CHALLENGES RELATED TO DISCOVERY, FOLLOW-UP, AND STUDY OF SMALL HIGH AREA-TO-MASS RATIO OBJECTS AT GEO

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ABSTRACT

A significant population of faint debris with high area-to-mass ratios in the range of 1 to 50 m^2/kg exists in the Geostationary Earth Orbit (GEO) region. The team of the authors discovered the population several years ago using the ESA 1-m Space Debris Telescope in Tenerife. Individual groups, partly in the context of internationally coordinated projects, have undertaken significant observational effort to investigate the properties of this new class of debris objects during the past two years. The current consensus is that these objects may be fragments of multi-layer insulation blankets.

The orbital elements of these high area-to-mass ratio objects heavily vary, mainly due to solar radiation pressure. In particular the eccentricity and the inclination change significantly on time scales of a few days. It became, moreover, evident, that even the effective area-to-mass ratio of some individual objects is changing considerably. The study of the characteristics of high area-to-mass ratio objects is supported by immediate follow-up observations shortly after the discovery, as well as by regular re-observation (tracking). Both are mandatory tasks, which involve some technical and practical challenges.

This paper describes challenges related to discovering and to following-up high area-to-mass ratio objects using several observing sites and coordinated telescopes. The work requires the build-up and maintenance of a catalogue of small-size objects in GEO and GEO-like orbits. These tasks include the near real-time orbit determination and scheduling of follow-up observations immediately after the discovery of objects, as well as the hand-over of objects between the ESA telescope in Tenerife and the 1-m ZIMLAT telescope of the Astronomical Institute of the University of Bern (AIUB) in Zimmerwald, Switzerland. The observation data are furthermore exchanged with international co-operating partners, in particular the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM) in Moscow. The resulting catalogue of orbital elements is used to provide ephemerides to other observation techniques and partners.

The continuous monitoring of high area-to-mass ratio objects allows further studies using technologies and approaches that imply the availability of accurate and up-to-date sets of orbital elements. As an example of recent studies, the investigation of optical properties by acquiring color photometry and light curves is presented. The paper concludes by summarizing additional recent results from the ESA and the AIUB telescopes.

1. INTRODUCTION

This paper describes results of the ESA efforts to understand the small-size debris population at high altitudes. In this context it became evident that an orbit catalogue of these debris objects is a necessary prerequisite to investigate their nature and sources. This is the relation of the work with the theme of the workshop, namely the 'development of a more complete catalogue'. The development of a 'more complete' catalogue is mainly focusing on the extension of the existing catalogues to include smaller size objects in Low Earth Orbits (LEO). The corresponding goals are primarily given by the safety requirements of manned missions in LEO, in particular of the International Space Station (ISS). An extended catalogue should eventually include precise orbits for all objects larger than a few centimeters, which cross the space station altitude. The minimum object size is given by the size limit for which the ISS can be protected by passive shields.

Why should we extend the catalogues in high altitudes, e.g. in GEO, by decreasing the size limit from the meter to the decimeter range? There are no manned space mission, currently or planned, in these orbital regions. Moreover the estimated spatial densities and the corresponding fluxes of small-size debris in the most populated GEO regions are still smaller than in LEO. There is, however, one distinct difference concerning the long term evolution of the debris environment in high altitudes compared to LEO, namely the fact that there is no natural clean-up mechanism or 'sink' in these regions, which means that debris will stay there virtually forever. As a consequence it is most important to efficiently limit the creation of debris at high altitudes in order to preserve unique regions like the GEO for future space operations. The development of efficient and cost-effective mitigation measures, on the other hand, require a detailed understanding of the current debris population in order to identify the major sources and release mechanism of space debris. Again, the sources dominating the evolution of the environment in the long term may be different at high altitudes from the ones in LEO, because of the different time scales involved (e.g. aging processes may become more important than in LEO). One might argue that statistical information is sufficient to identify these sources. Unfortunately this is not the case. A detailed analysis of the physical properties of the debris population requires observations of individual objects with large aperture telescopes having small fields of view, e.g. to obtain light curves, color information, or spectra. Tracking of individual objects with such telescopes, in turn, is only possible if precise ephemerides, or in other words, a catalogue of precise orbits is available. Some physical characteristics like the area-to-mass ratio can only be derived by monitoring the orbits over long time intervals.

The ESA debris surveys at high altitudes involve three major steps: the discovery of small size debris objects, the determination and maintenance of the orbits of a subset of the discovered objects, and eventually, the investigation of the physical properties of these objects. Objects are searched for and discovered by performing dedicated survey campaigns with the ESA 1-meter telescope in Tenerife, Canary Islands. First orbits are determined using real-time follow-up observations performed during the night of the discovery. These orbits are then shared in a network of observing sites, which acquire further observations allowing to maintain the orbits over long time intervals. The resulting catalogue is used to provide ephemerides to other observation techniques and partners, especially in the context of the Inter-Agency Space Debris coordination Committee (IADC) [1]. The ephemerides are in particular used to acquire light curves and color photometry observations with AIUB's 1-meter ZIMLAT telescope in Zimmerwald, Switzerland.

2. THE ESA OPTICAL SPACE DEBRIS SURVEYS

The optical GEO survey program uses the ESA telescope in Tenerife. The telescope is installed in the Optical Ground Station (OGS) at the Observatorio del Teide located at an altitude of 2,400m about 20km northeast of the Teide volcano. The OGS was built as a ground station for experiments with the optical communication payload of the ARTEMIS spacecraft in 1998. The telescope and the control system were modified to meet the requirements of space debris observations in 1999. The modifications included the procurement of a dedicated cryogenically cooled space debris camera consisting of a mosaic of CCD detectors with a total of 4,096 × 4,096 pixels. The resulting field of view of this camera is 0.7° × 0.7° so that a single pixel has a field of view of 0.6 arcsec. At the same time the necessary algorithms for the detection of debris on CCD frames were developed. In 1999 the optical GEO survey program became operational. The survey program has been continuously executed since 2001.

The operational GEO surveys for ESA are arranged in monthly campaigns of about 10 nights centered on New Moon, so that for a total of 120-140 nights per year the telescope is reserved for space debris observations. About 75% of the scheduled nights turned out to be of good quality, i.e. cloudless for more than four hours. AIUB performs the survey planning and processing on behalf of ESA.

Fig. 1 shows the total observation time and its repartition for the last 6 years. Originally the surveys focused on the detection of small-size debris in GEO. Since mid 2002 part of the observation time has been devoted to searches for objects in highly elliptical orbits following an adapted search strategy, optimized to find debris in low-inclined geostationary transfer orbits (GTO) near the apogee, in particular in the region occupied by Ariane upper stages. Near-real-time follow-up observations are performed for a subset of the detected objects, if there are indications that the object is in fact on a highly eccentric orbit. Details of the survey strategy and the detection techniques may be found in [2].

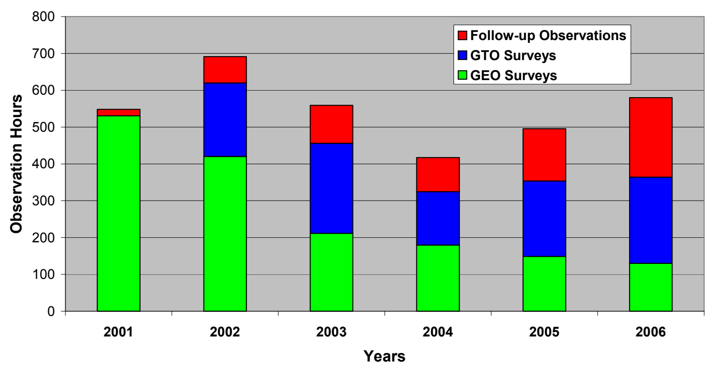

Fig. 1. Repartition of the observation time of the ESA space debris surveys.

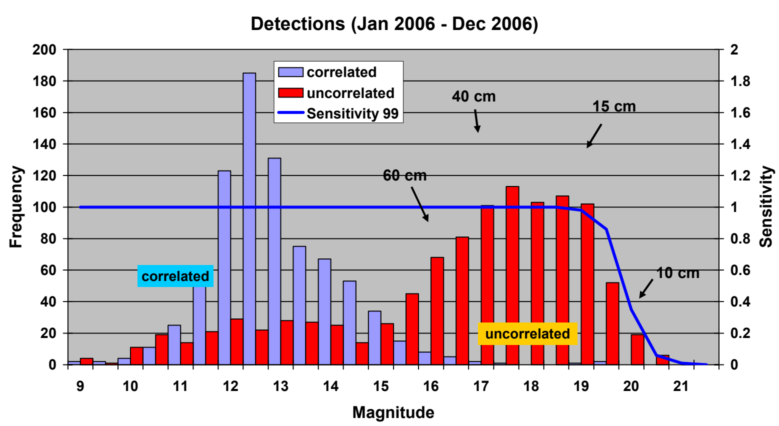

Fig. 2. Absolute magnitude distribution for the detections of the year 2006.

The important result of these surveys was the discovery of a hitherto unknown significant population of uncatalogued small-size debris objects in the 10-100 cm size range in the GEO. Fig. 2 shows the distribution of the measured absolute magnitudes for the year 2006. The solid line shows the instrument sensitivity as determined from independent calibration observations. The indicated object sizes were derived by assuming Lambertian spheres and an albedo of 0.1. The distribution is bimodal with the catalogued (correlated) objects clustered around magnitude 12.5, and a large population of uncatalogued (uncorrelated) objects in the range from magnitude 15 to 21. It is important to note that the decrease in the number of objects fainter than magnitude 19 is entirely due to the limiting magnitude of the observation system.

3. ORBIT DETERMINATION AND MAINTENANCE

The discovery observations are short tracks spanning a few minutes only. Observations from a single track do not allow determining a full 6-parameter orbit, but only circular orbits. The inclination i as a function of the right ascension of the ascending node Ω for the detections of the year 2006 is given in Fig. 3. For the correlated objects the 'evolution track' due to the precession of the orbital planes is the dominant feature in Fig. 3. The bulk of the uncorrelated objects lies also on this track but with a much larger spread. The most striking features, however, are the distinct clusters of objects. In addition there is a 'background' component with a more homogeneous distribution in the (Ω, i)-space noticeable in Fig. 3. It is suspected that the majority of the objects of this component are in fact in considerably elliptical orbits. We, therefore, perform near real-time follow-up observations during the discovery night for selected objects in order to derive full 6-parameter orbits. Note that currently about 30% of the available telescope time in Tenerife is used for follow-up observations. Additional follow-up measurements are performed with the ZIMLAT telescope (Fig. 4). These measurements are mostly used to improve and thereby 'secure' the orbits by observing the objects in the nights following the discovery and to maintain the orbits during periods where the ESA telescope is not available for space debris observations.

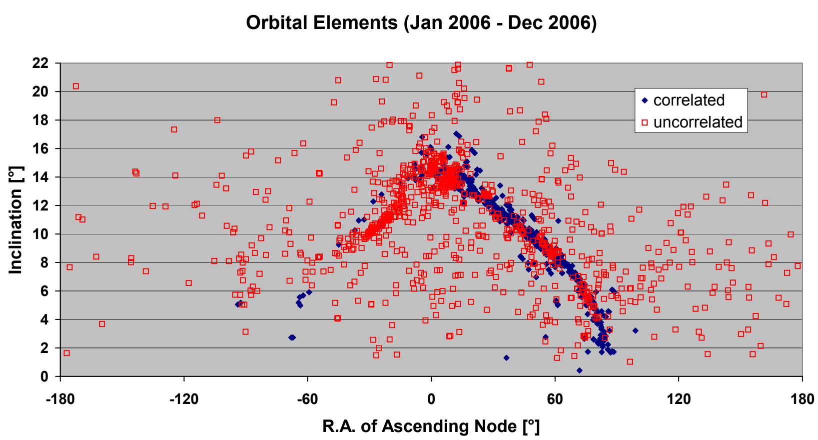

Fig. 3. Inclination i as a function of the right ascension of the ascending node Ω for the detections of the year 2006 (circular orbits).

The availability of 6-parameter orbits lead to the discovery of a population of objects with high eccentricities e and mean motions n with values close to the nominal GEO value [3]. Shortly thereafter it became clear that this new population consists of objects with high area-to-mass ratios [4]. In the observed e-n diagram (Fig. 5) the population of objects with high area-to-mass ratios is the concentration of uncorrelated objects with a mean motion near one and eccentricities ranging from 0.05 to 0.75. The distribution of the area-to-mass ratios for 134 objects is given in Fig. 6

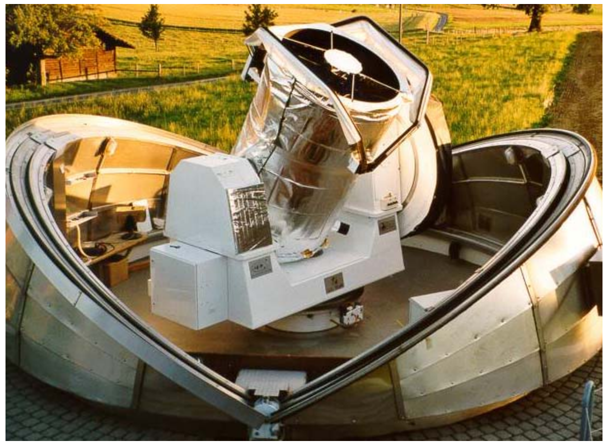

Fig. 4. The AIUB 1-m telescope (ZIMLAT) located in Zimmerwald, Switzerland.

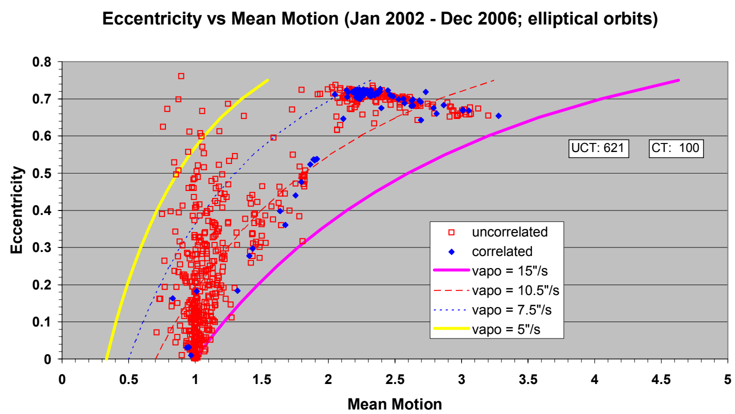

Fig. 5. Eccentricity as a function of the mean motion for 721 objects for which 6-parameter orbits were determined. ('UCT' and 'CT' denote the number of correlated and uncorrelated objects, respectively.)

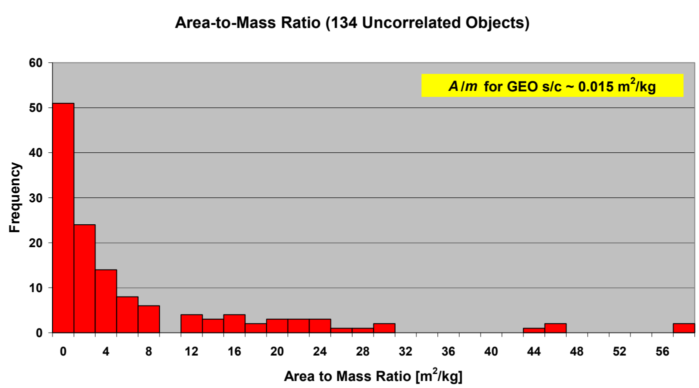

Fig. 6. Distribution of the area-to-mass ratios of 134 objects.

In order to investigate the nature of these objects it is mandatory to maintain the orbits over longer time spans. This is only possible by acquiring and sharing observations in a network of observing sites, which are well distributed in geographical longitude. In this context collaborations exist in particular with the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM) [5], [6]. The routine maintenance of a catalogue of orbital elements of high area-to-mass ratio objects is a prerequisite to study the temporal evolution of the orbital elements. Moreover it enables the generation of accurate ephemerides required to observe the objects with instruments and techniques with a small field of view. Such orbit information has been provided routinely to different groups, in particular to CNES, JAXA, and NASA, in the context of campaigns organized by the Inter-Agency Debris Coordination Committee.

4. INVESTIGATION OF THE PROPERTIES OF HIGH AREA-TO-MASS RATIO OBJECTS

In order to acquire more information on the sizes, shapes, and possibly the material of the debris objects with high area-to-mass ratios, light curves are acquired with the ZIMLAT telescope. The light curves show a wide variety of signatures, ranging from periodic or random variations of several magnitudes over time spans of a few minutes to constant brightness over 10 minutes. Moreover, the behavior may change completely for one and the same object from one observation to the next. All this is indicative of randomly tumbling objects with complicated shapes.

Fig. 7 shows two light curves of the object ‘EGEO21’. Both light curves show significant periodic variations. However, the amplitudes and the periods of these variations are very different. The peak-to-peak variations range from 1 to 2 magnitudes and the periods from 50 to 250 seconds. The apparent magnitude of this object is highly variable – although showing distinct periodic signatures over short time spans of a few minutes - indicating an object in a random tumbling motion with a rather complex shape and probably including some highly reflective surfaces.

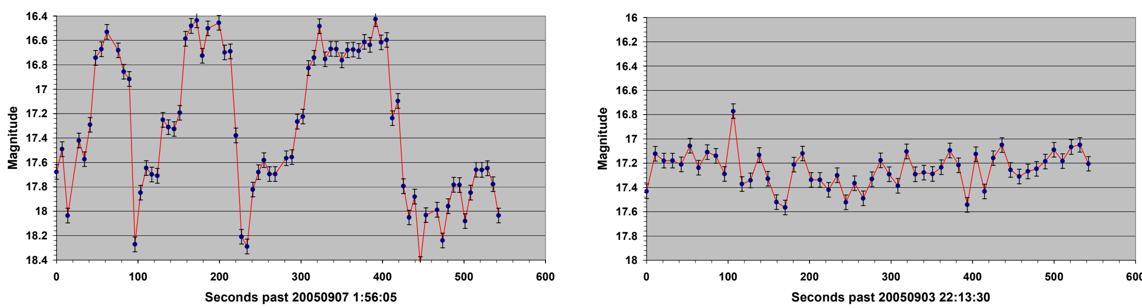

Fig. 7. Two light curves of the object ‘EGEO21’, which has an area-to-mass ratio of 4.6 m^2/kg.

In addition to light curves Johnson VRI photometry was obtained with the ZIMLAT telescope for some high area-to-mass ratio objects. Large series of consecutive exposures in the three different filters were acquired (V, R, I, V,… sequences). We then derived color indices for consecutive exposures and finally averaged them. However, the considerable short-term brightness variations of these objects resulted in large variations of the color indices. The standard deviation of the average values thus became too large to determine any meaningful colors.

A second approach consisted in the acquisition of consecutive light curves in different filters. Fig. 8 and Fig. 9 show light curves in the V and the R band for the objects EGEO45 and EGEO33, respectively. The measurements for EGEO45 seem to indicate a R–V color index of the order of 0.5mag, while the observations of EGEO33 are consistent with R–V=0mag. Given the high variability of these objects it is obvious that only simultaneous observations in different filters may provide sufficiently accurate colors.

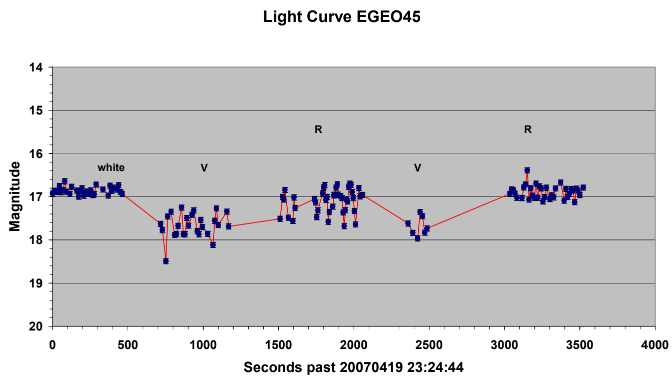

Fig. 8. Consecutive light curves of object EGEO45 (A/m = 17m^2/kg) in different filter bands.

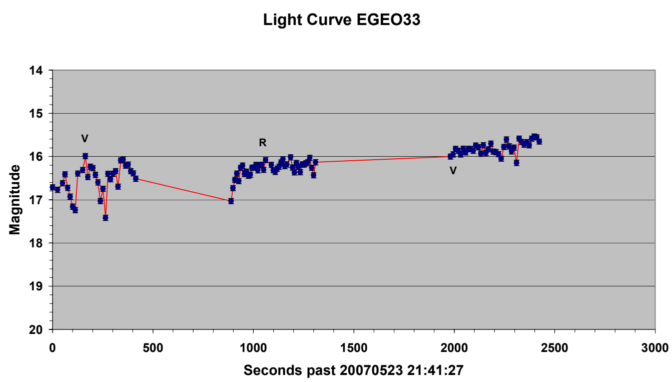

Fig. 9. Consecutive light curves of object EGEO33 (A/m = 4.6m^2/kg) in different filter bands.

5. SUMMARY AND CONCLUSIONS

ESA has established a long-term survey program to study the space debris environment at high altitudes. Since 2001 the ESA 1-meter telescope in Tenerife, Canary Islands, has been used during about 120 to 140 nights per year to search for space debris in GEO, GTO, and other high-altitude orbits. New, i.e. previously unknown, high area-to-mass ratio objects are routinely discovered during these surveys.

Near real-time follow-up observations are performed in order to determine full 6-parameter orbits of a subset of the discovered objects. Additional follow-up measurements are acquired with the AIUB 1-meter telescope ZIMLAT in Zimmerwald, Switzerland. The orbits of high area-to-mass ratio objects are maintained by acquiring and sharing observations in a network of observing sites in the context of a collaboration with the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM). Corresponding orbit information is provided to other groups in order to allow further investigation of the nature of these objects by applying a variety of different observing techniques.

In order to acquire more information on the sizes, shapes and possibly the material of the debris objects with high area-to-mass ratios, light curves were acquired with the ZIMLAT telescope. The light curves show a wide variety of signatures, ranging from periodic or random variations of several magnitudes over time spans of a few minutes to constant brightness over 10 minutes.

Johnson VRI color photometry measurements and light curves in these filter bands were obtained with the ZIMLAT telescope. The results seem to indicate different R–V color indices for different objects ranging from ~0 to ~0.5. Given the high temporal brightness variation of the objects, the measurements only provide first indications. It is obvious that accurate color information requires simultaneous observations in different filter bands.

6. ACKNOWLEDGEMENTS

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