Improving MASTER model quality through strategic sensor campaign design

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ABSTRACT

ESA's MASTER Model is essential for assessing the space debris environment and predicting long-term cumulative collision risks. To enhance its accuracy, designing sensor campaigns that provide optimal validation data is crucial.

Radar systems like TIRA and EISCAT, and optical telescopes such as the ESA-SDT, are pivotal in capturing high-quality data. These systems are calibrated to measure parameters like range, Doppler inclination, radar cross-section, visual magnitudes, and detection rates across various altitudes and diameters. By ensuring that these parameters are accurately measured, the data collected will be more reliable and useful for validating the MASTER model. On top of this, comprehensive validation requires diverse observation scenarios, including varying observation times, angles, and conditions to capture a wide range of data points. For instance, observations should be conducted on a regular basis to capture the dynamic nature of the space debris environment.

This paper will give an overview of the ongoing effort on preparing sensor campaigns with respect to the MASTER model validation and how different observation strategies are affecting the MASTER model accuracy.

1 INTRODUCTION

ESA's MASTER model provides the space community with a validated model of the space debris environment and allows for spatial density evolutions as well as flux- and collision probability estimates for medium- and long-term missions [1]. Hence, it has become one of the cornerstones for showing mission compliance w.r.t to ESA's Space Debris Mitigation Requirements which was introduced in November 2023. Therein, several requirements contain thresholds on cumulative collision probabilities against the 1cm-sized object of the space debris environment which makes it necessary to obtain flux estimates for each mission which is subject to these requirements. Because of this, the reliability of the MASTER model in the 1cm regime is crucial. An ongoing ambitious effort of ESA is to routinely validate the MASTER model and provide an updated population in an annual release cycle, starting from 2025. To achieve this, not only does the data processing needs to support this, but there needs to be observation data available to validate the population [2].

With the introduction of the PULSE framework, the data processing to create a validated MASTER population has been greatly optimised, leveraging on a high amount of multithreading, automation and traceability. It is essential to incorporate all validation data into the framework that performs the calibration. For the last 25 years, several sensors have performed observation campaigns that greatly support the MASTER model validation. For the Low-Earth-Orbit (LEO) regime, the Tracking And Imaging Radar (TIRA) and the European Incoherent Scattering (EISACT) radar provide valuable measurement data on the centimetre population in LEO. ESA's Space Debris Telescope (SDT) performs routine GEO observations throughout the year [1].

The planning of these campaigns is performed in agreement between the sensor operator and ESA. Therein, the observation strategy can vary greatly, dependent on the underlying sensor.

2 KEY PERFORMANCE INDICATORS

When planning dedicated space debris observation campaigns, there are multiple features that are of interest. In general, there three main indicators that are of interest in order to maximise the usability of data obtained from observations:

1. Confirming population in valuable orbital regimes
2. Maximise number of detections
3. Observing coverage gaps

This list is not exhaustive and is tailored to specific needs when it comes to the calibration of the MASTER model. The space debris environment is a dynamic ecosystem and with the increasing launch trend for constellation objects, it is essential to capture the change in the orbital environment, regardless of the regime. However there is an intrinsic priority list when it comes to capturing the aforementioned dynamics.

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

The environment is changing most rapidly in LEO, where increasing traffic into highly valuable orbital regions underscores the necessity of continuous monitoring. With the solar activity being the main driver of a dynamic re-entry behaviour of small objects, especially debris and small satellites, this region has to be observed on a regular basis to allow for an accurate model calibration that accounts for all objects that pose a threat to other operational satellites. In other words, there is one Key Performance Indicator (KPI) that captures the *confirmation of populations in valuable orbital regimes*. Especially with regard to the SDM requirements, the MASTER model population baseline has to reliably assess flux estimates. This is only feasible when validation data on these critical orbital regimes are available and the consequences of breakups, in terms of modelling, are understood. Valuable orbit regimes are Sun-Synchronous orbits, or other orbits at around 800 – 900 km.

Another KPI is to maximise the number of detections for a sensor in order to provide statistically relevant information. Observing most valuable orbital regions not necessarily yield most detections, because there might be regimes that accumulated more objects, e.g. due to recent fragmentations. Also orbits at constellation altitudes are of interest in order to assess the flux and hence, statistical collision probability for constellation objects.

The third KPI is a more scientific scenario where observation coverage gaps are identified with the goal of accepting a lower number of detections but exploring orbital regions where the MASTER model extrapolates otherwise. One particular example are low inclination bands in LEO, e.g. below 40°. In GEO, high inclination bands of greater than 30° can be of interest to observe potential High-Area-to-Mass-Ratio (HAMR) objects.

Usually, the campaigns are designed with one of those scenarios in mind. In particular, due to budget constraints and availability of sensors, the first choice is often to go for *Confirming population in valuable orbital regimes*. In the past, this also covered orbital regimes that yield most of detections.

3 SENSOR-SPECIFIC PARAMETERS

Every sensor has its own performance characteristics that describe, how it can detect space debris. During the MASTER model validation, the Program for Radar and Optical Observation Forecasting (PROOF) tool is used to assess the crossing- and detection-rates of a specified sensor for a given observation strategy [PROOF]. This is performed by virtually observing a MASTER population and generating detection features based on a specified campaign plan. In order to obtain detection rates, the performance of the sensor has to be known in order to setup PROOF to mimic the sensor. If the sensor performance characteristics are not (fully) known, it is still possible to obtain object crossings, because they only depend on the sensor observation geometry, i.e. observation Epoch, Line-of-Sight (LOS) and Field-of-View (FoV). Then, the expected detections are a subset of these crossings which at least allow to maximise the probability of having the most of detections.

Independent of the availability of the sensor performance characteristics are limitations in the LOS. There are multiple considerations such as a minimum local elevation because of atmospheric refraction or ground clutter. This is especially important, if low inclination bands are targeted for observation. A sensor at a high geographical latitude is not able to observe objects on low inclination orbits. Furthermore, geographical surroundings of the sensor may affect usable LOS, e.g. if certain buildings or terrain block the LOS.

But even if the performance of sensor is well known and the local surroundings allow for an optimal LOS, the ability to obtain accurate measurements which are usable for the MASTER validation might label a sensor as not suitable. Whereas the number of detections is one of the major spectra to calibrate the MASTER model against, so is the ability to assess the object size and orbital parameters. If a sensor is not capable to obtaining Radar-Cross-Sections for the detected objects, it is less suitable for validation than a system that has this capability. When assessing the orbit inclination of a detected objects, usually the range-rate (Doppler) is used to estimate the orbit inclination with the assumption of a circular orbit (cf. Section 4). However, this requires the sensor to have the local azimuth of the LOS at 90° or 270°, i.e. pointing East or West. When the LOS is deviating from this reference directions, the orbit inclination estimated degrade.

Regardless of the preferred sensor configuration, a greater availability of the sensor combined with an increased number of detections is an equally suitable sensor for the validation of the MASTER model. Since MASTER is a statistical model, a higher number of detections enables calibration based on a more representative dataset. Additionally, detecting more individual objects improves population coverage, thereby enhancing validation accuracy. While inclination cannot be assessed with reasonable accuracy, validation based on the altitude spectrum alone offers valuable insight into the total number of fragments from specific events occurring at distinct altitudes.

Hence, combining data from different sensors to obtain a bigger picture of the space debris environment is essential.

4 STRATEGIC SENSOR CAMPAIGN DESIGN

When designing a sensor campaign that shall be used to obtain suitable validation data for the MASTER model, all of the aforementioned considerations have to be considered. First, according to section 2, the observation scenario has to be clarified. When doing annual Beam Park Experiments (BPE) in LEO, the primary goal is to validate the full LEO population. Considering section 3, the sensor has to be capable of performing the campaign and obtain the desired measurements. Different LOS configurations yield different observation characteristics and hence, different detection performance. The evaluation of Number Of Assessed Detections (NOAD) for a specific sensor is captured in so called “LOS Assessment Maps”. An illustrative example is given for a campaign planning for the EISCAT UHF in Tromsø (cf. Figure 1) which is described in the following.

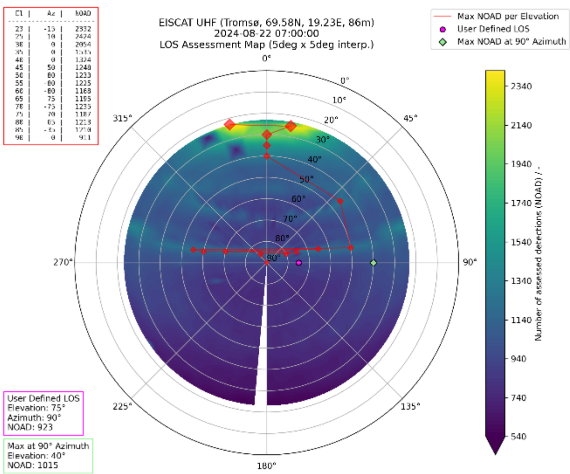

Figure 1. LOS Assessment Map showing Number of Assessed Detections (example for EISAT UHF in Tromsø).

A BPE can have an arbitrary LOS, however, to make best possible assessments about the orbit inclination, the LOS needs to point East or West (cf. Figure 2).

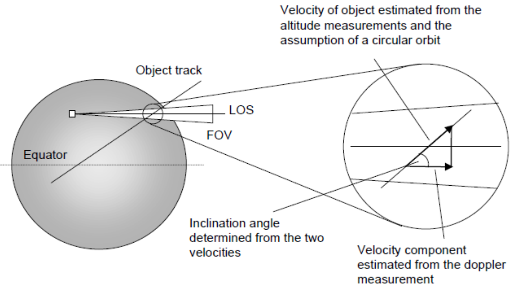

Figure 2. Assessment of Doppler Inclination [3]

With the geometric assumption of circular orbits (which most of the orbits exhibit), the orbit inclination can be derived based on the range-rate alone. If the azimuth is kept at 90°, the elevation of the LOS then only affects the observable inclination band. This technique still comes with a drawback of less overall detections. The dependency of LOS angles and expected detection rate is shown in LOS Assessment Maps as shown in Figure 1. In order to create these maps, the (dynamic) geometric conditions, as well as the performance characteristics of the sensor have to be known. This includes ground location, observation epoch and FoV dimensions as well as radar parameters such as the beam pattern, power and detection thresholds. PROOF is then configured to mimic the sensor setup, and multiple simulations are performed to observe every azimuth/elevation combination which is feasible for the sensor. In the EISCAT example, the minimum elevation is set to approx. 23°, because the UHF radar is surrounded by a valley which blocks lower elevation angles to observe space debris (cf. Figure 3).

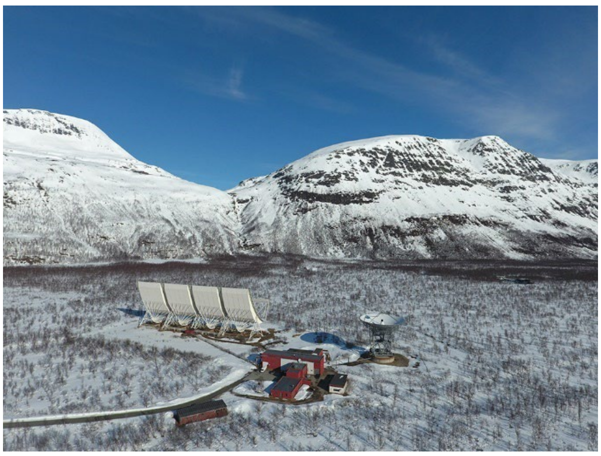

Figure 3. EISCAT Tromsø site (www.eiscat.se)

A BPE is usually conducted for 24h to rotate the antenna beam once through the full right ascension spectrum. Repeating another 24h cycle with the same configuration does not bring significantly more detailed information, because all crossing objects have been subject to the radar beam already. The simulation uses a 5° step size in both elevation and azimuth. Elevation ranges from 23° (20° adjusted for lower elevation limit) to 90°, and azimuth spans 0° to 360°, resulting in 1,080 PROOF simulations. Dependent on the LOS, the number of crossing objects can change significantly. This is not only due to different orbits passing through the FoV, but also because every radar has a maximum range. At 90° elevation, the covered orbit altitude spectrum is maximized. Lowering the elevation reduces the maximum detectable orbit altitude. The number of detections which is a subset of the crossings also is different dependent on the LOS. The main goal of the LOS Assessment Map (cf. Figure 1) is showing an estimate on the expected number of detections dependent on the LOS angles. When performing an East-starring campaign, the elevation can be selected to maximise the NOAD to 1,015 which gives the best estimate on orbit inclination. A typical BPE at this ground location configuration is having the LOS at 90° azimuth and 75° elevation in order to observe the SSO. An estimation of crossing and detected object orbits are exemplarity shown in Figure 4.

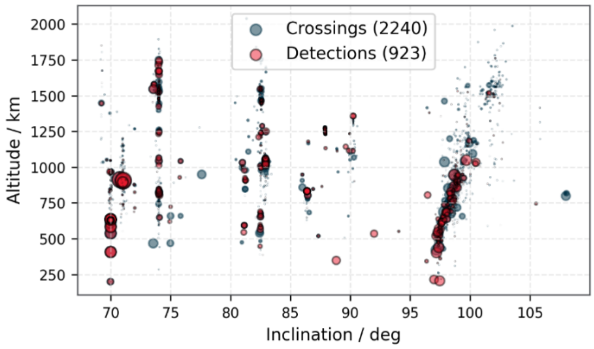

Figure 4. Example analysis on crossing and detectable objects for an East-starring BPE with an elevation of 75° conducted in Tromsø

In Figure 1, there is also a path highlighted in red which shows the azimuth-path for maximum NOAD as a function of elevation. Regarding this example, the maximum NOAD inside the allowed azimuth-elevation spectrum is not in vicinity of the 90° azimuth regime, where the orbit inclination has its best estimate. Instead, it is oscillating around 0° azimuth. Table 1 shows the maximum NOAD along the red path.

Table 1.Azimuth as a function of Elevation and maximum NOAD (sorted by elevation)

Elevation / °	Azimuth / °	NOAD
23	-15	2332
25	10	2424
30	0	2054
35	0	1535
40	0	1324
45	50	1248
50	80	1233
55	-80	1225
60	-80	1168
65	75	1195
70	-75	1235
75	70	1187
80	65	1213
85	-35	1210
90	0	911

Consequently, the NOAD can be increased by more than 100% using the same sensor performance but deviating from the 90° azimuth which negates a suitable assessment of orbit inclination. With these two goals in mind

1. Maximising NOAD
2. Obtaining orbit inclination

A standard 24h BPE design becomes an optimisation problem whereas the conditions to fulfil goal 1 contradicts goal 2. Hence, a combination of sensor campaigns can be performed. Choosing the follow-up campaign to change the LOS while keeping the rest of the radar parameters unchanged, the NOAD can be maximised and hence, allow for a statistically more relevant MASTER model calibration. Table 1 shows that LOS for maximum NOAD has to be defined by an elevation of 25° and an azimuth of 10°. Figure 5 shows the expected altitude-inclination spectrum detection spectrum.

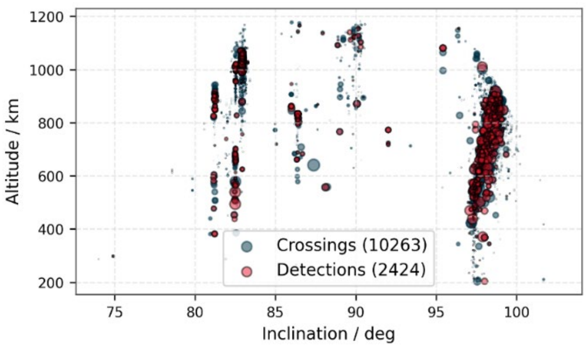

Figure 5. Example analysis on crossing and detectable objects for a North-starring BPE conducted in Tromsø

In conclusion, although both inclination and altitude spectra are reduced in this configuration, the NOAD increased. In general, this second campaign yields similar object detections, but with a stronger focus on altitudes below 1100 km. The Doppler-orbit inclination correlation is lost in exchange for maximizing the detection rate.

5 IMPACT ON MASTER MODEL ACCURACY

Integrating data from multiple sensors will enhance the robustness of the validation process. By combining data from radar and optical systems, a more complete picture of the space debris environment can be obtained.

The collected data must be systematically processed and compared against the MASTER model predictions to identify discrepancies and refine the model algorithms. This process involves several steps, including data cleaning, normalization, and analysis. Data cleaning ensures that any errors or inconsistencies in the raw data are corrected, while normalization ensures that the data is in a consistent format for analysis. The analysis phase involves comparing the observed data with the model predictions to identify any discrepancies. These discrepancies can then be used to refine the model algorithms, improving its accuracy and reliability. Furthermore, collaboration between different departments and organizations is crucial for the success of these sensor campaigns. By working together, researchers can share resources, expertise, and data, leading to more comprehensive and accurate validation efforts. For example, collaboration between space agencies, research institutions, and industry partners can provide access to a wider range of sensors and data sources, enhancing the overall quality of the validation data. By strategically designing sensor campaigns with these considerations, we can significantly improve the validation data quality for the MASTER model. This, in turn, will lead to more accurate assessments of the space debris environment, a more reliable population forecast and hence, more robust threshold which are included in the ESA’s Space Debris Mitigation Guidelines. Ultimately, the goal is to enhance the safety and sustainability of space activities by providing reliable data for the MASTER model. Based on successful model validation, which is based on the sensor detection data, new MASTER populations are provided by ESA [4] and a population report is published via ESA’s space-debris-forum that shows the main features of the new population [5].

6 OUTLOOK AND CONCLUSION

With PULSE introduced as the new MASTER population framework, the strategic sensor campaign design—particularly the creation of LOS Assessment Maps—will be integral to every campaign planning used for MASTER model validation. Future work will encompass the creation of the maps for all available sensors including ESA’s Space Debris Telescope. This will contain more limitations, because the observations are limited by the available nights and on the observation epoch.

In conclusion, periodic space debris observation campaigns are crucial for enhancing the accuracy and reliability of the MASTER model. By integrating detection data from a variety of sensors, a more comprehensive understanding of the space debris environment can be achieved, which is crucial for validating and refining the model. The MASTER model serves as a critical baseline for ESA’s Space Debris Mitigation (SDM) requirements, providing essential data for assessing the debris population, calculating cumulative collision risk and forecasting the evolution of the debris environment. Therefore, strategically designed sensor campaigns not only contribute to more accurate validation data but also support the development of robust mitigation guidelines, ensuring the safety and sustainability of space activities. Through collaboration and continuous improvement of the MASTER model, the challenges posed by space debris can effectively be addressed and measures to protect the space environment can be analysed and designed.

7 REFERENCES

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