CONCEPT FOR A CATALOGUE OF SPACE DEBRIS IN GEO

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ABSTRACT

The Astronomical Institute of the University of Bern (AIUB) was and is conducting several search campaigns for space debris in the geostationary ring (GEO). A substantial part of the detected objects could be correlated with the DISCOS catalogue. No search for multiple observations has been performed among the objects not correlating with the available catalogue. It is expected that quite a few objects have been observed several times. It is therefore of interest to correlate the previously uncorrelated objects with each other and to generate a catalogue of at least part of these mostly faint debris objects.

A simple correlation algorithm is already implemented in the software package used and developed at the AIUB. This algorithm correctly correlates most of the catalogued objects. Nevertheless, the algorithm fails if at least two objects are close together in space, e.g., like the objects in the ASTRA cluster. An improved correlation algorithm is presented in this paper.

For faint debris objects the catalogue has to be built up without information from external sources. Procedures to acquire initial orbits have been discussed in earlier papers. These orbits have to be maintained. Simulations are used to determine the needed temporal spacing between the observations in order to guarantee the recovering of the objects. The results from simulations are compared with results achieved with observations acquired by the 1-meter telescope on Tenerife.

A concept for a catalogue maintenance procedure is developed. The procedure includes the correlation with two catalogues, the DISCOS and the internal catalogue of newly detected objects. The orbit improvement technique used for successfully correlated objects is also outlined.

Tasked observations are performed to acquire the observations needed to update the orbits in the catalogue. The observations have to be planned taking into account the availability of the sensor and the visibility of the object from the sensor. A procedure for the observation planning is presented.

Key words: Catalogue; GEO; Optical Observations.

1. INTRODUCTION

Routine space surveillance is performed by the United States Strategic Command (USSTRATCOM) Space Surveillance Network (SSN). Radar and optical sensors are used to track objects in space. The sensors are well distributed worldwide and include one sensor in space. A catalogue of orbital elements is available in the TLE (Two Line Elements) format. The Russian military authorities are also maintaining a catalogue but with fewer objects, as the system does not cover the entire longitude range. The European Space Agency (ESA) has recently started to investigate the feasibility of a European Space Surveillance System (Donath et al. (2004)). The Astronomical Institute of the University of Bern (AIUB) is contributing to these studies (Flohrer et al. (2005)).

Currently, only GEO objects larger than about 1 m in size are catalogued. Until a few years ago, it was assumed that a large part of the population is covered with such a catalogue. But in recent years an unexpected large number of faint objects has been detected during search campaigns (surveys) for satellites and space debris in GEO performed by the AIUB. Furthermore, a previously unknown population of GEO objects with large eccentricities has been discovered. The results from the GEO surveys are published regularly, e.g., in Schildknecht et al. (2004a). The observations are acquired with the ESA space debris telescope (ESASDT) on Tenerife.

It would, of course, be nice to have a catalogue of at least part of the faint objects in GEO. The AIUB is currently performing first tests to build up such a catalogue of debris objects in GEO. The concept resulting from these first tests is presented below.

Table 1. Range of the orbital elements used for the simulation of 250 GEO orbits.

Semi-major axis	40164 km$< a <$ 44164 km
Eccentricity	$0.00 < e < 0.05$
Inclination	$0° < i < 15°$
R.A. of asc. node	$0° < \Omega < 360°$
Argument of perigee	$0° < \omega < 360°$
Longitude	$-70° < \lambda < 120°$

2. INITIAL ORBITS

Initial orbits are needed to secure the orbits of the detected objects. "Secured" orbits allow to recover an object after a few weeks. A concept for the acquisition of an initial orbit was presented in Musci et al. (2004). A short summary of the updated results is given here as they will be used in the following sections. In Musci et al. (2004), orbital elements were simulated for 100 objects. Here, 250 objects with slightly different ranges for the orbital elements (from now on called "true" orbits) were simulated instead. The ranges for the elements are given in Table 1. The concept, however, remains nearly the same as presented in Musci et al. (2004):

- 3-4 observation tracks spanning $\sim$ 3 hours;
- additional track during the following night;

Thus, each observation arc spans about one day. The orbit determined from these observations should be accurate enough to recover the object after a few days. The formal errors of the elements from the determined orbit should be approximately within the ranges given in Table 2. Orbits with formal errors within these ranges were determined using observations simulated from the 250 "true" orbits. Five tracks were simulated in total, the first four separated by one hour and the last one day after the first track. Ephemerides were propagated from both, the determined and the "true" orbits. The differences between the ephemerides were determined using Eq. 1:

$$\Delta = \arccos(\sin\delta_t\,\sin\delta_d + \cos\delta_t\,\cos\delta_d\,\cos\Delta\alpha) \quad (1)$$

δ_t and δ_d are the declinations from the "true" and the determined orbit and $\Delta\alpha = \alpha_t - \alpha_d$ is the difference of the right ascensions α_t and α_d. The differences as a function of time are shown in Figure 1. The differences are averaged over a time interval of one day, i.e., only one data point per day is plotted. With this filter, disturbing daily periodical errors, which are small compared to the scale, can be eliminated.

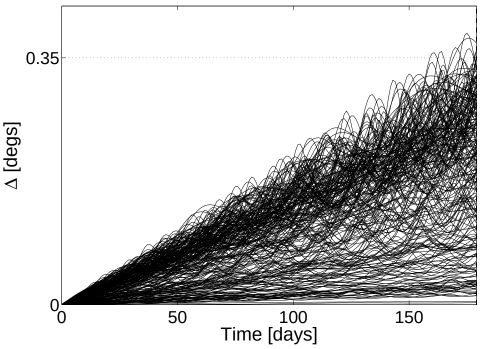

Figure 1. Difference Δ between "true" and determined elliptical orbit representing the observations from the initial orbit. Each curve represents the result from one of 250 simulations.

For a successful recovery of an object the difference between the propagated and the true position has to be smaller than half of the field of view (FOV). The FOV of the ESASDT is about 0.7°. Thus, almost all simulated objects would be recovered with the ESASDT after half a year.

3. MAINTENANCE OBSERVATIONS

Initial orbits have to be maintained, i.e., they must be regularly re-observed. As in the previous section, simulations were used to study the concept for the acquisition of 'maintenance' observations, especially the maximum allowed gap between the tracks. An RMS error of $\sigma = 0.5''$ was adopted for all simulated observations. This is approximately the accuracy of ESASDT observations after the processing. The time interval between the observations of a track was set to 30 s. All simulated tracks consist of 3 observations.

Elliptical orbits were determined in all cases. The methods for the orbit determination as well as the propagation used for this work are described in detail in Beutler (2004). A short description can be found in Beutler et al. (2003).

3.1. Follow-up Tracks

In order to study the behavior of the orbit determination for longer gaps between the tracks a follow-up track was simulated 30 days after the first track from the initial orbit. A gap of 30 days was chosen because the observation campaigns for the ESASDT always last for about 10 to 14 days and are scheduled around new moon. An average gap of 30 days therefore seems to be reasonable. The orbits were determined using the observations used for the determination of the initial orbits and the follow-up observations.

The differences between the positions of the determined orbits and the "true" orbits as a function of time are shown in Figure 2. Again, the differences

Table 2. Recommended ranges for the formal errors of the initial orbits.

a	e	i	Ω	ω	T_0
10-100 m	$10^{-6}-10^{-5}$	$1^\circ \cdot 10^{-5}-10^{-4}$	0.01°-0.1°	0.01°-0.1°	10-20 s

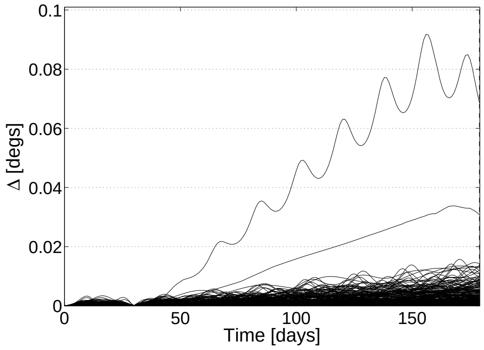

Figure 2. Difference Δ between "true" and determined elliptical orbit representing the observations from the initial orbit and from a follow-up track separated 30 days after the discovery. Each curve represents the result from one of 250 simulations.

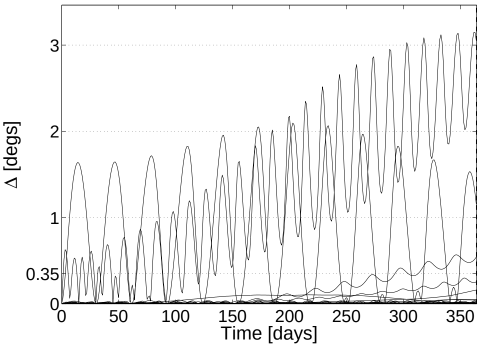

Figure 3. Difference Δ between "true" and determined elliptical orbit representing six maintenance tracks separated by 30 days. Each curve represents the result from one of 250 simulations.

are averaged over one day. The differences are very small. All objects would be re-observable with the ESASDT after more than half a year. The orbit determination was clearly worse for two objects. No reason could be found for this abnormal behavior.

3.2. Maintenance Tracks

The number of observations will get very large and the observation arc very long for the maintained objects during several years of observing. It is not meaningful to use all observations for the orbit determination, as this would slow down the determination process. Only the last portion of the observations from a few tracks should be used to improve the available orbit.

Six tracks with gaps of 30 days between them were simulated. The observations from the initial orbits were not included in the orbit determination. The initial orbits were used as a priori orbits for the orbit improvement process.

The differences between the positions of the determined orbits and the "true" orbits as a function of time are shown in Figure 3. The differences are averaged over one day. Note that observations are included for the first 150 days and the interpolation really starts afterwards. Two objects show large periodical variations. For these objects the orbit determination was not very successful and the resulting RMS of the order of about 10″, instead of about 0.35″ as for the other 248 objects. The variations for one of these two objects have a period of about 30 days. The reason could be a periodical effect on the orbit with the same period as the gaps between the tracks. The variations of the other object have a period of about 14 days. Some of the variations can be eliminated by varying the length of the gaps between the tracks.

The results from this section show that it is possible to determine very accurate orbits using only maintenance observations. The large variations of two objects show that the orbit determination can be problematic when long gaps occur between the observation tracks. Therefore, it is recommended to observe the objects more often than every 30 days, especially for GEO objects which are difficult to model, like the newly discovered population with large area-to-mass ratios.

3.3. Objects in Drift Orbits

Many catalogued objects in GEO are librating or drifting, with drift rates up to 35°/day. At the end of the year 2003, 395 of 835 catalogued GEO objects were classified as objects in drift orbits (Hernández & Jehn (2004)). Most uncontrolled objects, such as debris, are drifting. The drift rate Δn may be computed from the difference Δa of the semi-major axis with respect to the geostationary radius $a_0 \approx 42'164$ km using Kepler's third law to first order by (Schildknecht et al. (2004b))

$$\Delta n\,[^\circ/\text{day}] \approx -0.0128\,\Delta a\,[\text{km}]. \tag{2}$$

Table 3. Return intervals t_{ret} and visibility windows t_{vis} for an observer on Tenerife for drifting GEO objects ($i = 0$) with a semi-major axis differing by Δa from a_0 (minimum elevation above horizon: 20°).

Δa [km]	Δn [°/day]	t_{ret} [days]	t_{vis} [days]
-2000	27.2	13.2	4.2
-1000	13.2	27.3	8.7
-500	6.5	55.4	17.7
-200	2.6	139.7	44.6
-100	1.3	280.3	89.5
0	0	∞	∞

Objects in 'super-synchronous' orbits (semi-major axis larger than a_0) have negative drift rates (in longitude), whereas objects below GEO exhibit positive drift rates.

From a fixed location on the Earth, objects in drift orbits are visible during certain time intervals ('visibility windows') only. The visibility windows repeat with a period equal to the object's revolution period in an Earth fixed system. The drift rates Δn and the corresponding Earth-fixed revolution time t_{ret}, as well as the visibility windows t_{vis} for an observer on Tenerife are listed in Table 3. The minimum elevation above horizon is assumed at 20°. t_{ret} is longer for small Δn. To determine the length of the time interval for which the object is not visible, t_{vis} has to be subtracted from t_{ret}. An object with a drift rate $\Delta n = \pm 1.3$°/day would be hidden for half a year, whereas objects with large Δn are observable after a few weeks.

We can conclude from Figure 1 that a large part of the drifting objects can be recovered if accurate initial orbits are available. Some objects cannot be recovered, because the return time is too long. This could be the case for objects with drift rates smaller than 1°/day. If maintenance observations are available the accuracy will improve and the objects can be recovered after a longer time interval.

3.4. Examples of Real Observations

In the previous section we showed by simulations that it is in theory possible to recover a newly detected GEO object after several days if an accurate initial orbit is available. This theoretical result was checked using real observations from the ESASDT.

Three examples of objects observed with the ESASDT are given in Table 4. All objects were detected during GEO surveys. Tasked observations were performed during the night of the first detection and during the following nights and weeks. None of the objects could be correlated with the DISCOS catalogue. The three objects have magnitudes of about 18, 17, and 13.

Table 4. Difference Δp between the determined and the observed position for GEO objects observed with the ESASDT.

Object		i. o.	1. F.-up	2. F.-up
GEO 1	ΔT [*days*]	2.18	30.20	113.13
	Δp [°]		0.0014	0.0093
GEO 2	ΔT [*days*]	2.30	20.14	196.13
	Δp [°]		0.0224	0.0035
GEO 3	ΔT [*days*]	2.96	99.16	
	Δp [°]		0.0329	

ΔT is the time interval between the first detection and the follow-up tracks. The arc length of the initial orbit is given in the column 'i.o.'. This initial orbit was used to propagate the position of the first follow-up observation. Δp is the difference between this determined position and the observed position. The position for the second follow-up track was propagated using an orbit determined from the observations of the initial orbit and the first follow-up track. All differences are very small. Note that for object GEO 3 the initial orbit was accurate enough to recover the object after 99 days. The results clearly confirm the simulations.

4. CATALOGUE MAINTENANCE

Two different catalogues are suggested, a main and a temporary catalogue. The main catalogue consists of objects with "secured" orbits, i.e., with at least initial orbits. The temporary catalogue will provide orbits of objects during the acquisition of an initial orbit and other uncorrelated objects. Objects in this catalogue will be deleted as soon as they appear in the main catalogue.

Two major steps have to be performed to maintain a catalogue. The first step consists of planning the needed observations. The other consists of updating the catalogues with newly detected objects and the assosiated improved orbits. The latter requires a successful correlation procedure.

4.1. Planning

Tasked observations have to be planned in order to build up a catalogue, especially to acquire initial orbits for the objects. The planning depends on the number of available telescopes. If only one telescope is available, it is probably not possible to observe all objects from the catalogue during one night, depending on the size of the catalogue. A selection of the catalogued objects has to be considered. The parameters of the selection can be the visibility of the object and the age and the accuracy of the catalogue orbit.

If more than one telescope is available, a larger part of the objects in the catalogue can be scheduled for observing during one night. For each object, one of these telescopes has to be selected to perform the observations. The principal selection criteria are the availability of the telescope and the visibility of the object from the site of the telescope. A telescope might not be available due to weather conditions. If more that one telescope meets the selection criteria, the phase angle, the range, and the elevation of the object with respect to the telescope should be optimized, too.

An orbit propagator has to be used to determine the ephemerides of the planned object for the selected telescope. It is recommended that the propagator includes the same physical model as used in the orbit determination, especially for GEO objects with high area to mass ratios. This is the case in the celestial mechanics software developed by Beutler (2004). A search algorithm may also be applied to the planning, if the object was not recovered in earlier observations. Such an algorithm shall in particular include a search in along track direction.

Two observation strategies may be invoked for maintenance observations. One is to plan tasked observations for all objects in the catalogue (as described above). Another possibility is to perform surveys and to acquire all or some of the maintenance observations implicitly. This means that the same part of the GEO belt is observed every n days, where n should be below 30. A GEO survey strategy was described by Flohrer et al. (2005). Both strategies should comply with the concept outlined in the Sections 2 and 3.

4.2. Correlation

The AIUB has a long experience in the correlation of detected GEO objects with the DISCOS catalogue. The used algorithm is successful for most of the catalogued objects. Nevertheless, the algorithm for the correlation fails, if at least two objects have similar orbital elements and are apparently close together. This is the case for clusters like the ASTRA satellites. Therefore, the algorithm was expanded for the maintenance of a catalogue using orbit determination routines developed by Beutler (2004). To successfully distinguish objects in a cluster the quality of the orbit determination should be introduced as an additional correlation criterion.

The correlation procedure needs the orbital elements, the corresponding observations, and a catalogue providing orbital elements as input information. The correlation with the catalogue is done by comparing the input orbital elements and positions with the propagated elements and positions from each object in the catalogue. For GEO objects it is in most cases sufficient to compare the semi-major axes a, the inclinations i, the right ascensions of the ascending node Ω, and the positions. For GEO objects with high area-to-mass ratios, the eccentricity e must be included, too. As Ω is not defined for $i = 0$, the term $\Omega \cdot \sin i$ should be used instead.

The correlation routine results in a list of candidate objects from the catalogue, which all meet the correlation requirements. In addition, the algorithm selects the best of these candidates. This information will especially be used during the first phase of the catalogue creation when no observations from previous nights are available.

The list of candidates is used as input for the second selection criterion. Observations from previous nights have to be selected for each object in the list. If observations are available, they are merged with the observations of the newly detected object. An orbit is then determined using all observations. If more than one orbit could be determined, the best of these orbits will be selected, i.e., the one with the smallest RMS. If the RMS is smaller than about 2-3 times the pointing accuracy, the correlation is marked as successful. If no orbit could be determined, e.g., when no observations from previous nights were available for all candidate objects, the best candidate will be proposed as possible correlation of the new object. After the correlation procedure, one of the two catalogues will be updated, depending on the accuracy of the determined orbit.

The procedure described above is applied if a survey has been performed. The procedure is almost the same if tasked observations were acquired. In this case, the objects detected during the tasked observations are candidates for the tasked object. Therefore, the objects do not have to be correlated with a whole catalogue but only with one tasked object. This clearly reduces the processing time of the procedure. Still, all objects detected in addition to or instead of the tasked object must be correlated with the catalogue. If none of the detected objects could be correlated with the tasked object, the tasked object has to be observed again or removed from the catalogue, if several attempts to observe it failed. Objects that could not be correlated with an object from one of the catalogues will be added to the temporary catalogue. These are newly detected objects or maneuvered objects. It is recommended to cross-correlate the objects in the temporary catalogue from time to time, as some objects might be observed several times. The same procedure as described above can be used for the cross-correlation.

Test of the Procedure

A computer program was written to test the correlation procedure described above. Observations from the ESASDT were used for this purpose. All tests

Table 5. Orbital accuracy for the combination of observations of the ASTRA satellites.

	Obs2_1	Obs2_2	Obs2_3	Obs2_4	Obs2_5	Obs2_6	Obs2_7
Obs1_1	**0.53″**	n/o	28.90″	35.83″	63.21″	24.67″	20.97″
Obs1_2	45.82″	**0.80″**	74.05″	304.08″	59.11″	17.38″	302.66″
Obs1_3	32.42″	76.52″	**0.39″**	7.12″	37.38″	55.32″	44.67″
Obs1_4	40.15″	84.75″	7.62″	**0.36″**	30.36″	n/o	38.44″
Obs1_5	28.36″	18.81″	58.61″	288.75″	94.05″	**0.29″**	98.97″
Obs1_6	n/o	n/o	n/o	n/o	n/o	n/o	n/o
Obs1_7	n/o	126.80″	54.48″	n/o	11.29″	460.75″	**0.32″**

were successful. Let us present one example here.

As mentioned, the correlation can be critical for clusters like the seven ASTRA satellites. Various observations of this cluster were acquired with the ESASDT during the survey campaigns. Observation tracks separated by one day were selected for this example. The tracks of both days consist of 2-3 observations and span one or half a minute.

The tracks from the second day were processed with the test program, while the observations from the first day were only used for the orbit determination. The result of the correlation with the catalogue was ambiguous. Every satellite of the cluster was proposed as candidate for each of the observed objects. The proposed best candidate was the same for most of the objects. The problem is due to the inaccuracy of the elements in the DISCOS catalogue, which are insufficient to correlate the objects. The quality of the orbit determination is therefore essential to distinguish the satellites of the cluster.

The result from the orbit determination is shown in Table 5. The observations from the first day are named ‘Obs1_1-7’, while the ones from the second day are named ‘Obs2_1-7’. The result shows a clear correlation for six of the seven objects (bold values). No orbit (n/o) could be determined for combinations with the object ‘Obs1_6’. This is probably because only two inaccurate observations from the first day were available for this object.

The example shows that the performance of the correlation procedure is sufficient in most cases encountered in practice.

5. CONCLUSIONS

A concept for the maintenance of catalogued GEO objects was presented. Simulations were performed to assess the allowed temporal spacing between the detection and the first maintenance tracks. A gap between the maintenance tracks below 30 days is recommended. The concept was successfully checked with observations acquired by the ESASDT.

It is proposed to generate two different catalogues, a main catalogue for the objects with “secured” orbits and a temporary catalogue for all other objects. Both catalogues will be used for the planning and the correlation procedures.

A correlation procedure including the comparison of the orbital elements and the positions, as well as the comparison of the accuracies of the determined orbits, was presented. The correlation procedure was successfully applied to observations acquired by the ESASDT.

ACKNOWLEDGMENTS

The observations from the ESASDT were acquired under ESA/ESOC contract 15836/01/D/HK.

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