OPTICAL OBSERVATIONS OF SPACE DEBRIS IN HIGH-ALTITUDE ORBITS

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ABSTRACT

The space debris population in the low Earth orbit (LEO) region, which is defined as the region up to 2000 kilometers altitude, has been extensively studied during the last decade and reasonable models covering all size ranges were produced. Information on the distribution of objects in the geostationary ring (GEO) and the geostationary transfer orbits (GTOs), however, is still comparatively sparse. Recognizing the paramount importance of protecting the geostationary ring from contaminating space debris, ESA initiated an optical search for fragments in the geostationary ring in order to improve the knowledge about the debris population in GEO and to understand the future evolution of this population.

The Astronomical Institute of the University of Bern (AIUB) performs the observations on behalf of ESA at ESA's 1-meter Telescope in Tenerife. Regular survey campaigns covering the GEO region have taken place since autumn 1999. New search scenarios to detect objects in highly elliptical orbits, particularly optimized for the GTO region, have been applied since June 2002 during about 50% of the observation time. For a subset of the detections we perform real-time follow-up observations shortly after the discovery. This allows estimating full six-parameter orbits for this subset, whereas for the remaining objects we are only able to determine circular orbits.

The measurements reveal a significant population of small-sized debris in GEO and GTO orbits, but also in some unexpected elliptical orbit regimes. In particular a population of faint, uncatalogued objects with mean motions around 1 rev/day and eccentricities as high as $e < 0.6$ has been identified. This population was definitely unexpected by the space debris community. A first analysis of the orbits of a subset of the objects yielded very high area-to-mass ratios for these objects. This in turn supports the hypothesis that the new population is actually debris generated in GEO, which is driven into highly eccentric orbits by solar radiation pressure.

1. INTRODUCTION

Recognizing the unique value of the geostationary region (GEO) for both, commercial and scientific missions, ESA established an optical search program to detect uncatalogued space debris objects in GEO. The results of this survey program should first of all improve our understanding of the current space debris population in GEO by acquiring statistical information on the number of objects, their sizes and their orbital parameters. This information will enable analysts to identify the major sources of debris in this region and finally to devise the most effective approaches to mitigate debris in future. Eventually a catalogue of existing space debris in GEO shall be produced in order to increase the safety of active spacecrafts by allowing them to perform collision avoidance maneuvers if necessary.

Long-term monitoring of the GEO will furthermore allow to directly observe the evolution of the debris population in GEO, both in terms of number of objects and in terms of their orbits. This data in turn will be indispensable to validate space debris evolution models.

In the context of this program ESA has set-up a 1-meter telescope at the Izaña observatory in Tenerife, Canary Islands. The telescope is located at 2500 meters altitude at a site with excellent atmospheric quality for astronomical observations. The instrumentation includes a dedicated cryogenically cooled space debris camera consisting of a mosaic of CCD detectors with a total of 4096 x 4096 pixels. The field of view of this camera is 0.7 x 0.7 degrees and a single pixel corresponds to 0.6 arcseconds.

First observations took place in autumn 1999 and regular space debris surveys are performed since January 2001. The observations are acquired during 12-night-intervals centered on New Moon. During the last years about 80 to 100 observation nights per year were devoted to space debris surveys.

2. SURVEY TECHNIQUE

The survey technique essentially consists in repeatedly observing the same field in the sky. This means that the stellar 'background' will be the same on consecutive frames, but any moving object will show up at different positions in the field of view. This fact is used to search for the moving objects by comparing consecutive frames. In order to optimize the signal-to-noise ratio for the moving objects the telescope 'blindly' tracks during the exposures with the angular velocity expected for the

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objects of interest (Schildknecht et al., 1995). A GEO object will move with about 15 arcseconds per second with respect to the stars and thus cross the field of view in 2.8 minutes. Objects in geostationary transfer orbits (GTO) at their apogee have a lower apparent velocity and may spend up to 5 minutes in the field of view. Given the frame repetition rate of the ESA CCD camera of about two frames per minute an object is usually detected on a few frames only.

The astrometric position accuracy of the observations is of the order of 0.5 arcseconds for objects with reasonable signal-to-noise ratios and reduces to 1 arcsecond at the detection limit. The exposure time is limited to a few seconds – again in order to optimize the signal-to-noise ratio – and the corresponding limiting magnitude determined by calibration measurements is about 20.5.

For each detected object the short series of observations from the field of view crossing are used to determine an orbit. It is obvious that the very short observation arc of a few minutes does not allow to determine a full 6-parameter orbit but merely circular orbits may be inferred. While a circular orbit is a reasonable assumption for larger GEO objects this is probably not the case for fragmentation debris. The assumption, of course, is not at all applicable for GTO objects. In order to determine elliptical orbits observation over a time interval of at least 15 to 30 minutes are necessary, i.e. the objects need to be followed up in real time. Such follow-up observations are time consuming and reduce the telescope time available for survey observations considerably. During the ESA surveys only a very limited number of the discovered objects are followed up. Elliptical orbits are thus eventually available for this small subset only.

The surveys are primarily intended to search for objects in GEO and in low-inclination GTO (Ariane-type orbits). Consequently the survey fields cover a declination band of 40 degrees centered on the equator. The fields are chosen in a way to optimize the illumination conditions, i.e. near the shadow cone of the Earth.

3. MONITORING DEBRIS CLOUDS IN GEO

The ESA surveys since 1999 provide a large amount of statistical information. By statistical we mean first of all that no attempt was made to catalogue the objects, which would have required follow-up observations for all objects. Objects may therefore have been observed multiple times. The data is also 'statistical' in the sense that the survey is not complete. The small field of view of the ESA telescope does not allow to perform a 'leak-proof' survey. These facts are complicating the interpretation of the results considerably as all sorts of observational selection biases must be taken into account. The corresponding analysis is the topic of several studies currently under way.

Fig. 1 shows the magnitude distribution of the data from the year 2004. The diagram is representative for the entire data set. The 'correlated' detections denote detections of objects which could be identified in the ESA DISCOS catalogue (Klinkrad, 1991). The DISCOS catalogue essentially contains the unclassified USSPACECOM space object catalogue. 'Uncorrelated' detections correspond to objects which were not found in DISCOS. The solid lines indicate the system sensitivity as determined from independent calibration measurements. All magnitudes have been reduced from apparent magnitudes to so-called absolute magnitudes by correcting for the illumination phase angle. For the scattering properties we assumed a simple Lambertian sphere. No reduction to a common distance has been done because of the uncertainties of the inferred circular orbits. The value of this correction would be less than 0.5 magnitudes in most cases. The magnitudes are astronomical 'V magnitudes' and have an accuracy of a few 0.1 magnitudes except for the very faint objects where errors could amount to 0.5 – 1 magnitude. Object sizes derived by assuming Lambertian spheres and a Bond albedo of 0.1 are indicated for convenience. Both assumptions, however, are uncertain, as long as we don't know the nature of the observed objects.

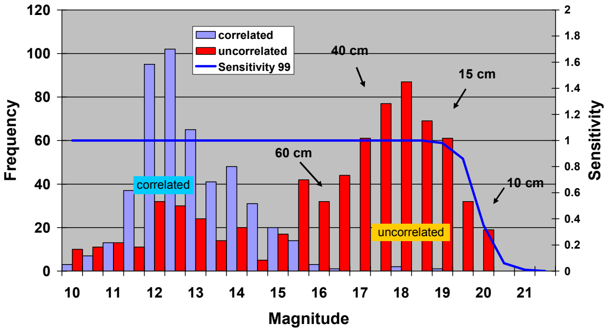

Figure 1. Absolute magnitude distribution for the detections of the year 2004.

The distribution is clearly bimodal with the 'correlated' objects centered on magnitude 12.5 and with an apparent peak for the uncorrelated objects at about 18th magnitude. The distribution for the 'correlated' detections is slightly asymmetric with the slope on the fainter end being shallower. However, it reflects the property of the current catalogue population. 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 18 is in fact not a peak, because the cutoff in 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 luminosity function beyond magnitude 19 could therefore still increase! The bright objects in the secondary peak of the 'uncorrelated' population are objects which are either missing in the DISCOS catalogue (e.g. classified objects) or objects which could not be identified due to the limited accuracy of the catalogue.

For GEO objects the inclinations *i* and the right ascensions of the ascending nodes Ω are strongly correlated. This is due to the fact that the orbital planes of uncontrolled objects in GEO are precessing around the so-called Laplacian plane with a period of about 53 years. For objects which started with orbits of 0 degree inclination the inclination will gradually increase and reach a maximum of 15 degrees after 26.5 years and decline afterwards to reach again 0 degrees after 53 years. Fig. 2 and Fig. 3 give both elements for all correlated and uncorrelated detections from the year 2004.

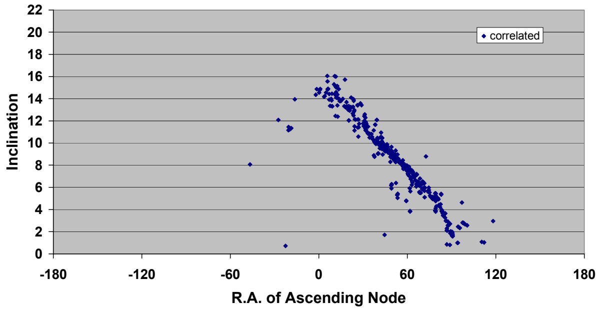

Figure 2. Inclination *i* as a function of the right ascension of the ascending node Ω for the correlated detections of the year 2004.

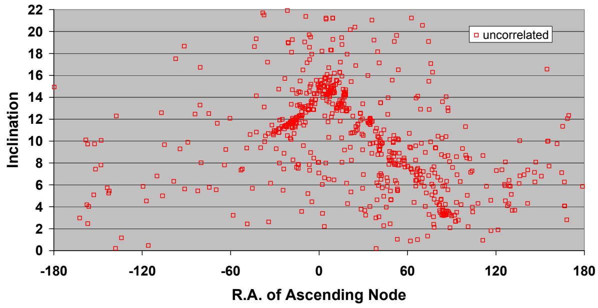

Figure 3. Inclination *i* as a function of the right ascension of the ascending node Ω for the uncorrelated detections of the year 2004.

For the correlated objects this ‘evolution track’ due to the mentioned precession of the orbital planes is the dominant feature in Fig. 2. The bulk of the uncorrelated objects lies also on this track but with a much larger spread. In addition there is a ‘background’ component with a more homogeneous distribution in the (Ω, *i*)-space noticeable in Fig. 3. The most striking features, however, are the distinct clusters of objects. Prominent concentrations are found in Fig.3 at Ω≈20° / *i*≈13°, Ω≈15° / *i*≈14.5°, Ω≈10° / *i*≈15° (all with an elliptical shape), and at Ω≈-20° / *i*≈12° (‘banana-shaped’).

We have checked some of the clusters for multiple sightings of the same objects and conclude that they are real (a pure selection effect can be excluded). The only reasonable explanation for the origin of these clusters are explosive events. In other words the survey discovered clear evidence for several *debris clouds* in GEO. An additional test for this hypothesis consists in comparing the (Ω, *i*)-diagrams of the results for different years. Fig. 4 shows the evolution of some clouds (marked with circles) through the years 2001 to 2004.

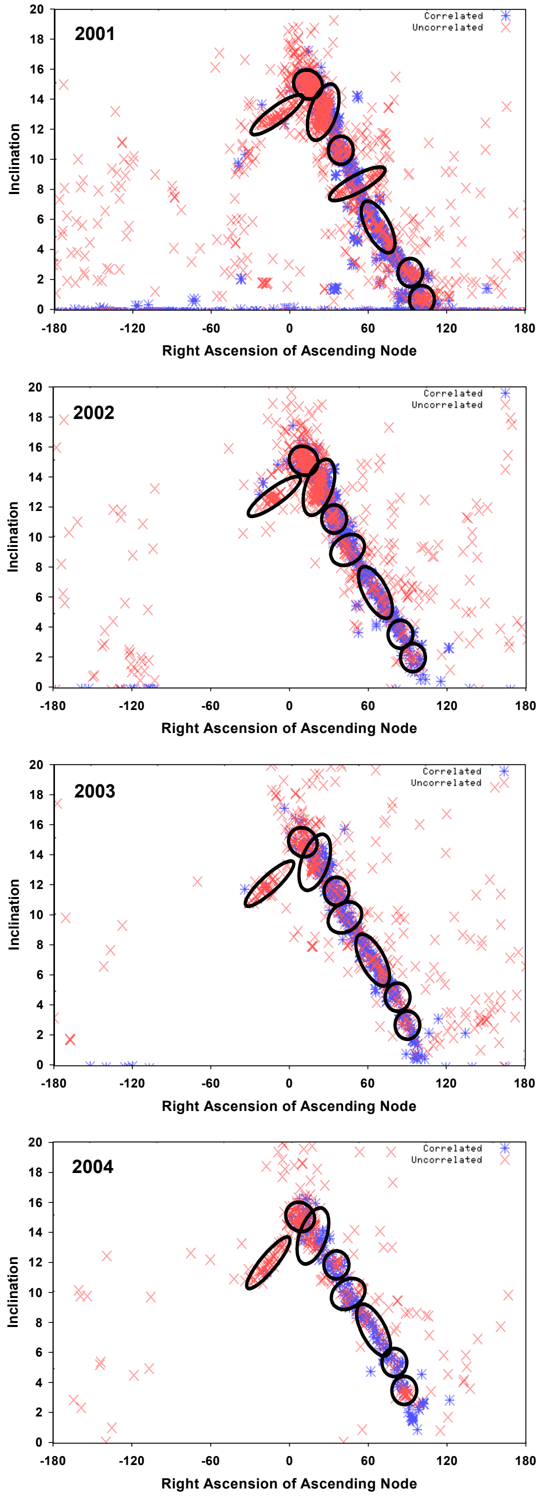

Figure 4. Evolution of debris clouds (marked with circles) through the years 2001 to 2004 (uncorrelated detections are marked with crosses and correlated detections with asterisk respectively).

To first order the clouds obviously follow the expected evolution along the mentioned track over the four years. In addition to the change in position in the (Ω, i)-space we would also expect the shape of the clouds to change gradually (Pardini and Anselmo, 2004; Grigoriev, 2005). A detailed analysis will be necessary to test the latter hypothesis.

4. SURVEYS FOR OBJECTS IN HIGHLY ECCENTRIC ORBITS

Since July 2002 about half of the survey time is devoted to the search for objects in GTO orbits with inclinations below 20 degrees. The primary motivation was to find debris of known break-ups of Ariane upper stages. Technically the only difference between these GTO surveys and our traditional GEO surveys is the telescope tracking during the exposures. While for GEO searches the telescope is tracking with 15”/sec in right ascension (telescope fixed in the horizon system) we track during GTO surveys either with 7.5”/sec or 10.5”/sec – the range of expected apparent motion of GTO objects at apogee. The inferred circular orbits for GTO objects have, obviously, no meaning at all. We therefore try to follow-up all objects for which the circular orbit determination yields semimajor axes well outside the range expected for GEO objects. Eventually a reliable 6-parameter orbit could be determined for 332 objects.

Fig. 5 gives the magnitude distribution for this data set. The magnitudes were corrected for the phase angle but not yet reduced to a common distance. It is therefore not possible to assign an object size to a given magnitude (the indicated sizes are upper limits). The solid line is again indicating the instrument sensitivity. Most of the uncorrelated objects are fainter than magnitude 16 and thus quite small in size.

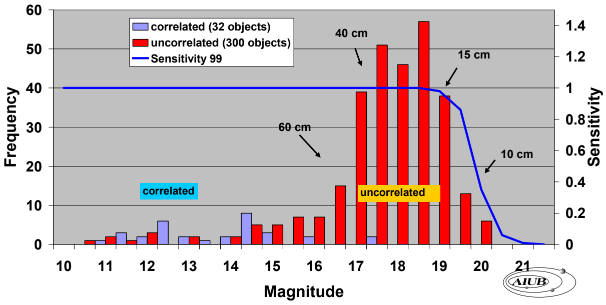

Figure 5. Magnitude distribution for 332 objects with elliptical orbits.

The distribution of the mean motion n for the same data set is given in Fig. 6 There seem to be two maxima: a broad maximum with a peak at mean motion n=1 and a second maximum in the range from n=2.1,…,2.8. The latter is the typical range for GTO orbits. The corresponding distribution for the objects in the catalogue is given in Fig. 7. (The catalogue data was filtered for with e={0.1, 0.9}, i={-20.0, 20.0}, n={0.3, 6.0}.) The first peak at n=1 is completely missing in the catalogue data whereas the GTO region is fairly populated.

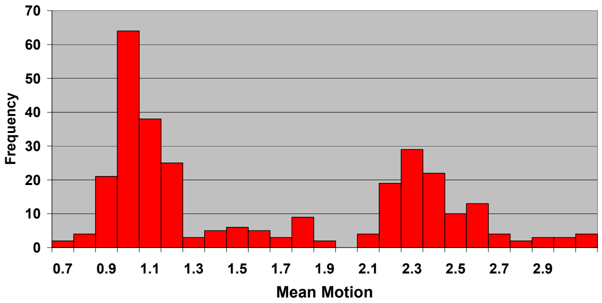

Figure 6. Distribution of the mean motion for 323 objects with elliptical orbits. (Mean motion in revolutions per day.)

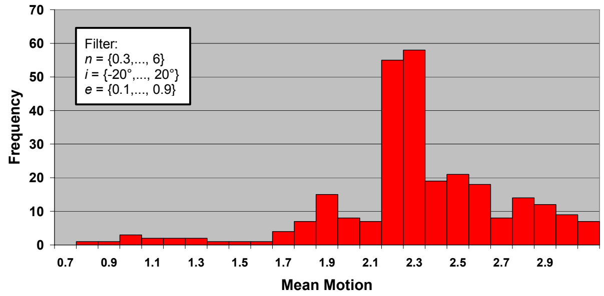

Figure 7. Distribution of objects in the catalogue. (Mean motion in revolutions per day.)

Fig. 8 and Fig. 9 show the eccentricity as a function of the mean motion for the same objects and the corresponding catalogue data respectively (catalogue filtered in the same way as above).

The lines indicate locations of constant apparent motion in right ascension when the objects are in the apogee. The solid lines define the boundaries of the region where the GTO survey was able to detect objects. Objects moving slower than about 5”/sec or faster than 15”/sec would not have passed our detection filter or the subsequent selection criteria to initiate follow-up observations. The region where the surveys were most sensitive lies between the dotted and the dashed lines. Comparing the two figures we note that a) there is a population of small objects in the region of the GTO orbits (near-horizontal branch at upper right), and b) that there is a considerable population of objects with a mean motion near one and eccentricities ranging from 0.05 to 0.6 – a region with almost no corresponding objects in the catalogue. This new population was completely unexpected and the nature and origin of these objects was unknown at the moment of discovery.

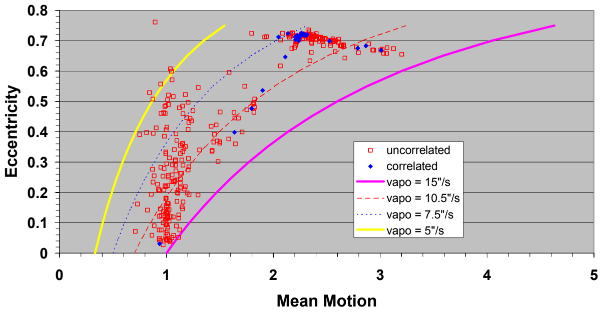

Figure 8. Eccentricity as a function of the mean motion for 332 objects with elliptical orbits.

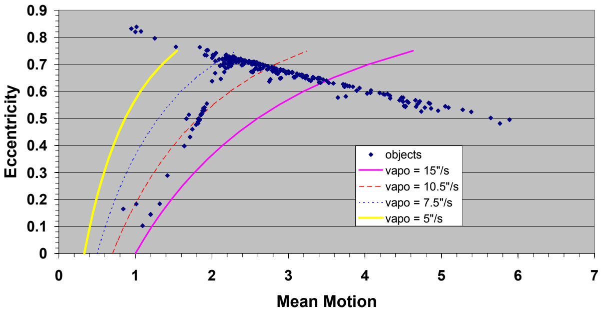

Figure 9. Eccentricity as a function of the mean motion for the objects in the catalogue.

5. THE HIGH AREA-TO-MASS RATIO POPULATION

There are no potential parent objects in the region of the new population of objects found during the GTO survey. If the objects are explosion debris or debris from disintegrating thermal insulation of spacecrafts they must have been produced in a different orbit region and then been gradually moved into their current orbits by natural perturbations. The mean motion and thus the orbital energy of the objects in the new population is concentrated around the nominal value for GEO objects. An appealing explanation would therefore be that these objects were originally generated in GEO and that their eccentricities were changed by a perturbing (conservative) force. A corresponding analysis revealed that resonance effects in the gravity field would not produce the observed eccentricities. On the other hand, solar radiation pressure acting on very lightweight objects, i.e. on objects with exceptionally high area-to-mass ratios, could drive GEO objects into orbits with very high eccentricities.

With this in mind we determined area-to-mass ratios for 28 objects of the new population (Fig. 8). Technically this was done by estimating a direct radiation pressure coefficient in the orbit determination. Standard values of the area-to-mass ratio for entire spacecrafts range from about 0.01 to 0.02 square meters per kilogram. The measured values for the new population are larger by two to three orders of magnitude! These objects must be truly lightweight (a sheet of standard paper has an area-to-mass ratio of about 13 m^2/kg). The formal errors of these measurements are less than 10% of the values in the worst cases. Possible candidate materials are foils used in multilayer insulations of spacecrafts (Liou and Weaver, 2005).

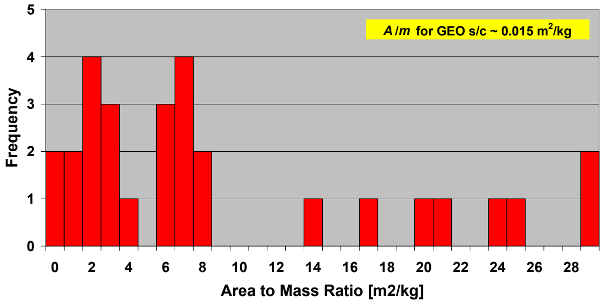

Figure 10. Distribution of the area-to-mass ratios for 28 uncorrelated objects of the new debris population found during the GTO survey.

The solar radiation pressure is perturbing the orbits of these objects considerably. The main effects are periodic variations of the eccentricity and of the inclination. Fig. 11 and Fig. 12 show the evolution of the eccentricity and the inclination for one of the objects over the next ten years. The result was produced by propagating the observed orbit using the estimated area-to-mass ratio of 24 m^2/kg.

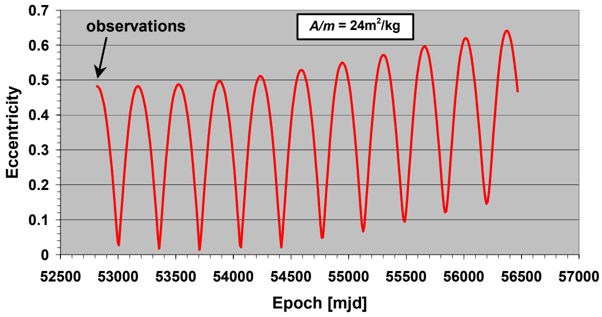

Figure 11. Evolution of the eccentricity for an object of the new population over the next ten years.

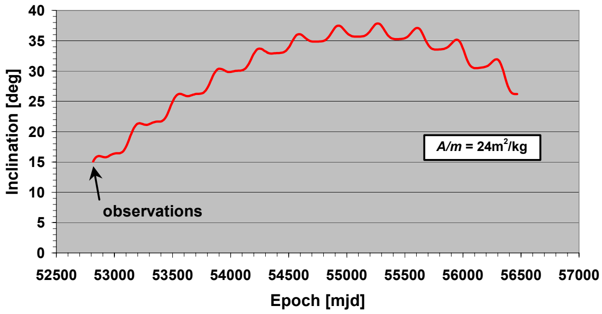

Figure 12. Evolution of the inclination for an object of the new population over the next ten years.

6. CONCLUSIONS

ESA is continuously conducting optical surveys for space debris in high-altitude orbits since 1999. The surveys revealed a substantial population of small debris in GEO. The detection limit of the ESA 1-meter telescope is of the order of 10 cm in GEO. The size distribution of the observed population is steadily rising until the sensitivity limit.

There is clear evidence of several debris clouds in the orbital element space. The evolution of about half a dozen clouds could be monitored over the time interval from 2000 to 2004. The results are consistent with evolution models for debris clouds produced by explosions.

Since 2002 about 50% of the observations are devoted to searches for debris in low inclination GTO orbits. Real-time follow-up observations are performed for a limited number of the discovered objects and precise 6-parameter orbits determined for this subset. We thereby discovered an unexpected, but considerable population of objects with a mean motion near one and eccentricities ranging from 0.05 to 0.6.

Orbit determination provided estimates for the area-to-mass ratio of a small sample of this new population. The measured values are two to tree orders higher then for standard spacecrafts or ‘normal’ explosion debris. The new population thus consists of high area-to-mass objects – potentially pieces of multi-layer insulation material – which are driven into orbits with periodically varying eccentricity and inclination.

7. REFERENCES

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