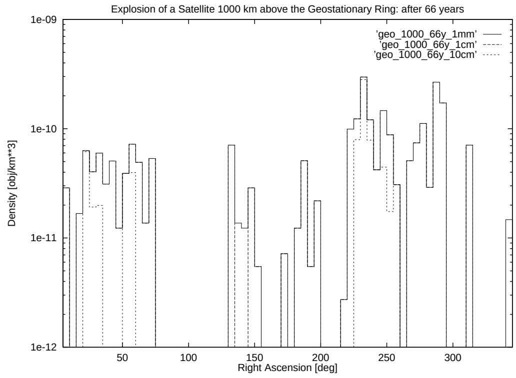

Explosion of a Satellite 1000 km above the Geostationary Ring: after 6 years
'geo_1000_6y_1mm'
'geo_1000_6y_1cm'
'geo_1000_6y_10cm'
Density [obj/km**3]
Right Ascension [deg]

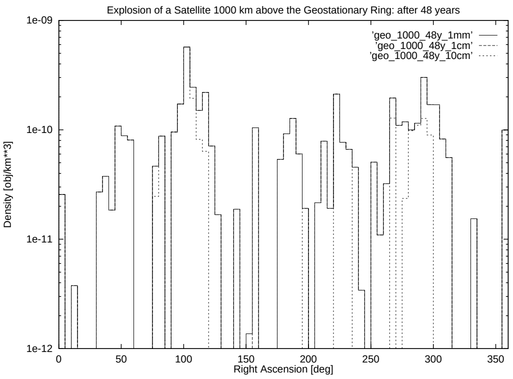

Explosion of a Satellite 1000 km above the Geostationary Ring: after 30 years
'geo_1000_30y_1mm'
'geo_1000_30y_1cm'
'geo_1000_30y_10cm'
Density [obj/km**3]
Right Ascension [deg]

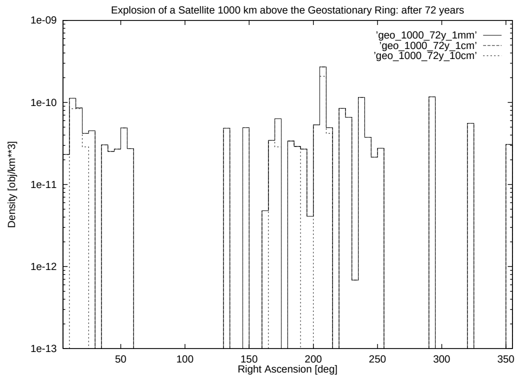

Explosion of a Satellite 1000 km above the Geostationary Ring: after 12 years
'geo_1000_12y_1mm'
'geo_1000_12y_1cm'
'geo_1000_12y_10cm'
Density [obj/km**3]
Right Ascension [deg]

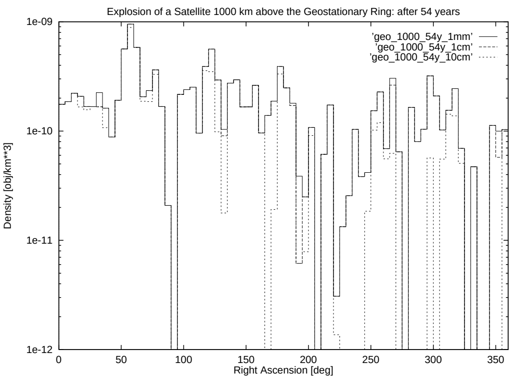

Explosion of a Satellite 1000 km above the Geostationary Ring: after 36 years
'geo_1000_36y_1mm'
'geo_1000_36y_1cm'
'geo_1000_36y_10cm'
Density [obj/km**3]
Right Ascension [deg]

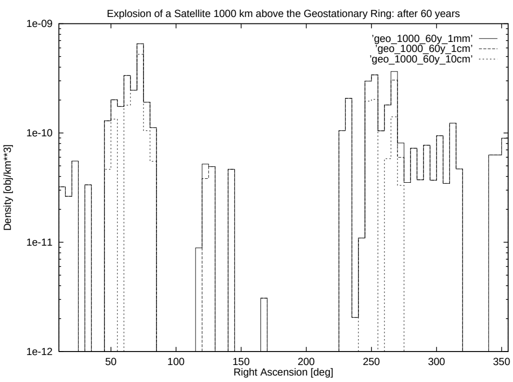

Explosion of a Satellite 1000 km above the Geostationary Ring: after 42 years
'geo_1000_42y_1mm'
'geo_1000_42y_1cm'
'geo_1000_42y_10cm'
Density [obj/km**3]
Right Ascension [deg]

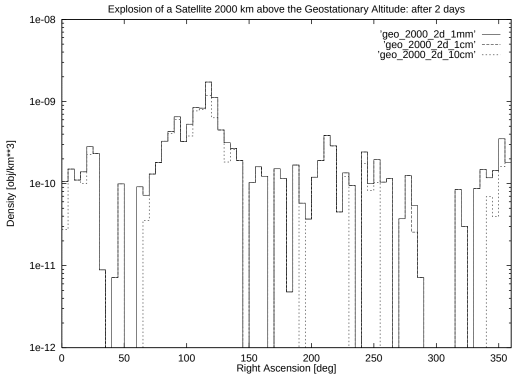

Explosion of a Satellite 1000 km above the Geostationary Ring: after 66 years
'geo_1000_66y_1mm'
'geo_1000_66y_1cm'
'geo_1000_66y_10cm'
Density [obj/km**3]
Right Ascension [deg]

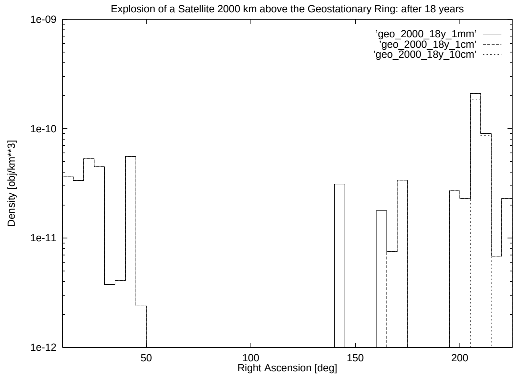

Explosion of a Satellite 1000 km above the Geostationary Ring: after 48 years
'geo_1000_48y_1mm'
'geo_1000_48y_1cm'
'geo_1000_48y_10cm'
Density [obj/km**3]
Right Ascension [deg]

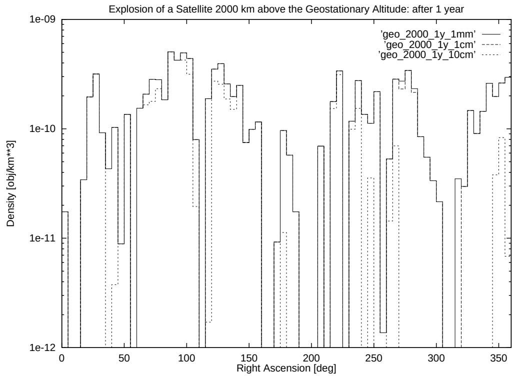

Explosion of a Satellite 1000 km above the Geostationary Ring: after 72 years
'geo_1000_72y_1mm'
'geo_1000_72y_1cm'
'geo_1000_72y_10cm'
Density [obj/km**3]
Right Ascension [deg]

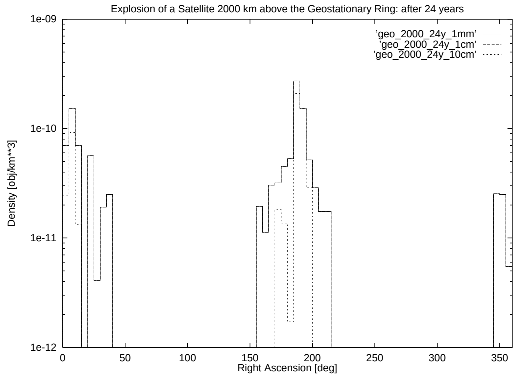

Explosion of a Satellite 1000 km above the Geostationary Ring: after 54 years
'geo_1000_54y_1mm'
'geo_1000_54y_1cm'
'geo_1000_54y_10cm'
Density [obj/km**3]
Right Ascension [deg]

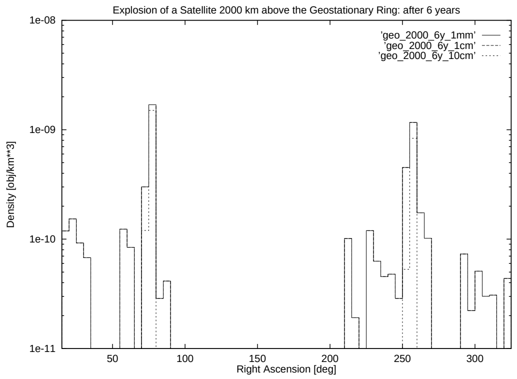

Explosion of a Satellite 1000 km above the Geostationary Ring: after 60 years
'geo_1000_60y_1mm'
'geo_1000_60y_1cm'
'geo_1000_60y_10cm'
Density [obj/km**3]
Right Ascension [deg]

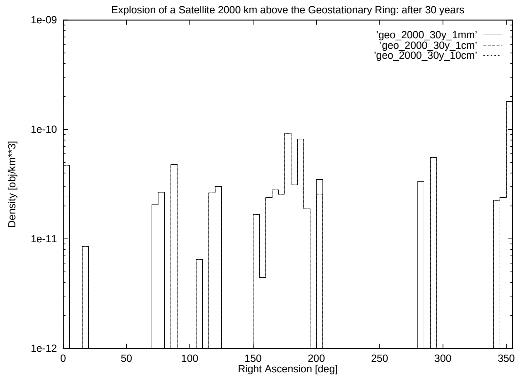

Explosion of a Satellite 2000 km above the Geostationary Altitude: after 2 days
'geo_2000_2d_1mm'
'geo_2000_2d_1cm'
'geo_2000_2d_10cm'
Density [obj/km**3]
Right Ascension [deg]

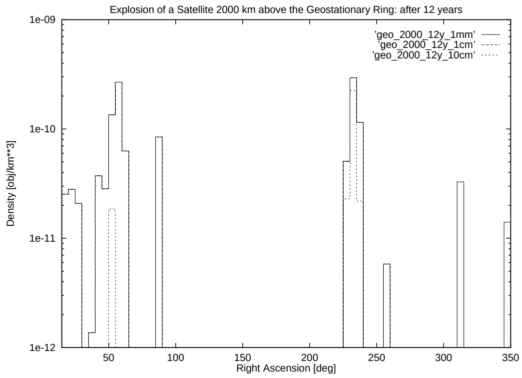

Explosion of a Satellite 2000 km above the Geostationary Ring: after 18 years
'geo_2000_18y_1mm'
'geo_2000_18y_1cm'
'geo_2000_18y_10cm'
Density [obj/km**3]
Right Ascension [deg]

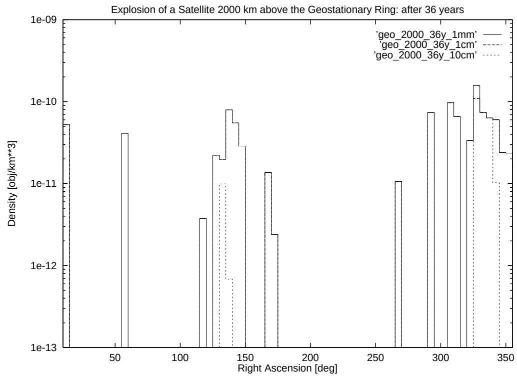

Explosion of a Satellite 2000 km above the Geostationary Altitude: after 1 year
'geo_2000_1y_1mm'
'geo_2000_1y_1cm'
'geo_2000_1y_10cm'
Density [obj/km**3]
Right Ascension [deg]

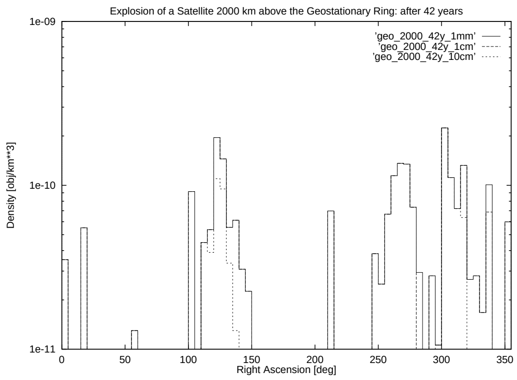

Explosion of a Satellite 2000 km above the Geostationary Ring: after 24 years
'geo_2000_24y_1mm'
'geo_2000_24y_1cm'
'geo_2000_24y_10cm'
Density [obj/km**3]
Right Ascension [deg]

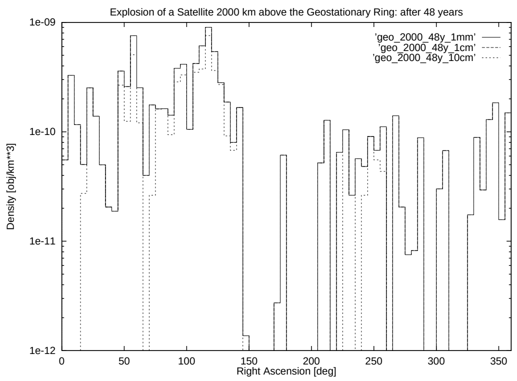

Explosion of a Satellite 2000 km above the Geostationary Ring: after 6 years
'geo_2000_6y_1mm'
'geo_2000_6y_1cm'
'geo_2000_6y_10cm'
Density [obj/km**3]
Right Ascension [deg]

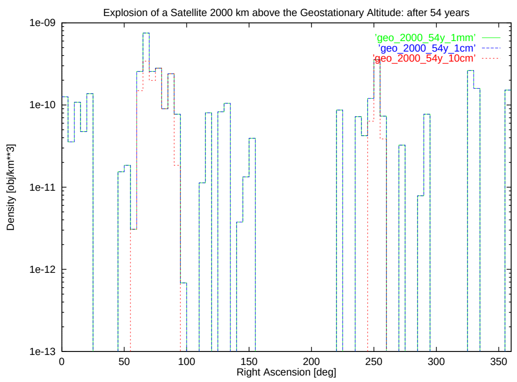

Explosion of a Satellite 2000 km above the Geostationary Ring: after 30 years
'geo_2000_30y_1mm'
'geo_2000_30y_1cm'
'geo_2000_30y_10cm'
Density [obj/km**3]
Right Ascension [deg]

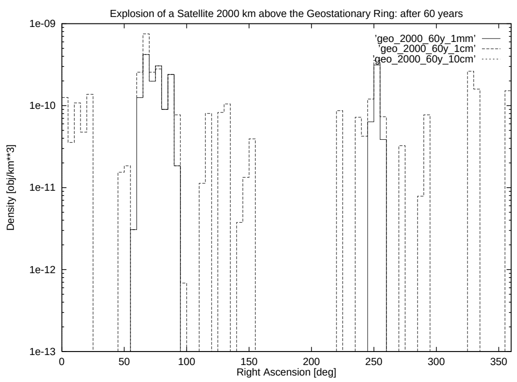

Explosion of a Satellite 2000 km above the Geostationary Ring: after 12 years
'geo_2000_12y_1mm'
'geo_2000_12y_1cm'
'geo_2000_12y_10cm'
Density [obj/km**3]
Right Ascension [deg]

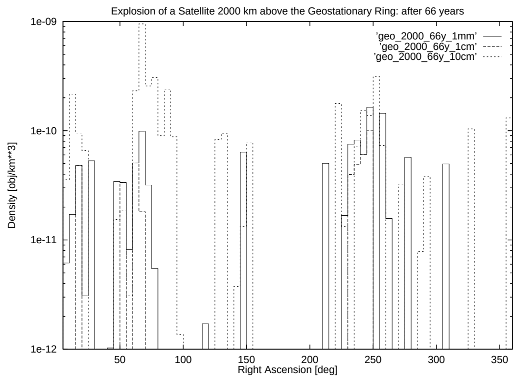

Explosion of a Satellite 2000 km above the Geostationary Ring: after 36 years
'geo_2000_36y_1mm'
'geo_2000_36y_1cm'
'geo_2000_36y_10cm'
Density [obj/km**3]
Right Ascension [deg]

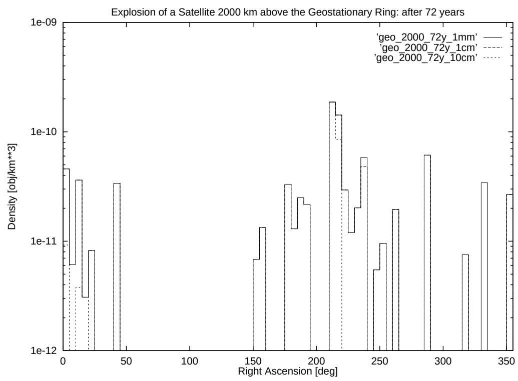

Explosion of a Satellite 2000 km above the Geostationary Ring: after 42 years
'geo_2000_42y_1mm'
'geo_2000_42y_1cm'
'geo_2000_42y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 2000 km above the Geostationary Ring: after 48 years
'geo_2000_48y_1mm'
'geo_2000_48y_1cm'
'geo_2000_48y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 2000 km above the Geostationary Altitude: after 54 years
'geo_2000_54y_1mm'
'geo_2000_54y_1cm'
'geo_2000_54y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 2000 km above the Geostationary Ring: after 60 years
'geo_2000_60y_1mm'
'geo_2000_60y_1cm'
'geo_2000_60y_10cm'
Density [obj/km**3]
Right Ascension [deg]

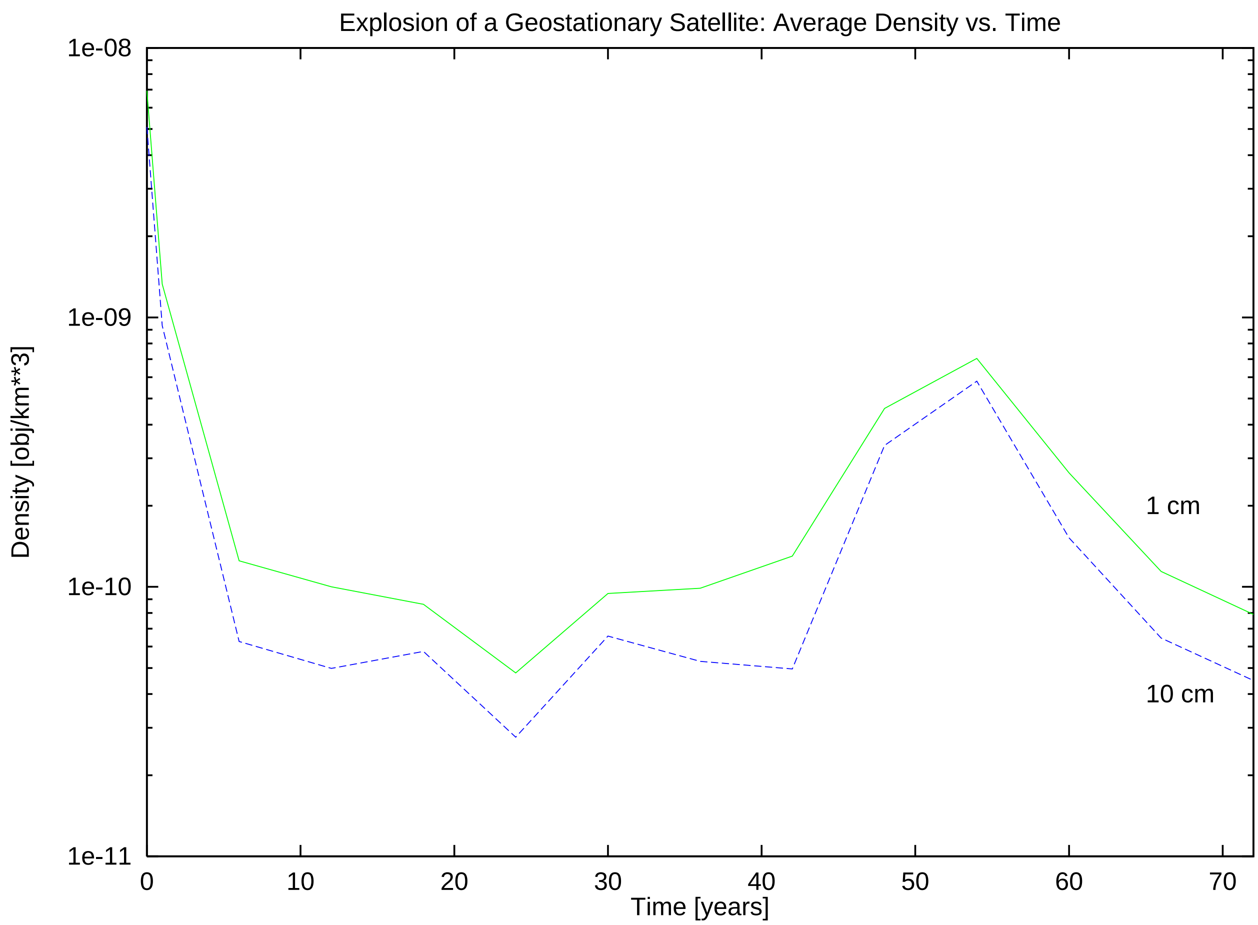

Explosion of a Satellite 2000 km above the Geostationary Ring: after 66 years
'geo_2000_66y_1mm'
'geo_2000_66y_1cm'
'geo_2000_66y_10cm'
Density [obj/km**3]
Right Ascension [deg]


Explosion of a Satellite 2000 km above the Geostationary Ring: after 72 years
'geo_2000_72y_1mm'
'geo_2000_72y_1cm'
'geo_2000_72y_10cm'
Density [obj/km**3]
Right Ascension [deg]

EXPLOSION OF A GEOSTATIONARY SATELLITE

Table 3

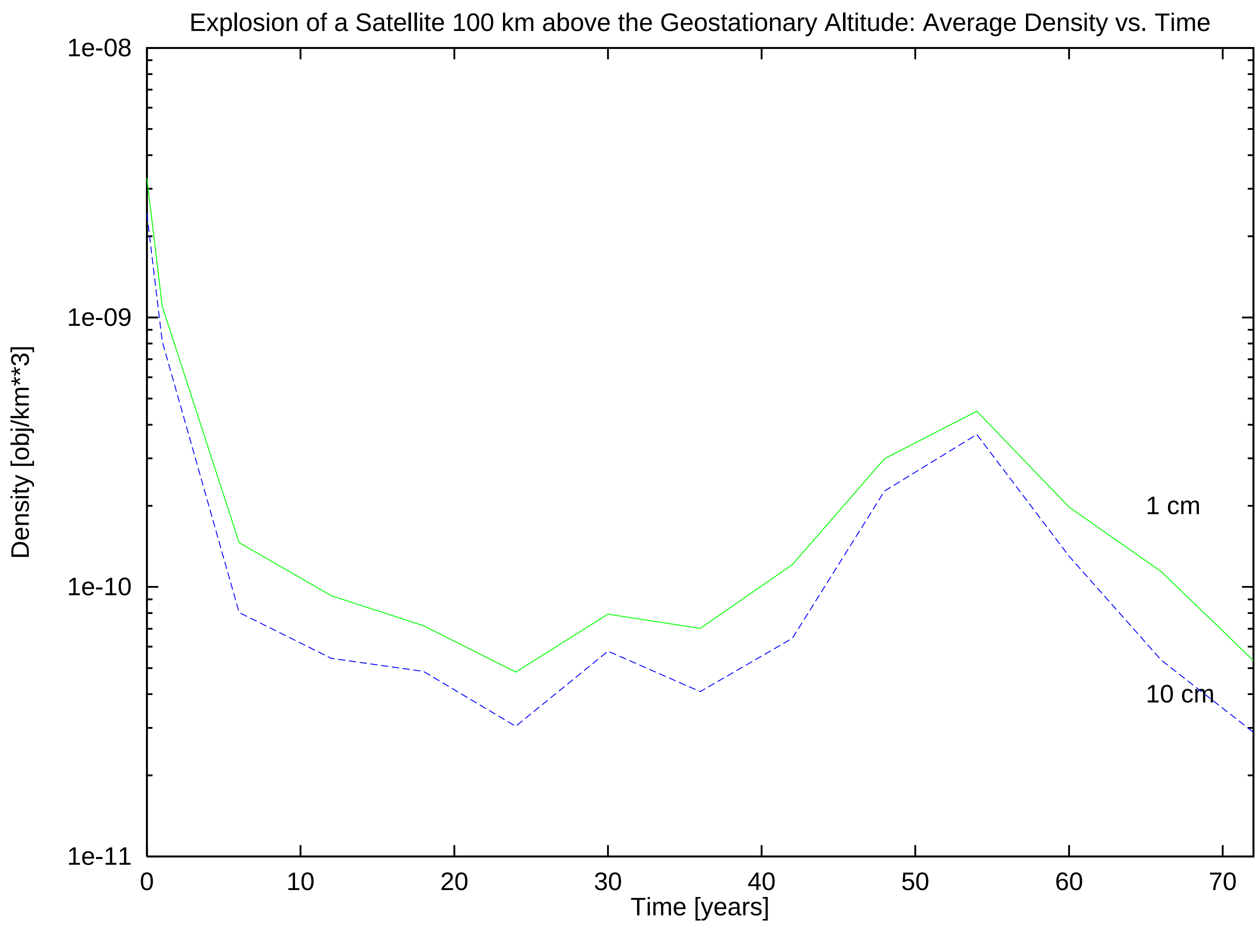
Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.694E-08	0.189E-06	295.00	0.509E-08	0.102E-06	295.00
1.0	0.133E-08	0.132E-07	305.00	0.932E-09	0.702E-08	275.00
6.0	0.125E-09	0.282E-08	255.00	0.627E-10	0.213E-08	255.00
12.0	0.100E-09	0.162E-08	45.00	0.498E-10	0.128E-08	50.00
18.0	0.862E-10	0.181E-08	25.00	0.576E-10	0.162E-08	25.00
24.0	0.479E-10	0.656E-09	5.00	0.277E-10	0.594E-09	5.00
30.0	0.945E-10	0.146E-08	160.00	0.657E-10	0.118E-08	155.00
36.0	0.988E-10	0.130E-08	145.00	0.529E-10	0.121E-08	145.00
42.0	0.130E-09	0.889E-09	300.00	0.496E-10	0.658E-09	120.00
48.0	0.459E-09	0.365E-08	280.00	0.335E-09	0.311E-08	280.00
54.0	0.704E-09	0.375E-08	265.00	0.580E-09	0.349E-08	265.00
60.0	0.265E-09	0.234E-08	285.00	0.152E-09	0.108E-08	250.00
66.0	0.114E-09	0.130E-08	35.00	0.646E-10	0.109E-08	35.00
72.0	0.790E-10	0.769E-09	25.00	0.449E-10	0.625E-09	25.00



EXPLOSION OF A SATELLITE 100 km ABOVE THE GEOSTATIONARY ALTITUDE

Table 4

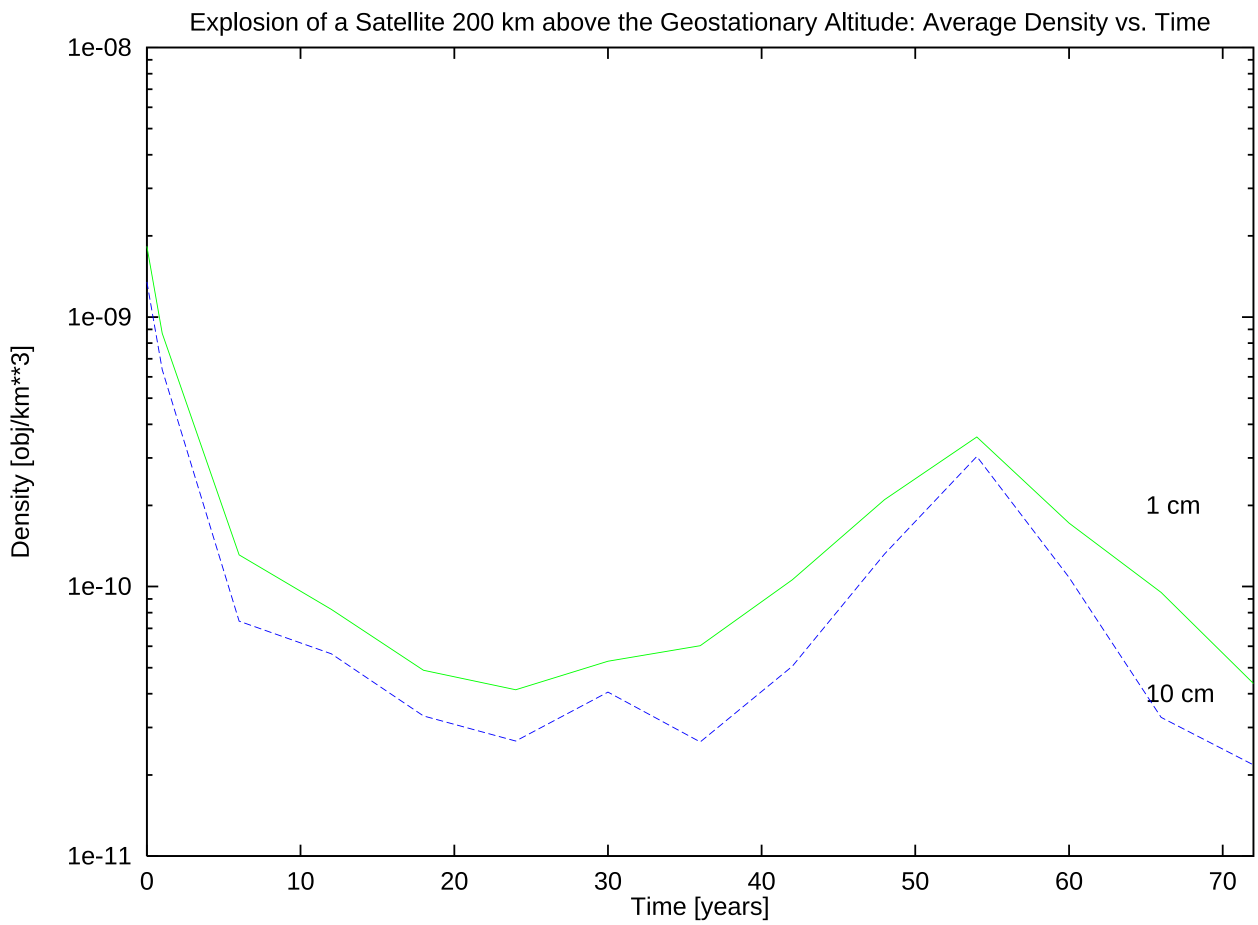
Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.329E-08	0.325E-07	300.00	0.242E-08	0.202E-07	290.00
1.0	0.110E-08	0.629E-08	275.00	0.815E-09	0.571E-08	275.00
6.0	0.146E-09	0.337E-08	255.00	0.804E-10	0.312E-08	255.00
12.0	0.927E-10	0.181E-08	50.00	0.543E-10	0.154E-08	50.00
18.0	0.718E-10	0.167E-08	25.00	0.486E-10	0.149E-08	25.00
24.0	0.483E-10	0.732E-09	185.00	0.304E-10	0.616E-09	185.00
30.0	0.793E-10	0.107E-08	160.00	0.578E-10	0.938E-09	160.00
36.0	0.702E-10	0.793E-09	145.00	0.409E-10	0.694E-09	145.00
42.0	0.121E-09	0.658E-09	275.00	0.645E-10	0.488E-09	275.00
48.0	0.299E-09	0.230E-08	285.00	0.227E-09	0.174E-08	285.00
54.0	0.449E-09	0.163E-08	265.00	0.368E-09	0.155E-08	240.00
60.0	0.198E-09	0.148E-08	250.00	0.130E-09	0.121E-08	245.00
66.0	0.114E-09	0.676E-09	45.00	0.536E-10	0.600E-09	40.00
72.0	0.533E-10	0.448E-09	20.00	0.289E-10	0.431E-09	20.00



EXPLOSION OF A SATELLITE 200 km ABOVE THE GEOSTATIONARY ALTITUDE

Table 5

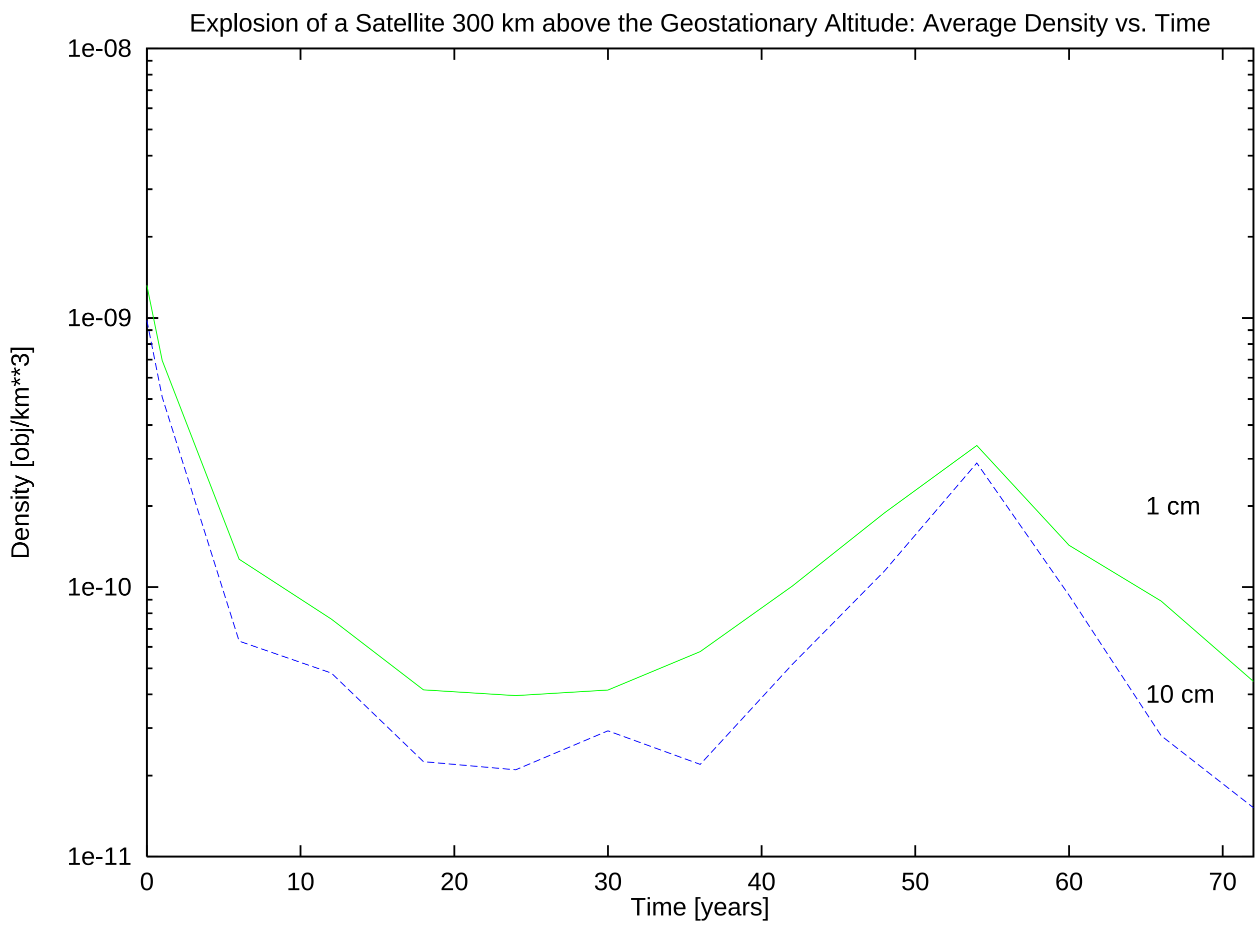
Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.183E-08	0.107E-07	290.00	0.135E-08	0.665E-08	285.00
1.0	0.870E-09	0.513E-08	275.00	0.638E-09	0.442E-08	275.00
6.0	0.131E-09	0.353E-08	255.00	0.744E-10	0.286E-08	255.00
12.0	0.823E-10	0.192E-08	50.00	0.563E-10	0.174E-08	50.00
18.0	0.489E-10	0.126E-08	25.00	0.331E-10	0.974E-09	25.00
24.0	0.414E-10	0.486E-09	185.00	0.267E-10	0.441E-09	185.00
30.0	0.528E-10	0.692E-09	170.00	0.406E-10	0.559E-09	170.00
36.0	0.603E-10	0.555E-09	305.00	0.265E-10	0.425E-09	135.00
42.0	0.106E-09	0.763E-09	280.00	0.506E-10	0.388E-09	280.00
48.0	0.210E-09	0.132E-08	265.00	0.132E-09	0.749E-09	280.00
54.0	0.359E-09	0.196E-08	255.00	0.304E-09	0.193E-08	255.00
60.0	0.172E-09	0.123E-08	250.00	0.108E-09	0.980E-09	250.00
66.0	0.951E-10	0.604E-09	260.00	0.327E-10	0.414E-09	50.00
72.0	0.437E-10	0.400E-09	15.00	0.218E-10	0.312E-09	15.00



EXPLOSION OF A SATELLITE 300 km ABOVE THE GEOSTATIONARY ALTITUDE

Table 6

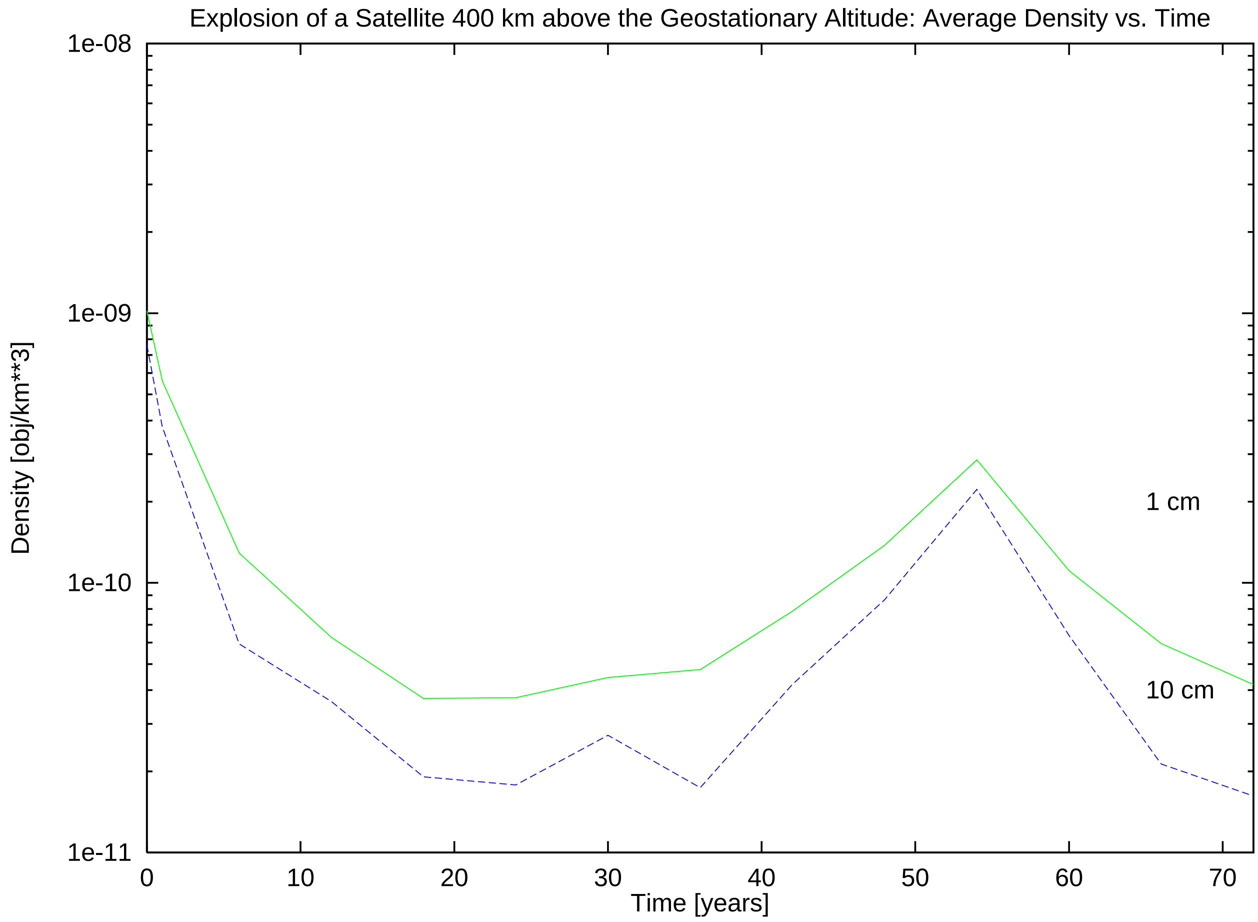
Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.132E-08	0.515E-08	305.00	0.978E-09	0.352E-08	280.00
1.0	0.694E-09	0.375E-08	275.00	0.508E-09	0.310E-08	265.00
6.0	0.127E-09	0.267E-08	255.00	0.631E-10	0.223E-08	75.00
12.0	0.761E-10	0.156E-08	50.00	0.480E-10	0.131E-08	50.00
18.0	0.416E-10	0.770E-09	25.00	0.225E-10	0.579E-09	25.00
24.0	0.396E-10	0.453E-09	185.00	0.210E-10	0.448E-09	185.00
30.0	0.415E-10	0.649E-09	165.00	0.293E-10	0.608E-09	165.00
36.0	0.577E-10	0.540E-09	305.00	0.220E-10	0.292E-09	145.00
42.0	0.101E-09	0.632E-09	300.00	0.517E-10	0.462E-09	120.00
48.0	0.189E-09	0.112E-08	270.00	0.115E-09	0.761E-09	280.00
54.0	0.336E-09	0.163E-08	230.00	0.289E-09	0.154E-08	230.00
60.0	0.143E-09	0.917E-09	70.00	0.933E-10	0.917E-09	70.00
66.0	0.888E-10	0.615E-09	265.00	0.281E-10	0.330E-09	40.00
72.0	0.447E-10	0.327E-09	310.00	0.152E-10	0.186E-09	10.00



EXPLOSION OF A SATELLITE 400 km ABOVE THE GEOSTATIONARY ALTITUDE

Table 7

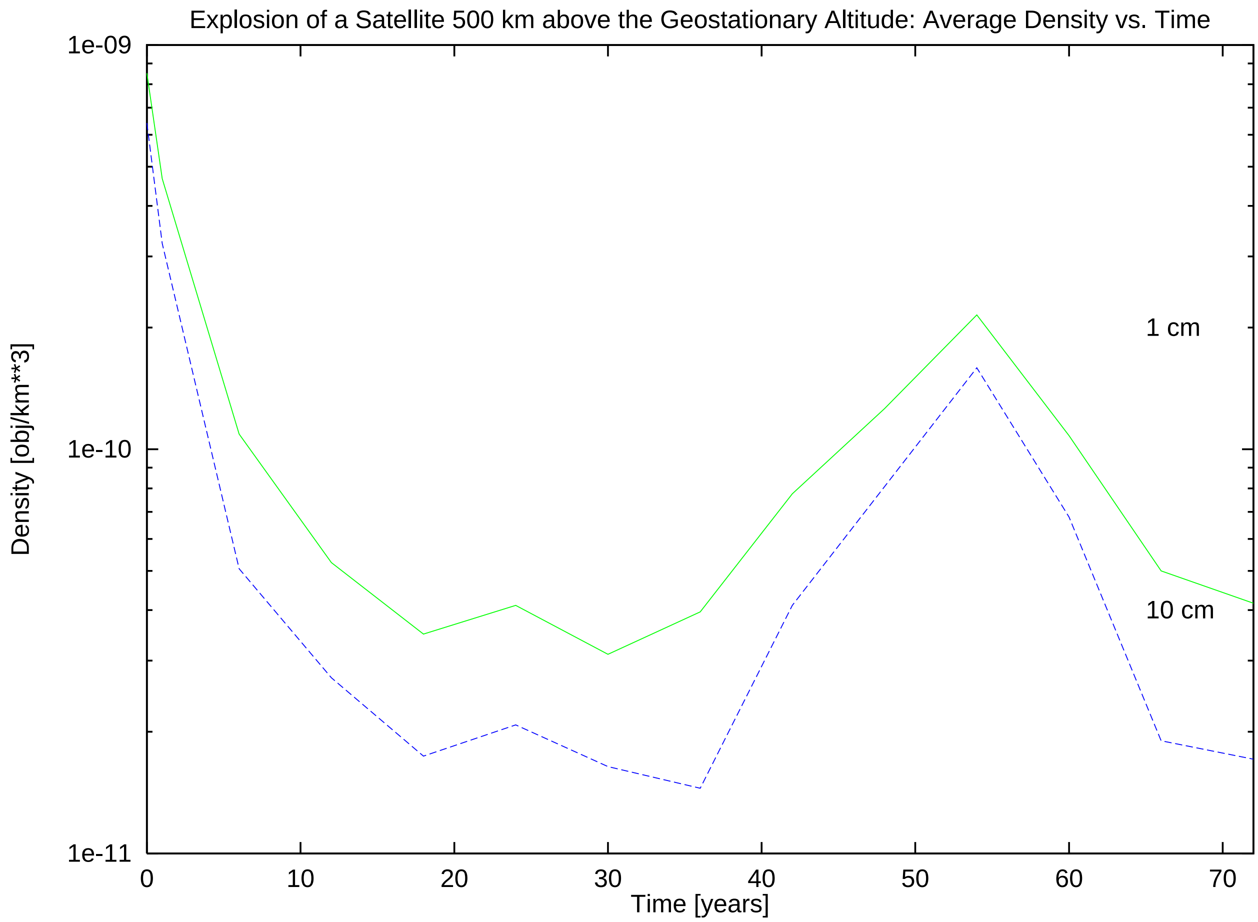
Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.102E-08	0.299E-08	305.00	0.763E-09	0.204E-08	320.00
1.0	0.561E-09	0.431E-08	275.00	0.380E-09	0.332E-08	275.00
6.0	0.129E-09	0.255E-08	255.00	0.594E-10	0.214E-08	255.00
12.0	0.628E-10	0.111E-08	50.00	0.363E-10	0.100E-08	45.00
18.0	0.373E-10	0.641E-09	25.00	0.191E-10	0.458E-09	25.00
24.0	0.375E-10	0.317E-09	5.00	0.178E-10	0.317E-09	5.00
30.0	0.446E-10	0.707E-09	165.00	0.272E-10	0.616E-09	165.00
36.0	0.477E-10	0.425E-09	325.00	0.174E-10	0.262E-09	325.00
42.0	0.785E-10	0.514E-09	290.00	0.420E-10	0.389E-09	290.00
48.0	0.138E-09	0.792E-09	270.00	0.866E-10	0.643E-09	270.00
54.0	0.286E-09	0.960E-09	230.00	0.222E-09	0.866E-09	230.00
60.0	0.111E-09	0.720E-09	245.00	0.638E-10	0.610E-09	260.00
66.0	0.596E-10	0.408E-09	260.00	0.213E-10	0.240E-09	45.00
72.0	0.420E-10	0.394E-09	205.00	0.162E-10	0.263E-09	205.00



EXPLOSION OF A SATELLITE 500 km ABOVE THE GEOSTATIONARY ALTITUDE

Table 8

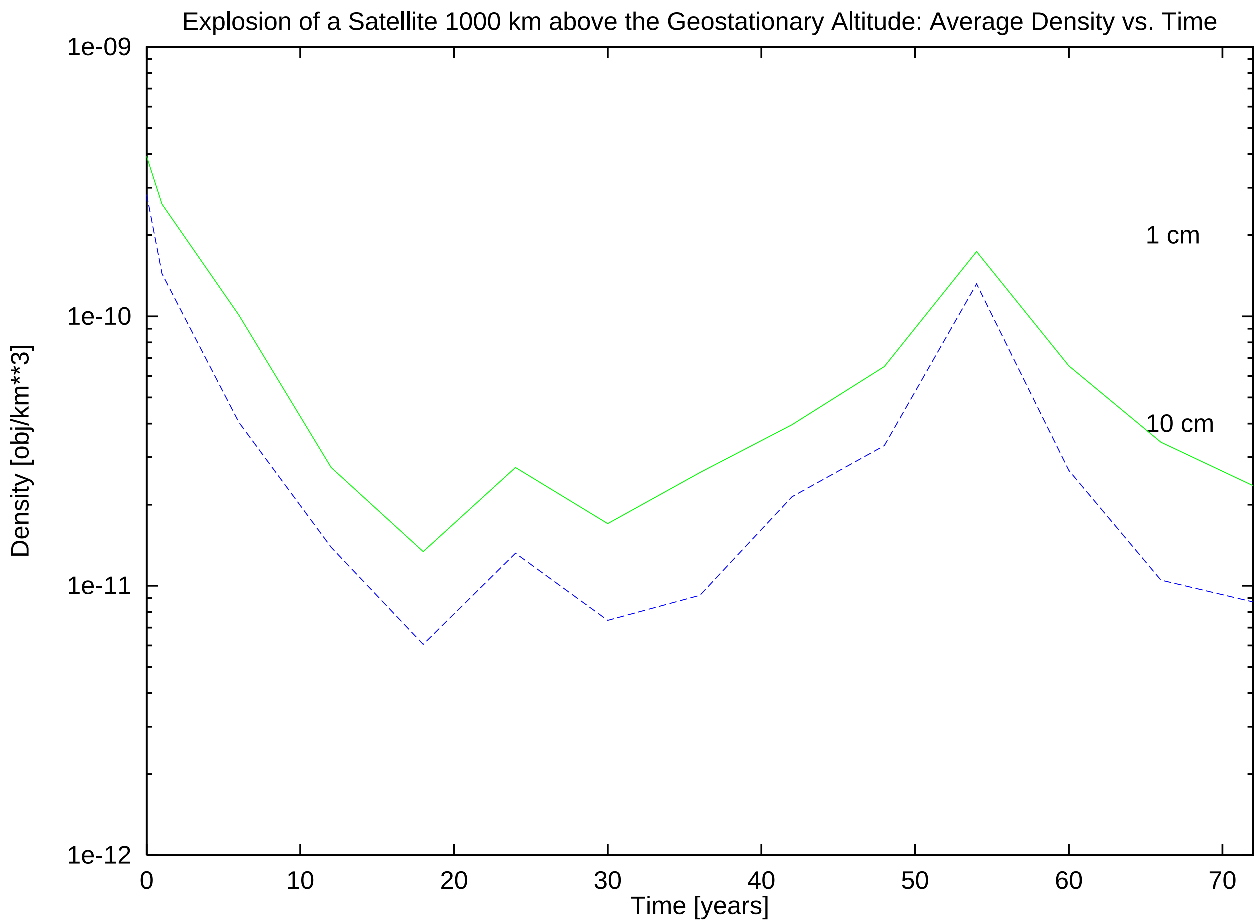
Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.852E-09	0.373E-08	115.00	0.641E-09	0.282E-08	115.00
1.0	0.467E-09	0.277E-08	275.00	0.323E-09	0.227E-08	275.00
6.0	0.109E-09	0.241E-08	255.00	0.506E-10	0.199E-08	255.00
12.0	0.524E-10	0.109E-08	50.00	0.272E-10	0.821E-09	50.00
18.0	0.349E-10	0.581E-09	20.00	0.174E-10	0.448E-09	20.00
24.0	0.411E-10	0.440E-09	185.00	0.208E-10	0.431E-09	185.00
30.0	0.311E-10	0.406E-09	165.00	0.164E-10	0.275E-09	170.00
36.0	0.396E-10	0.324E-09	305.00	0.145E-10	0.208E-09	140.00
42.0	0.776E-10	0.555E-09	290.00	0.411E-10	0.436E-09	290.00
48.0	0.126E-09	0.654E-09	270.00	0.808E-10	0.573E-09	235.00
54.0	0.215E-09	0.651E-09	235.00	0.159E-09	0.580E-09	235.00
60.0	0.108E-09	0.101E-08	260.00	0.679E-10	0.763E-09	260.00
66.0	0.500E-10	0.329E-09	50.00	0.190E-10	0.238E-09	50.00
72.0	0.416E-10	0.410E-09	205.00	0.171E-10	0.320E-09	205.00



EXPLOSION OF A SATELLITE 1000 km ABOVE THE GEOSTATIONARY ALTITUDE

Table 9

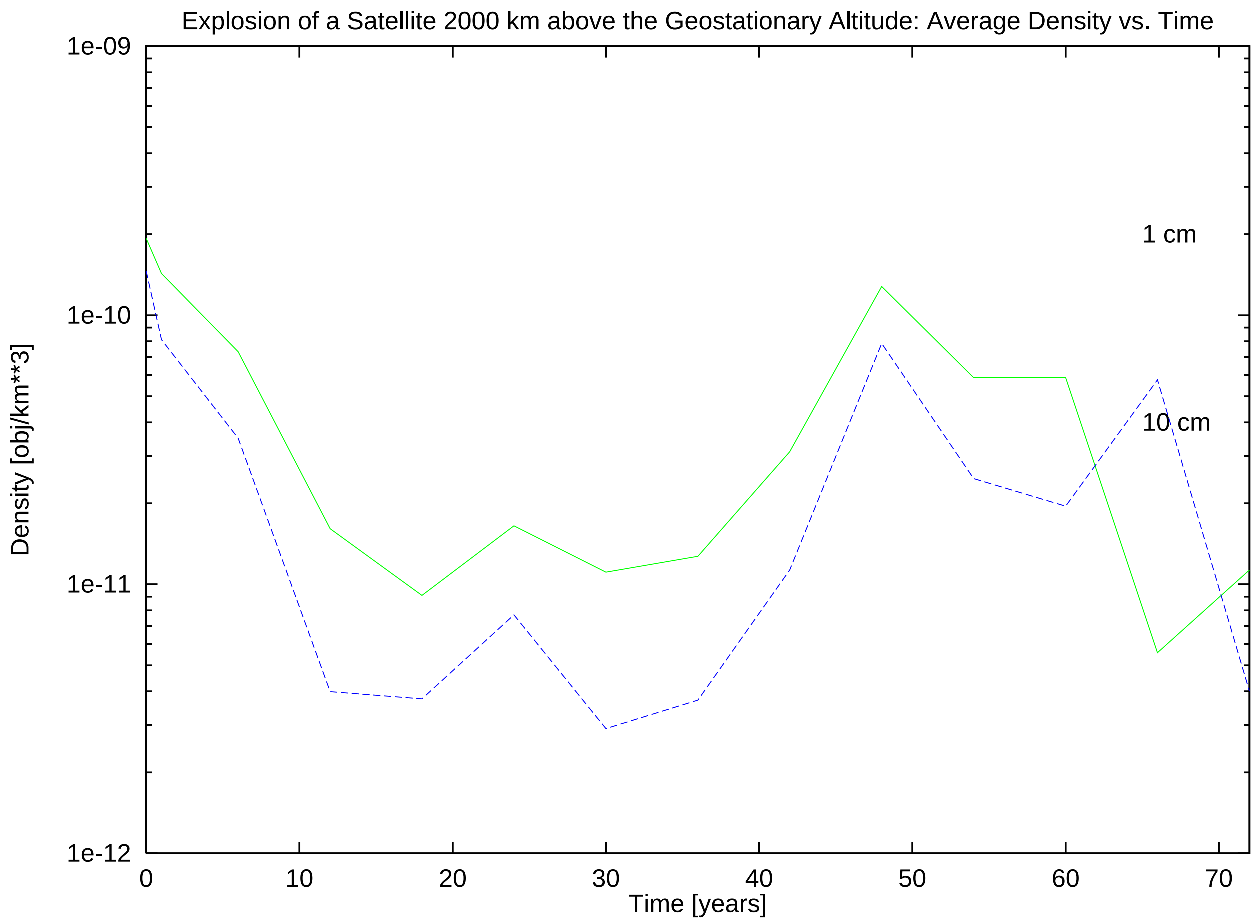
Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.392E-09	0.208E-08	115.00	0.283E-09	0.166E-08	115.00
1.0	0.261E-09	0.118E-08	280.00	0.144E-09	0.760E-09	250.00
6.0	0.101E-09	0.185E-08	255.00	0.404E-10	0.128E-08	75.00
12.0	0.275E-10	0.538E-09	230.00	0.139E-10	0.492E-09	230.00
18.0	0.134E-10	0.305E-09	205.00	0.606E-11	0.272E-09	205.00
24.0	0.275E-10	0.285E-09	185.00	0.132E-10	0.224E-09	185.00
30.0	0.170E-10	0.193E-09	350.00	0.744E-11	0.185E-09	350.00
36.0	0.263E-10	0.308E-09	330.00	0.922E-11	0.197E-09	330.00
42.0	0.396E-10	0.288E-09	300.00	0.214E-10	0.213E-09	300.00
48.0	0.651E-10	0.571E-09	100.00	0.331E-10	0.571E-09	100.00
54.0	0.174E-09	0.952E-09	55.00	0.132E-09	0.886E-09	55.00
60.0	0.655E-10	0.655E-09	70.00	0.268E-10	0.525E-09	70.00
66.0	0.341E-10	0.297E-09	230.00	0.105E-10	0.281E-09	230.00
72.0	0.235E-10	0.271E-09	205.00	0.871E-11	0.209E-09	205.00

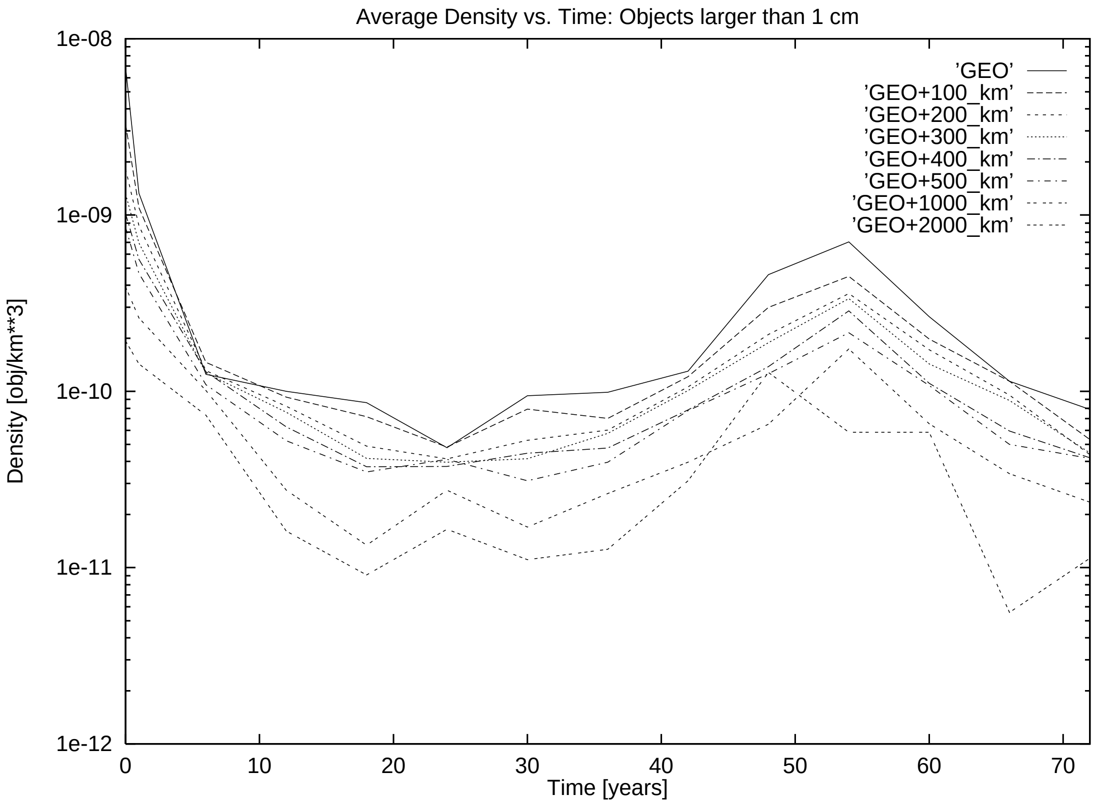


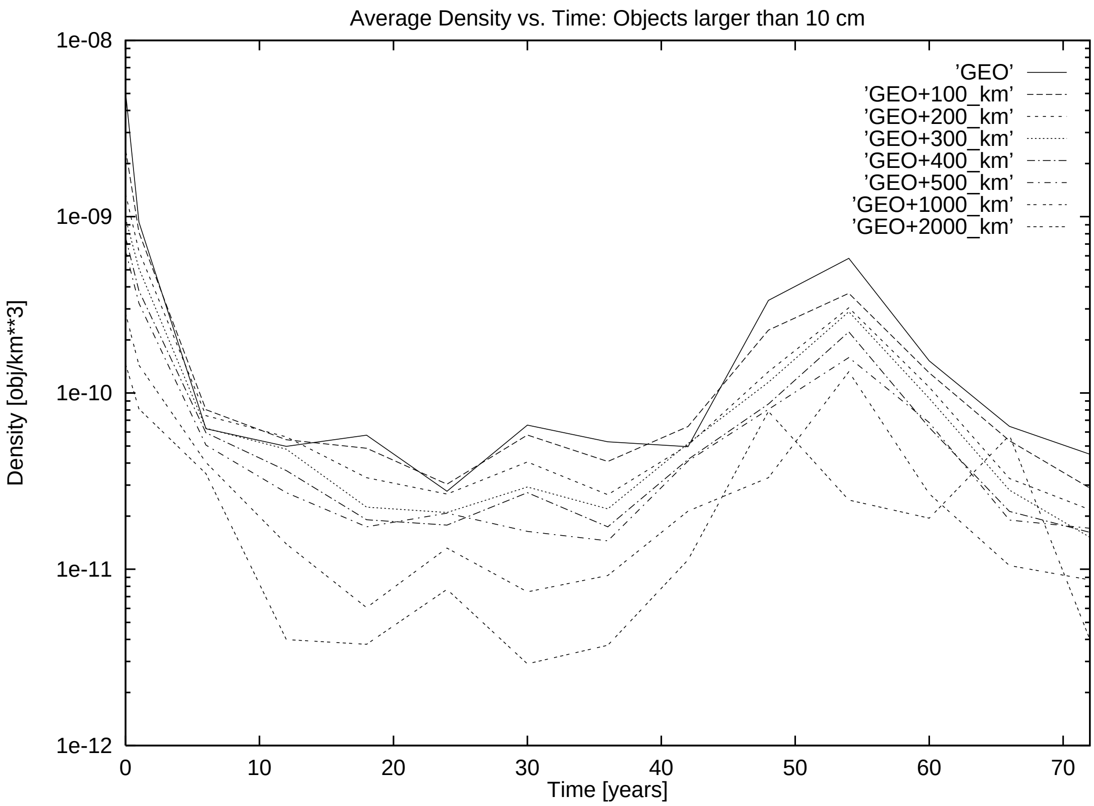
EXPLOSION OF A SATELLITE 2000 km ABOVE THE GEOSTATIONARY ALTITUDE

Table 10

Time (years)	1cm_ave	1cm_max	ra_max	10cm_ave	10cm_max	ra_max
0.0	0.193E-09	0.173E-08	115.00	0.146E-09	0.119E-08	115.00
1.0	0.143E-09	0.505E-09	85.00	0.812E-10	0.505E-09	85.00
6.0	0.732E-10	0.169E-08	75.00	0.349E-10	0.150E-08	75.00
12.0	0.161E-10	0.294E-09	230.00	0.399E-11	0.224E-09	230.00
18.0	0.909E-11	0.210E-09	205.00	0.375E-11	0.183E-09	205.00
24.0	0.165E-10	0.272E-09	185.00	0.770E-11	0.209E-09	185.00
30.0	0.111E-10	0.180E-09	350.00	0.291E-11	0.161E-09	350.00
36.0	0.127E-10	0.109E-09	325.00	0.371E-11	0.109E-09	325.00
42.0	0.311E-10	0.224E-09	300.00	0.113E-10	0.224E-09	300.00
48.0	0.128E-09	0.902E-09	115.00	0.786E-10	0.757E-09	115.00
54.0	0.586E-10	0.751E-09	65.00	0.247E-10	0.357E-09	250.00
60.0	0.586E-10	0.751E-09	65.00	0.195E-10	0.421E-09	65.00
66.0	0.557E-11	0.101E-09	245.00	0.575E-10	0.950E-09	65.00
72.0	0.113E-10	0.187E-09	210.00	0.400E-11	0.187E-09	210.00




Average Density vs. Time: Objects larger than 1 cm
'GEO'
'GEO+100_km'
'GEO+200_km'
'GEO+300_km'
'GEO+400_km'
'GEO+500_km'
'GEO+1000_km'
'GEO+2000_km'
Density [obj/km**3]
1e-08
1e-09
1e-10
1e-11
1e-12
0
10
20
30
40
50
60
70
Time [years]


Average Density vs. Time: Objects larger than 10 cm
'GEO'
'GEO+100_km'
'GEO+200_km'
'GEO+300_km'
'GEO+400_km'
'GEO+500_km'
'GEO+1000_km'
'GEO+2000_km'
Density [obj/km**3]
1e-08
1e-09
1e-10
1e-11
1e-12
0
10
20
30
40
50
60
70
Time [years]

Conclusions

The effect of spacecraft breakups over 72 yr, as a function of the end-of-life re-orbiting altitude (0-2000 km), was analyzed in terms of the additional contribution to the object density in the GEO ring, both short and long-term.

In the short-term, the explosions in geostationary orbit are the most detrimental for the GEO ring environment, producing for several months density peaks higher or comparable to the existing background. The natural perturbations mitigate considerably the problem after one year, but after 54 yr – corresponding to one orbital plane libration cycle – peak densities just one order of magnitude less than the background can be observed again. However, the average fragment density in the ring ($d \geq 1$ cm) is never higher than 1/5 of the background, decreasing to less than 1/100 of the existing environment after 4 yr (apart for the density rebound five decades later). This means that a few satellite breakups could produce short-term effects matching the existing debris background, while several tens of explosions are needed to match, on the long-term, the density of the objects accumulated in the GEO ring after 600 launches and three known explosions (Johnson et al., 1998).

The spacecraft end-of-life re-orbiting is a possible mitigation solution. But the re-orbiting altitude is critical if explosions continue to occur. Just 100 km above the geostationary altitude may be sufficient to maintain the short-term peak density in the GEO ring at a comparable level, or below the background. But in order to reduce the post-event average density by an order of magnitude with respect to an explosion occurring in GEO, more than 500 km of re-orbiting are needed. This value is generally quite higher of that obtained by applying Eq. 1, close – for typical satellites – to 300 km.

Concerning the long-term environmental impact, the link with the re-orbiting altitude is less strong. In other words, the improvement grows quite slowly as a function of the altitude above GEO. The strategy supported by IADC (Eq. 1) seems adequate to guarantee, after 2-3 years, a long-term average density of fragments in the GEO ring at least two orders of magnitude below the existing background, even during the density rebound observed after 54 yr. But at least 1000 km of re-orbiting are needed to stay below that 1/100 threshold also in the short-term.

In conclusion, the optimal debris mitigation strategy in GEO should be a compromise between:

- Spacecraft end-of-life passivation effectiveness;
- Spacecraft end-of-life re-orbiting altitude;
- Acceptable debris background in the GEO ring.

Assuming as a goal the maintenance of the existing background, the recommended end-of-life re-orbiting altitude should depend critically on the long-term effectiveness of satellite passivation. The re-orbiting strategy recommended by IADC is in fact totally adequate only if satellite passivation is extensively and successfully carried out. However, if this is not the case, higher re-orbiting altitudes must be considered.

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