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Search for space debris in the MEO region with ZimSMART

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Nowadays, the MEO region is mostly populated with satellites of the Global Navigation Satallite Systems NAVSTAR GPS and GLONASS. Satellites were launched since 1978 (GPS) and 1982 (GLONASS), respectively. Due to the replacement of old satellites and the deployment of new systems like Galileo and Compass the number of satellites will increase. As a consequence, the number of space debris will also increase.
The search for space debris objects in the MEO region at the AIUB is performed with the small aperture telescope ZimSMART, located in Zimmerwald, 10 km South of Bern (Switzerland). To minimise the processing steps, the tracklets (sets of at least three observations belonging together) from the MEO surveys are analysed in the same processing pipeline as those from GEO surveys. MEO and GEO surveys are observed alternating during one night.
The surveys are performed by scanning the orbital planes of former as well as of active GNSS satellites. The survey strategy consists of tracking pseudo-objects with equidistant spacing in an orbital plane. So, a homogeneous coverage of the orbital plane is guaranteed.
We will present survey results of the investigated orbital planes. Between April 2011 and February 2012, orbital planes of four satellites were observed: GIOVE-A, MOLNIYA 1 − 93, NAVSTAR 23 of NAVSTAR GPS and COSMOS 2442 of GLONASS.

I. The telescope ZimSMART

The observation facility of the AIUB is located in Zimmerwald, 10 km South of Berne (Switzerland). It consists of the **Zim**merwald **L**aser and **A**strometric **T**elescope (ZIMLAT, est. 1996) and the telescope ZimSMART, decribed below. Although the telescope is used for experimental observations, we also perform routine measurements.

The set-up of the **Zim**merwald **Sm**all **A**perture **R**obotic **T**elescope (see Fig. 1) changed since its installation in 2006. Currently in its third set-up, it has a primary mirror with a diameter of 18 cm and a focal length of 500 mm. The field of view is $4°6' \times 4°6'$. The mount is the "ASA DDM85" developed by Astrosysteme Austria and is currently used since 2010.

The camera we use is an FLI 16803 with a PL16803 CCD of KODAK. The chip has a size of 4096×4096 pixel, which results in an angular resolution of about 3.6″/pixel. For this camera the readout time is 16 s. The limiting magnitude is about 15 mag.

The MEO surveys of this study were all per-

Figure 1: The telescope ZimSMART in its third set-up

formed with this set-up.

II. The Medium Earth Orbit region

A great part of the Medium Earth Orbit region (MEO) is covered by satellites of the Global Navigation Satellites Systems (GNSS). The individual systems are operated by different countries and institutions: NAVSTAR GPS by NASA (USA), GLONASS by ROSKOSMOS (Russian Federation), Galileo by ESA (Eurpean Union) and Beidou by China. Satellites were launched since 1978 and meanwhile there are already many defunct spacecraft an spent upper stages in this orbital region. Other satellites are telecommunication satellites, like Globalstar or Molniya.

Inactive objects are a potential source for space debris and observing their orbits may provide information about the space debris population in this region.

III. Survey strategy for the MEO region

For this study we focused only on orbits of satellites of the GNSS and the Molniya satellite systems. In near future more satellites, e. g. with the deployment of "Galileo" and "Compass" navigation systems, will be located in this region, while older satellites may be moved into graveyard orbits. Thus, the probability of space debris being created will increase.

III.I Explosion scenario analysis

Simulations of explosion populations in the MEO region (see e. g. [4]) showed, that fragments of these explosions stay approximately in the same orbital plane as the satellites they stem from. The term "explosion" stands for fragmentation as well as for collision. A collision can be approximated in first order as an explosion of two objects at the same location at the same time.

Two explosion scenarios were studied: an explosion at the passage of the ascending node and an explosion in the upper culmination. An explosion in one of these points in the orbit causes the biggest changes of the orbital plane, defined by the right ascension if the ascending node (RAAN) Ω and the inclination i.

An explosion at the passage of the ascending node (or at the descending node) will lead to a Gaussian distribution of the inclination of the fragments around the inclination of the parent object, but values of the RAAN of the fragments will be similar to the RAAN of the parent object. The standard deviation, which was calculated in [4], was $\sigma_\Omega = 7°$.

On the other hand an explosion in the upper culmination (or at the lower culmination) will lead to a Gaussian distribution of the RAAN around the RAAN of the parent object. In this case the values of the inclination will be similar to the inclination of the parent object, with a standard deviation of $\sigma_i = 1.58°$ (see again [4]).

Explosions at any other point of the orbit will lead to a combination of both, i. e. the values of the inclination and RAAN will be distributed around the values of the parent object.

The apparent motion of the objects with respect to the celestial background is very different compared to GEO objects. Because their orbits having semi-major axes between 25 500 km to 29 600 km, they perform between 1.70 and 2.13 revolutions per sidereal day. This corresponds to orbital periods between 11 h 16 min and 14 h 7 min. While the object is orbiting, the Earth also rotates around itself and the projection of the orbital plane onto the celestial background as seen from a ground-based observer is complicated. Figure 2 shows the track of a GPS satellite (NSSDC ID: 91047A) in the night of May 13th, 2012 as seen the horizon system (red

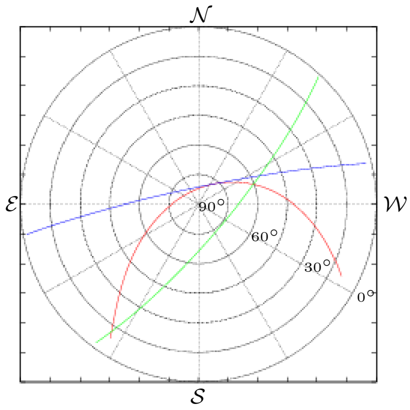

Figure 2: Red line: track of the GPS satellite 91047A on May 13th, 2012, green line: projected orbit of 91047A at 21:30 UTC, blue line: projected orbit of 91047A at 1:00 UTC

line). The green line is the projection of the orbit onto the sky at 21:30 UTC and the blue line at 1:00 UTC. The displacement of the orbital plane is visible.

III.II Observation scenario

According to the explosion model mentioned above, space debris stays in or at least near the orbital plane of the parent object. With the calculated standard deviations of $\sigma_\Omega = 7°$ and $\sigma_i = 1.58°$, many objects may stay within the field of view of $4°6'$ if the latter is centered on the orbital plane of the parent object. We therefore decided to survey the orbital planes of the GNSS satellites.

We selected the orbital parameters of a satellite (the base object, e. g. GPS satellite 91047A) in the Two Line Element set (TLE) format and varied the eccentric anomaly E. A typical TLE is presented in Figure 3 (first three lines). The value $E = 0\,(\widehat{=}\,0°)$ represents the direction of an object's perigee and $E = \pi\,(\widehat{=}\,180°)$ the apogee. TLEs provide the mean anomaly M, which can be determined from the eccentric anomaly:

$$M = E - e \cdot \sin(E) \qquad [1]$$

The surveys were performed by tracking pseudo-objects in the orbital plane to be investigated. To get a homogeneous coverage of an orbit the angular distance between two pseudo-objects must be equal to the field of view of the telescope. The number of pseudo-objects is then 360° divided by the size of the field of view (FoV). For simplicity the value of the FoV of ZimSMART was set to 4° to get an integer number of 90 pseudo-objects. The eccentric anomaly was varied from 4° to 360° in steps of 4°, and the corresponding mean anomaly, replaced the original TLE set to obtain TLEs for each pseudo-object (MEO001, MEO002 and so on in Figure 3); the other entries in the TLE sets were kept, which ensures that all pseudo-objects are in the same orbital plane.

Due to the homogeneous coverage of the orbit, one survey field must contain the base object. Because the mean anomaly of this object is known also the field of the corresponding pseudo-object is known. This fact is used to check the survey method. In the example above, the GPS satellite has a mean anomaly of 317.0752° (uppermost red box in Fig. 3) and it will be on the frame of pseudo-object MEO079, because the difference is smaller than the FoV of the telescope.

Figure 4 shows the set-up of the MEO surveys using pseudo-objects. The blue filled circle is the Earth in one focal point of the orbit (red curve). The light coloured arrows represent the calculated directions of the pseudo-objects. The black arrows give the direction to the auxiliary circle. The angular separation between two consecutive arrows is 4° as defined before.

Within a night all visible fields are scheduled for observations. If possible each field is then observed multiple times. The aim is to observe the entire orbital plane without gaps. After observing each frame several nights, the orbital plane is changed, which means that a new base object is selected.

This strategy is optimised for objects close to the orbital plane of the base object. Nevertheless, some objects in other orbital regions are also detected when they are crossing the line of sight. There are critical cases where an object is not found when the frame is observed a second time within one night:

1. The object has moved out of the field in along-track direction. This corresponds to a semi-major axis much different than the one of the base object or an object with an eccentric orbit. If the inclination does not differ very much from the base object the observed object may be found in one of the neighbouring frames.

```
NAVSTAR 23 (USA 71)
1 21552U 91047A   12128.14103930  .00000055  00000-0  10000-3 0  5115
2 21552 054.3249 179.2762 0023249 043.1971 317.0752 01.91859343152492
Testobjekt 1
1 T-001U MEO001   12128.14103930  .00000055  00000-0  10000-3 0  5115
2 T-001 054.3249 179.2762 0023249 043.1971 003.9907 01.91859343152492
Testobjekt 2
1 T-002U MEO002   12128.14103930  .00000055  00000-0  10000-3 0  5115
2 T-002 054.3249 179.2762 0023249 043.1971 007.9814 01.91859343152492
...
Testobjekt 78
1 T-078U MEO078   12128.14103930  .00000055  00000-0  10000-3 0  5115
2 T-078 054.3249 179.2762 0023249 043.1971 312.0989 01.91859343152492
Testobjekt 79
1 T-079U MEO079   12128.14103930  .00000055  00000-0  10000-3 0  5115
2 T-079 054.3249 179.2762 0023249 043.1971 316.0925 01.91859343152492
Testobjekt 80
1 T-080U MEO080   12128.14103930  .00000055  00000-0  10000-3 0  5115
2 T-080 054.3249 179.2762 0023249 043.1971 320.0856 01.91859343152492
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Figure 3: Two line element sets of the base object (first lines) and the MEO survey fields of the pseudo-objects

2. The object has moved out of the field in cross-track direction. This corresponds to an object with an inclination much different from the one of the base object. In this case the object will not be found in a neighbouring frame, but when this object crosses the observed orbital plane once more it might be observed again.

The observation mode is a mixture of ephemeris tracking and rate (blind) tracking.

IV. Processing pipeline

If an object is detected on at least three frames, a tracklet is created. A tracklet is a set of observations with information about epoch and coordinates, at least. Tracklets are created for each individual object, so the total number of tracklets of a night is identical with the number of detections. As ZimSMART observes in survey-only mode only, there is no a priori information about the observed objects. The object identification has to be done in a subsequent process, which is described in detail in [3] for GEO surveys. The processing of MEO survey tracklets does not differ from those of GEO survey tracklets and a short overview about the individual processing steps is given below.

The basis for the processing are object catalogues. We use TLE catalogues, namely the USSTRATCOM catalogue and two AIUB internal catalogues.

First, all tracklets are filtered via the measured apparent positions and velocities computed thereof, by means the tool *COROBS*, developed by C. Früh ([2]). The positions and velocities are compared to the computed ones from the catalogues for each observation epoch. The result is a quality categorisation which provides probabilities whether or not the analysed tracklet belongs to a catalogued object. There are two categories, the first one gives a probable connection of the tracklet to an object, the second one eliminates any possibility of connection.

The left-over tracklets are checked pair-wise if some of them can be associated with each other. These possible associations are identified by determining a circular orbit, which is a sensible approach for tracklets of only one night. Successful associations are stored in a separate file, which are then investigated with a second filter step via their orbital elements.

The elements of the catalogued objects from the last successful orbit determination are propagated to the current observation night and compared to the elements resulting of the circular orbit determination of the associated tracklets. If the analysed

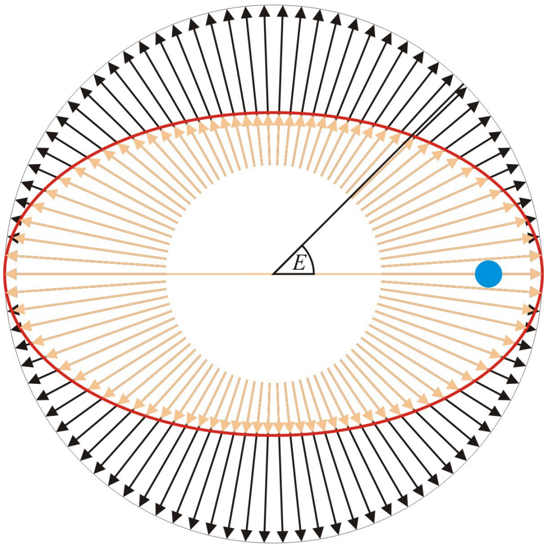

Figure 4: Set-up of the pseudo-objects for the MEO surveys (sketch)

elements agree within certain limits, then the new tracklets are added to the catalogue.

An orbit determination is used to confirm that the new tracklets really belong to the associatedc objects. Orbit determinations are performed with the CelMech tool *SATORB*, developed by G. Beutler in [1].

V. Results

To analyse the MEO region we focused on four orbital planes of objects in the MEO region:

- Galileo, represented by GIOVE-A (05051A)
- Molniya, represented by MOLNIYA 1 – 93 (04005A)
- NAVSTAR GPS, represented by NAVSTAR 23 (91047A)
- GLONASS, represented by COSMOS 2442 (08046A)

These four orbital planes stand for different orbit geometries in the MEO region: circular or eccentric as well as a range in semi-major axes. They were observed subsequently and the base objects were changed when each field was observed in several nights. Observations in several nights are important to get a sufficient quality of the orbit.

Figure 5 shows the distributions of the number of nights per field for each object. It is not an equal distribution, because of the different lengths of the night and the different orbital periods, respectively, some fields are more likely to observe than others. The observable periods for each field will changed during the observation period. After a certain time span, depending mostly on the orbital period, each field was visible and observable during the night. Due to the orbital period of the NAVSTAR GPS satellites it took a long time until each frame could be observed. Therefore we had to stop the surveys of one orbital plane, switch to another orbital plane and continue observing the former lateron.

A second criterion to characterise the success of surveying an orbital plane is the number of detected catalogue objects. Especially the GLONASS and NAVSTAR GPS orbits are populated with several satellites and rocket bodies. One would expect to detect not only the base object of each plane, but also other objects near that orbital plane. The individual orbital planes are not perfectly identical and we accepted a deviation from the orbital plane of the base object of $\pm 4°$ in right ascension of the ascending node (RAAN) and $\pm 5°$ in inclination. The limits for the semi-major axis are quite wide open to cover the complete MEO region.

V.I GIOVE-A (05051A)

This satllite is a test satellite for the European Galileo GNSS, which is currently in deployment Galileo. The distribution of nights (Fig. 5(a)) with observations is nearly equal, each pseudo-object field was observed at least three times. The coverage of this orbital plane is therefore complete.

Within our limits for the RAAN and inclination there were four catalogued objects including the base object, and all of them could be detected within the investigation period.

V.II MOLNIYA 1 – 93 (04005A)

Satellites of the Russian Molniya system are not part of the GNSS, but they have comparable semi-major axes and therefore similar orbital periods. They also have high eccentricities which are the main difference compared to classical GNSS orbits. This orbital plane was included as a test case for ZimSMART concerning observations of highly eccentric orbits. The coverage of the orbit is not complete as shown by Fig. 5(b).

There were seven objects near the base orbital plane which could have been observed, from which one object was detected. The detected object was not the base object but a rocket body, because the base object was only visible for ver short time at the beginning of each night throughout the observation period and was therefore not observed.

V.III COSMOS 2442 (08046A)

This satellite is from the Russian GNSS GLONASS. The distribution of nights with observations of the pseudo-object fields is not equal, but each frame was observed at least three times, resulting again in a complete coverage of the orbital plane (Fig. 5(c)).

Within our limits for the RAAN and inclination there were 50 objects which could have been detected. Thereof, 34 objects were actually observed in the observation period, including the base object.

V.IV NAVSTAR 23 (91047A)

The orbital period of the US-American GNSS NAVSTAR GPS satellite system is exactly half a sidereal day. That means some pseudo-object fields cannot be observed for a certain time span. The observation period had to be enlarged to cover the whole orbit. The other pseudo-object fields show nearly an equal distribution of nights with observations.

Around that orbital plane there were six objects, which could have been detected. One of the objects was not visible the entire period. Two of the other five objects were detected. The base object was observed but the observations were not associated to the object. These observations were stored into the AIUB internal ZimSMART catalogue as a newly detected object (called Z11317A).

In contrary to the first determined orbits, further analysis showed that the object Z11317A is equal to 91047A.

Why some objects near the orbital plane of the base objects were not detected, is an open question, a further investigation must be performed. One possibility is that although the orbital elements were within our limits, but the objects were not observed where the orbits crossed each other and were out of the filed of view at any other point of their orbits.

VI. Conclusion

We presented surveys of the MEO region with ZimSMART, aimed at searching for large uncatalogued debris objects. These surveys consist of equally distributed fields along the orbit of a base object covering the entire orbital plane. Although the strategy is optimised for objects in the MEO region, all objects, which crosses pseudo-object fields, may be detected.

We investigated three GNSS orbital planes (circular orbits) with a range in semi-major axes and one highly eccentric orbit. The three GNSS orbital planes were investigated completely, the coverage of the Molniya orbtial is not complete. In some cases the base objects could not be observed, but other objects near the orbital plane were detected. The majority of invisible objects would have been detected if the observation periods would have been longer.

During the investigation of the orbit of 91047A, a preliminary uncatalogued object was found initially but eventually the new orbit turned out to be the base object 91047A itself.

In the investigated orbital planes with complete coverage, uncatalogued objects were not found. That means that there are no objects brighter than 15mag, the limiting magnitude of ZimSMART. For the other orbital planes, the coverage has to be completed.

VII. Acknowledgements

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VIII. References

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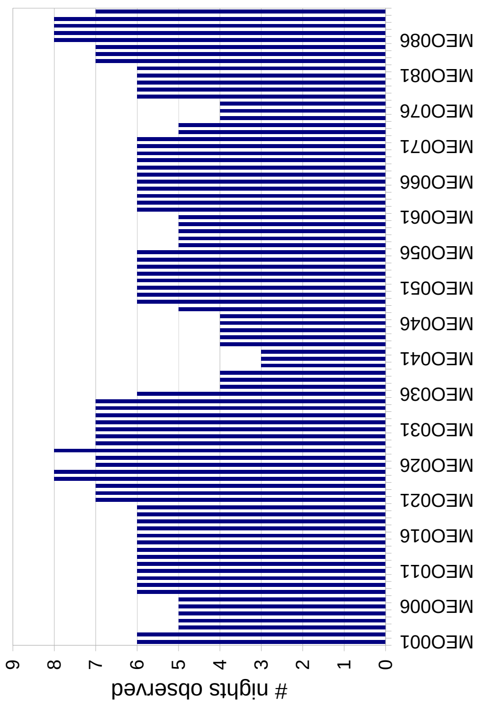
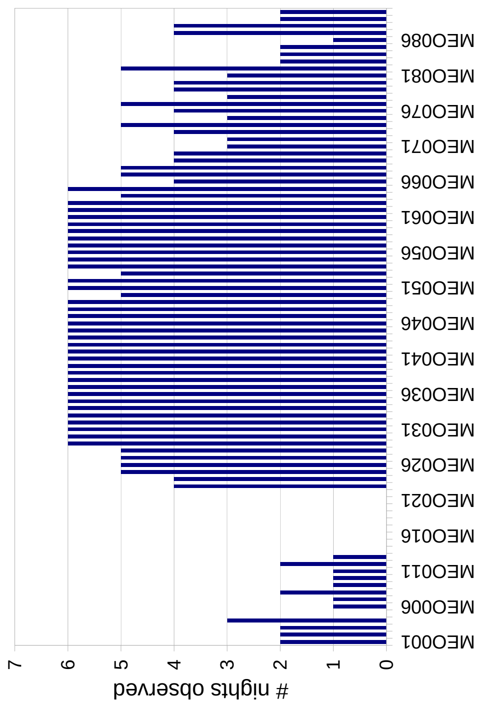
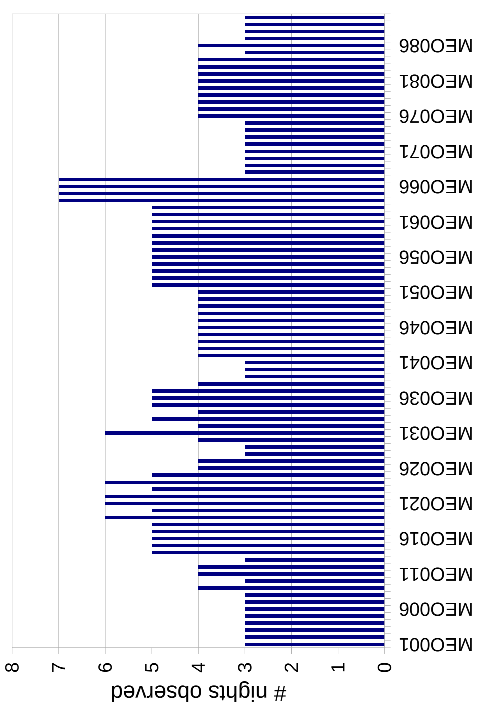


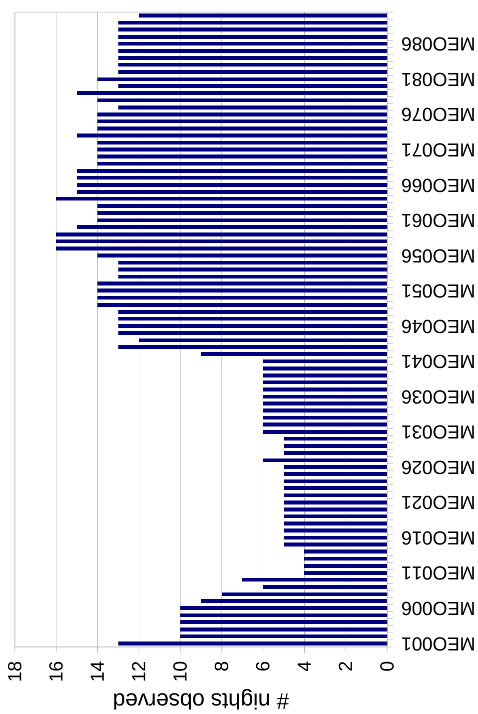
(a) 05051A



(b) 04005A



(c) 08046A



(d) 91047A

Figure 5: Distributions of nights with observations per field for each object of this study

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