Using Optical Observations to Survey, Track, and Characterize Small-Size Objects at High Altitudes

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Since more than a decade the Astronomical Institute of the University of Bern (AIUB) is investigating the small-size space debris environment in high-altitude orbit regions. Originally the efforts concentrated on statistical optical surveys with the primary goal to derive fluxes as input data for statistical environment models. It became, however, obvious that important characteristics of the debris population could not be determined by this technique.
One essential task of the space debris research is to find and understand the sources of debris, which in turn will enable to devise efficient mitigation measures – a prerequisite for the sustainable use of outer space. In order to understand the nature and eventually the origin of small-size debris objects, observations allowing to derive orbital parameters and physical characteristics like size, shape and material are required.
This paper gives a short summary of the different discoveries which resulted from the early surveys with ESA's 1-meter telescope in Tenerife and AIUB's 1-meter ZIMLAT telescope followed by a discussion of AIUB's current activities to build-up and maintain an orbit catalogue of small-size debris enabling physical characterization of the debris objects trough photometry, light curve and reflectance spectroscopy observations.

Key Words: space debris, optical surveys, debris characterization

1 The ESA Optical surveys at the OGS

When started 15 years ago, the ESA optical space debris surveys were primarily focusing on investigating the small-size debris environment in the geostationary ring (GEO). During the first years, the efforts concentrated on the acquisition of statistical data concerning the number of objects, their sizes and their orbital parameters. Since 2002 the GEO surveys are complemented by dedicated surveys for debris in the geostationary transfer orbit (GTO) region.

A regular observation program was established at ESA's 1-meter Space Debris Telescope (ESASDT) in Tenerife, Canary Islands, Spain. The Astronomical Institute of the University of Bern (AIUB) is implementing and operating this observation program on behalf of ESA. During the past 8 years the ESASDT was dedicated to debris surveys for about 110 nights every year. On average ~500 hours of data were collected during 85 good nights.

For the GEO surveys the search area is covering GEO orbits with 0-20° inclination (objects in orbits with higher inclinations are also detected but with less efficiency). The tracking during the exposures ('blind tracking') is optimized for objects in GEO. The search region and the blind tracking for the GTO surveys, on the other hand, are both selected such that they optimally cover GTO orbits with 0-20° inclination (Ariane GTO launches). The first test observations to search for debris in the orbits of the current navigation satellite constellations (medium Earth orbits (MEO)) have started at the end of 2009.

With the inception of GTO surveys we also started performing real-time follow-up observations of objects during the night of their discovery. Such observations are mandatory in order to determine 6-parameter orbits, as the discovery observations span only a few minutes in time. These 6-parameter orbits, which are derived from observation arcs of one night only, are still of statistical nature and do not allow building a deterministic catalogue of orbits, but are perfectly suitable to build and validate environment models like ESA's MASTER model.

The GEO/GTO surveys at the ESASDT are highly successful and resulted in the detection of a large population of small-size objects in these orbit regions. Fig. 1 shows the distribution of magnitudes of all detections from the 2008 campaign (GEO and GTO surveys combined). The indicated object sizes were derived by assuming Lambertian spheres and a Bond albedo of 0.08. The distribution of the correlated objects has its peak at about magnitude 12 to 12.5 and spreads from about magnitude 10 to 16. The uncorrelated objects in the range from magnitude 15 to 21 are smaller than the minimum size of the objects in the catalogue. The apparent main peak of this population at about magnitude 17.5 is in fact not a peak in the real object population, because the cutoff in the number of objects fainter than about magnitude 19 is entirely due to the sensitivity limit of the observation system (see the line indicating system sensitivity). The real distribution beyond magnitude 19 could, therefore, still increase!

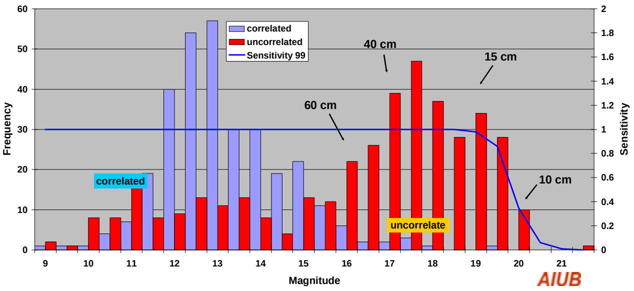

Fig. 1. Magnitude distribution for the detections of the 2008 surveys. The solid line indicates the system sensitivity (scale at right-hand side) as determined from independent calibration measurements.

Among the most notable results of these surveys is the discovery of GEO debris clouds in the orbital element space. Some distinct clouds in the (Ω, *i*)-space can be seen in the data from all years (Fig. 2). The evolution of the orbits of these clouds could be monitored closely and compared with theoretical models. The only rational explanation for the origin of these clouds is breakup events.

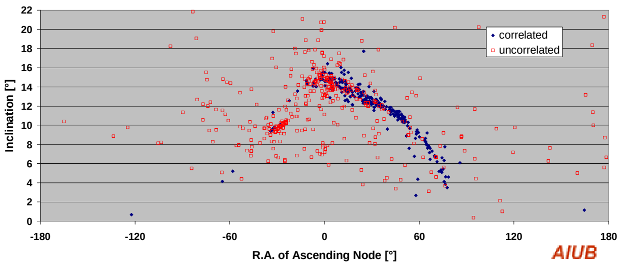

Fig. 2. Inclination versus right ascension of ascending node for the detections of the 2008 surveys.

2 The AIUB/ESA high Area-to-Mass Ratio Debris Catalogue

One of the major objectives of the surveys is to understand the nature and sources of the small-size debris in order to help devising efficient space debris mitigation measures. As early as 2003 it became obvious that any further investigations would require more closely observing and characterizing individual objects, which in turn is only possible if precise orbits are available. As a consequence AIUB decided to build up and maintain an internal catalogue of orbits for a subset of the objects discovered at the ESASDT. Among the first objects in this catalogue were a handful which had semimajor axes with values close to the nominal GEO value, but eccentricities ranging from 0.13 to 0.49 [1]. This was the first indication of a new population of debris objects in an orbital region where no potential parent object could be identified. Shortly thereafter it became clear that this new population consists of objects with high area-to-mass ratios (AMR) [2, 3]. The idea is that these high AMR objects – potentially pieces of multi-layer insulation material – were originally produced in GEO, but the solar radiation pressure is strongly perturbing their orbits, resulting in periodically varying eccentricities and inclinations.

The build-up and maintenance of this internal catalogue is done in close collaboration with the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM). Faint debris objects are mostly discovered with the ESASDT. Follow-up observations are performed with the same telescope and with AIUB's 1-meter ZIMLAT and its 0.3-meter ZimSMART-2 telescopes in Zimmerwald, near Bern, Switzerland. Long-term maintenance of the orbits is jointly done by AIUB and KIAM using in addition observations from the telescopes of the International Scientific Optical Network (ISON).

The AIUB/ESA catalogue as of April 2011 contains 1153 uncorrelated small-size objects in GEO, GTO and GEO-like orbits for which 6-parameter orbits were determined. For 274 objects the AMR could be determined. As can be seen in Fig. 3, 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 the majority 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 Fig. 4, 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 effective AMR of some objects with AMR > 1 m^2/kg is changing by up to a factor of 3 over times scales of days and weeks. The maintenance of the orbits of these objects is very demanding and requires frequent follow-up observations. Many of these objects have been lost over time after observation gaps (sometimes as short as a week or two).

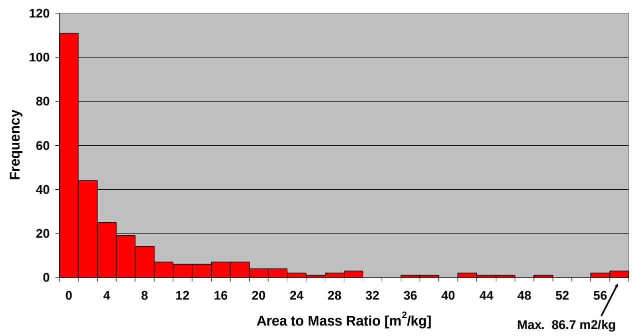

Fig. 3. Distribution of the area-to-mass ratio of 274 uncorrelated objects in the AIUB/ESA catalogue.

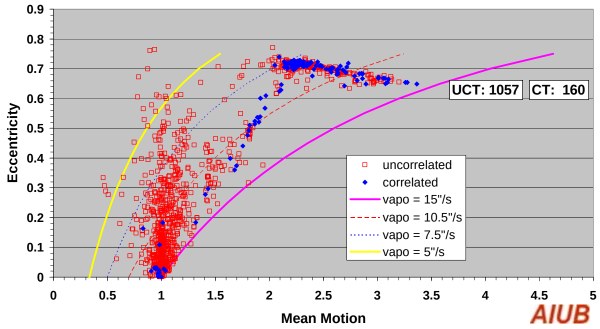

Fig. 4. Eccentricity as a function of the mean motion for 1217 objects for which 6-parameter orbits were determined. ('UCT' and 'CT' denote the number of correlated and uncorrelated objects, respectively.)

3 Characterization

Most of the small-size objects in the AIUB/ESA catalogue are likely breakup fragment or pieces which detached from intact objects due to material degradation. In order to design an efficient and cost effective mitigation measure it is necessary to know the predominant sources and, hence, first of all to assess the nature of the observed objects.

Additional observations should, therefore, investigate the physical characteristics of the objects, in particular their sizes, shapes, attitude states, and material type. Different observation techniques like light curves, color photometry and spectroscopy were used to characterize objects. An example of a light curve from ZIMLAT is given in Fig. 5 (object E06321D; AMR = 2.5 m^2/kg). Light curves may generally be used to determine shapes and attitude motions. One conclusion from this particular light curve is that the object is rotating or tumbling at a high rate.

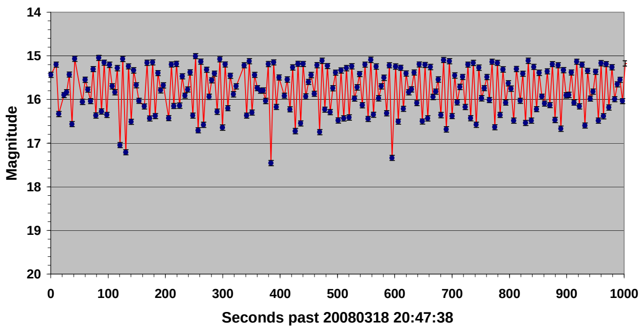

Fig. 5. Light curve of object E06321D (AMR = 2.5 m^2/kg).

In order to determine materials, spectroscopic observations are performed with a low-resolution spectrograph mounted at the RC-focus of the 1-meter ESASDT telescope. The aim of these observations is the quantitative measurement of the reflection properties of the target objects as a function of wavelength. The observations are rather demanding due to the faintness of the objects and the limited accuracy of the ephemerides (during the measurement the object must be tracked such that it remains within the 2-5 arcseconds wide slit of the spectrograph). The calibration and reduction of the spectra is equally challenging as we actually aim at a quantitative comparison of the measured spectrum with the spectrum of the illuminating source, in our case, the Sun (stellar spectroscopy in most cases does not require absolute calibration). As an example the reflectance spectra from two nights of the faint, high AMR object E06293A are given in Fig. 6. (The increased noise for wavelengths larger than about 750 nm is due to interference fringes produced inside the detector of the spectrograph.) The differences between the spectra of the two nights are real and not due to calibration uncertainties. Nevertheless the overall characteristics of both spectra are very similar. More details on the technique, as well as additional results can be found in [4), 5)].

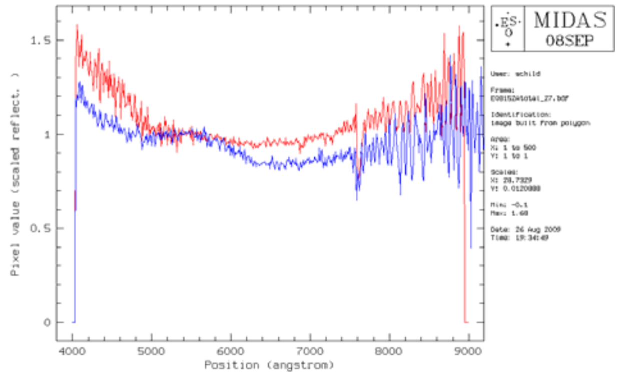

Fig. 6. Normalized reflectivity of object E06293A as measured during two separate nights (blue and red curve). AMR = 16 m^2/kg, magnitude = 16.8 ±0.8.

4 Summary

ESA has established a long-term optical space debris survey program which focuses primarily on investigating the small-size debris environment in high-altitude orbits (GEO/GTO/MEO). Until December 2010 more than 800 nights of observations were acquired, which revealed a significant population of uncorrelated, small-sized GEO and GTO debris in the size range from one meter to one decimeter. During the first years the efforts concentrated on the acquisition of statistical data concerning the number of objects, their sizes and their orbital parameters. This data was and is used to build and validate ESA's space debris environment model MASTER.

A major objective of the surveys is to understand the nature and sources of the small-size debris. To allow studying individual objects the orbits of a subset of the discovered debris are maintained in the AIUB/ESA catalogue. This effort led to the discovery of a category of objects with very high AMR, semimajor axes with values close to the nominal GEO value, but eccentricities ranging from 0.1 to 0.8. Maintaining the orbits of these objects is only possible thanks to substantial observational support by AIUB's ZIMLAT and ZimSMART telescopes in Switzerland, as well as by the sensors of the ISON network. The support from the ISON network is provided in the framework of a collaboration between AIUB and the Keldysh Institute of Applied Mathematics of the Russian Academy of

Sciences (KIAM). The catalogue contains a unique set of high-altitude objects with AMR > 1 m^2/kg.

Different observation techniques are applied to investigate the physical characteristics of the objects, in particular their sizes, shapes, attitude states, and material type. Light curves from the ZIMLAT telescope together with analyses of the correlations between the magnitudes and the phase angles are used to determine shapes and attitude motions. Attempts to assess the material types of the high AMR debris are done by comparing reflection spectra from ESA’s low-resolution spectrograph at the ESASDT in Tenerife with laboratory measurements of material used in spacecraft construction.

The efforts to characterize debris should help identifying the predominant sources of debris in high-altitude orbits and eventually help devising efficient and cost effective debris mitigation measures.

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