Searching for Small Debris in the Geostationary Ring

– Discoveries with the Zeiss 1-metre Telescope

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More than 800 satellites and rocket upper stages have been inserted into the geostationary ring or its vicinity over the years, but only about 250 to 270 of these satellites are currently being used operationally. Geostationary satellites are therefore increasingly at risk of colliding with uncontrolled objects. Contrary to the situation with satellites at very low altitude, there are no effective natural removal mechanisms for objects in Geostationary Earth Orbit (GEO). Ground-based radars and optical telescopes belonging to the United States' Space Surveillance Network (SSN) are able routinely to detect objects larger than 1 m across in GEO. ESA has recently upgraded a telescope at the Teide Observatory in Tenerife (E) with an optimised debris-detection system. Its early observations show a hitherto unknown but significant population of uncatalogued objects with diameters as small as 10 cm in the geostationary ring. Objects smaller than 10 cm are also expected to exist, but these are unobservable even with the 1 m Teide telescope. Further observations are urgently needed to determine the extent and origin of this debris population, and the resulting hazard to operational spacecraft.

Introduction

One of the most important and valuable regions in space for telecommunications, Earth observation and space science is the Geostationary Earth Orbit (GEO). The concept of the geostationary orbit was born many years before rockets carried satellites into space. In his book 'Das Problem der Befahrung des Weltraums – Der Raketenmotor' issued in 1929 under the pseudonym Hermann Noordung, Hermann Potocnik (1892–1929) described a space station in the geostationary orbit for meteorological observations. Later, in 1945, Arthur C. Clarke published his famous article on 'extraterrestrial relays' in the journal 'Wireless World', where he explained the advantages of geostationary satellites for communication. Many years later, Potocnik's and Clarke's vision became a reality, and the geostationary ring, which comprises all geostationary orbits suitable for practical use, is now one of the most important and most valuable regions in space.

Since the launch of Syncom-3 in 1964, more than 800 satellites and rocket upper stages have been put into GEO or its vicinity. Routine surveillance with ground-based radars and optical telescopes by the United States' Space Surveillance Network (SSN) is able to catalogue objects more than 1 m in size in GEO, providing orbital information (the NASA Two-Line Elements, or TLEs) as well as other characteristics such as the object's radar cross-section. At least one satellite and a rocket upper-stage have exploded in the geostationary ring, but the locations and spatial distributions of the fragments are unknown. The search for fragments in the geostationary ring and a better knowledge of the current debris population are of paramount importance in order to understand its future evolution, to assess the risk of collisions, and to define suitable and cost-efficient mitigation measures. Optical telescopes with 1 m apertures and equipped with a suitable CCD camera, such as ESA's 1 m Zeiss telescope at the Teide Observatory on Tenerife, have the ability to detect 10–20 cm sized objects in GEO.

CHARACTERISTICS OF THE GEOSTATIONARY ORBIT

The ideal geostationary orbit is circular, its orbital plane coincides with the equatorial plane, and its orbital period is one sidereal day (23 h 56 m 4 s). In practice, the orbits have a small eccentricity and inclination as a consequence of perturbations. Each satellite is usually assigned a longitude/latitude box, within which it has to stay, typically to within ± 0.1 deg for direct-TV satellites. For satellites serving mobile users, a larger latitude excursion is permitted, which may be more than 1 deg.

A geostationary satellite's orbit has to be adjusted periodically, otherwise it will leave its nominal station-keeping box because of perturbing accelerations due to:
– anomalies in the Earth's gravitational field
– gravitational effects of the Sun and Moon
– solar radiation pressure.

The longitude-dependent spherical harmonics associated with the Earth's gravity potential lead to resonance effects. The primary effect is a long-term perturbation of the semi-major axis, with a corresponding variation in longitude. The dominant longitude perturbation is a librational pendulum-like motion around the nearest stable point, at either 75° E or 105° W. The gravitational effects of the Sun and Moon and the oblateness of the Earth (J2) cause a precessional motion of the pole of the orbital plane with a period of about 53 years. An ideal geostationary orbit will reach an inclination of about 15 deg after about 26.5 years, which will decrease to zero after another 26.5 years. Solar radiation pressure induces a small eccentricity, which in turn leads to a radial variation, which in extreme cases may reach ± 75 km.

The geostationary ring is thus effectively a segment of a spherical shell of thickness 150 km and delimited by ± 15 deg in latitude (Fig.1).

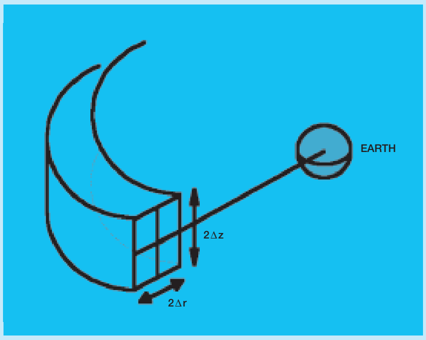


Figure 1. The geostationary ring

Current population of man-made objects in GEO

The usual way of putting a spacecraft into geostationary orbit is for the launcher to insert it into a Geostationary Transfer Orbit (GTO), from which it is then transferred using its own propulsion module to a near-geostationary orbit. This transfer may be accomplished with a single burn of a solid-propellant motor (Apogee Boost Motor, or ABM), or with a series of smaller burns if a liquid-fuelled motor is used. In many cases the ABM is separated from the spacecraft after the burn. The alternative is direct insertion of the spacecraft into a near-geostationary orbit by the launcher itself (examples being the Proton and Titan launch vehicles). In this case, the rocket's upper stage also ends up in near-geostationary orbit.

Since 1989, NASA has provided ESA with the TLEs of all unclassified catalogued objects. These data are stored in ESA's Database and Information System for the Characterisation of Objects in Space (DISCOS). There are currently more than 840 satellites and rocket upper stages (rocket bodies, or RBs) in the geostationary ring and its vicinity. Figure 2 shows the time history of objects in the US SPACECOM catalogue (731 objects as of 31 Dec. 1999 in the DISCOS database). Another 111 objects are known to be in GEO, but their TLEs are not publicly available.

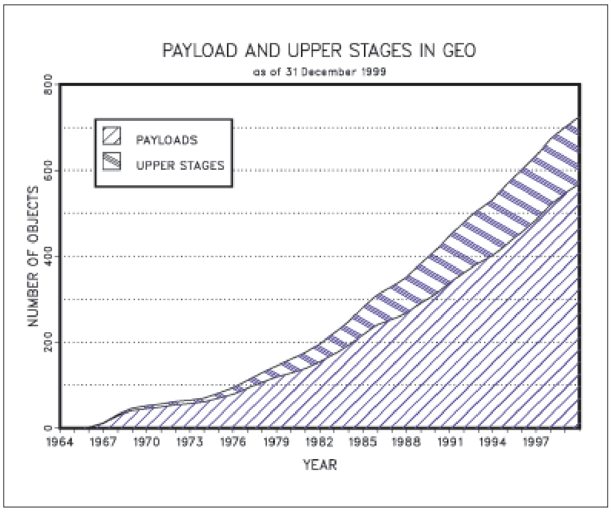


Figure 2. Time history of catalogued objects in GEO

The 731 catalogued objects can be categorised as follows:

– operational spacecraft	242
– spacecraft in librational mode	115
– spacecraft/RBs in drifting mode	323
– TLEs not updated during the last 6 months	21
– indeterminate status	30

The true number of operational spacecraft exceeds 242, since classified objects are not included in the DISCOS database.

Spacecraft in librational mode are those that are no longer controlled and which, unfortunately, were not removed from the geostationary orbit at the end of their operational lifetimes. They follow an oscillatory motion around the nearest stable point (75° E or 105° W). In addition, the inclination of their orbits will vary cyclically between 0 and 15° with a period of about 53 years. Since they cross the equatorial plane twice per day, they constitute a collision hazard for operational spacecraft. At the maximum inclination of 15 deg, their relative velocity with respect to operational spacecraft is about 800 m/sec.

Geostationary satellites are thus at some risk of colliding with uncontrolled objects, particularly old geostationary satellites. In recent years, the practice has developed of transferring spacecraft at the end of their operational lives into a 'disposal orbit' above the geostationary ring. This simple but effective measure reduces significantly the risk of collision in GEO.

An average of 25 – 30 new spacecraft are put into the geostationary ring every year (Fig. 3), a figure that is not expected to vary significantly in the coming years. Consequently, there are some 580 – 600 large debris objects (old spacecraft, separated ABMs and rocket bodies) in the geostationary ring and its vicinity. In addition, fragments from an exploding satellite (battery explosion on an Ekran spacecraft in 1978) and a rocket upper stage (Titan upper stage that launched the LES-8 spacecraft in 1968 fragmented in 1992) must also still be in GEO.

In 1996, ESA put a micro-debris and dust detector in the geostationary orbit on board the Russian Express-2 spacecraft at 80°E. The device, which is identical to the dust detectors flying on the Ulysses and Galileo spacecraft, detects sub-millimetre-sized objects which normally cause no significant hazard to operational spacecraft.

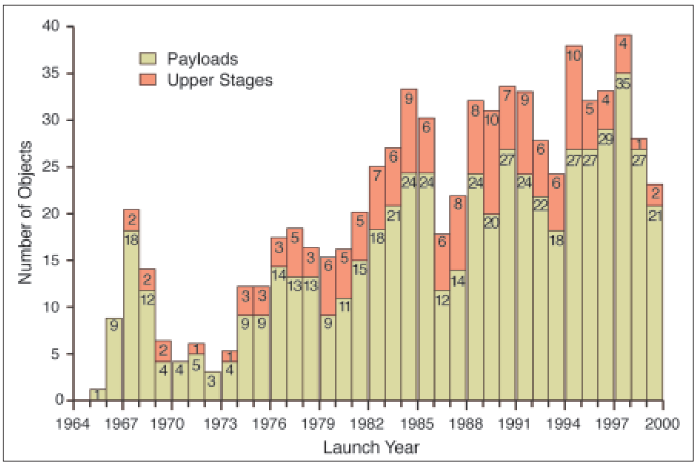


Figure 3. Annual launch rate into GEO

Space surveillance in GEO

Space surveillance involves detecting, tracking and determining the orbital parameters (e.g. the NASA Two-Line Elements) of orbiting objects. The United States Space Command regularly tracks and updates the parameters of about 10 000 objects orbiting the Earth. For lower altitudes, i.e. below a few thousand kilometres, powerful radars (classical dish radars and phased arrays) are used. For GEO, primarily optical telescopes with an aperture of 1 m are used (Ground-based Electro-Optical Deep Space Sensors), but some powerful radars can also track objects in the geostationary orbit. The minimum size of the objects routinely tracked in GEO is about 1 m (Fig. 4), but suitable telescopes have the sensitivity to detect sub-metre objects.

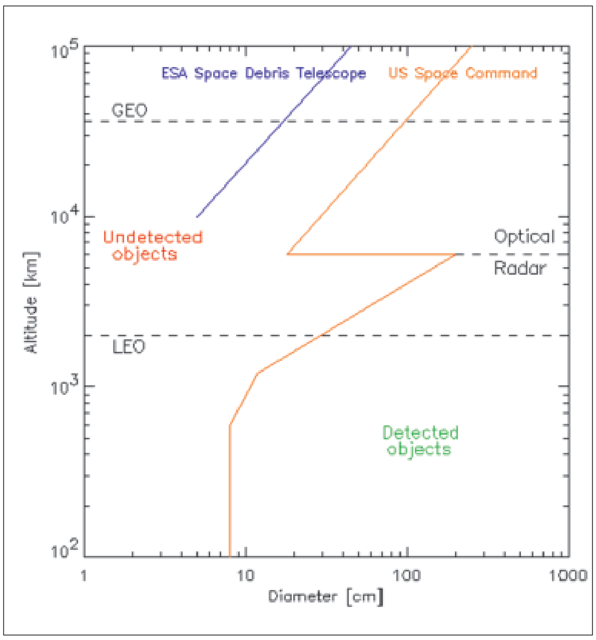


Figure. 4 Sensitivity of radars and optical sensors

Optical observation is an efficient ground-based method of observing space debris at high altitudes, say 6000 km and above. At low altitudes, optical observations are less suitable because the object being observed must be illuminated by the Sun, while the observer must be in darkness. In the Low Earth Orbit (LEO) region, this condition can only be met for short periods at the beginning or end of a night.

The ESA Space-Debris Telescope

The ESA Space-Debris Telescope is installed in the Optical Ground Station (OGS) at the Teide Observatory on Tenerife, Canary Islands. The OGS was originally established by ESA in the framework of the Data Relay and Technology Mission for the in-orbit checkout of the payload of the Artemis spacecraft. The upgrading of the telescope for space-debris observations was initiated later. The Observatory is located on top of Izaña Mountain (2393 m), about 20 km northeast of Teide. The site has excellent seeing conditions, but light pollution from the densely populated coastal areas of Tenerife prevents optimum use of telescopes with mirrors larger than about 2 m. ESA's 1 m Zeiss telescope is unaffected by this problem.

The ESA Space-Debris Telescope is a classical astronomical telescope with a 1 m primary mirror and an English mount, which has two rotating axes, one being parallel to the Earth's rotation axis. For sidereal tracking, rotation is only needed around one axis. Another advantage is that for an instrument mounted on the telescope, the field of view is not rotating whilst the telescope is tracking the sky.

The telescope has two different focus configurations: Ritchey-Chrétien and Coudé. The space-debris system uses a modified Ritchey-Chrétien configuration. Its field of view has been increased to 1° with a new secondary mirror and a set of lenses to reduce the focal length to 4.47 m. A large field of view is essential for an efficient debris search (Fig. 6).

The telescope is equipped with a large-array CCD camera. The array consists of a mosaic of four 2048 x 2048 pixel detectors, which form a 4096 x 4096 pixel-square device. At the space-debris focus, one pixel covers a field of view of 0.6 arcsec. The total field of view of the device is about 0.7° x 0.7°. The CCDs are cooled with nitrogen to 160 K to reduce the dark signal produced by thermal motion. The detectors and the preamplifiers are located in a vacuum chamber and are thermally connected to a cryostat chamber filled with liquid nitrogen. To ensure a constant operating temperature, the detectors are also electrically heated.

Together with the large field of view, a short image readout time is essential for space-debris observations. Each CCD chip is therefore equipped with two readout channels and is controlled by a separate amplification

Figure 5. The Optical Ground Station at the Teide Observatory

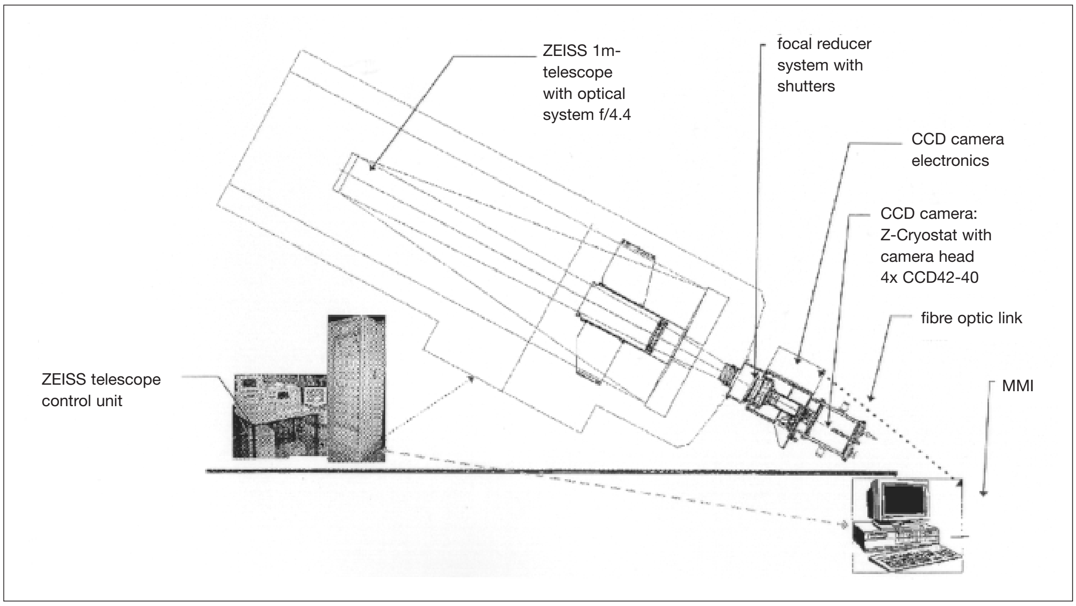


Figure 6. Telescope configuration for space-debris observation

and digitisation unit. The units are read out in parallel. The shortest readout time for a full image is 19 s, with a readout noise level of 4–6 electrons per pixel. This allows the detection of 20–21 magnitude objects with 1–2 s exposure times. For debris in GEO, this roughly translates into objects with diameters of 20–10 cm.

The upgrading of the optical system and the design and development of the 4 k x 4 k CCD camera were carried out by Carl Zeiss GmbH (Jena) and SIRA Ltd. (Chislehurst/London). The software for observation planning, data acquisition and processing was developed by the Astronomical Institute at the University of Bern (CH) and the Astrophysical Institute of the Canary Islands (IAC).

Observation control

The space-debris observations require accurate coordination of the telescope motion and image acquisition. The main control of the observations is assigned to the Central Control Computer (CCC), a Sun SparcStation 20, which directly controls the camera. The telescope is controlled by the Telescope Control Computer (TCC), which receives pointing commands from the CCC via a serial link. The TCC computes the atmospheric-refraction and pointing corrections.

For accurate telescope pointing, a so-called 'pointing model' must be established, which relates the pointing direction of the optical axis with the reading of the angular encoders of the mount. It must include terms for the non-perpendicularity of the telescope axes, the periodic errors of the angular encoders, as well as terms for the changing mechanical bending of the telescope at different positions. The parameters of the pointing model are determined by observing catalogued stars with known positions. The pointing corrections derived from the model are applied each time (every 100 ms) when updated pointing values are calculated. The resulting pointing accuracy for any position on the sky is better than 10 arcsec, while the tracking error is less than 2 arcsec per hour.

The accurate timing of the observations is important for the orbit determination. The system clock in the TCC is driven by a GPS receiver. The shutter can be commanded with an accuracy of better than 1 ms.

During the observations, 2–3 images per minute are acquired. The telescope is re-pointed between each exposure and the acquired data stored. Clearly, these tasks cannot be performed manually, especially over several hours, and so the CCC executes them automatically according to a predetermined observation plan. The progress of the observations can be followed from messages on the screens of the CCC, where each acquired image can also be displayed.

Observation planning

For both short- and long-term observations, a special planning tool is available in the OPC. It allows the planning of: surveys, follow-up observations for newly discovered objects, and calibration measurements for the telescope and camera, and creates an observation-plan file for the CCC's central controller.

Currently, observations are focussing on objects in GEO and GTO. These objects, especially those in GEO, are stationary or slow-moving with respect to an Earth-fixed frame. To optimise the signal-to-noise ratio for objects of interest, we track them during the exposures.

The detection technique is based on an algorithm comparing several consecutive frames of the same field in the sky. Fixed background stars are identified on a series of 10 to 30 frames, and the remaining parts of the frames are scanned for any additional objects. The telescope is therefore moved after each exposure so that the same area of the sky is passing the field of view at the next exposure (Fig. 7). With this method, the telescope slowly scans the sky from east to west whilst it is following the stars.

The exposure frequency has to be selected so that any object detected will be visible in three consecutive frames. Given this three-fold-coverage requirement, the current set-up allows one to observe up to three different

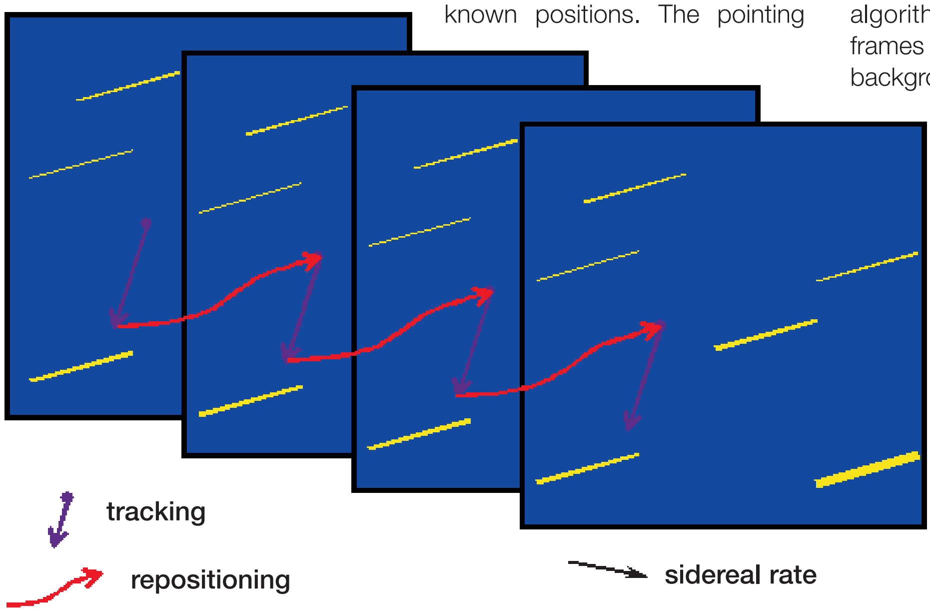


Figure 7. Tracking scenario for surveys. The telescope tracks the object during the exposure and is then repositioned between exposures to always observe the same field in the sky

nearby areas of the sky in parallel. The 2 – 3 parallel fields are selected to be adjacent fields of view in the north-south direction. This approach maximises the observable area.

During the tracking of known objects, the ‘re-pointing to the same sky position’ scenario is followed, so that the image analysis method does not need to be changed. However, instead of stopping the telescope, it follows the object during the exposure in order to collect more photons at the same position on the CCD, thereby improving the signal-to-noise ratio for that object.

Data analysis

The data analysis is performed in quasi-real-time on the OPC. The offline data-processing system is controlled through a user-friendly interface (Fig. 8). This tool allows autonomous interactive processing of the available data using Processing Unit Lists (PULs), which combine several elementary tasks, such as calibration of the camera and the telescope and analysis of the debris observations. In normal observations, the data processing is largely carried out in an automated mode. The processing begins once the first set of frames has been stored and the log file from the observations becomes available.

The search procedure for unknown objects is based on a ‘masking technique’ (Fig. 9), whereby the known objects (e.g. stars) in the frame are masked, so that those still visible are the unknown ones. The first step is to generate a median frame from the entire series of observations. This allows one to eliminate objects that do not appear on the majority of the frames at the same position (e.g. moving objects, cosmic-ray events, etc.). Another processing unit generates the mask from the median frame.

A cosmic-ray detection filter marks the corresponding objects accordingly (cosmic-ray events are discriminated by virtue of the shape of the intensity profile). Since the search procedure is operating at the level of single frames only, it is necessary to correlate the detected objects from the individual frames. This is achieved using mean-motion criteria (upper and lower bound for expected mean motion). The result is a list of objects found in more than one frame, as well as individual lists of objects found in single frames only. Objects found in several frames are given a working name and designated as moving objects.

When an object is detected, its sky position is calculated using catalogued stars in the image as a reference. Its orbit can be determined by analysing consecutive frames. If the object is detected for the first time, only 2 - 4 observed positions will be available. The epoch difference between consecutive positions is about 1 min, which is not sufficient to determine the orbit accurately. Therefore as a first approximation a circular orbit is assumed, and this is then improved with the new data when the object is re-observed.

Results of the observations

A first, very limited series of preliminary system

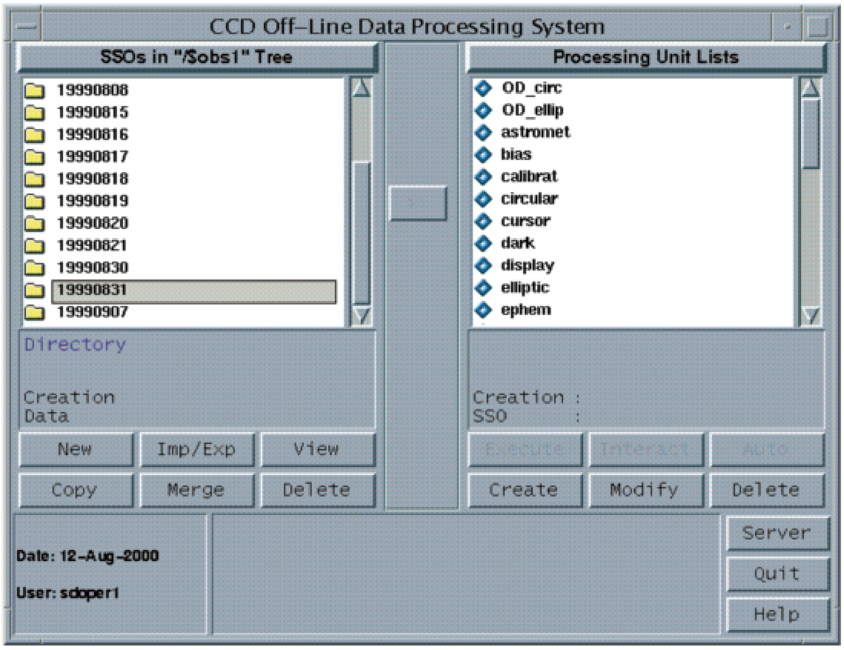


Figure 8. The main window of the offline data-processing system

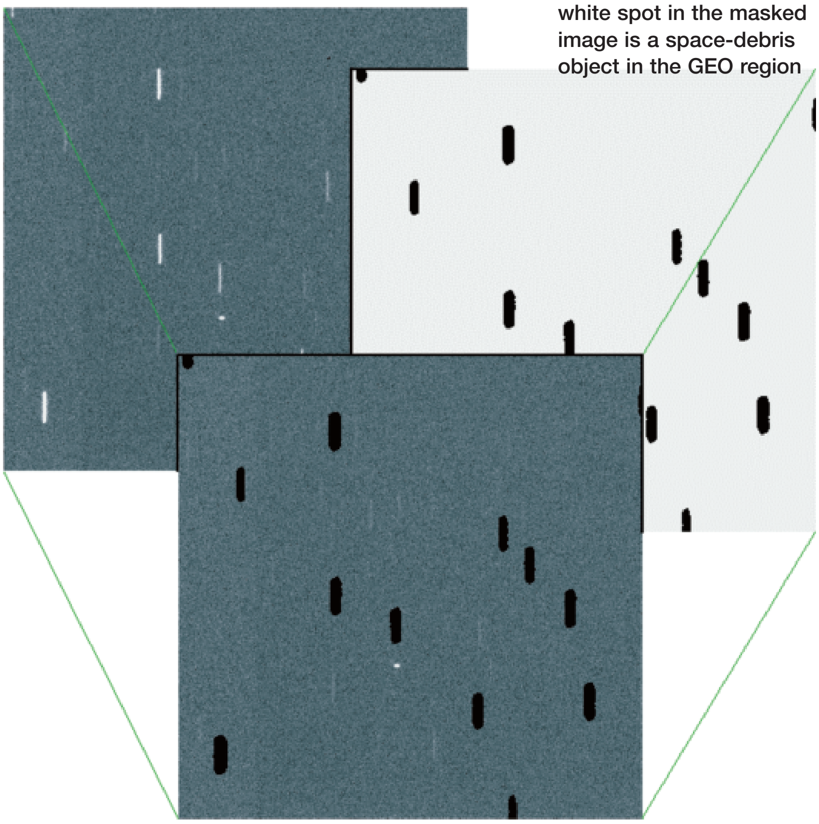


Figure 9. A sub-image (top left) is taken from the observation frame together with the generated mask (top right). In the bottom image the original image is displayed after the masking. The stars form stripes because the telescope pointing is Earth-fixed during exposure; these stripes are masked. The white spot in the masked image is a space-debris object in the GEO region

tests with the ESA 1 m telescope was performed between July and September 1999. The campaign lasted for 13 nights, with a total observing time of 49 hours (Table 1). The observation directions were chosen such that GEO objects were optimally illuminated by the Sun, which implies a direction near the Earth's shadow cone. All frames were exposed for 2 s and the series arranged so that a GEO object would appear on average in three consecutive frames.

Table 1. Observation statistics for the autumn 1999 test campaign

	Surveys		Follow-ups
Number of series	100		102
Number of frames	5439		1034
Scanned area		895 deg^2	
Total observing time		49 hours	
Total image data		52 GB	

The observation scenario consisted of survey series interrupted by follow-up observations for uncorrelated objects (UCOs = objects not listed in the US SpaceCom Catalogue). The latter were scheduled using orbit information from the on-line processing. Figure 10 shows the distribution of the fields searched, as seen in the horizon system from Tenerife. The survey was not homogeneous, either in terms of sampled longitude/latitude space, or in orbital element space (we were most interested in objects on 'high-inclination' orbits). All observation series were analysed on-line. The process identified 360 single detections of correlated, and 696 detections of uncorrelated objects. An off-line correlation over all series for all nights using orbit determination revealed 56 correlated and 150 uncorrelated objects.

Brightness distribution

The magnitude distribution of the detected correlated and uncorrelated objects is shown in Figure 12. The solid line shows the instrument sensitivity as determined from independent calibration observations. The distribution is bimodal with the correlated objects clustered around magnitude 12.5, and a large population of uncorrelated objects in the range from magnitude 15 to 21. There are a few bright objects that did not correlate with the available catalogue, most likely due to poor quality of the corresponding elements in the catalogue (e.g. objects that had recently been manoeuvred). In addition, some objects were not contained in the reference catalogue.

It is important to note that the decrease in number of objects fainter than magnitude 18 is due entirely to the limiting magnitude of the observation system. The luminosity function beyond magnitude 18 could therefore still increase! In all likelihood, the UCOs with magnitudes above 16 are mission-related objects and fragments of breakups.

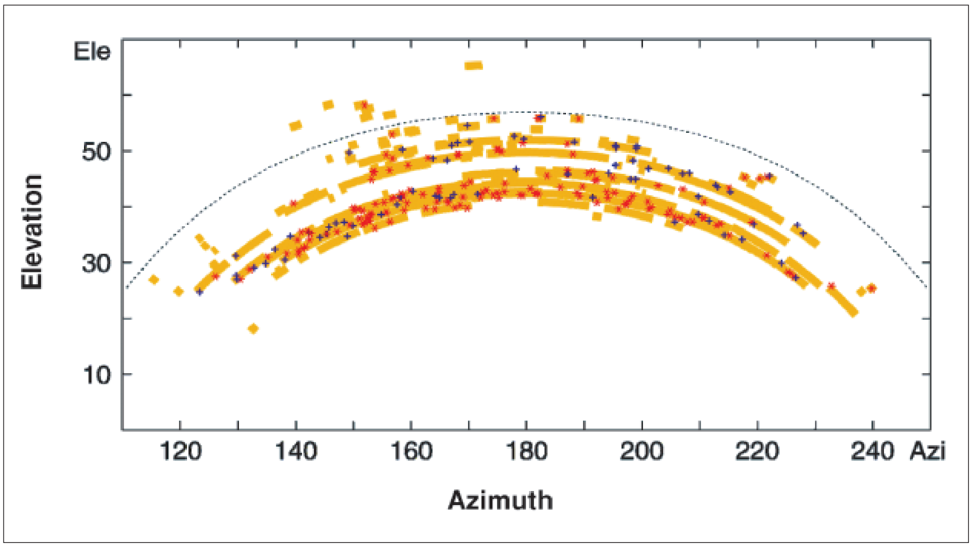
Inclination distribution

Figure 13 shows the distribution of inclinations of all observed objects. It is important to realise that the observed distribution is not the real distribution of the population, but merely reflects the selection of the survey fields. When surveying a field at a given declination, we can only find objects with inclinations greater than or equal to the absolute value of this declination. The correlation between the distribution of the observation time per declination bin given in Figure 14 and the distribution in Figure 13 is obvious.

RA of ascending-node distribution

The distribution of the orbital elements, in particular that of the inclination as a function of

Figure 10. Search fields of the autumn 1999 test campaign. The dashed line indicates the location of the GEO ring as seen from Tenerife, crosses indicate detections of correlated objects, and asterisks indicate detections of uncorrelated objects



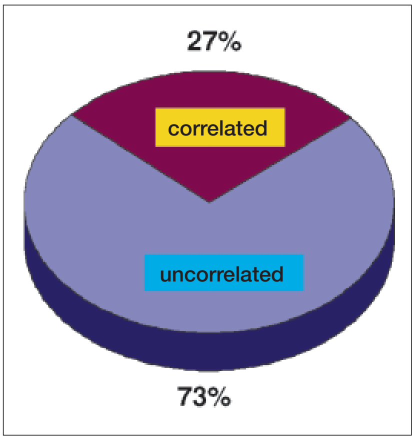


Figure 11. Percentages of catalogued and unknown objects detected by the survey

the right ascension of the ascending node (Fig. 15), may provide some indications concerning the potential sources of debris objects.

The well-known structure observed in Figure 15 is caused by the precession of the orbital planes, due to the Earth's oblateness and luni-solar perturbations. There are, however, uncorrelated objects in unexpected regions, e.g. at high inclinations for ascending nodes between 100° and 150°. A more detailed interpretation of this figure is difficult because of the very inhomogeneous sampling of the orbital element space by the observations. Apparent 'clumping' (e.g. at 30 deg ascending node and 16 deg inclination) may be a pure observational selection effect.

Conclusions

The population of anthropogenic objects in the geostationary ring is steadily increasing. There is no natural cleaning mechanism, such as air-drag, which removes objects from the ring. Objects therefore remain in this region, carrying out complicated motion patterns with periodicities ranging from 1 day to about 53 years.

About 250 – 270 satellites in GEO are controlled, but more than 100 have been left there at their end-of-life rather than being transferred to a 'disposal orbit'. The latter constitute a hazard for operational spacecraft in GEO and are therefore a burden for the future. To reduce the collision hazard for the operational spacecraft, they should have been transferred to a disposal orbit above the geostationary ring at the end of their operational lifetimes. Unfortunately, the recommendations of IAA, ITU and IADC for the

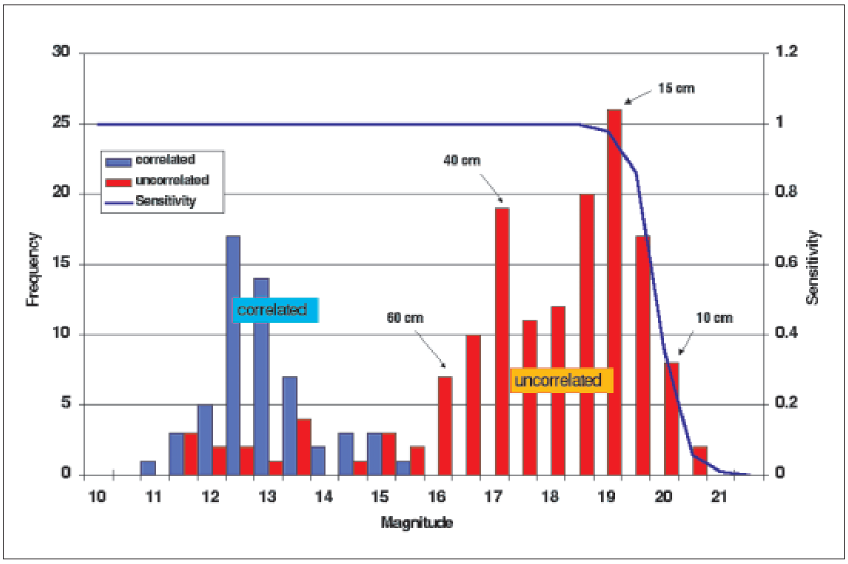


Figure 12. Magnitude distribution of correlated and uncorrelated objects. The solid line shows the instrument sensitivity as determined from independent calibration observations

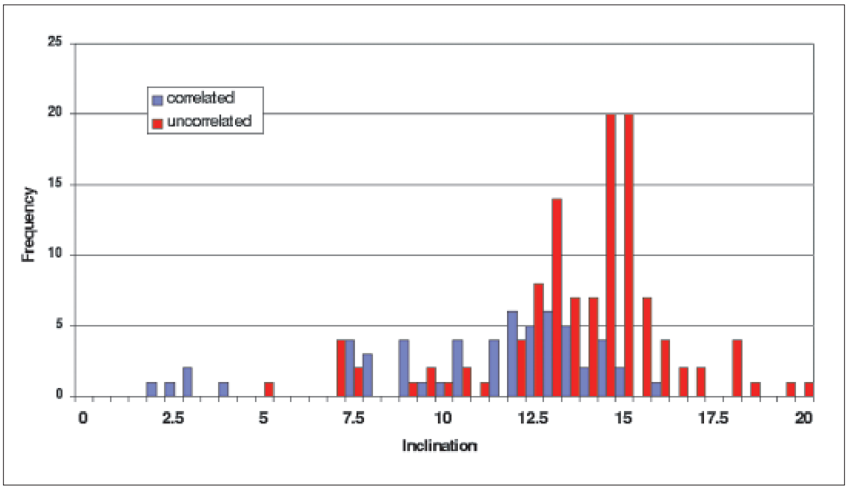


Figure 13. Distribution of inclinations

THE INTER-AGENCY SPACE-DEBRIS COORDINATION COMMITTEE (IADC)

The Inter-Agency Space-Debris Coordination Committee (IADC) currently has eleven members: ESA, NASA, the Russian Aviation and Space Agency (Rosaviakosmos), Japan, ASI (Italy), BNSC (United Kingdom), CNES (France), the Chinese National Space Administration (CNSA), DLR (Germany), ISRO (India) and the National Space Agency of the Ukraine (NSAU).

IADC was founded 1993 in Darmstadt (Germany) on the occasion of the First European Conference on Space Debris. The Committee is concerned with all technical issues associated with space debris. Its main objectives are to exchange the results of existing research, to cooperate in new research activities, and to identify and recommend debris mitigation options. The IADC comprises a Steering Group and four Working Groups: WG1 Measurements; WG2 Environment and Data Base; WG3 Protection; and WG4 Mitigation. It also provides technical support to the deliberations on space debris at the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

The 19th IADC Meeting, scheduled for 22 - 23 March 2001, will be hosted by DLR, in Cologne, Germany.

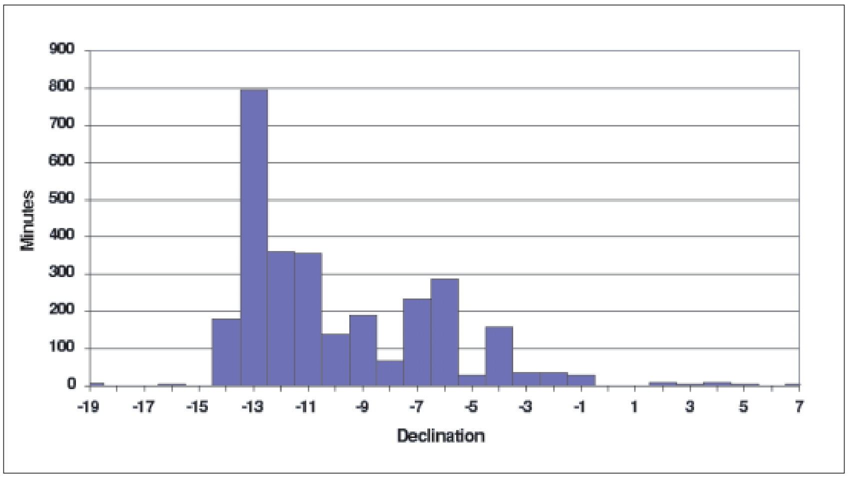


Figure 14. Observation time per declination bin

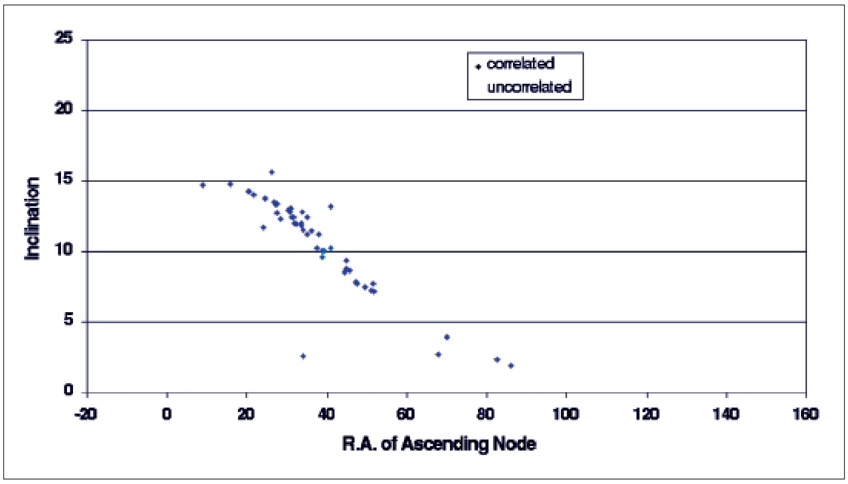


Figure 15. Distribution of inclinations as a function of right ascension of ascending node

re-orbiting of geostationary satellites at end-of-life are only vaguely followed by spacecraft operators. In order to keep the risk of collisions in the geostationary ring within acceptable limits, a code of conduct or some regulation would be beneficial.

Preliminary observations with ESA's Zeiss telescope in Tenerife have shown that there is a significant population of small-debris objects in the 10 – 100 cm size range in the geostationary ring. Extrapolations indicate an uncatalogued population of about 1600 debris objects between 10 – 15 cm and 1 m in size in GEO. The only plausible source for this debris population is breakups of spacecraft, ABMs and rocket upper stages. These objects will remain indefinitely in the GEO region and therefore constitute a real safety hazard for operational spacecraft.

ESA is now in a position to monitor independently objects in about one third of the geostationary ring. The next step will focus on the Geostationary Transfer Orbit (GTO) region.

Acknowledgement
The efficient support and expertise in computer matters of Santiago Llorente (ESOC) is gratefully acknowledged.

THE GRAVEYARD FOR DECOMMISSIONED GEOSTATIONARY SATELLITES

Collisions between decommissioned spacecraft and operational spacecraft in GEO can easily be avoided by transferring the spacecraft at end-of-life into a disposal orbit. Because of potential radio interference and satellites in GTO space, the disposal orbit should be located above the geostationary ring. The costs of the altitude increase can be formulated in terms of the velocity increment of 3.64 m/sec required for every 100 km increase in semi-major axis.

Recommendations concerning the minimum altitude of the disposal orbit have been issued by the International Academy of Astronautics (IAA), the International Telecommunications Union (ITU), and the Inter-Agency Space Debris Coordination Committee (IADC). Both the IAA Position Paper and the ITU Recommendation ITU-R S.1003 stipulate a minimum re-boost altitude of 300 km or more. The IADC recommends that the minimum perigee altitude min ΔH (in km) above the geostationary altitude of 35 786 km should be not less than

$$\min \ \Delta H = 235 \text{ km} + Cr \times 1000 \times A/M$$

where Cr is a coefficient between 0 and 2, A is the cross-sectional area (m^2), and M the spacecraft mass (kg). The perigee increase should be executed as a multi-burn series of manoeuvres, to minimise the probability that errors in estimating the residual propellant will leave the spacecraft in a GEO-crossing orbit.

The IADC recommends that when relocated to the super-synchronous disposal region, the spacecraft should be depleted of all other sources of stored energy, pressurant gases, battery energy, etc. in order to avoid accidental explosions and the ejection of debris back into GEO. Unfortunately, many operators ignore the IAA, ITU and IADC recommendations. About 40 geostationary spacecraft have been retired from service during the last two years; about one third of them were properly disposed of, while two thirds were either left in geostationary orbit or their orbital altitude was increased by an insufficient amount.