Statistical Analysis of Space Debris Surveys in High-Altitude Orbital Regions

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ABSTRACT

The Astronomical Institute of the University of Bern (AIUB) performs optical surveys for sub-catalogue space debris in high-altitude orbits since more than two decades. The bulk of the data is acquired on behalf of ESA with the ESA 1-meter telescope at the Optical Ground Station (OGS) in Tenerife, Spain. Additional surveys are performed with the 0.8-meter Zimmerwald Multiple Applications Telescope ZimMAIN at AIUB's Zimmerwald Observatory in Switzerland.

The main results from 22 years of surveys will be reviewed. Preliminary findings of a larger effort to re-analyse this data set are presented with a particular focus on the statistical analysis of the data.

1. INTRODUCTION

ESA has recognized the paramount importance of protecting the geostationary ring from contaminating space debris long time ago [1], [2], [3]. It was and is evident that the search for fragments in the geostationary ring and a better knowledge of the debris population in GEO are required to understand the future evolution of the debris population, to assess the collision risk and to define suitable and cost-efficient mitigation measures. Consequently, ESA initiated around 1990 a program to establish optical debris searches in GEO and high-altitude regions [4].

The main sensor of ESA's optical survey program to investigate and monitor the space debris population in high-altitude orbits is the ESA 1-meter telescope at the OGS in Tenerife, Spain (Figure 1). During the 90ies of the last century the sensor was deployed together with a dedicated space debris camera. The necessary planning, data acquisition, and data processing software was developed at the same time by AIUB on behalf of ESA. Both, the camera hardware and the software components experienced a major upgrade over the past 25 years. In 1999 the optical survey program became operational. After an interruption due to hardware issues the surveys program is continuously executed since 2001.

Figure 1: ESA 1-meter telescope at the Optical Ground Station (OGS) in Tenerife, Spain.

The original main objective of these surveys was to derive statistical data on the small-size debris population in the GEO region as input for the ESA Meteoroid And Space debris Terrestrial Environment Reference (MASTER) population model [5]. For this purpose, flux data was thought to be sufficient and during the first years of the survey project no attempt was made to derive 6-parameter orbits from the observations. The surveys resulted in short series of observations, also called tracklets, each consisting of 2 to 3 observations spanning an arc of only about one minute. A circular orbit was then inferred for each of these tracklets. The resulting radii were clustered around the nominal GEO radius, but a substantial amount of "outliers" showed radii many thousand kilometres larger than this, indicating that objects on elliptical orbits were observed near their apogee.

Even the very first observations revealed a hitherto unknown population of small-size debris in high-altitude orbits in and near GEO (all observations were correlated with the publicly available data from USSTRATCOM). Figure 2 shows the magnitude distribution for the objects discovered during the time period from June 2002 to December 2006. The indicated object sizes were derived by assuming Lambertian scattering spheres and an albedo of 0.1. There is a steep rise in terms of numbers for objects smaller than about 1m with a peak at about 20cm diameter. 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.

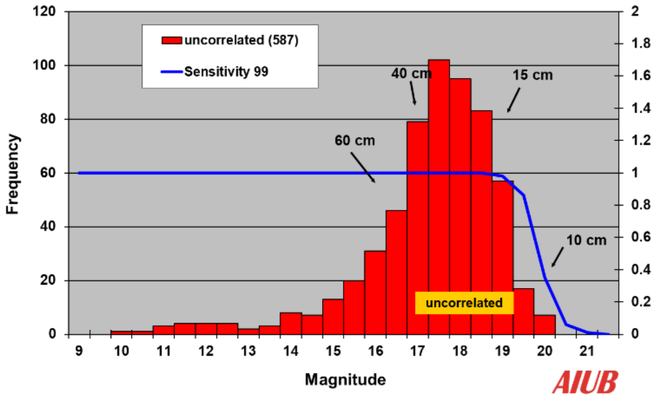


Figure 2: Magnitude distribution for the objects discovered during the time period from June 2002 to December 2006 (only objects for which elliptical orbits could be determined). The indicated object sizes were derived by assuming Lambertian scattering spheres and an albedo of 0.1. The solid line shows the instrument sensitivity as determined from independent calibration observations.

From these observations it became clear, that these objects must be fragments released either due to aging processes from intact spacecraft or produced during breakup events. The latter would show up as clusters in the distribution of the orientation of the orbital planes. Such clusters can be clearly identified in the data presented in Figure 3. The evolution of the clusters from 2004 to 2005 is consistent with the expected precession of the orbital planes due to gravitational perturbations.

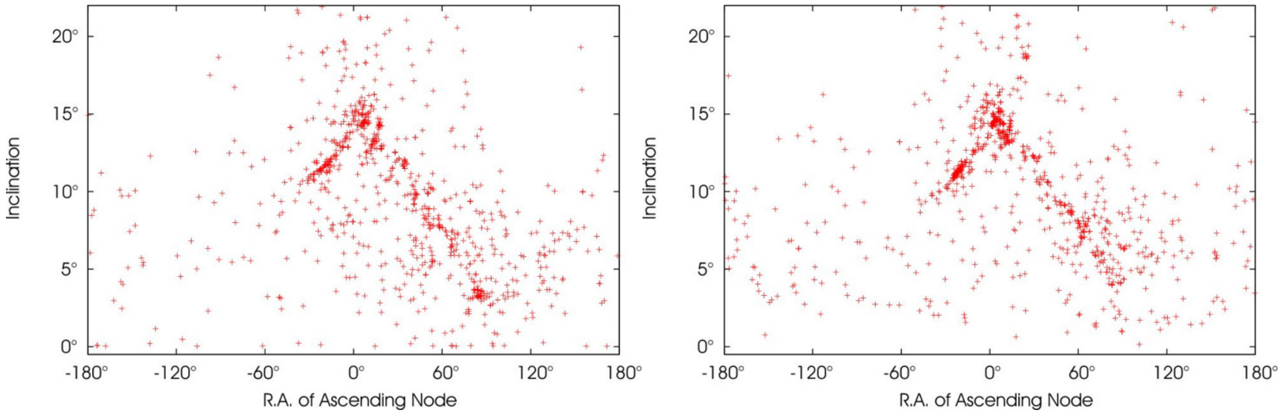
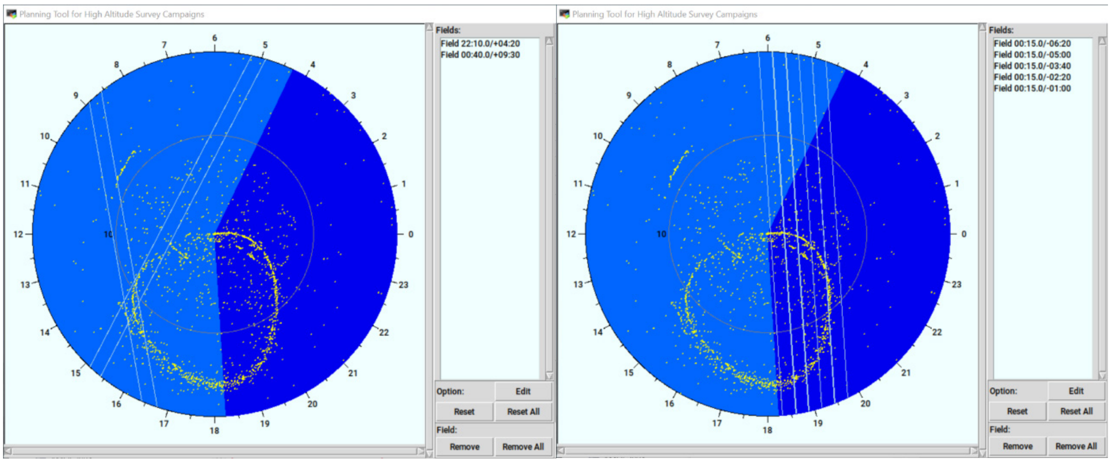


Figure 3: Inclination i as a function of the right ascension of the ascending node Ω for the detections of the year 2004 (left) and 2005 (right) (circular orbits assumed).

The scatter "background" in these figures is partially related to objects with large circular orbits, again pointing at possible elliptical orbits. 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 ESA telescope.

2. OBSERVATION CAMPAIGNS

The survey observations are scheduled for 4 to 10 nights during 6-12 months per year around the New Moon periods. The surveys are performed using series of observations of the same star field. During the exposures, however, the telescope is in ‘staring mode’, i.e., not tracking the stars, but tracking with the expected velocity of the objects of interest. The exposure time is set to 2 seconds limiting the area covered by star trails to less than 7%. It is reasonable to adopt the hypothesis that the catalogued GEO objects trace the debris population and the survey fields are thus selected accordingly. An example of the placement of the survey fields is given in Figure 4. For more details on the survey technique see [6]



Fields:
Field 22:10.0/+04:20
Field 00:40.0/+09:30

Fields:
Field 00:15.0/-06:20
Field 00:15.0/-05:00
Field 00:15.0/-03:40
Field 00:15.0/-02:20
Field 00:15.0/-01:00

Figure 4: Selection of survey fields: the polar plots represent the poles of the orbital planes of the known population (yellow dots); the stripes show the regions covered by the survey fields in the 5 nights of the September 2021 survey campaign.

A series of constraints are observed for all surveys. The most important conditions – apart from the moonlight, which is constrained by the selection of the observation periods – are the minimum elevation of 20 degrees and the minimum distance of 20 degrees from the galactic plane, and the minimization of the phase angle. Over the years the pattern of survey fields is kept similar and a homogenous coverage of the GEO region in the inclination band from -15° to +15° is attempted.

All observations are processed in real time at the OGS. For all uncorrelated discoveries near real-time follow-up observations are performed during the discovery night in order to derive full 6-parameter orbits (“elliptical orbits”). If the follow-up observations are successful, these objects are handed over to the AIUB sensors to maintain their orbits. Full orbits are derived for only about 20% of the discoveries. In most cases the first near-real-time follow-up observation is failing to rediscover the object, although about 30% of the telescope time is spent for such observations.

For various reasons the number of observation nights and thus also the number of discoveries varied over the years. Figure 5 shows the discovery rates of the program over the past 22 years. Only objects for which 6-parameter orbits could be determined are shown.

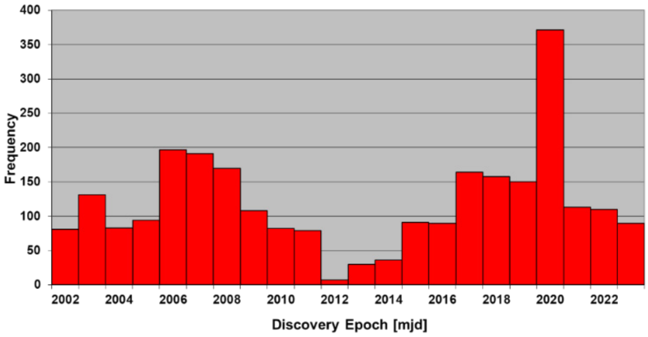


Figure 5: Discovery rates of ESA’s optical survey program to investigate and monitor the space debris population in high-altitude orbits (Jun 2002 to May 2023). Note that these rates do not reflect changes in the environment, but rather

in the number of survey observations and the survey strategy. Only objects for which 6-parameter orbits could be determined are shown.

3. SMALL-SIZE HIGH AREA-TO-MASS RATIO (HAMR) DEBRIS

AIUB decided to build up and maintain an internal catalogue of orbits for a subset of the objects discovered at the OGS in order to allow further characterizing these debris objects. 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 [7]. 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) [8], [9]. 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. Figure 6 shows the eccentricity as a function of mean motion for all objects for which an elliptical orbit could be determined.

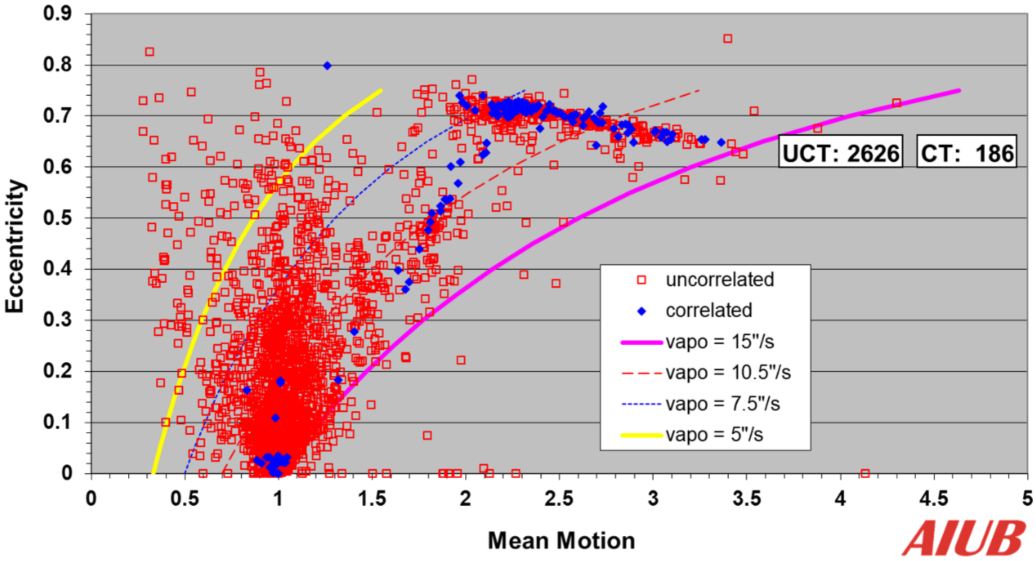


Figure 6: Eccentricity as a function of the mean motion in revolutions per day for 2626 objects for which 6-parameter orbits were determined (Jan 2002 to May 2023; elliptical orbits). 'UCT' and 'CT' denote the number of correlated and uncorrelated objects, respectively.

Using all available follow-up observations the AMR of 329 objects could be determined (Figure 7). There is a significant population of objects with AMR larger than 1 m2/kg (note that the AMR of an intact spacecraft is of the order of 0.02 m2/kg, and the one of ordinary office paper of the order of 12 m2/kg). A closer analysis reveals that the majority of the objects with AMR larger than 1 m2/kg are objects with a mean motion near 1 rev/day and eccentricities ranging from 0.05 to 0.8. This population is the vertically dispersed cloud concentrated at a mean motion of 1 rev/day in Figure 6.

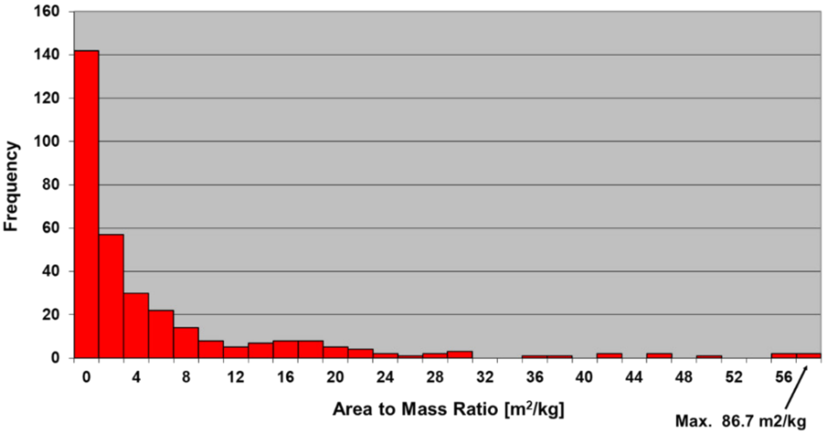


Figure 7: Distribution of the area-to-mass ratio of 329 uncorrelated objects in the AIUB/ESA catalogue.

4. EVOLUTION OF THE SPACE DEBRIS POPULATION IN HIGH-ALTITUDE ORBITS OVER THE PAST 22 YEARS

A compilation of the results from all observation campaigns of the past 22 years is given in Figure 8. The data covers all objects for which 6-parameter orbits could be determined. The magnitude distribution of the overall sample is still very similar to the one for the subset of the first 4 years of the survey (Figure 2). This is not the case for the distribution of the orbital planes, which is not surprising as the orbital planes are subject to gravitational perturbations, and the figure thus contains a mix of information for different epochs. In fact, the orbital plane of an uncontrolled object in the GEO will precess around the so-called Laplacian plane with a period of about 53 years. In Figure 8 (right) this would correspond to an evolution from R.A./Incl. 90°/0° over 0°/15° to -90°/0° within 53 years.

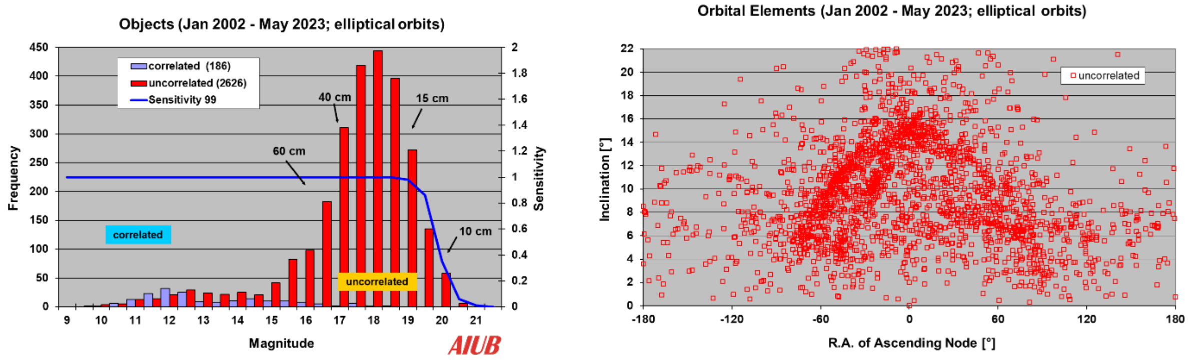


Figure 8: Magnitude distribution for the objects discovered during the time period from June 2002 to December 2023 (left), and orientation of the orbital planes for the same objects (right). (Only objects for which 6-parameter orbits were determined.)

In order to monitor the evolution of the orbital planes over time and to identify changes like the appearance of new fragmentation clouds, the data has been grouped into shorter time intervals in Figure 9 to Figure 12. The clouds along the line (0°/13°, -50°/9°) in Figure 9 seem to have evolved as expected in Figure 10. On the other hand, a new concentration along the line (-30°/14°, -70°/7°) seem to appear in Figure 10. This new concentration persists in Figure 11, similarly the concentration at (-25°/10°) in Figure 10 moved to (-45°/5°) in Figure 11, while a new concentration appears along the line (-60°/5.5°, -75°,/6.5). During the last 5 years (Figure 12) a prominent cloud appears along the line (-40°/12°, -60°/8°)

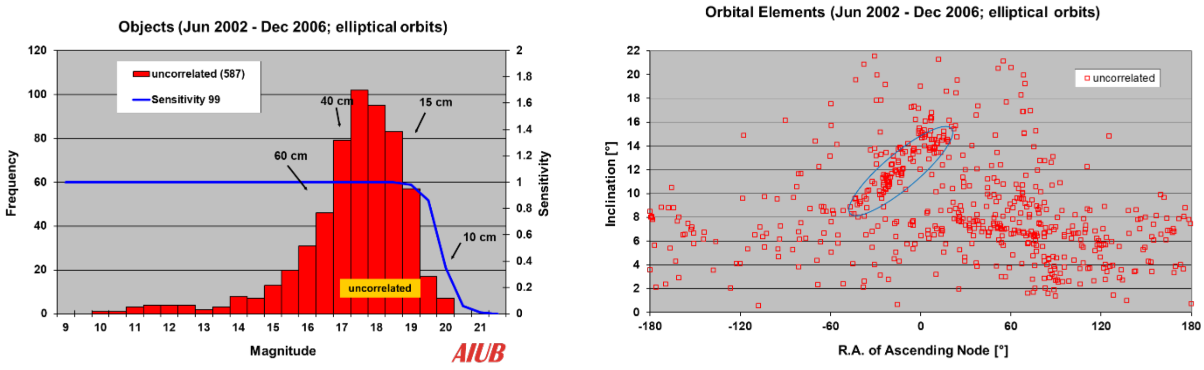


Figure 9: Magnitude distribution (left), and orientation of orbital planes (right) for the period of June 2002 to December 2006.

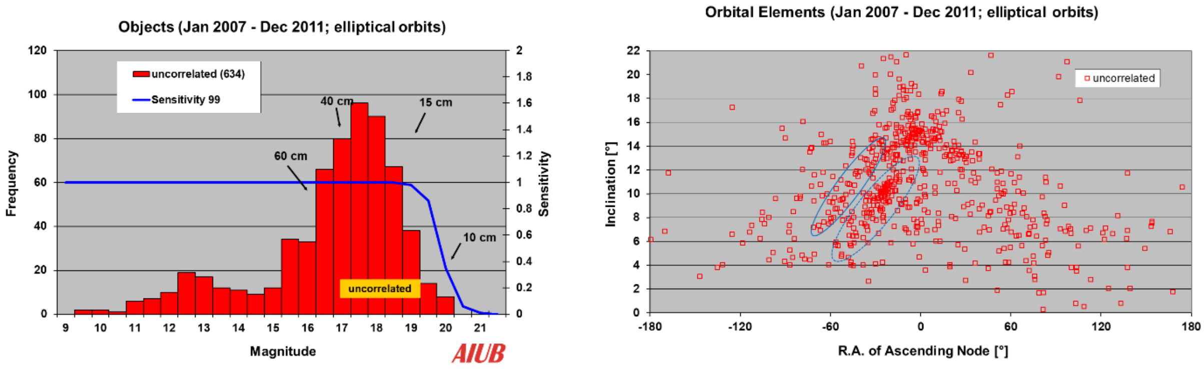


Figure 10: Magnitude distribution (left), and orientation of orbital planes (right) for the period of January 2007 to December 2011.

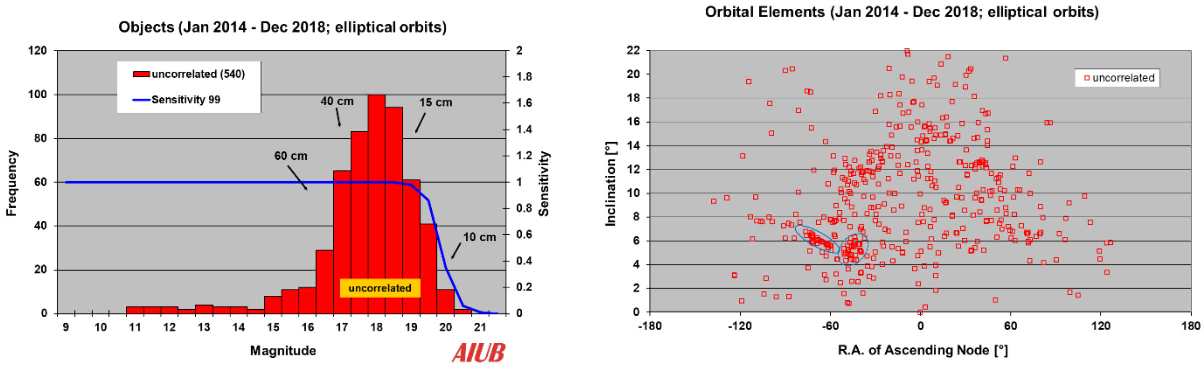


Figure 11: Magnitude distribution (left), and orientation of orbital planes (right) for the period of January 2014 to December 2018.

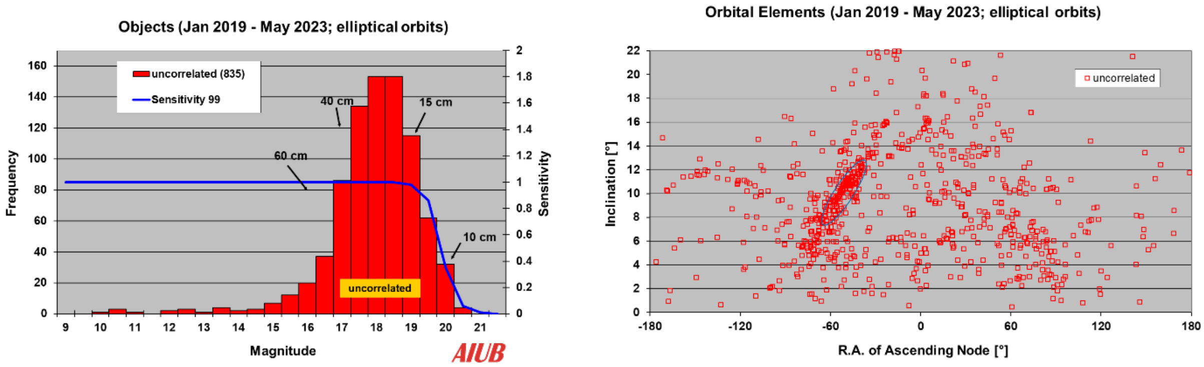


Figure 12: Magnitude distribution (left), and orientation of orbital planes (right) for the period of January 2019 to May 2023.

5. SUMMARY

ESA is aware of the importance to limit the proliferation of space debris in GEO and near-GEO high-altitude orbits since the end of the 80ies of the last century. A better knowledge of the debris population in GEO was required to understand the future evolution of this population, to assess the collision risks and to define suitable and cost-efficient mitigation measures. Consequently, ESA initiated a program to establish optical debris searches in GEO and high-altitude regions. The first survey observations at the ESA 1m telescope in Tenerife started in 1999 and were followed by continuous observation campaigns during 25 to 80 nights every year since 2002. All data was used as input data to validate the ESA MASTER environment model.

The early data revealed a substantial population of debris objects in the size range from 1m to 10cm in the GEO region. In 2003 it became obvious that flux data was not sufficient to further characterize the debris environment and follow-up observations became necessary to allow determining full 6-parameter orbits for a subset of the population. This effort resulted in the discovery of the high area-to-mass (HAMR) population in 2004. The latter is an important input for the division of efficient mitigation measures.

The continuous observation campaigns are key to monitor the GEO environment for new sources of space debris. Results from the last 5 years indicate the appearance of several new clusters of fragments in the GEO region.

6. REFRENCES

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