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Strategy for GEO survey and results from NEEMO-T03 telescope in Romania

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As the worldwide interest in observing and cataloging artificial satellites and in mitigating space debris is rising, based on European Union Space Surveillance and Tracking (EU SST) Support Framework, a working partnership was established by the Romanian Space Agency (ROSA), between research parties at the Astronomical Institute of the Romanian Academy (AIRA) and Institute of Space Science (ISS), with the goal of surveying and tracking artificial satellites. Furthermore, since 2020, GMV Romania has been providing operational data processing services, in a fully automated manner for ROSA in the context of EU SST and is also collaborating with all the above-mentioned entities for performing specific SST-related activities as part of an RD national grant. We present the results of two years of observations using NEEMO-T03 telescope located in Romania. Our work is focused on the geosynchronous orbits, but another significant group of objects detected are located on Medium Earth or Highly Elliptical Orbits (MEO/HEO).

Astrometric measurements for the period 2020-2021 count 32 535 tracks for 1 230 unique objects, either satellites or space debris. NEEMO-T03 is able to detect GEO objects of 30 cm^2 in size. Photometry of some targets was also recorded and presented as additional science.

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1. Introduction

Currently, our society depends a lot on spatial infrastructure and data, which has led to the emergence and development of key programs in the Space Situational Awareness (SSA) domain, with emphasis on the Space Surveillance and Tracking (SST) segment, whose main purpose is to accurately monitor the artificial space objects orbiting the Earth. At European level, by adopting the Decision 541/2014 by the European Parliament, the European Consortium for Space Surveillance and Tracking was established (EU SST), where Romania is a member since 2018, together with 7 other European countries. At national level, Romanian Space Surveillance and Tracking (RO SST) partnership is in charge of developing and improving the national sensor network, of planning and coordination of these sensors for observations and processing and analyzing the astronomical data that is further used for orbit determination and refinement. For this purpose, the National Centre for Space Surveillance and Tracking (COSST) was established within ROSA in 2018.

In this paper, are presented observational results obtained in two years (2020 and 2021) of Geosynchronous Earth Objects (GEO) survey with a 0.3 m f/2.2 telescope - NEEMO-T03 [1, 2], owned by the Institute of Space Science (ISS) and operated by the Astronomical Institute of the Romanian Academy (AIRA). The telescope is located in Bucharest, Romania and it is used in the EU SST sensor network to gather precise astrometric data for geosynchronous (GEO) and Medium Earth orbit (MEO) satellites.

2. Equipment and observations strategy

Our observing station is a mobile platform [1] currently located at the Astronomical Institute of the Romanian Academy, in Bucharest-Romania (International Astronomical Union Observatory code 073). This platform consist of a container in which an alt-azimuthal direct drive L-600 Planewave mount is installed that is capable of tracking objects from LEO to HEO, using only Two-Line Elements (TLE) of satellites. Two telescopes are supported by the same mount, namely the 0.5 m f/7 Riccardi Dall-Kirkhamn (NEEMO-T05) and the 0.35 m f/2.8 Riccardi-Honders astrograph (NEEMO-T03), produced by Officina Stellare.

The NEEMO-T03 telescope is equipped with a FLI Kepler4040 sCMOS camera. The Scientific CMOS sensor has a 4096 X 4096 pixels array, 9 μm size pixels and 70% Quantum Efficiency between 450-750 nm. Together with T03 telescope parameters, the setup has field of view of 2.1°X 2.1°, with a resolution of 1.85"/px.

During several runs the asset was tested and calibrated, thus allowing to fix the margins and limits of the system in terms of exposure time, total time of observation, magnitude of target, signal-to-noise ratio, accuracy of astrometry, and the time-lag between two consecutive targets. After several months of tests the configuration of the observational strategy was defined and used as reference in a routinely way.

In our observing program, we mainly monitor the GEO objects, which are located at -6,5° of declination, within the limits of the field of view (satellites and space debris visible during the run).

The strategy consists in observations which are beginning on the Eastern horizon and the acquisition of three consecutive images on the same field using 2.5 seconds of exposure time. After the exposure, the telescope moves to the West and new set of three images are acquired. In this operating mode, we can observe the GEO satellites above the horizon in about 40 minutes (Figure 1). We perform several runs each night,

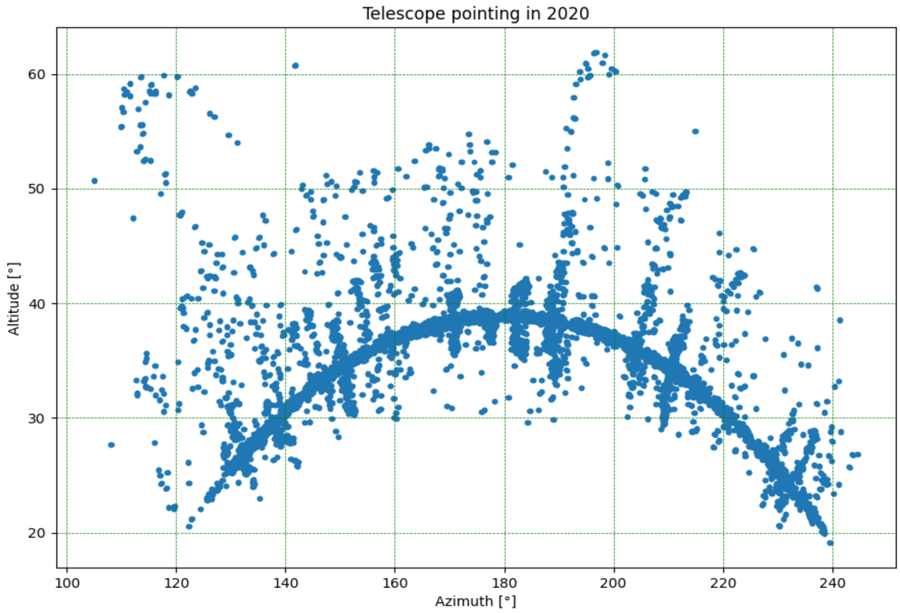

Figure 1: Telescope sky pointings in 2020.

depending on the observing conditions. On average, we acquire $\approx$ 800 images per night and the current accuracy of the astrometric reduction have a mean value of 1.9 arcsec per dataset of images. This is driven by the large field of view of the telescope, which ensures a high astrometry success rate since a sufficient amount of stars are usually captured. Overall, this accuracy (i.e. mean RMS error) is appropriate when considering the platescale of the telescope.

The strategy adopted during one night of observation is a trade-off between the number of objects observed and the number of individual images acquired. In the case of GEO, this strategy privilege the number of monitored objects rather than a large number of astrometric data for only one object.

Due to our survey strategy designed to cover the accessible GEO region at least twice every night, most tracks have three measurements. The partially overlapping survey fields and objects entering or exiting the field explains the tracks with 4,5 and 6 measurements. Tracks with more than 6 measurements are associated with NEEMO-T03 operation in tracking mode that is used for EU SST calibration purposes (Figure 2) or for additional science. Finally, during the pre-operational phase (01-03/2020), tracks with a single point were acquired for hardware testing and for the validation of our data reduction and correlation pipeline.

The astrometric reduction of each dataset is performed through sequential pipelines, such as image calibration, background removal, detection and discrimination of objects, astrometry and tracklet generation, followed by correlation, quality check and validation.

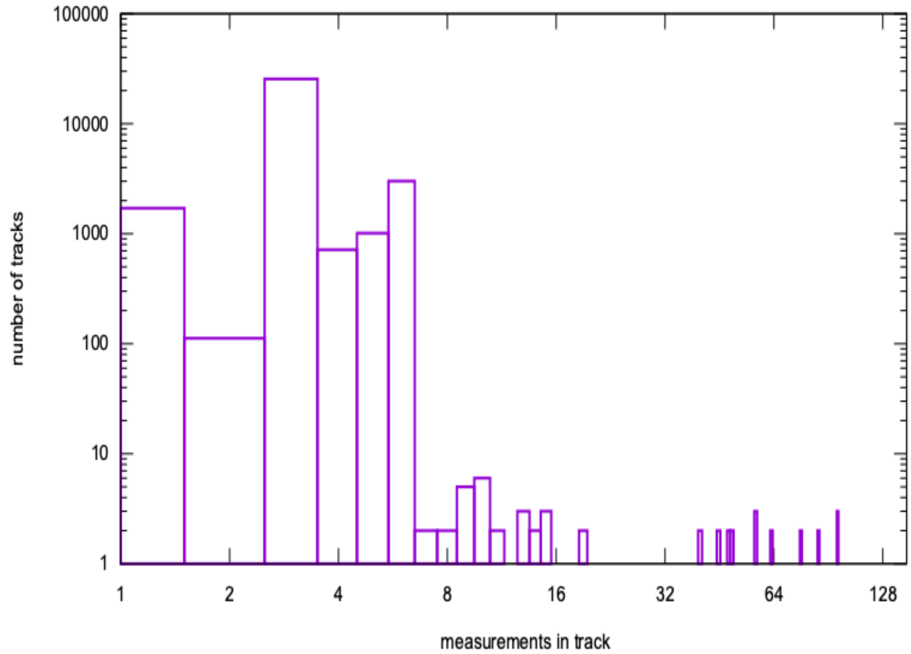

Figure 2: **Number of tracks and measurements obtained during 2020-2021.**

3. Results

During 2020-2021 we observed 1 230 unique objects, while also gathering photometric data for satellite rotations analysis. We performed a statistical analysis of our observations in terms of type of objects identified (Table 1), their orbital characteristics (Table 2), and their limit size. The smallest objects observed have a Radar Cross Section (RCS) of 30 cm^2, and the size of the orbit between 21 000 - 45 000 km.

Table 1: **Distribution of observed objects by orbital regime.**

	PAYLOAD	ROCKET BODY	DEBRIS	Total
GEO protected region	303	55	3	361
Graveyard GEO	205	42	1	248
Other (MEO, OTH)	119	402	98	619
Total	627	499	102	1 228

Table 2: **Statistics on type of objects observed and their orbital characteristics range**

	PAYLOAD	ROCKET BODY	DEBRIS
eccentricity	0 - 0.7638	0-0.8464	0-0.7248
inclination [°]	0.01-98.7	0.1-74.1	0.5-65.0
semi-major axis [km]	6 868-66 930	6 793-46 371	13 005-44 848

We have obtained in two years of operations 32 535 tracks for 1 230 unique objects. One of the objects (2018-107C) has since reentered into the atmosphere and another one has been associated with a conjunction alert and currently there is no information about it. For the remaining 1 228 unique objects, we have extracted the most recent orbital elements and have plotted their orbital distribution (Figure 3).

Our survey strategy lead to a large number of GEO satellites observations while also detecting objects on MEO, including rocket bodies and debris.

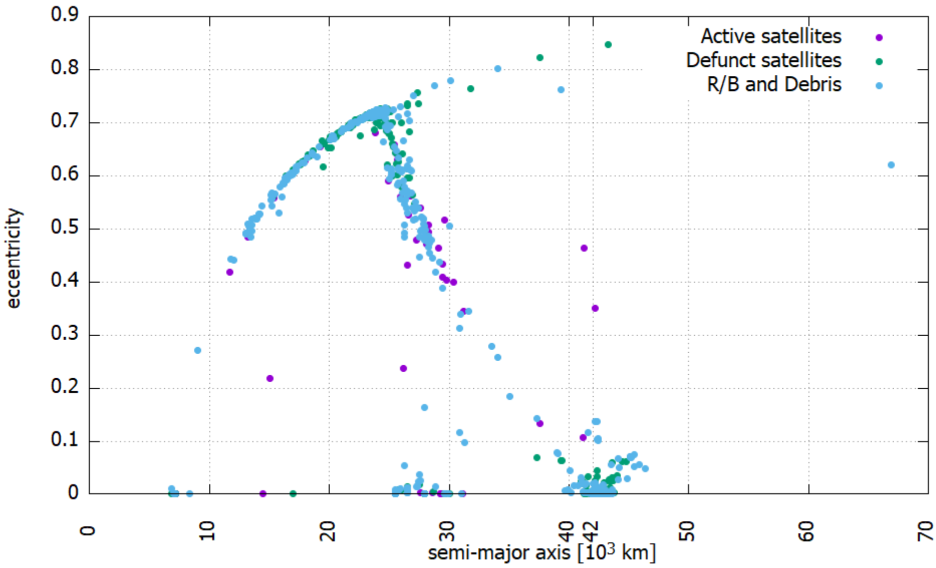

Figure 3: Semi-major axis vs eccentricity for all observed objects

From the total of 994 objects [1] that are orbiting in the GEO protected zone, situated at ±200 km with respect to true GEO height of 35 785 km and inclination within ±15° of the equator, we observed a total of 303 objects, representing roughly one third of the total population. A number of 248 satellites observed were found to be outside these limits (Figure 4), from the total population of 675.

4. Additional results

Other Romanian telescopes participating the EU SST network detected, during tracking operations, objects with a significant brightness variations. Given its fast acquisition rate, NEEMO-T03 has been tasked with tracking observations for a specific set of objects to confirm these findings.

For a few objects we analysed the brightness variations and performed relative photometry in order to find the rotational period. We used Tycho Tracker package [3], which allows to reduce and align images, to select reference stars for photometry and to measure datasets of many images. The software can also be used to search for periods in the data, using Fourier analysis.

Every satellite observed was tracked for as much as 2 hours, while the background stars changed every few minutes. We measured every series of images with common stars using UCAC 4 catalogue [4]. We used circular apertures for the satellite

[1] as of February 2022

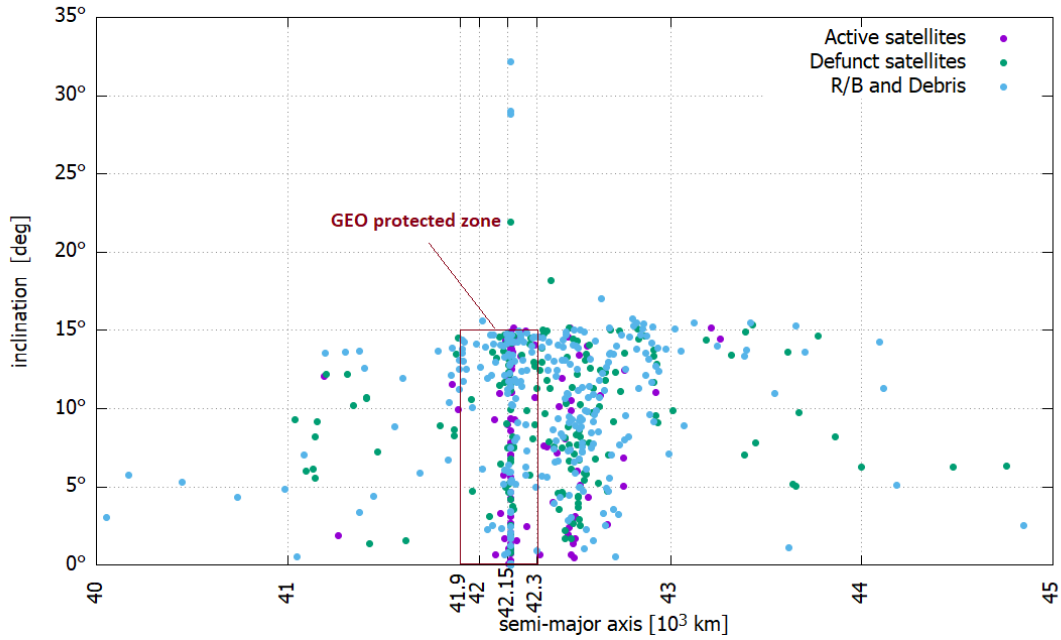

Figure 4: **Semi-major axis vs inclination for objects in GEO orbits.**

and stars, including all available reference stars for photometric analysis. For simple lightcurves, with sinusoidal shape, we used a 2nd degree Fourier fit to identify the rotational period, but in some cases we were not able to secure a period.

The satellites for which we performed photometry are on graveyard orbits and subjected to chaotic rotation (non principal axis rotation). Also, because of the complex shape of one of the satellites, the lightcurve presents more than two uneven brightness minima and maxima per cycle, and a clear rotational period could not be found. This is the case of FLTSATCOM 5 (1981-073A), a defunct satellite in circular orbit at altitude of 36 000 km. We have observed this satellite on two different nights for approximately 30 minutes each time, using the telescope in tracking mode and with exposure time of 1 sec. We searched for the satellite's rotational period, but we did not identify any significant periodic components in the time series. The phased plot, represented in Figure 5, show no clear rotational period for this satellite, a probable indication of a tumbling rotation state for this object.

Another satellite on which we performed a photometric analysis is Raduga 15 (1984-063A), a defunct satellite orbiting in the GEO protected region. Based on one hour of continuous observations obtained on 09/02/2022 we detected an important brightness variation. The phased plot, presented in Figure 5, shows a good match for the data with a 2nd order Fourier fit. The rotational period obtained is 4.303 $\pm$ 0.009 minutes.

5. Conclusions

This paper presents the current strategy used to observe artificial space objects on Geosynchronous orbits using the NEEMO-T03 telescope. The results, obtained over 2 years of continuous operations, allow us to evaluate the performance of the telescope in terms of survey completeness of objects orbiting in the GEO protected region at

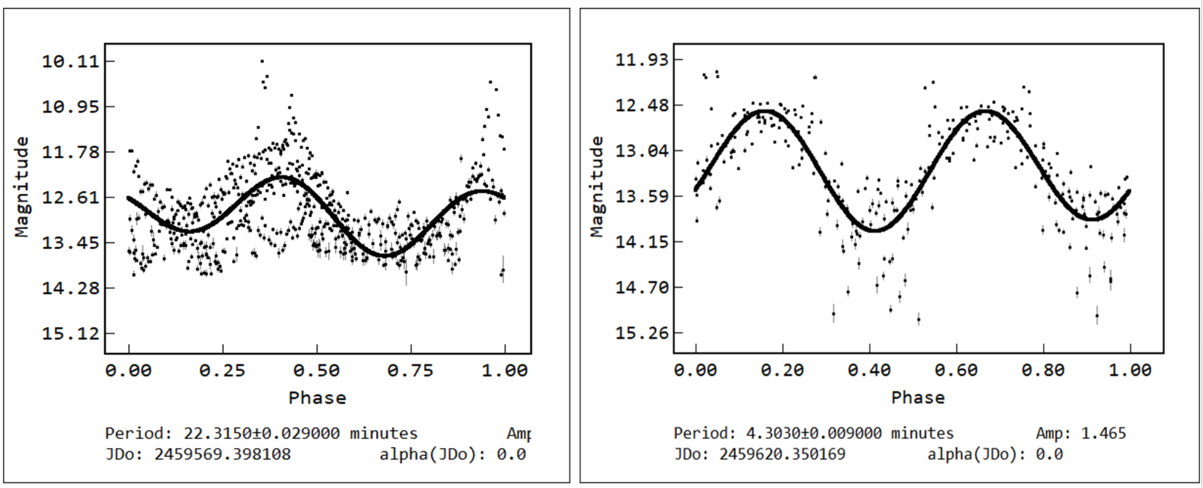

Figure 5: Phased plots for two defunct satellites, 1981-073A (left) and 1984-063A (right).

$\approx$ 1/3 of the total population. This number is explained by the visibility constraints due to the inner city location of the observatory. Even under these conditions, the telescope can detect GEO objects of 30 cm^2 in size. During our survey runs, we have also detected a significant population of objects with highly eccentric orbits at altitudes between MEO and GEO and an important number of defunct satellites in the graveyard region. A group of active MEO satellites often observed during calibration campaigns is represented by the Galileo Navigation Satellites.

We used the telescope in tracking mode to monitor two defunct satellites in order to obtain their lightcurves and to determine their rotational period. For one object, a clear brightness variations was detected and the rotational period could be extracted from the photometric analysis. For the second object however, the light curve presented several uneven maxima and minima per cycle and a rotational period could not be determined accurately, indicating that the object may be in a tumbling state.

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