LONG-TERM EVOLUTION OF HIGH AREA-TO-MASS RATIO OBJECTS IN DIFFERENT ORBITAL REGIONS

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ABSTRACT

Objects with high area-to-mass ratios (HAMR) in high-altitude orbits were first discovered in 2004. The orbits of these objects had semimajor axes near the nominal value of geosynchronous objects but eccentricities considerably different from zero. They are believed to stem from parent objects which reside (or resided) in or near the geostationary ring (GEO). The mechanisms of their production are, however, still unknown. Several hypotheses were put forward, including breakup events and aging processes leading to delamination of spacecraft surface materials. Similar HAMR populations as found in GEO-like orbits may be expected in other orbital regions. Optical surveys of the Astronomical Institute of the University of Bern (AIUB) revealed HAMR objects in a variety of geostationary transfer orbits (GTO). This paper will analyze the long-term evolution of HAMR objects in different orbital regimes including the GEO disposal orbits, Medium-Earth orbits of the navigation satellite constellations and Molniya orbits. The characteristics of the hypothetic HAMR populations will be based on the observed population in GEO and GTO. The simulation results allow assessing the future threats stemming from HAMR objects.

1. THE AIUB/ESA CATALOGUE OF SMALL-SIZE HIGH AREA-TO-MASS RATIO DEBRIS

AIUB is searching space debris in high-altitude orbits on a regular basis since more than 15 years. The orbit regions include the GEO ring, low inclination (<25°) GTO orbits, and more recently the region of today's navigation satellite systems GPS, GLONASS, Galileo and Beidou (see eg. [1], [2]). First observations to search for debris in Molniya orbits will follow in autumn 2012. Surveys of all these regions are performed with a variety of sensors, in particular with the ESA 1m space debris telescope in Tenerife, and AIUB's small-aperture, wide field telescope ZimSMART located at the Zimmerwald Observatory, Switzerland. A subset of these objects discovered by the surveys is followed up by means of the AIUB 1m telescope ZIMLAT, also located at the Zimmerwald observatory, and by sensors of the International Scientific Optical Network (ISON). The support of the ISON sensors is provided in the context of a scientific collaboration between the AIUB and the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM RAS). Figure 1 shows a typical magnitude histogram of objects discovered during a 1-year survey campaign using the ESA telescope. The blue line represents the calibrated sensitivity of the sensor. Sizes were computed assuming a Lambertian scattering sphere and an albedo of 0.1.

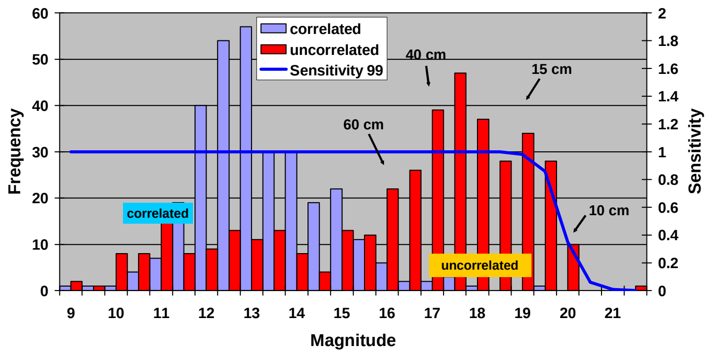

Figure 1: Magnitude histogram for the objects discovered during a typical 1-year survey campaign. Correlated objects are in blue, uncorrelated objects in red, respectively (USSTRATCOM catalogue).

The follow-up observations allow building and maintaining an orbit catalogue of these debris objects, which in turn is a prerequisite to determine their area-to-mass ratios (AMR). This catalogue is furthermore used to generate the required ephemerides to determine physical characteristics of the objects by means of photometric, spectroscopic and light curve observations. The catalogue contains a significant fraction of HAMR objects with AMR larger than $1 m^2/kg$. These objects require constant monitoring to maintain their orbits as the latter are strongly perturbed by non-gravitational forces, in particular solar radiation pressure, which are difficult to predict (see [3]).

The AIUB/ESA catalogue as of January 2012 contains 1018 uncorrelated small-size objects in GEO, GTO and GEO-like orbits for which 6-parameter orbits were determined. For 345 objects the AMR could be determined. As can be seen in Figure 2, there is a significant population of objects with AMR larger than $1\ m^2/kg$ (note that the AMR of an intact spacecraft is of the order of $0.02\ m^2/kg$, and the one of ordinary office paper of the order of $12\ m^2/kg$). A closer analysis reveals that a large fraction of the objects with AMR larger than $1\ m^2/kg$ are objects with a mean motion near 1 rev/day and eccentricities ranging from 0.05 to 0.8. In Figure 3, which shows the eccentricity as a function of the mean motion for the objects of the AIUB/ESA catalogue, this population is the vertically dispersed cloud concentrated at a mean motion of 1 rev/day. The objects of this population are believed to stem from parent objects which reside (or resided) in or near the geostationary ring (GEO). Radiation pressure effects are changing the eccentricity of their orbits significantly (and to a lesser extent also the inclinations) resulting in the distribution seen in Figure 3. The production mechanisms of this debris are, however, still unknown. Several hypotheses were put forward, including breakup events and aging processes leading to delamination of spacecraft surface materials.

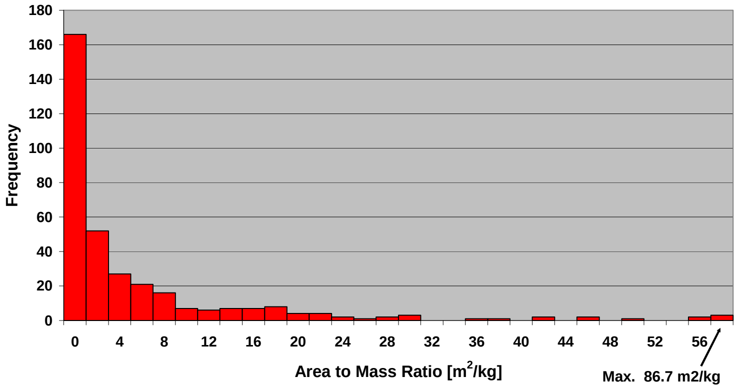

Figure 2: Distribution of the area-to-mass ratio of 345 uncorrelated objects in the AIUB/ESA catalogue.

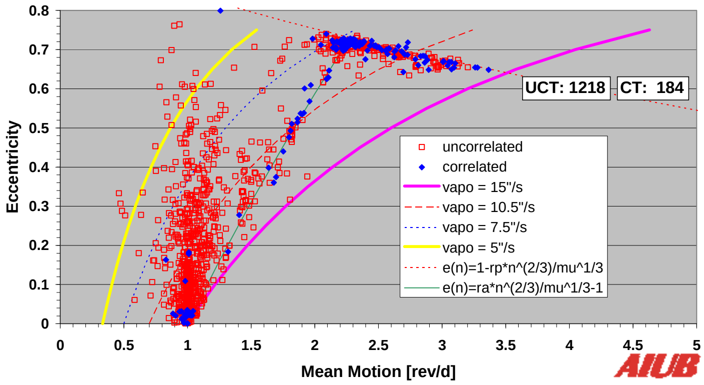

Figure 3: Eccentricity as a function of the mean motion for 1402 objects for which 6-parameter orbits were determined. (‘UCT’ and ‘CT’ denote the number of correlated and uncorrelated objects, respectively).

2. LONG-TERM EVOLUTION OF ORBITS OF HAMR OBJECTS

The fact that a large population of HAMR debris was found in GEO and GTO supports the hypothesis that sources of HAMR debris will exist in all orbital regions where objects are left in space for a long time span. The latter is particularly the case in disposal orbit regions (also called “graveyard” orbits). In the following we thus analyze the long-term evolution of HAMR objects in the established GEO disposal zone and in hypothetical GPS or GLONASS disposal obits. In contrary to investigations of other authors (e.g. [4]) we will use the orbits of actually observed debris objects as input for the following simulations.

1.1. Model Populations

A sample of 30 objects in super-GEO orbits has been chosen from the AIUB/ESA catalogue to represent a population of debris in the GEO disposal region. The orbit characteristics are the following:

a > 42464km (>300km above GEO), and

e < 0.05,

where a is the semimajor axis and e the eccentricity of the orbits. For the actual simulations the eccentricity was set to 0.001 for all objects in order to best represent the initial orbits of these objects (assuming that the orbits of their parent objects were circularized during the disposal maneuvers).

For the model population in the hypothetical disposal regions of the GPS and GLONASS constellations a different approach was chosen. As there are no HAMR debris objects in the AIUB/ESA catalogue for these regions we decided to choose a set of 14 known intact objects in super-GEO orbits and a sample of 11 intact objects related to the GLONASS constellation, all with low AMR. The objects have the following characteristics:

a > 27400km for super-GPS objects (>900km above GPS), and

a > 25508km for the GLONASS objects.

For the GLONASS objects this corresponds to the nominal GLONASS altitude, as there are no known super-GLONASS objects. The catalogue values of the eccentricity (and all other orbital elements) were used in this case.

1.2. Orbit Propagation

The numerical orbit propagator SATORB of the CelMech suite was used to integrate all orbits (see [5]). The force model included:

- Earth gravity field of order and degree 12,
- gravitational perturbations from:
  - Sun,
  - Moon,
- Earth tides,
- corrections due to general relativity,
- direct radiation pressure (Sun only),
- eclipses (Earth, Moon).

The orbits were propagated over a time interval of 50 years, starting at 2009-06-18 (mjd 55000). All objects were propagated assuming 5 different AMR values: 0.02, 0.02, 1, 5, 15m^2/kg.

1.3. Evolution of Orbits in the GEO Disposal Region

Figure 4 shows the evolution of the semimajor axis of 30 objects in the GEO disposal region over a time span of 50 years and for different AMR values. As expected, there are only minor variations, even for an AMR value of 15m^2/kg. The eccentricities given in Figure 5, however, show considerable variations with an annual period (actually a period of one nodal year) for AMR values greater than 1m^2/kg. As a consequence the perigee height is also changing substantially (Figure 6). We may conclude that objects in GEO disposal orbits (>300km above GEO) will cross the GEO altitude if AMR>0.2m^2/kg. For particular combinations of the inclination and the argument of perigee they will also cross the 0°-inclination GEO ring (the orbital plane and the argument of perigee are both changing over time).

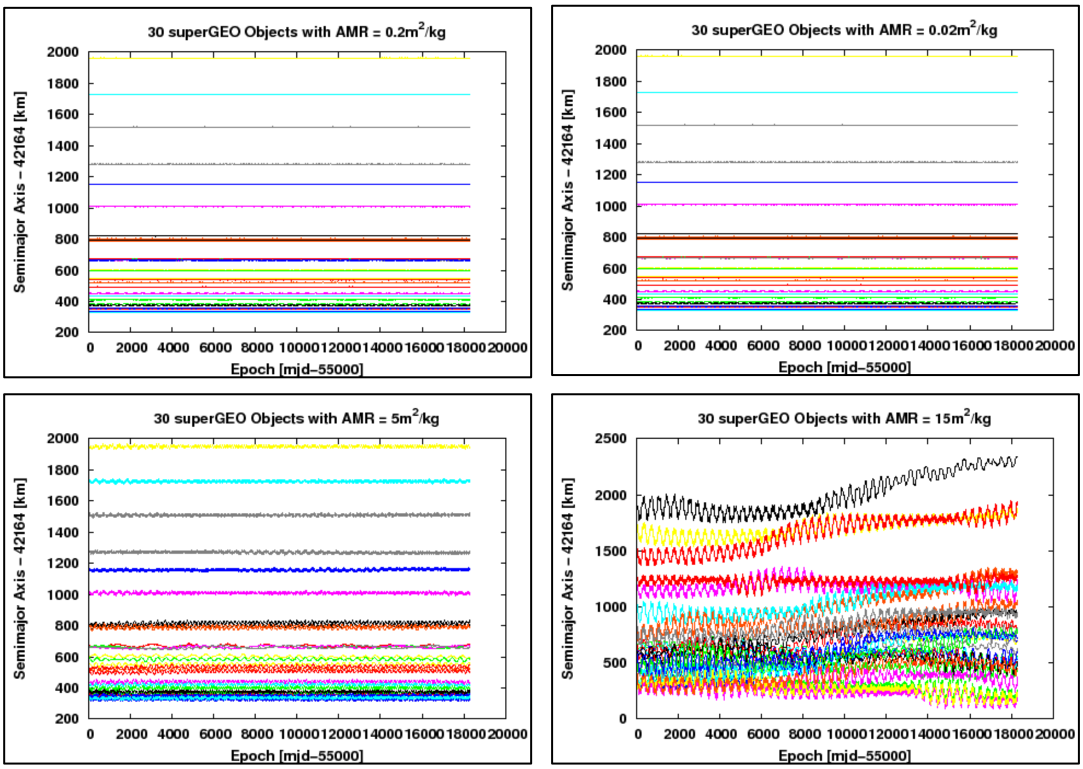

Figure 4: Evolution of the semimajor axis for 30 super-GEO objects and different AMR values.

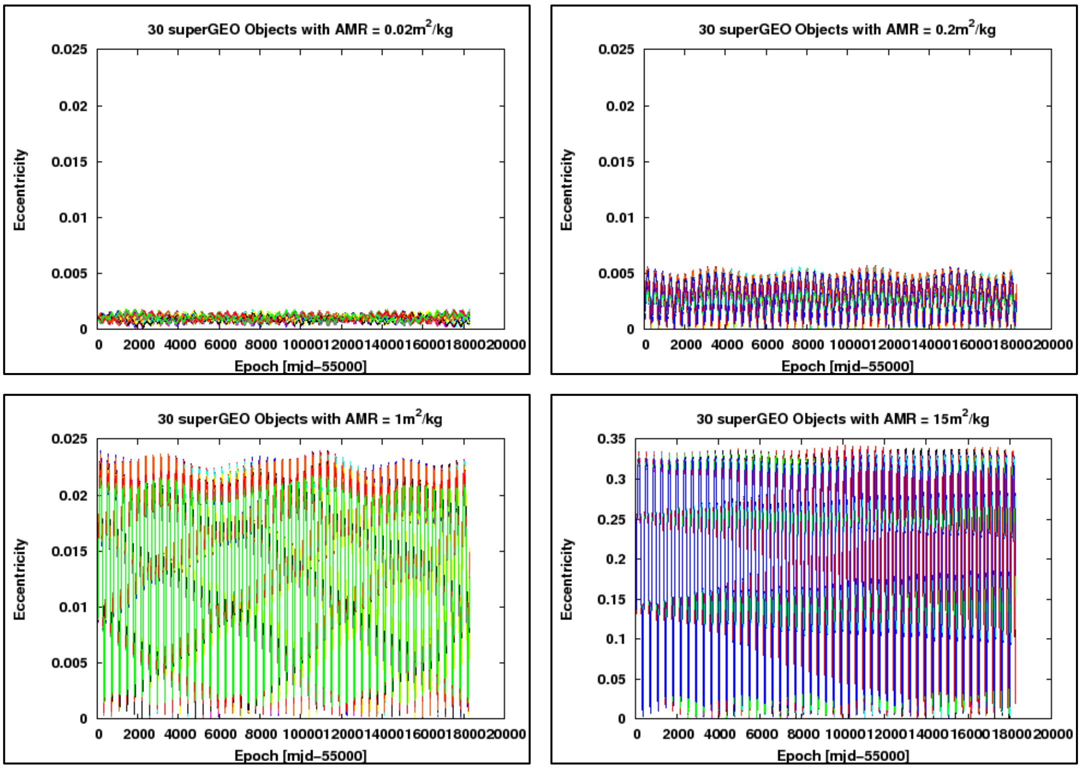

Figure 5: Evolution of the eccentricity for 30 super-GEO objects and different AMR values.

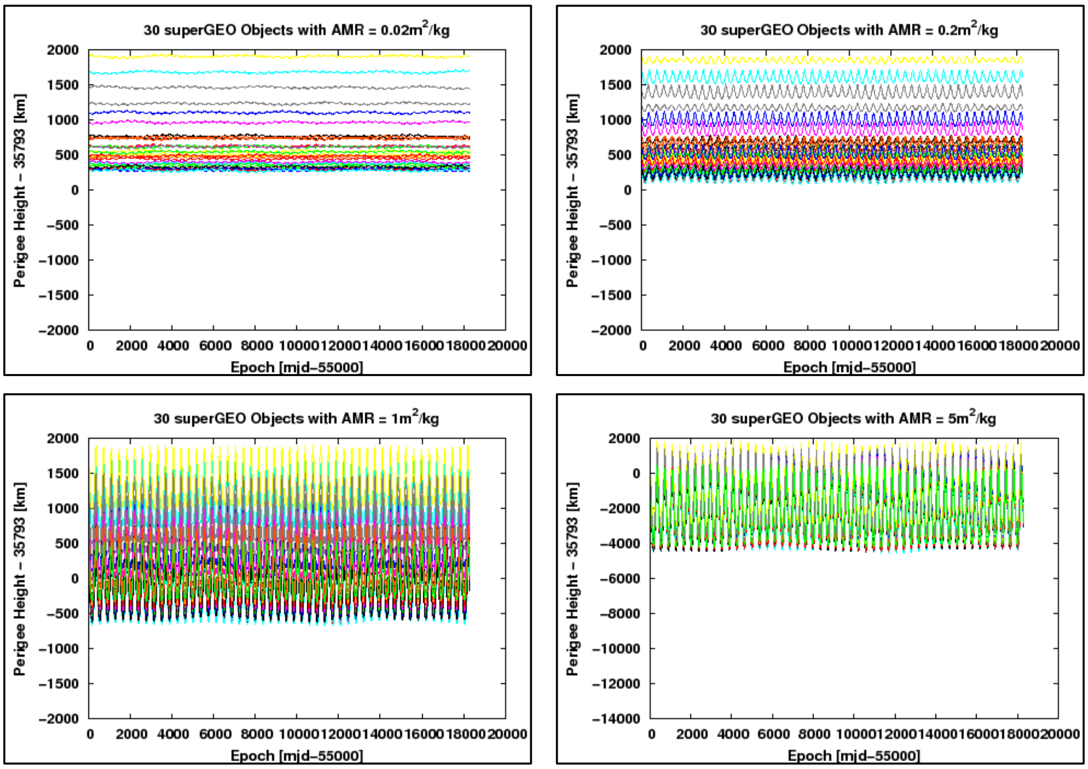

Figure 6: Evolution of the perigee height for 30 super-GEO objects and different AMR values.

This finding is consistent with the Inter-Agency Space Debris Coordination Committee (IADC) deorbit guideline:

ΔHmin = 235 + 1000*Cr*AMR [km],

where ΔHmin is the minimum increase of the perigee altitude required, and Cr is a parameter describing the reflection properties of the object with a value between 1 and 2. Assuming Cr=1 we obtain a minimum perigee altitude increase of 435km for AMR=0.2m^2/kg (to be compared with Figure 6, upper right). The IADC guideline is, however, obviously applied using the AMR of the spacecraft to be disposed not taking into account any HAMR debris which could originate from this spacecraft when left in the disposal orbit over long time.

1.4. Evolution of Orbits in the GPS and GLONASS regions

Figure 7, Figure 8, and Figure 9 show the evolution of the semimajor axis, the eccentricity, and the perigee height, respectively, for 14 super-GPS and 11 GLONASS objects and different AMR values. The semimajor axes remain again very constant over the entire time span and for all AMR values.

The perigee height of the super-GPS objects (>900km above nominal GPS height) cross the nominal GPS altitude for the majority of objects when the AMR is >1m^2/kg.This is again the result of the radiation pressure changing the eccentricities. Individual objects with e>0.01 initially may cross this altitude even for very low AMR values (Figure 8, upper left). This is due to the strong mean motion resonance of the GPS orbits with the rotation of the Earth.

The perigee height of the GLONASS objects (Figure 9), on the other hand, does also change by more than 1000km for objects with AMR >1m^2/kg. For objects with smaller AMR values there are no strong resonance effects which could change the eccentricity considerably.

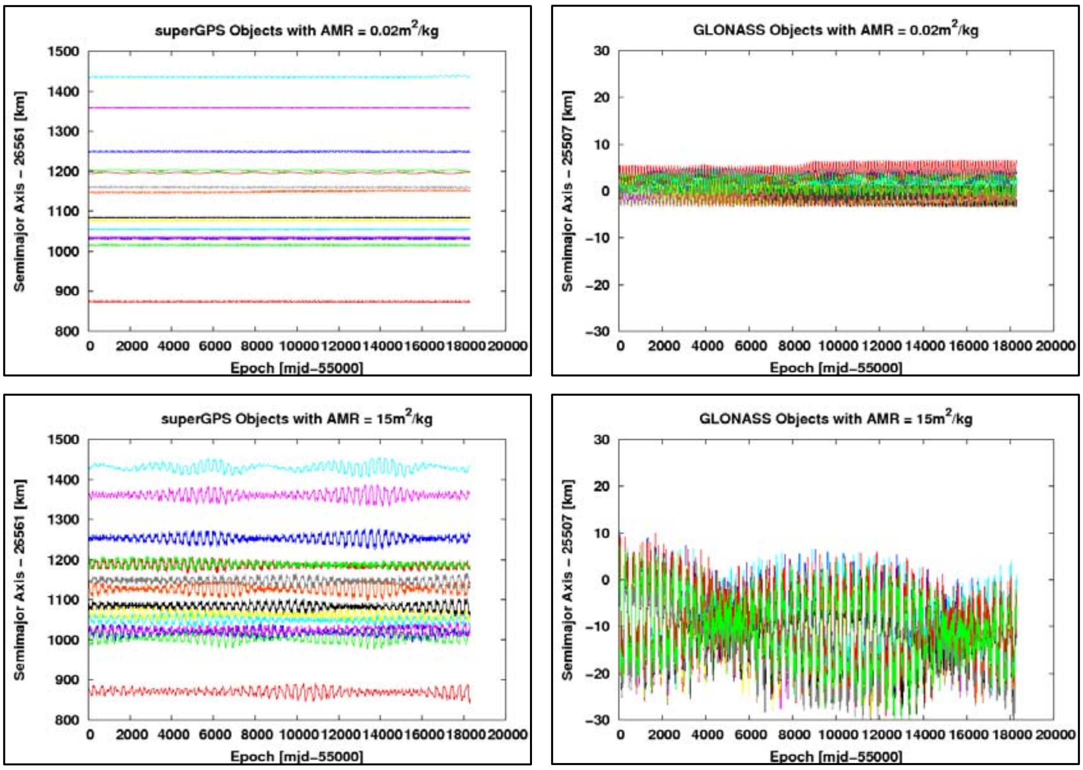

Figure 7: Evolution of semimajor axis for 14 super-GPS and 11 GLONASS objects and different AMR values.

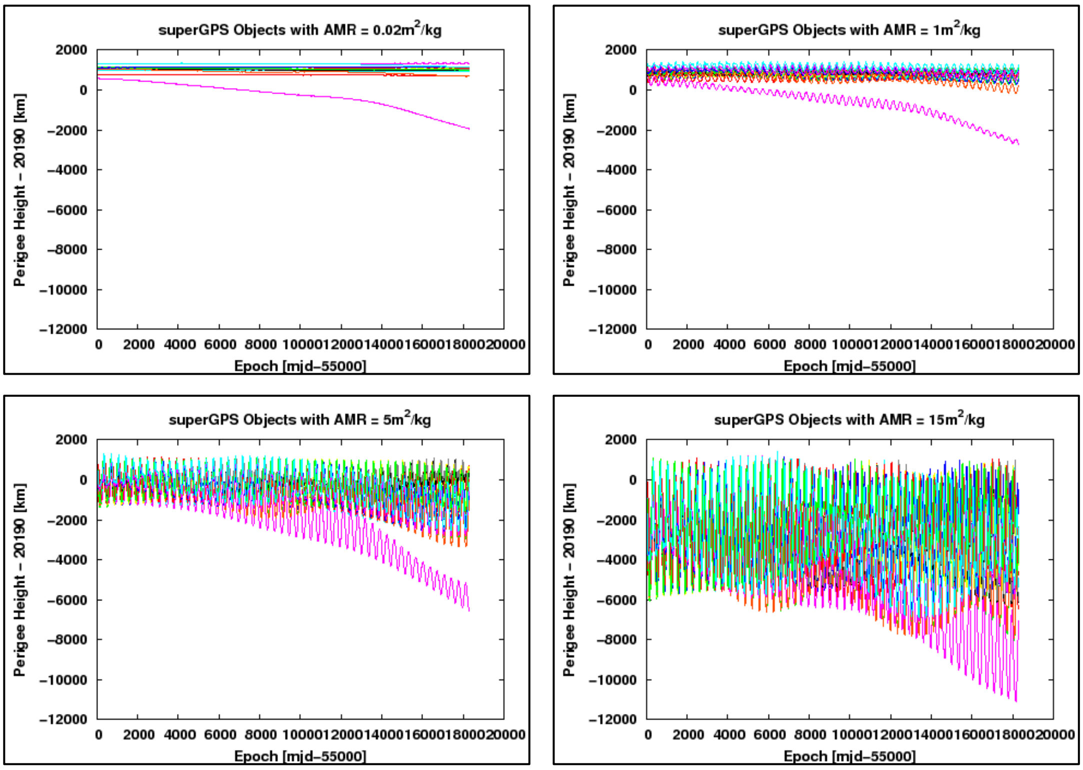

Figure 8: Evolution of the perigee height for 14 super-GPS objects and different AMR values.

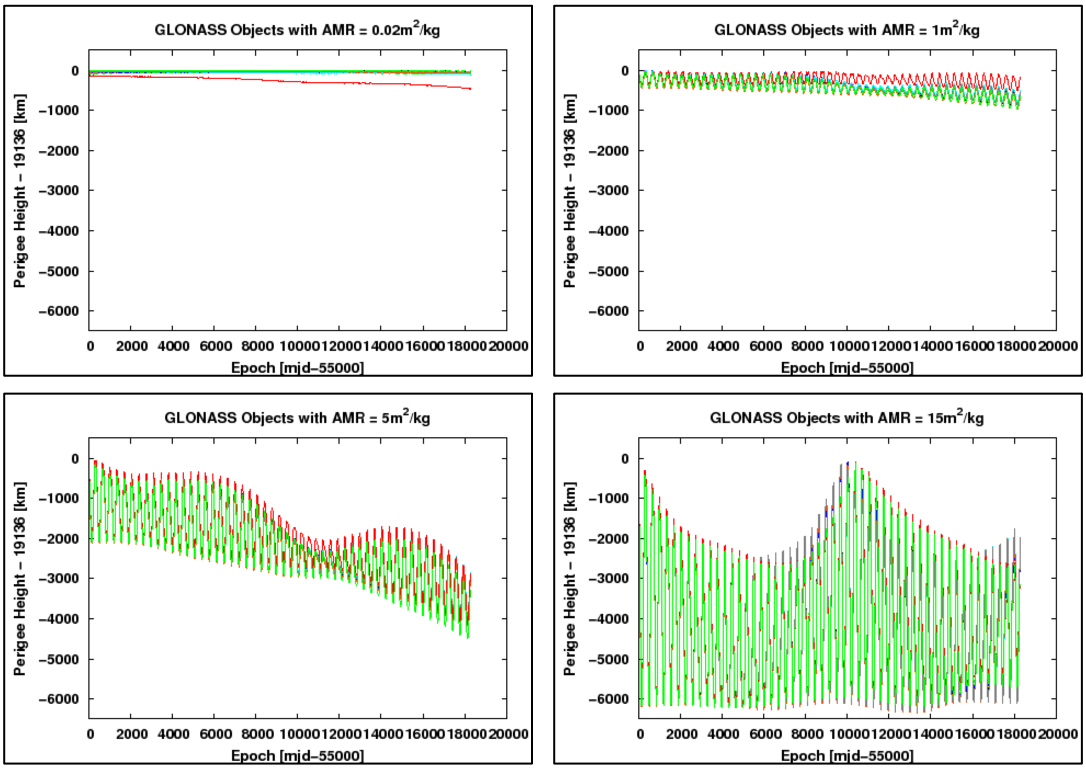

Figure 9: Evolution of the perigee height for 11 GLONASS objects and different AMR values.

3. SUMMARY AND CONCLUSIONS

AIUB maintains an orbit catalogue of debris objects in high-altitude regions, particularly in the GEO and the GTO region. The catalogue is maintained on a regular basis performing survey and follow-up observations with a variety of optical sensors. The catalogue maintenance is supported by observation from ISON in the context of a scientific collaboration with KIAM. A large fraction of the objects in this catalogue have AMR values higher than $1m^2/kg$.

From these results we may expect sources of HAMR debris (due to break-up events or aging effects) in all orbital regions where objects are left over a long time span. This is particularly true for all disposal orbits. In order to asses the long term evolution of orbits in such regions, a subset of super-GEO objects from the AIUB/ESA catalogue, as well as a subset of known intact super-GPS and GLONASS object were chosen and their orbits numerically propagated over 50 years.

The main findings are that objects in GEO disposal orbits (300km above GEO) will cross the GEO altitude if their AMR values are $>0.2m^2/kg$ and that the perigee of objects GPS/GLONASS orbits will change by more than 1000km for AMR values $>1m^2/kg$. We have also seen the known effect that objects in GPS orbits may change their eccentricity, and thus perigee height, even when they have a very small AMR due to mean motion resonance effects with the rotation of the Earth. The results are consistent with the IADC guideline for disposing GEO spacecraft, but this guideline does not consider HAMR objects generated in the disposal region.

There is now “safe graveyard” orbits when taking into account the possible sources of HAMR objects. Further analysis is required to assess the risks for lethal and catastrophic collisions involving HAMR objects originating from disposal orbits.

4. ACKNOWLEDGMENTS

The ESA observations were acquired under ESA/ESOC contracts. The collaboration with the Keldysh Institute of Applied Mathematics (KIAM) and the ISON was and is instrumental in maintaining the orbits of the AIUB/ESA catalogue.

5. REFERENCES

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