ADDITIONAL OPTICAL SURVEYS FOR SPACE DEBRIS ON HIGHLY ECCENTRIC AND INCLINED MEO ORBITS

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In the frame of ESA projects several optical surveys campaigns were performed by the Astronomical Institute of the University of Bern (AIUB) to improve the knowledge about the debris environment in the geostationary ring (GEO), the geostationary transfer orbit (GTO) region, and in the medium Earth orbit (MEO) region of the global navigation satellite constellations. For all these campaigns observation strategies, processing techniques and cataloguing procedures have been developed and successfully applied.

Comparably less experience (both, in terms of actual observations and strategy definition) is available for eccentric orbits in the MEO region, in particular for Molniya-type orbits. Several breakup events and deliberate fragmentations are known to have taken place in such orbits.

Different survey scenarios for searching space debris objects in highly-eccentric MEO orbits, and follow-up strategies to acquire orbits which are sufficiently accurate to catalogue such objects and to maintain their orbits over longer time spans, were developed. Simulations were performed to compare the performance of different survey and cataloguing strategies. Eventually, optical observations were conducted 2013 and 2014 in the framework of an ESA study using ESA's Space Debris Telescope (ESASDT) the 1-m Zeiss telescope located at the Optical Ground Station (OGS) at the Teide Observatory at Tenerife, Spain. In addition to the ESASDT, also instruments available at the Zimmerwald observatory, such as the 1-m ZIMLAT and new 0.4-m ZimSPACE telescopes were and are used for additional follow-ups.

I. INTRODUCTION

The Low Earth Orbit (LEO) population is regularly tracked by the USSTRATCOM and their data are available in so-called Two Lines Elements (TLE) format. For this population we have pretty good knowledge down to some cm particles in diameter. TLEs are also available, e.g., for Geosynchronous Earth Orbits (GEO), Geo-Synchronous Transfer Orbit (GTO), , Medium Earth Orbits (MEO), such as GNSS (Global Navigation Space System) orbits, or Molniya-type orbits. The knowledge about space debris in these orbits higher than LEO altitudes increased during the last 15 years, when additional surveys were performed for GEO, GTO and GNSS regions. Such measurements were performed, among the others, by AIUB within ESA's projects [1,2]. Molniya, as a relatively large and not very much investigated population was chosen as the next possible region for the research.

In our paper we present the Molniya population, as well the proposed and tested dedicated survey strategy. As a sensor the ESA's Space Debris Telescope (ESASDT), i.e. the 1-m Zeiss telescope located at the Optical Ground Station (OGS) at the Teide Observatory at Tenerife, Spain was used. The primary task was to develop the observation survey optimized for Molniya objects and for the ESASDT.

We performed surveys in 2013, as well in 2014 within 23 nights of observations. A considerable number of newly discovered objects was obtained. We present the results from observation nights, as well the dynamical and physical properties of discovered Molniya objects.

II. MOLNIYA POPULATION

For Molniya type of orbits their high eccentricities (> 0.5), as well inclinations are typical. In order to minimize the secular perturbation for the argument of perigee due to the Earth oblateness, Molniya orbits are placed at inclinations close to 63.4° [3]. The observations strategy was developed from the the available TLE population (to January 2012) catalogued by US Strategic Command (USSTRATCOM). Molniya objects were selected by using the following criteria for orbital elements. The inclination was defined between 60° and 67°, the semi-major axis between 20,000 and 30,000 km and the eccentricity was between 0.5 and 0.8.

There were in total 171 Molniya objects in the TLE catalogue which fulfilled given criteria including the Molniya satellites, Meridian and Oko satellites, rocket bodies, upper stages and other types of debris. We used the given population and we predicted its orbital elements 20 years into the future to see if the orbital distribution would change considerably during the investigated period [4]. For all objects we assumed a sphere with an area-to-mass ratio (A/M) of 0.009 m^2/kg. Predictions showed that the orbital distribution would change only slightly, except the right ascension of the ascending node (RAAN) where a permanent decrement for all objects was observed. This can be seen in Fig. 1. The drift of nodes is about -31 to -73 °/year with a median value around -45°/year.

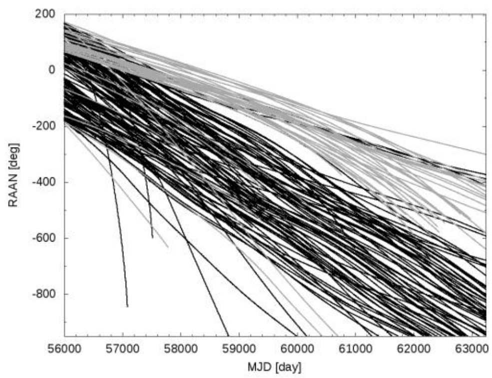

Fig. 1: Evolution of the right ascension of the ascending node during 20 years of evolution for the Molniya TLE population.

Because distributions between current and integrated orbital elements were very similar, we continue for further investigations by assuming the current TLE population as a representative population sample for the Molniya orbits.

III. SURVEYS STRATEGY

The selected TLE population was used to investigate typical angular velocities for Molniya objects, as well as culmination points (highest declination) observable for this population from the OGS. Once the object tracking mode is used and its value is very similar to the angular velocities of the objects of interest, their signal to noise ratio (SNR) can be increased, hence also the probability that object will be detected. The culmination point on the other side, indicatesthe densest regions with the best observation conditions, hence where to look during surveys. From our investigation we decided to use during Molniya surveys an object tracking mode with the tracking velocity of 5.5 arc-sec/s. As probably the best declination we have chosen the value of 63° [4].

Finally, we constructed the survey strategy for Molniya population. One night survey consisted always of one field defined by the declination (DEC) which was always 63° and right ascension (RA) with the best illumination conditions (close to the Earth shadow). If more nights were available during the month, in our case three continuous nights, every night the field was shifted in RA by 10°. This is demonstrated in Fig. 2. Observations were always performed few days around the New Moon to secure the best observation conditions. We were always avoiding the Milky Way to increase the detection efficiency.

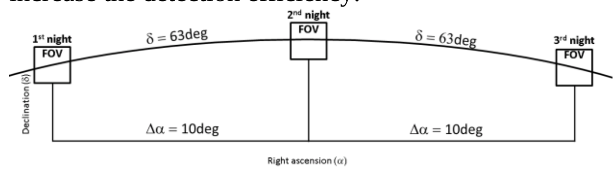

Fig. 2: Survey strategy with 3 fields per month (one field per day) displaced by 10° in right ascension.

The chosen observation strategy cannot, in any case, cover the whole Molniya region. This would be impossible with the ESASDT telescope's FoV 0.7°x0.7° and with available three observation nights per month at OGS. However, from our applied strategy we can obtain a statistical sample from different regions for this population and this can give us a very good idea of how large and how distributed this population really is.

IV. SURVEYS PERFORMED IN 2013

First surveys with the ESASDT were performed in January 2013 when we had three successful consecutive nights dedicated to the Molniya observations. We detected a considerable number of Molniya objects per night. Additionally three nights of surveys were performed in February, May, and June and one night in August 2013. Together there were 13 nights of observations with 13 different fields scanned. All the time the observation strategy discussed in the previous section was applied. The geocentric coordinates of scanned fields in 2013 can be seen in Fig. 3. Assumed was a distance between the sensor and field position of 41,000 km.

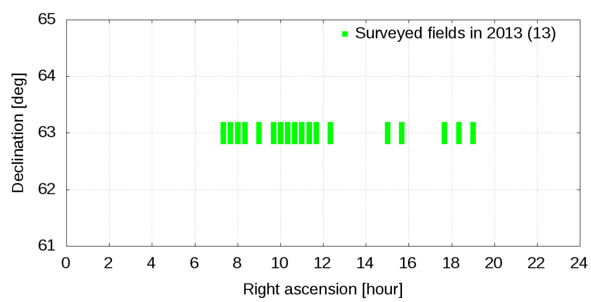

Fig. 3: Molniya fields surveyed in 2013. Plotted are geocentric right ascension and declination. The used field of view had size 0.7°x0.7° and is not to scale in the plotted figure.

There were in total 30 newly discovered Molniya objects, uncorrelated targets (UCTs), from which 26 were included into the ESA/AIUB's internal catalogue that allows to schedule follow-up observations. For all 26 Molniyas the follow-up observations were performed for more than one day. Some of these objects were lost few days after their discovery, but on the other side, some of them were inside the catalogue and regularly observed for few months to more than one year.

The objects discovered in 2013 showed different physical characteristics, as magnitudes or area-to-mass ratios (A/M). We catalogued objects with magnitudes from 15^{th} to 19^{th}, which is the limiting magnitude for the OGS system with given settings. For A/M ratios we got very low values equal to 0.01 m^2/kg. However, we also discovered two objects which can be marked as High Area-to-Mass Ratio (HAMR) objects, while they had A/M higher than 3.0 m^2/kg.

VI. SURVEYS EFFICIENCY AND COVERAGE

In order to evaluate our surveys efficiency, hence to investigate how many objects, which crossed our FoV we actually detected, we performed simulations with the ESA's Program for Radar and Optical Observation Forecasting (PROOF)[5] and with the USSTRATCOM TLE population. For every of the 13 survey nights we took the TLE catalogue of the given date. We set up the same observation parameters in PROOF that we used during observation nights, meaning that we used the same exposure time, line of sights (LOSs), gap/readout times, and scanning durations. In the end we simulated as realistically as possible the observations performed with the ESASDT in 2013.

There were 26 Molniya objects, so-called correlated targets (CTs), which crossed the FoV during PROOF simulations and had at least two positions. From these 26 CTs, 15 were detected by the ESASDT recognition software during the observations. That means the detection efficiency for Molniya objects during our 2013 surveys was 57.7%. The PROOF simulation allowed also to qualify the percentage of covered objects from the Molniya population. We know that there were on average 169 Molniya objects in the TLE catalogue, from which 26 crossed our FoV. This means that for the Molniya population our survey theoretically reached a coverage equal to 15.4% of the whole population assuming a 100% detection efficiency.

There were at least 30 Molniya UCTs which crossed our FoV and which were afterwards detected and additionally observed (at least two tracklets were acquired for them). By applying the survey efficiency of 57.7%, one could expect that there were in total about 52 UCTs which crossed our FoV. By applying the survey coverage according to the Molniya population 15.4% and by assuming that the UCT population has a similar distribution as the CT population, we can estimate the number of the UCTs. Finally, there could be about 338 UCTs in Molniya orbits, which are theoretically detectable by the ESASDT by applying our observation strategy (assuming object pseudo-tracking and an exposure time of two seconds). This number is just a very raw estimation, what to expect from our future observations. This number should be taken with a caution, as the overall coverage, as well the detection efficiency for Molniya objects were both relatively low to this point.

VI. SURVEYS PERFORMED IN 2014

In 2014 we used an identical observation strategy as we used in 2013 for Molniya surveys. This time due to the technical constraints we performed during some nights scanning of two fields in parallel, instead of only one field in 2013. Until August 2014, in total, 10 nights of surveys were performed with the ESASDT telescope during which 15 fields were scanned. These fields are marked as blue rectangles in Fig. 4.

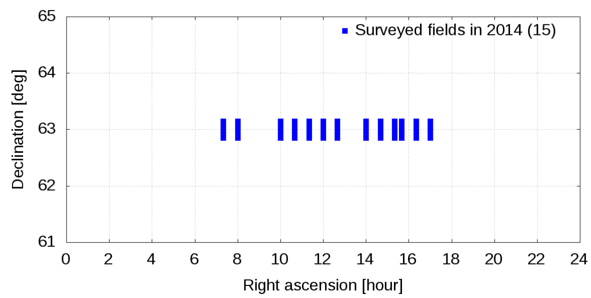

Fig. 4: Molniya fields surveyed in 2014. Plotted are geocentric right ascension and declination. The used field of view had size 0.7°x0.7° is not to scale in the plotted figure.

There were in total tracked 11 UCTs which fulfil the criteria for Molniya objects, from which we catalogued 7 UCTs. Their dynamical parameters distribution like the inclination, eccentricity, argument of perigee and RAAN are plotted in Fig. 5 and Fig. 6 together with the parameters for UCTs tracked in 2013 and for CTs objects (TLE) of October 2013.

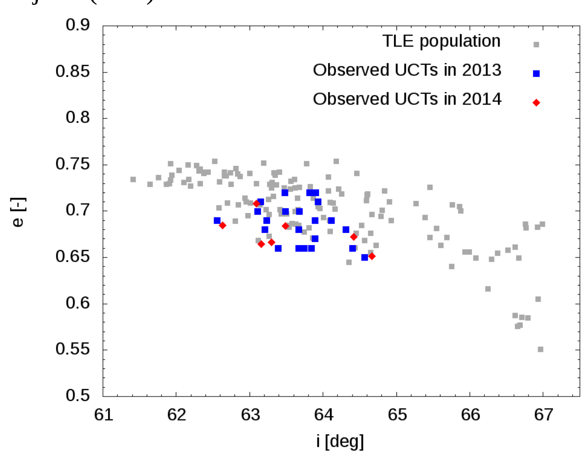

Fig. 5: A comparison of orbital elements, namely inclination versus eccentricity between the TLE population (gray squares) (to October 2013), and UCTs catalogued in 2013 (26) (blue squares) and in 2014 (7) (red diamonds).

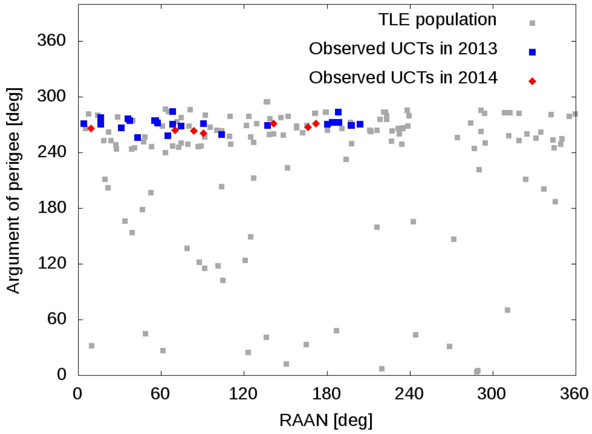

Fig. 6: A comparison of orbital elements, namely RAAN versus argument of perigee between the TLE population (gray squares) (to October 2013), and UCTs catalogued in 2013 (26) (blue squares) and in 2014 (7) (red diamonds).

Unlike the detections in 2013, from the newly discovered objects in 2014 we tracked also some very bright UCTs. There were two bright objects with 13.2 and 14.1 magnitudes, where the brightest object (13.2 mag) is tracked till present (to September 2014). It can be stated, that none of the 2014 UCTs had the A/M ratio higher than 1.0 m^2/kg, where for some of the cases only few hours were used to determine this parameter.

VII. FUTURE WORK

The main goal of the presented surveys is to scan the Molniya region to investigate the uncatalogued population, its size and distribution in this orbital regime. For that reason we will continue to scan this region to cover its major part. Planned are 10 additional nights which will take place in the fall 2014. Fields for these surveys were chosen accordingly to the regions which were already surveyed to fill the gaps. These are marked as pink rectangles in Fig. 7.

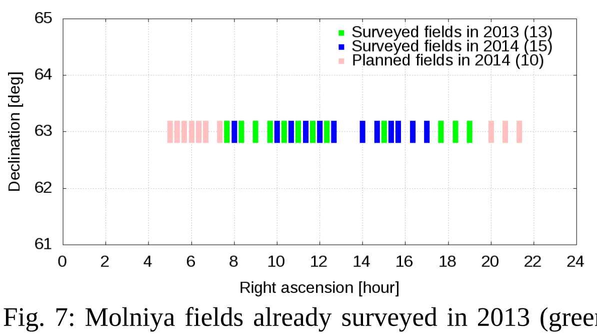

Fig. 7: Molniya fields already surveyed in 2013 (green rectangles), in 2014 (blue rectangles) and planned for 2014 (pink rectangles). Plotted are geocentric right ascension and declination. The used field of view had size 0.7°x0.7° and is not to- scale in the plotted figure.

As we showed in Fig. 1 one can assume that the orbital planes of Molniya type orbits to drift in the RAAN with a median equal to -45°/year. By applying this drift velocity to the used scanned fields one can derive the distribution of fields for one specific date, in our case 24th of May 2014. Such a distribution is plotted in Fig. 8. Due to this our effective coverage of the Molniya region is slightly larger than we originally expected (see a comparison between Fig. 7 and Fig. 8), while the already scanned orbital planes are slightly shifted. Because the geometry is changing during the time due to RAAN drift, one should be cautious not to observe the same field over and over again, i.e. to introduce selection biases, if the goal is to acquire a statistical sample for Molniya population. For that reason the drift must be taken into account during the planning of new survey fields.

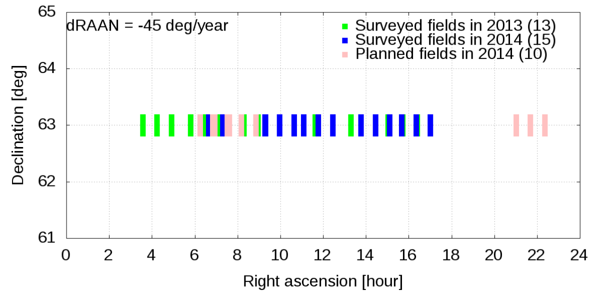

Fig. 8: Molniya fields already surveyed in 2013 (green rectangles), in 2014 (blue rectangles) and planned for 2014 (pink rectangles). Plotted are geocentric right ascension and declination assuming a drift in RAAN equal to -45°/year. The used field of view had size 0.7°x0.7° degrees and it's not in scale in the plotted figure.

Every of the scanned field represents a specific orbital plane, or a range of orbital planes defined by the inclinations and RAAN that the given field covers. After all surveys planned for this year will be scanned and processed, the obtained data for years 2013 and 2014 will be used to evaluate the overall Molniya population. We will take into account all fields coordinates, their RAAN drift during the time, the total number of objects tracked during their survey, the total time dedicated to scan the given field, and the phase angle under which the field was observed. Finally, by applying all these parameters we will evaluate each of the fields (regions) to estimate how many objects with what sort of physical and dynamical properties (brightness and its variation, A/M, orbital distribution) are placed in that region.

As already mentioned, we are also focusing on the physical characteristics of tracked objects. Interesting for us are objects brightness and its variation, area-to-mass ratios, and orbital characteristics. For that reason for every catalogued object there is the aim to keep it in the AIUB catalogue as long as possible. Hereby, also some additional follow up observations will be acquired with AIUB's optical sensors situated at Zimmerwald observatory.

VIII. CONCLUSION

We briefly presented the observation survey developed for the Molniya region with the ESA's Space Debris Telescope (ESASDT), the 1-m Zeiss telescope located at the Optical Ground Station (OGS) at the Teide Observatory at Tenerife, Spain. This was done by the Astronomical Institute University of Bern (AIUB) within an ESA project. We applied the developed observation survey during 23 nights in total, namely 13 nights in 2013 and 10 nights in 2014 with a plan to acquire at least 10 additional nights in the fall 2014. Together we discovered 41 un-correlated targets (UCTs) for which their circular orbits were determined. From these 41 UCTs we put into our internal catalogue 33 UCTs, which means their elliptical orbits were determined and they were further scheduled for follow-up observations.

There were in total 25 scanned fields defined by geocentric right ascension and declination by assuming the sensor-point distance equals 41,000 km. These fields were scanned under different conditions, depending on the technical and geometrical properties. During all nights in 2013 only one field was surveyed the whole night, while in 2014 we surveyed two fields per night in some cases, which led to less time dedicated to scan a specific field. Also, in order to avoid pointing into high dense star regions caused by the presence of the Milky Way, we sometimes had to choose the field with not optimal phase angles, which slightly compromised the survey efficiency.

The newly discovered Molniya objects showed different physical properties. Their apparent visual magnitudes varied from 13 to 19, where some objects showed very rapid brightness variations. For area-to-mass (A/M) ratios we determined different values. There was a considerable amount of objects with very low A/M ratios, less than 0.01 m^2/kg. On the other side, we also catalogued two UCTs which had A/M > 3.0 m^2/kg and which could be marked as High Area-to-Mass Ratio (HAMR) objects.

We will continue in scanning the Molniya region with the ESASDT telescope with support observations from Zimmerwald in order to improve our knowledge about this population and possibly to improve also the current models like the ESA MASTER model. After the 10 additional nights, which are planned for the fall 2014, will be acquired and processed, we will summarize all the observations from 2013 and 2014 in order to evaluate the Molniya region by assuming all relevant parameters used during the surveys.

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