THE PRELIMINARY SIMULATION RESULTS OF DETECTING SMALL OBJECTS IN LOW EARTH ORBIT (LEO) WITH AN SST RADAR SYSTEM PLACED IN POLAND

Anna Kurowska[(1,2)], Kamila Matela [(1,2)], Artur Gromek [(2)], Jacek Misiurewicz [(2)], Ioannis Nestoras [(3)], Reuben Wright [(3)], Adam Edward White [(4)]

[(1)] The Polish Armaments Group. S.A, ul. Nowy Świat 4A, 00-497 Warszawa, Poland, Email: anna.kurowska@pgzsa.pl, kamila.matela@pgzsa.pl
[(2)] Warsaw University of Technology, Nowowiejska 15/19, 00-665 Warszawa, Poland, Email: a.kurowska@elka.pw.edu.pl, k.matela@elka.pw.edu.pl, a.gromek@elka.pw.edu.pl, jmisiure@elka.pw.edu.pl
[(3)] DEIMOS Space UK Ltd., Building R103 Fermi Avenue,Harwell Oxford, OX11 0QR, UK, Email: ioannis.nestoras@deimos-space.com, reuben.wright@deimos-space.com
[(4)] Email: adamewhite1@gmail.com

ABSTRACT

In this paper, we present the preliminary ideas of SST radar sensors to be developed and deployed in Poland. They are supported by results of simulations regarding detection of small objects (around 10 cm diameter) in Low Earth Orbit (LEO) for the sensors.

We propose the configuration, radar parameters and innovative techniques which may be used for the future radar system development in Poland. In the end, the results of simulations done with the AS4 simulator using MASTER catalogue data will be included to verify the validity of the proposed solution.

Keywords: Surveillance Radar System, Tracking Radar System, Space debris, Object detection, Radar parameters, Simulations

1 INTRODUCTION

Over the last decade, we observe increased human activities in space. The number of operational satellites in orbit has risen to 1 980 in 2018; 65 countries operate these satellites and 10 nations have direct launch capability. Together with increased utilisation of outer space, the number of space debris objects also increases and the probability of a collision with an active LEO satellite grows.

Nowadays, radar systems seem to be the most effective way of observing, identifying and tracking space objects in Low Earth Orbit (LEO) below 2000 km altitude. To meet the upcoming needs of SST services: Collision Avoidance (CA), Fragmentation Analysis (FA), Re-entry analysis (RE) and Manoeuvre Analysis (MA) new types of radar systems should be developed and built (providing detection of smaller objects ~10 cm diameter, faster, less power consumption). These will help produce an effective SST system which is crucial for all LEO operators and end users.[1,2]

Europe has few radars to observe and track space objects (six surveillance radars: GRAVES, BIRALES, S3TSR, MSSR, ABISS and GESTRA and four tracking radars: BIRALET, CASTR, MFDRR and TIRA). All are located in West Europe.

To help achieve European needs for SST data in LEO two gaps should be filled:

- Develop and build a civil European surveillance radar, which will have a high enough detection capability, accuracy and performance to catalogue consistently and accurately objects capable of causing catastrophic collisions in LEO.
- Develop and build European high-performance tracking radars with sufficient revisit time or detection rates to be capable of enhancing the Orbit Determination (OD) process of known small space objects and to manage re-entry campaigns.

Poland, located in the centre of Europe, has an excellent location (reasonable latitude to observe most LEO objects with good LEO object revisit times) for either a surveillance or a tracking radar.

In this paper, we present the first idea of the radar sensors, describing the innovative ideas proposed to employ in these radars. We propose the configuration and radar parameters which may be used for the future radar system development in Poland. In the end, preliminary results of simulations regarding detection of small objects (around 10 cm diameter) in Low Earth Orbit (LEO) for SST radar system development in Poland, done with the AS4 simulator using MASTER catalogue data are included to verify the validity of the proposed solution.

2 GENERAL CONCEPT OF SENSORS

Proc. 1st NEO and Debris Detection Conference, Darmstadt, Germany, 22-24 January 2019, published by the ESA Space Safety Programme Office Ed. T. Flohrer, R. Jehn, F. Schmitz (http://neo-sst-conference.sdo.esoc.esa.int, January 2019)

Following the need to fill gaps presented in the introduction, as well as considering the economical constraints, a concept of upgradeable sensors has been presented. In the run of the STRADA project an architectural design of a tracking radar as well as a surveillance radar has been developed.

The radar physical principles analysis indicates clearly that a tracking radar benefits from shortening the wavelength. With constant other parameters (mean power, antenna size, measurement time), shorter wavelength results in higher accuracy of velocity and angle measurement. The limiting factor for the frequency increase is the propagation loss in the atmosphere as well as the cost and complexity of the RF electronics. Thus for the tracking radar X-band was chosen. Then, a natural choice for achieving good angular accuracy is a dish-type antenna. Choosing a pulsed waveform enables a simple monostatic design.

For a surveillance radar with a fixed search volume, the wavelength choice does not influence the detection performance, except for the reflection properties related to wavelength/object size ratio. Thus L-band was chosen to be used in surveillance radar design as the compromise between the cost (lower for longer waves) and reflection properties of small targets (poor for longer waves). The need for scanning a large extent of sky makes AESA-type antenna the first choice. In the consequence, a solid-state transmitter design was chosen, favouring a bistatic, continuous-wave configuration.

3 INNOVATIVE TECHNIQUES FOR POLISH SST RADAR

A number of innovative techniques were proposed in order to design a state-of-the-art radar in both the tracking and surveillance case.

3.1 Multi-dish array

A multi-dish array was proposed as an upgrade path for the tracking radar.

The concept of radioastronomical arrays (VLBI – Very long baseline interferometry) is already widely used, where a virtual antenna is synthesized by digital processing of signals from multiple receive antennas, located close to each other (e.g. VLA at NRAO) or with a very large distance (e.g. LOFAR in Europe). A similar concept is proposed for the Polish radar, with a significant difference of using the array both on receive and on transmit.

With a multi-radar system, which is composed of a number of elementary radars, three factors contribute to the improvement of radar detection potential:

- more power received because of bigger total area of Rx antenna (equivalent to higher Rx antenna gain)
- more power transmitted
- better concentration of illumination energy on target due to larger total Tx antenna (this is equivalent to higher Tx antenna gain and is achieved if the transmit signals can be made coherent).

This was experimentally confirmed in the BMD Radar experiment [3] with an X-band radar, which is much more difficult than in the L-band. The experiment verified that with N elementary radars:

- in cohere-on-receive mode, when orthogonal waveforms are combined, an N^2 signal-to-noise ratio (SNR) gain is achieved (for a tracking radar upgraded to four dishes, i.e. with N=4, it is 12 dB);
- in cohere-on-transmit mode, where full coherence is used on both transmit and receive, an N^3 SNR gain is achieved (with N=4, it is 18 dB).

3.2 Noise-like waveform

Modern transmitter design allows employment of almost arbitrary modulation of the waveform with the use of fast ADC or DDS (direct digital synthesis) block. This will be used for the waveform management with pseudorandom modulation.

The pseudorandom modulation allows to achieve thumbtack-like cross-ambiguity function (CAF). This translates into good and unambiguous detection in the range and Doppler dimension [4]. Moreover, the range and Doppler measurements are not coupled (as it happens for the traditional LFM modulation).

Pseudorandom (pseudonoise, noise-like) modulation has not been widely adopted in traditional radar designs because of the computational complexity of the receive signal processing; nowadays the computational power needed is readily available and all the benefits of this waveform are exploited in modern radars.

3.3 MIMO illumination

In a bistatic system, as proposed for the surveillance radar, the Tx and Rx antennas are separate. Thus the illumination beam may be shaped differently than receive beam. In the extreme case a transmit beam may cover the whole area of interest (FOR) at once, and multiple narrow receive beams may be synthesized to cover the instantaneously illuminated area. The illumination beam with classical beamforming does not cover whole FOR at once, however it is possible with use of MIMO technique.

MIMO technique [5] is based on transmitting different orthogonal signals from different antenna elements or subapertures. Then the signals can be separated on receive with matched filters and processed independently.

With MIMO technique the needed number of virtual transmit beams are synthesized on receive and the integration time can be chosen arbitrarily – for example equal to the time when a given target is visible in the illuminated area. This time can be range-dependent (longer for farther targets), which makes the power budget for far targets slightly easier than it is with fixed integration time.

To summarize, benefits of using MIMO transmit technique in a surveillance radar are the result of continuous illumination of the whole area - so the FOV and FOR is the same.

- Use of all time when target is in the fence area for the Doppler measurement allows more precise velocity estimation.
- The integration time is determined on the receive side, so it may be freely adapted to each target properties: range, time spent in the FOV etc.;
    - some targets (with high SNR and long time in FOV) will yield more than one measurement, enabling precise orbit determination.
    - longer range (or smaller detectable RCS) will be achieved than with fixed integration time.

4 RADAR PARAMETERS

For this paper we present two sets of the radar parameters which may be used for the future radar system development in Poland.

4.1 The tracking radar

The tracking radar is the radar which detects one target at the time, determines its location and predict its trajectory path. It measures the target's relative position in range, azimuth angle, elevation angle, and velocity.

In the Tab. 1 and Tab. 2 we present the design goals and radar parameters which are used for the simulations study.

Table 1 Design goals for the tracking radar

Reference diameter d_{ref}	7 cm
Reference height h_{ref}	800 km
Range accuracy σ_R	5 m
Doppler velocity accuracy σ_v	0.1 m/s
Angle accuracy	0.05°

Table 2 Radar system parameters

System geometry	monostatic
Operating band	X (~9.4 GHz)
Antenna size and type	5.4 m diameter parabolic dish
Transmit power (average)	300 W
Integration time	15 s

Figure 1 shows the detection performance calculated analytically for the assumed parameters.

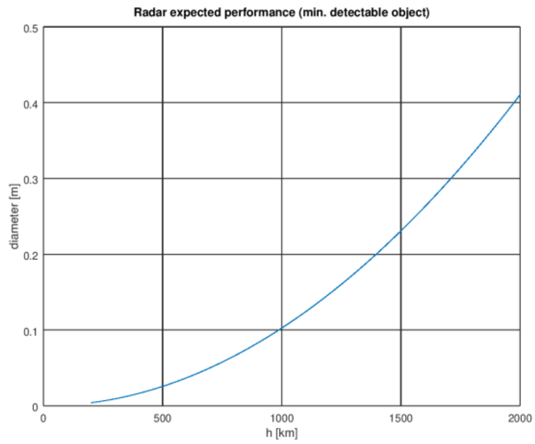

Figure 1 Expected minimum detectable object in tracking radar

4.1.1 Radar upgradeability

For the upgrade path of this radar, it is proposed to use an array of dishes of the same size and design as in the base system – this brings the multiplication of the antenna area and transmit power, as well as increase of the angle measurement baseline. The inevitable cost lies in the synchronization of the subsystems for coherent work and calibration of phase relations between dishes. Some additional benefits are also worth considering.

- The four-dish system is a straightforward upgrade of a one-dish system – except the synchronization/calibration and signal fusion, the whole design of tracking system can be reused.
- The dishes can work in different modes – depending on current mission they may be, for example:

- ○ synchronized for tracking a weak target
  - ○ separated to track four different strong targets
  - ○ combined in pairs.
- The maintenance work on one dish does not require switching the whole system off.
- The upgrade path is flexible – any number of dishes can be added in sequential steps; each upgrade step requires only minor modification of the signal processing software.

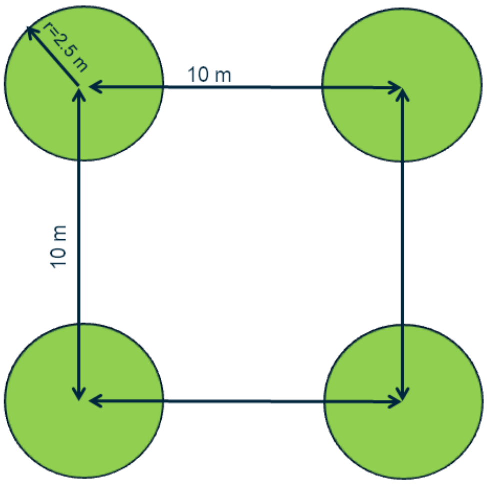

Figure 2. A concept of tracking radar upgrade

4.2 The surveillance radar

The surveillance radar is a radar to search for known and unknown object entering the sky above the radar. The search is performed in a "fence" area, where:

ϕ - the fence length; α - the fence width., ω- angular velocity, T_{fs} - revisit time.

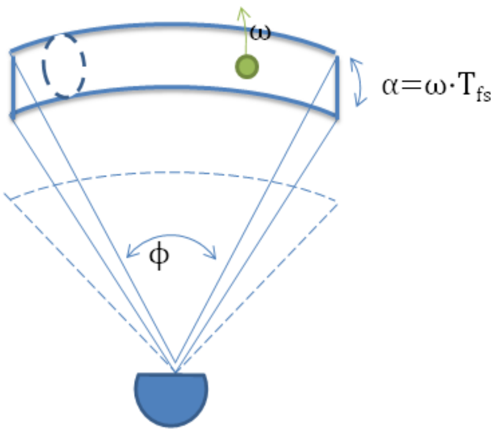

Figure 3 Definition of fence parameters

In the Tab. 3 and Tab. 4 we present the design goals and radar parameters which are used for the simulations study.

Table 3 Design goals for the surveillance radar

Reference diameter d_{ref}	10 cm
Reference height h_{ref}	400 km
Range accuracy σ_R	20 m
Doppler velocity accuracy σ_v	0.5 m/s
Angle accuracy	1°
left-right fence length	+/- 40°
Fence tilt angle from zenith	30°
surveillance revisit time (full-fence scan time)	10 s max

Table 4 Radar system parameters

System geometry	bistatic
Operating band	L
Antenna size and type	5.5 m diameter circular Rx antenna with 1780 modules 5.5x0.8 m elliptical Tx antenna with 260 modules of 100 W each

With a special, elliptical design of the Tx antenna and a MIMO waveform transmitted, the Tx antenna illuminates the whole fence area at once. The detection of targets is performed with a number of synthesised Rx beams. Then the direction (angle) estimation is then done with use of all the Rx elementary signals – this allows to mitigate the grating lobes ambiguity problem.

Figure 4 shows the detection performance calculated analytically for the assumed parameters.

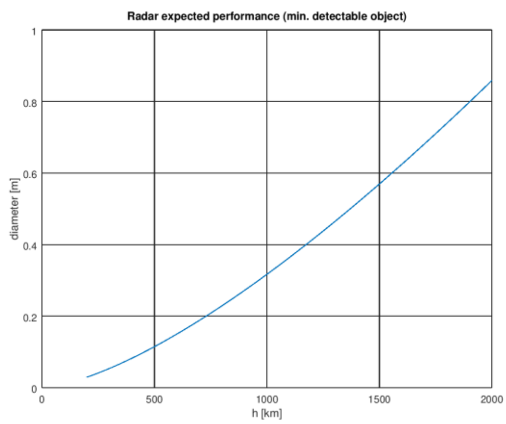

Figure 4 Expected minimum detectable object in surveillance radar

4.2.1 Radar upgradeability

For the upgrade path of this radar, it is proposed to:

- add more modules in transmitting and receiving antennas to increase transmitting power/ receiving aperture,
- use AESA beam management with MIMO technology,
- increase the fence length from +/-40° to +/-60°, using a transmit antenna with three sections illuminating three angular sectors with less deflection losses.
- proper chose bistatic radar sites location.

5 SIMULATION RESULTS

5.1 Simulation tool description

The simulations for verifying the performance of proposed radars were performed with use of the DEIMOS Advanced Space Surveillance System Simulator (AS4). It is an end-to-end simulator for space surveillance, consisting of: population environment, measurements generation, initial and routine orbit determination tasks, correlation and cataloguing activities (for radar and optical measurements, both tracking or surveillance, accounting also for space-based sensors) and delivery of products (collision risk computation, re-entry events reporting, fragmentation analysis, and launch detection and ephemerides generation). The AS4 architecture is presented in Fig.5.

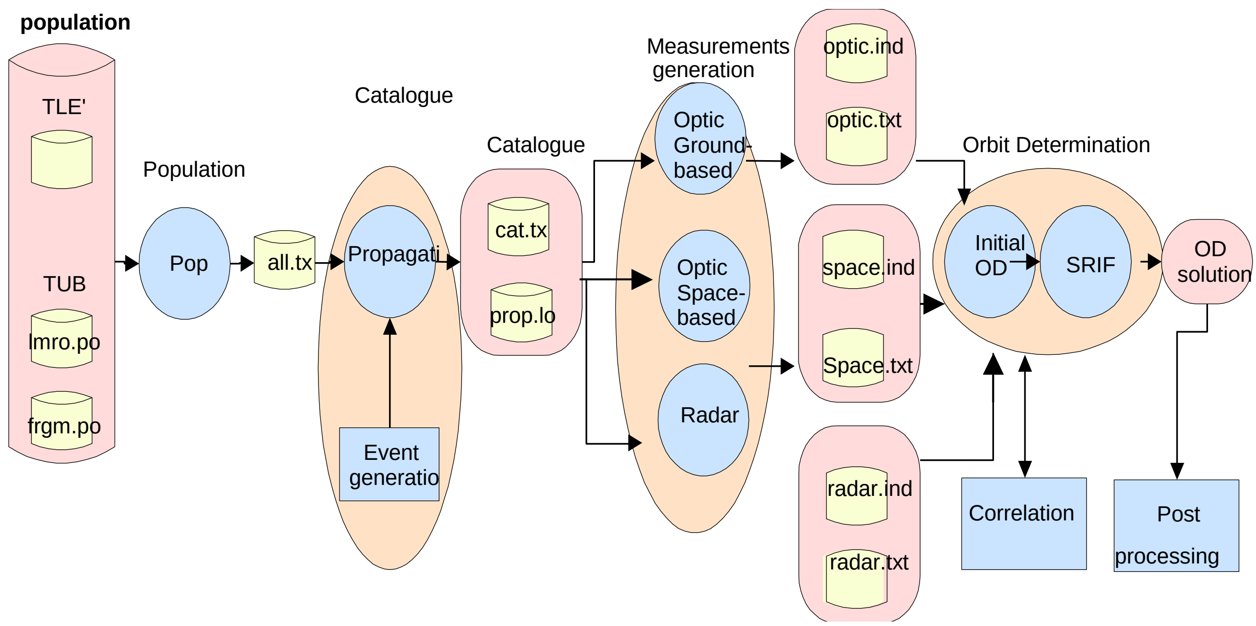

Figure 5 AS4 Architecture

It can be used in Windows and Linux environment. It is a DEIMOS IPR tool, developed since 2004 for preliminary evaluation of the future ESA SSA systems.
In this project, there were upgrades to model these particular radar configurations and simulations were then made using the population environment, measurement generation and statistical post-processing modules.
The MASTER-2009 population for the epoch May 1st 2009 were used as a baseline population. We have filtered this population to take a number of objects that is smaller and thus manageable to perform a simulation in a reasonable time. The filters that applied sequentially are:

- Objects with size larger than 5cm
- Selecting randomly the 10% of the remaining objects after the application of the previous filter.

Regarding the radar simulations, different field of regards configurations were considered, and tracking and surveillance analysis was executed, accounting for the observational constraints of these sensors. The probability of detection was based on a so-called radar curve.

5.2 Simulation results for the tracking radar

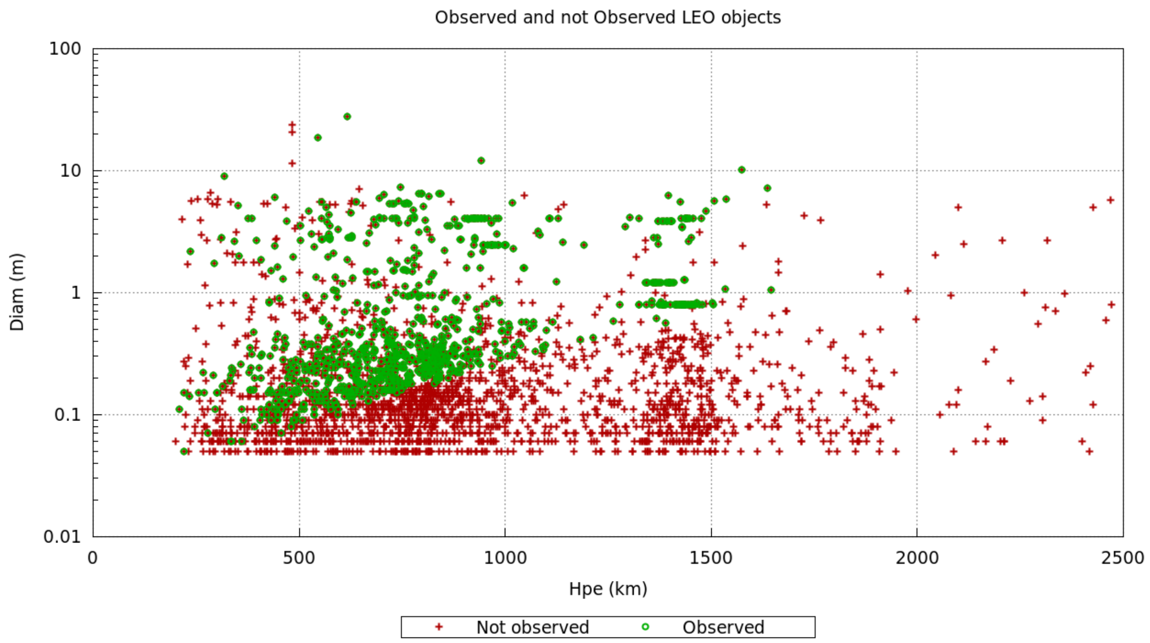

Figure 6 Observed and not observed LEO objects for tracking radar

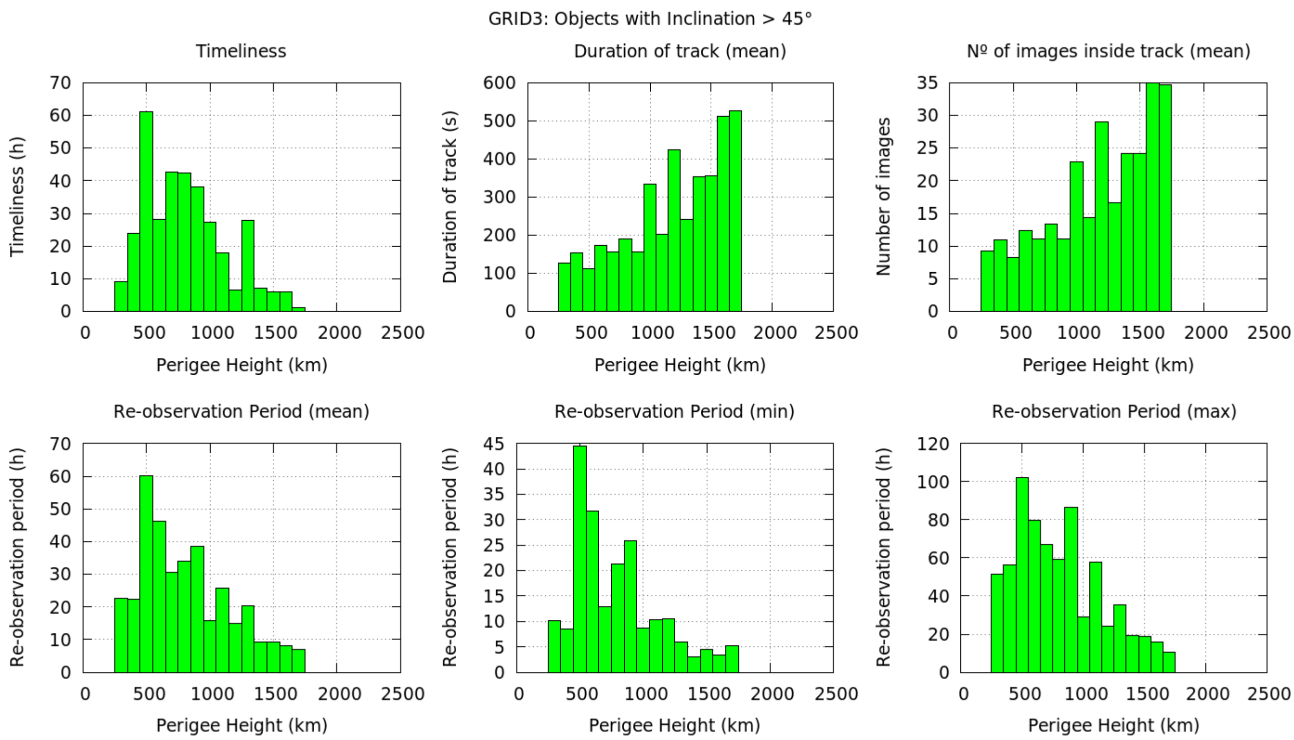

Figure 7. Performance indicators for the tracking radar

From the simulations (Fig. 6) we've seen that the proposed tracking radar is able to track 7 cm objects up to 800 km orbit and proportionally bigger objects on higher orbits. In Fig. 7 presented are performance indicators of the simulated tracking radar, calculated for the objects with orbit inclination greater than 45 deg. Orbits with inclinations lower than 45 deg are seldom visible from the considered geographical location.

.

5.3 Simulation results for the surveillance radar

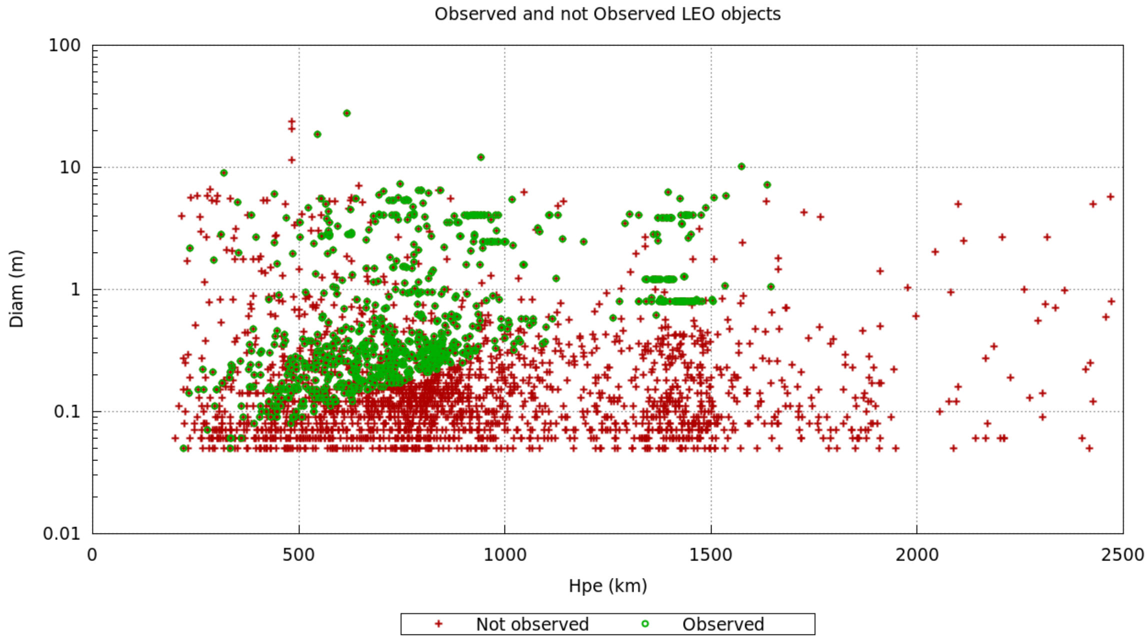

Figure 8 Observed and not observed LEO objects for surveillance radar

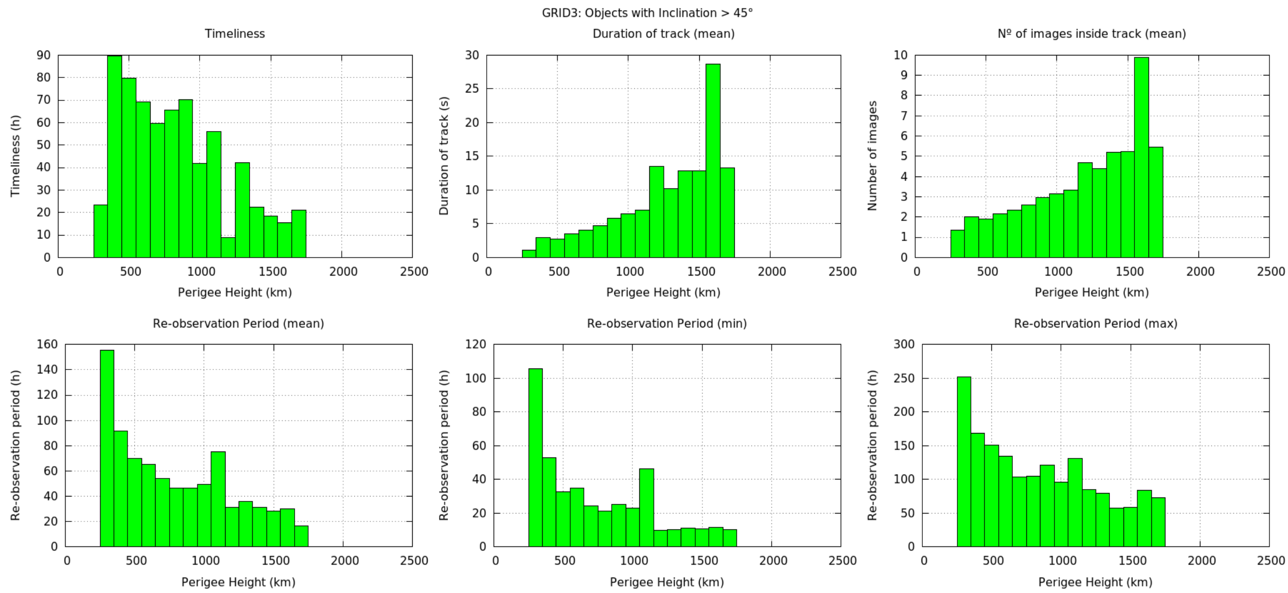

Figure 9 Performance indicators for the surveillance radar

From the simulations (Fig. 8) we've seen the proposed surveillance system is able to survey the 400-1000 km orbits, detecting 10 cm objects at 400 km and 40 cm objects at 1000 km within an azimuthal sector of +/-40 degrees. In Fig. 9 presented are performance indicators of the simulated surveillance radar. It was also calculated for the objects with orbit inclination greater than 45 deg. The plots shown in Fig 8 are very similar to ones from Fig 6 - this is the result of similar setting of reference object parameters in design goals for both radars.

6 CONCLUSIONS

In this paper, we proposed the configuration and radar parameters which may be used for the future radar system development in Poland. Using MASTER catalogue data we confirmed, that these radars may detect the small objects (around 10 cm diameter) in Low Earth Orbit (LEO) for SST radar system.

The paper shows that building surveillance or tracking radar in Poland would provide key data inputs to a European SST system. Taking into account the expected costs of components and simulation results, the tracking radar, especially with the possibility of successive upgrades, seems to be the most practical first step to fill in the missing capabilities, and a surveillance radar will be worth adding as a future step towards building full European capability for acquiring SST data in LEO.

ACKNOWLEDGMENTS

This project has received funding from the European Space Agency under the project titled "SSA P3-SST-VI-Surveillance Radar System Phase 1", acronym STRADA.

REFERENCES

1. PB-SSA, Programme Proposal, Period 3 (2017-2020) pp 26-28

2. Steps Towards a European SST System for Objects Beyond LEO Altitudes – Romanian Insights, Octavian Cristea, Vlad Turcu, Mircea Cernat https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/Forms/All%20MPs.aspx?RootFolder=%2Fpublications%2FSTO%20Meeting%20Proceedings%2FSTO-MP-SCI-283

3. S. Coutts, K. Cuomo, J. McHarg, F. Robey and D. Weikle, "Distributed Coherent Aperture Measurements for Next Generation BMD Radar," Fourth IEEE Workshop on Sensor Array and Multichannel Processing, 2006., Waltham, MA, 2006, pp. 390-393

4. K. Kulpa, "Signal Processing in Noise Waveform Radar," Dedham: Artech House, 2013

5. A. Hassanien and S. A. Vorobyov, "Phased-MIMO Radar: A Tradeoff Between Phased-Array and MIMO Radars," in IEEE Transactions on Signal Processing, vol. 58, no. 6, pp. 3137-3151, June 2010