THE SMALL SIZE DEBRIS POPULATION IN THE GEO BELT

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ABSTRACT

This paper presents an analysis of sources, orbital evolutions and distributions of small size debris near the geostationary ring. Paint flakes and MLI fragments were identified as potential sources for much larger populations of space debris in the microns to cm size range than predicted by present reference models. The orbital evolution of these particles was studied. In the absence of atmospheric drag, small particles will accumulate and spread over a relatively thin belt around GEO under the well known gravitational forces. Solar radiation pressure is the only perturbing force which can remove particles from the GEO region if they have high area-to-mass ratios.

Population densities of small size space debris near GEO are presented for different but realistic assumptions on debris sources, production rates and size distributions. These results are compared to predictions from the MASTER-2005 model. It is concluded that small size (sub-cm) debris could form already now or in the near future a belt of particles around GEO (G-belt) that is visible in infrared or optical wavelengths by suitably located space sensors.

1. INTRODUCTION

Little information is available on the cm and smaller size space debris population in and near the geostationary orbital region. Recent optical measurements [1, 2] indicate the presence of at least 2000 objects larger than 15 cm near the geostationary orbit (GEO). Measurements made by the GORID in-situ impact detector in GEO between 1996 and 2001 indicate that, in the sub-mm size range, debris fluxes exceed the fluxes of natural meteoroids by at least a factor 5 [3]. Predictions of the sub-cm debris populations near GEO by reference models like MASTER-2005 [4] are largely based on break-up simulations and ad-hoc assumptions on the creation of surface degradation products like paint flakes and secondary ejecta. As these models could not be based on real measurements they inevitably have large uncertainties. On the other hand it is well known that spacecraft surfaces degrade in the harsh space environment. Ground tests and retrieved space hardware have shown that paint and other coatings are flaking off and multi-layer insulation (MLI) foils become brittle, peel off and crumble.

This paper presents an assessment of potential degradation products resulting from spacecraft near GEO. Different assumptions were made on the sources, location, size distribution and total area of degradation products. This is followed by an analysis of the orbital evolution and resulting distribution of the debris objects. The results are then compared to predictions from the MASTER-2005 tool. The paper concludes by estimating total densities of sub-cm size particles near GEO and by a discussion of the potential visibility of a resulting small size debris belt around GEO.

2. SPACECRAFT DEGRADATION PRODUCTS

2.1 Evidence for small size debris near GEO

Ground based measurements with optical telescopes can detect GEO space debris objects down to about 15 cm in size (depending on albedo). In 2008, about 1100 near-GEO objects were catalogued [5]. Recent measurements [1, 2] indicated at least twice this number of objects if the threshold is lowered to 15-20 cm. This relatively large number in the size range 15-100 cm exceeds model predictions which are mainly based on spent satellites, released objects and on known and assumed break-ups and collisions. Many of the newly observed objects in the size range 15-50 cm have a large area-to-mass ratio (AMR) indicating that they could be thin foils, potentially from MLI fragmentation or degradation. No cut-off was seen towards smaller sizes. If a large number of foil debris in the 15 –50 cm size range is present in GEO it can be assumed that a much larger number of smaller debris exists as well, which is not visible from ground.

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Evidence for a considerable number of small size debris near GEO comes also from the GORID in-situ impact detector. GORID had a total sensor surface of 0.1 m^2 and operated in GEO between 1996 and 2001 on-board of the Russian EXPRESS 2 satellite [3]. GORID indicated that, in the sub-mm size range, debris fluxes exceed the fluxes of natural meteoroids by at least a factor 5. Unfortunately, GORID was not designed to measure relatively slowly drifting debris and it could not provide much information on the actual size and velocities of the impacting particles. It did however find that most of the presumed man-made debris objects impact in event clusters and must be part of debris clouds [3].

2.2 Evidence of surface degradation

Retrieved hardware (only available from LEO) and ground tests showed that paint and MLI degraded and sometimes crumbled to dust. Fig. 1 shows damaged MLI on the solar array drive of the Hubble Space Telescope (HST) which was retrieved in 2002. Cracks and a rough edge, indicating torn-off pieces, are visible near the center of the picture. Fig. 2 shows a detached piece (1-2 cm^2 in size) of thermal metal coating of an antenna piece following thermal tests. Paint on the retrieved exposure facilities LDEF and EURECA was also found to be cracked and sometimes detached.

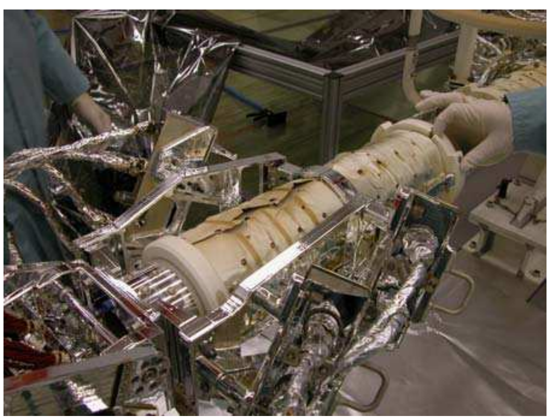

Figure 1. Damaged MLI on HST solar array drive after retrieval

2.3 Degradation products

Fig. 3 shows a sketch of a modern large telecommunication satellite aimed for GEO. The largest outer surfaces are the solar arrays, the thermal insulation foil, the antennae and the radiators. All these surfaces (which combined can have an area of 100-200 m^2) are potential sources of debris from degradation products.

Figure 2. Damaged metal coating on antenna following thermal tests

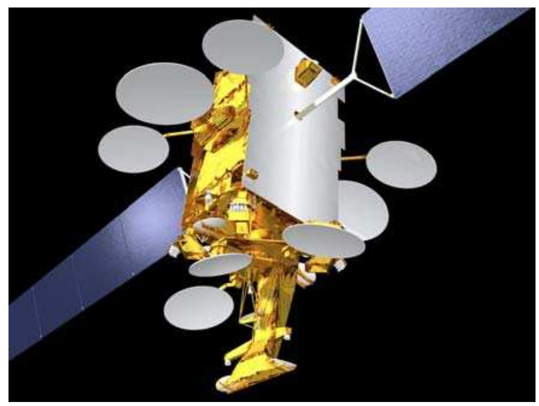

Figure 3. Sketch of a modern large GEO telecommunication satellite showing the main exposed surfaces

Potential degradation products include:

- MLI patches (large and small)
  - Patches for thermal fine trimming
  - Outer (and perhaps inner) MLI layers
  - Single thermal layers on e.g. solar array rears
- Solar cell sections (likely not individual cells, as they are attached by the connectors)
- Solar cell cover glasses (they are glued individually to the cells)
- Flakes from paint and other coating (antennae, upper stages)

Table 1 lists the surface materials identified as potential debris sources. Two typical thicknesses of 100 μ and 200 μ were assumed for paint. MLI comes in different varieties, for example with and without outer layers of beta cloths, FEP Teflon or thicker light block layer, with different number of layers (typically 10-30) and with inner layers of either Kapton or Mylar with typical thicknesses between 4 µ and 8 µ. Different sizes of solar cells are used with a tendency towards increasing sizes. Most are of rectangular shape but square cells exist as well. Solar cell cover glasses have a typical thickness of 150 µ. For the present study the representative set of materials in Table 1 was used.

Table 1. Surface materials identified as potential debris sources and their typical thicknesses

Material	Thickness, t [µ]
Paint type 1	100
Paint type 2	200
FEP	125
Kapton	50
Mylar	6
Solar cell cover glass ($2x4\ cm^2$, $3x6\ cm^2$, $4x8\ cm^2$)	150

It was noticed that retrieved paint and FEP Teflon crumble when touched into small dust of millimetre size or smaller [6]. The quantitative size distribution of these flakes and dust is unknown. For the present analysis the following ad-hoc assumptions on the number and sizes of the space debris objects from surface degradation were made: Every second object of the catalogued near GEO objects [5] looses 3 m^2 of each of the materials listed in Table 1. These 3 m^2 produce box shaped flakes of 3 different sizes from 1 m^2 each. These particles have constant thickness, t, (as given in Table 1) and surface areas of t^2 μ^2, 1 mm^2 and 1 cm^2, respectively. That means the smallest particles are little cubes with dimension t, while the other two are rather thin flakes. Solar cell cover glasses are treated with the sizes and thickness given in Table 1 because it is assumed that they only detach from its parent cell without breaking apart.

One important parameter for the orbital evolution of the debris particles is their area-to-mass ratio. Table 2 gives a summary of the particle characteristics and their resulting $AMRs_n$ for the 3 different flake sizes, respectively. The values for a Kapton particle of 1 µ thickness are added as demonstration only to show the extreme AMR values of such a thin particle. For the AMR the cross-sectional area is used which is equal to ¼ the surface area of the particles.

Table 2. Area-to-mass ratios (AMRs in units of m^2/kg) of typical materials on exposed spacecraft surfaces

Material	Density [g/cm^3]	Thickness, t [µ]	AMR_1 $V_1 = t^3$	AMR_2 $V_2 = 1\ mm^2\ t$	AMR_3 $V_3 = 1\ cm^2\ t$
Paint 1	2.5	100	6	2.4	2.04
Paint 2	2.5	200	3	1.4	1.04
FEP	2.17	125	5.53	2.3	1.89
Kapton	1.44	50	20.8	7.64	7.01
Mylar	1.0	6	250	84.33	83.43
Glass	2.2	150	1.53 ($2x4cm^2$)	1.53 ($3x6cm^2$)	1.52 ($4x8cm^2$)
Kapton	*1.44*	*1*	*1042*	*348*	*347*

3. ORBITAL EVOLUTION

Once released from the parent body with no or very low velocities the debris objects move under the effect of gravitational field and external perturbing forces. Particles near GEO encounter no air drag from the residual atmosphere. Main perturbing forces are the non-spherical gravity field of Earth, the luni-solar perturbations and the solar radiation pressure. Although most particles are charged in space magnetic field perturbations are only relevant for particles of sub-micron-size and this perturbation was neglected.

The Focus-1 tool [7] was used to propagate the debris particles in time. This tool uses analytical approximations to speed up the computations. This procedure implies that results of simulations with high AMRs are not accurate and have to be treated with caution. For most simulations the initial distribution of the catalogued objects near GEO was used w.r.t. their inclinations (see Fig. 4.) with an even distribution of 10^o along the longitude. It was assumed that the degradation products are released with zero relative velocity. Different start and end times were used in the calculations to sample the complete spatial range of the orbiting particles. Evolution runs were performed for up to 100 years.

Perturbations of particles with low AMR (< 1) are dominated by the gravity from Earth, Moon and Sun and these objects follow the known orbital evolution. The orbital inclination increases for about 26.5 years to a maximum value of around 15^o and then decreases again during the next 26.5 years to an inclination near zero. The objects move north/south, crossing the equator twice per day. At maximum inclination of 15^o

these equator crossings occur at a relative velocity of about 800 m/s. In addition, the particles oscillate around two stable points at longitudes of 75° East and 105° West. The semi-major axis and eccentricities are little changed.

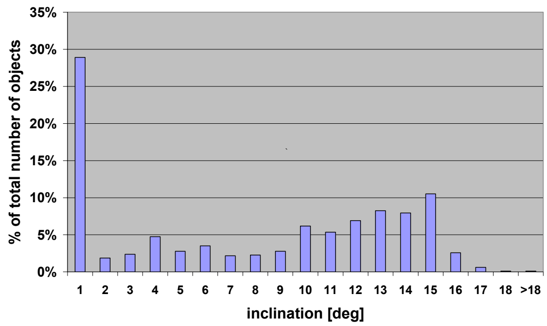

Figure 4. Distribution of catalogued objects near GEO per bins of 1° inclination

Particles with larger AMR encounter a larger additional perturbation from the solar radiation pressure. This leads to an increase and decrease in orbital eccentricity with a period of 1 year. The orbital period stays close to 1 day. In addition these particles also show a secular increase in eccentricity. As example of the results obtained by the Focus-1 tool, Fig. 5 shows the eccentricities of particles with different AMRs over a period of 1 year.

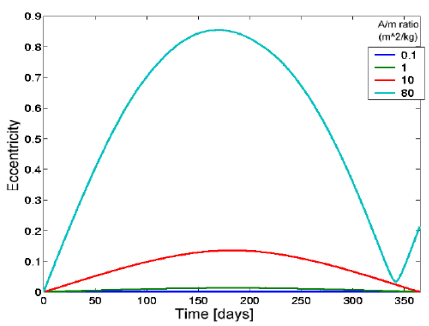

Figure 5: Change of eccentricity of particles with different AMR over a period of 1 year.

Depending on the AMR this can lead to such high eccentricities that the particle re-enters into Earth's atmosphere or is propelled out of Earth orbit. Solar radiation pressure can remove micron sized particles from GEO within weeks. It should be noted that it was not intended to precisely calculate the orbit of individually particles. With the approximations made within the Focus-1 tool that would not be possible. The present study aimed at the final statistical distribution of the surface degradation products. The decay rates and final positions of individual 6 µ particles are probably not very precise but reliable enough for the relevant results and conclusions of the present study.

4. RESULTS

A total of around 100,000 particles with different AMR, initial locations (all near GEO) and start and end times were propagated for 100 years. Fig. 6 shows the debris distribution of all paint and MLI particles with thickness of 6 µ or larger after 100 years. It should be noted that this is not a snapshot of the distribution at a given time. The simulations were stopped at different times of day to give an impression of the overall extent and shape of the region accessible to the debris. The band like structures are artefacts as well caused by the release of clouds of particles at certain times and locations. The particles with the highest AMRs show the largest spread in eccentricity and inclination. Many of the 6 µ objects had even decayed or were ejected from orbit. The debris of 50 µ size and larger, however, formed a fairly stable ring around GEO. The denser parts of that ring extended to about +/- 30° in declination (high ARM particles typically exceeded the maximum increase in inclination of 15°) and spread over a radial distance of 500-1000 km. This can qualitatively be seen in Fig. 6.

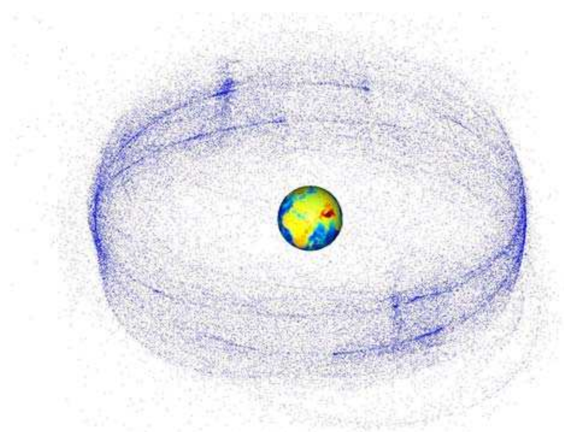

Figure 6. Distribution of paint and MLI particles > 6 µ after 100 years

For the orbital calculations specific particle sizes and initial conditions were used. This should give an envelope of the particle distributions. In reality space debris will have a full size distribution between the largest and smallest particles analyzed in this study. For a realistic qualitative analysis and comparison with existing debris reference models, like MASTER-2005, additional assumptions of the final distribution of particles have to be made.

Based on the results of the orbital evolutions different cases can be defined for the final real distribution of small size debris near GEO:

1. The distribution of small debris is identical to the distribution for catalogued objects as in Fig. 4.

2. Small debris is evenly distributed over a shell occupied by the catalogued objects.
3. Small debris is evenly distributed over a shell occupied by the propagated small particles.

The average spatial density of debris decreases from Case 1 to Case 3. For an assessment of the present situation and a comparison with the MASTER-2005 space debris model Case 1was assumed. Most current debris near GEO exists far shorter than the 100 years used for the propagation. Their orbits, although modified by solar radiation pressure, might not have yet evolved drastically from that of their parent bodies.

Fig. 7 shows a comparison between predictions of MASTER-2005 (reference epoch May 2005) and the present study for flakes larger than 100 μ as function of the inclination. For MASTER-2005 the results for paint only are shown as this model does not include MLI debris. For the present study the results for paint alone and for paint plus MLI are shown. This study predicts much higher densities, especially at lower inclinations (note the logarithmic scale for density). The present study makes several ad-hoc assumptions on debris production by surface degradation; however, we believe that these are not unrealistic. The comparison with MASTER-2005 shows that much more debris could be present near GEO than predicted by present reference models.

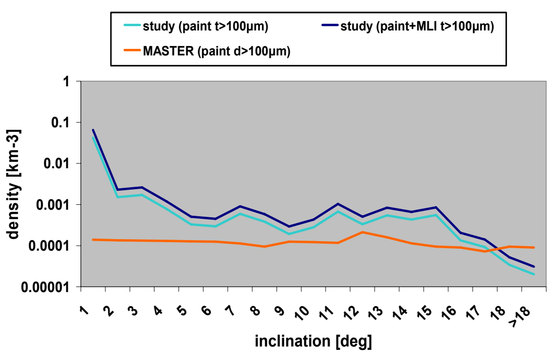

Figure 7. Spatial density of paint and MLI particles vs. inclination (bins of 1^o). Comparison between MASTER-2005 and present study

Fig. 8 compares the total number of particles near GEO as predicted by MASTER-2005 and the present study for various particle sizes from 1 μ to 1 mm. The results are given for each debris source individually. For MASTER-2005 the reference epoch May 2005 is used. For the 1 μ results of the present study it was simply assumed that the volume of the degradation products is broken down into 1 μ square particles. It should be mentioned again that 1 μ particles were not included in the orbital propagation as they will be removed rather quickly from orbit by solar radiation pressure. The 5 μ particles of MASTER are compared with the 6 μ Mylar particles of the present study. The results in Fig. 7 show larger debris numbers for the present study for almost all sizes. It should be pointed out that the results of the present study only include paint and MLI, whereas the MASTER-2005 results include other debris sources like SRM (solid rocket motor) dust and ejected particles from impacts. In principle these contributions should be added to the debris from the present study.

5. CONCLUSIONS

It was shown that surface degradation processes could lead to large numbers of space debris near the geostationary orbit. The total spatial densities of these debris particles could far exceed predictions of present flux models.

Under the perturbing forces acting in GEO, these debris objects will form a belt around the GEO ring. Typical particle sizes will be tens of microns to cm. Smaller particles will be removed by solar radiation pressure. The main part of this G-belt of space debris has a thickness of several 100s to 1000 km and extends up to +/-30^o declination (see Fig. 6).

Within the present study it was assumed that debris from a total surface area of 7500 m^2 (500 parent objects x 5 materials x 3 sizes from 1 m^2 each) is released. Given the large and increasing number of satellites in GEO this scenario is not seen as unrealistic. Most of these objects will stay within about +/- 15^o declination and within a radial distance of less than 500 km from GEO for many years. A central part of this belt composed of debris particles with low inclinations and eccentricities could be much more localized and denser than the rest.

The orbital behaviour of high AMR particles has to be analyzed in more detail and investigated further in order to perform more reliable simulations of the spatial distribution. However, particles below 10 μ (resulting in a very high AMR) will be removed from orbit within months or even weeks.

If we assume that 1/10 of the debris is visible along the line of sight of a suitably located space sensor and distributed over a column with cross section of 500 x 3000 km^2 (to represent the denser part of the belt) one obtains an optical depth of $5x 10^{-9}$. This value is still below the range of optical visibility, but not by much.
The actual spatial density of debris particles could be lower, but it could also be higher for several reasons: debris from other sources (e.g. from fragmentations, SRM slag, solar cell cover glasses etc.) is not considered and has to be added, the debris creating

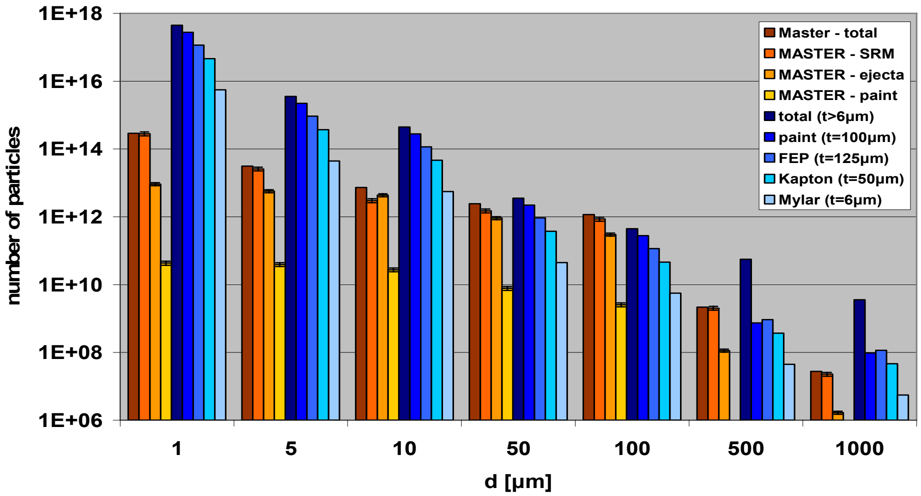

Figure 8. Total number of debris particles near GEO for different minimum sizes. Comparison between MASTER-2005 and present study

paint or MLI surfaces could be larger than assumed in the present study, the central part of the belt could be smaller or denser. Any of these factors could bring the optical depth of the G-belt to within the visible range of 10^{-7} –10^{-8}.

The orbital motion of the individual debris particles leads to a constant change of the spatial density of the belt. Every ½ day many objects will be near the GEO ring during their north/south oscillation leading to a relatively high spatial density. In these high density regions the debris G-belt of Earth might be visible (already now or in the near future) by a space based optical or infrared sensor which is suitably located to see the belt edge-on.

6. REFERENCES

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