A Validation Method of ESA's MASTER 1 cm Population in Low Earth Orbit

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ABSTRACT

This paper explains the validation phase within ESA's Meteoroid And Space Debris Terrestrial Environment Reference (MASTER) model for the large object population in Low Earth Orbit (LEO) (diameter $\geq$ 1 cm). It answers three questions: 1) How is the MASTER population calibrated against observation results 2) Do recent fragmentation events affect the validation phase and 3) Does the space debris model represent reality sufficiently? Since all on-orbit fragments are modeled event-based, one of the main calibration parameters for each fragmentation is the number of objects that are tracked by the Space Surveillance Network (SSN). However, to further calibrate the LEO population, radar surveys such as the Tracking and Imaging Radar (TIRA) Beam park experiments (Fraunhofer Institute/FHR, Germany) and European Incoherent SCATter Radar systems (EISCAT) observations (three radar systems in northern Scandinavia) are performed within dedicated observation campaigns. These space debris observation campaigns can detect objects in LEO down to 1 cm in diameter. For the validation, the observation campaigns are simulated with the Program for Radar and Optical Observation Forecasting (PROOF-2009) using the MASTER population. The results are compared against those from the observation campaigns.
One important aspect during the validation is that observation campaigns can be susceptible to recent fragmentation events due to the sensors' detection sensitivity. This is shown by comparing radar observations, which were performed shortly after a fragmentation event, and a state-of-the-art MASTER population snapshot at the same epoch. Evaluations are based on the Fengyun-1C fragmentation event and the contemporary radar observations.

1 INTRODUCTION

Meteoroid And Space Debris Terrestrial Environment Reference (MASTER) is an European Space Agency (ESA) software that allows to assess the debris and meteoroid flux imparted on a spacecraft in Earth orbit. In addition, spatial densities of artificial satellites in altitudes up to 1000 km above Geostationary Earth Orbit (GEO) can be evaluated. The most recent version is based on the reference population May 1st, 2009 with a new version currently in development [6]. Fig. 1.1 shows all included space debris sources with diameters down to 1 µm covering a variety of different man-made debris sources. Additionally, models to evaluate the natural micro meteoroid population are included to evaluate background flux and seasonal meteoroid streams. Space debris modeling is an integral part of mission safety analyses since it enables an assessment of the impact risk for a payload on a specified target orbit. Other space debris tools also make use of the MASTER population such as Debris Risk Assessment and Mitigation Analysis (DRAMA) [2], Program for Radar and Optical Observation Forecasting (PROOF-2009) [4], Particle Impact Risk and Assessment Tool (PIRAT) [9] or ESABASE2 [15]. As of May 2009 and included in the MASTER-2009 population, there were approximately 750 000 objects larger than 1 cm and over 29 000 objects larger than 10 cm in orbit. Over 160 million objects are modelled with diameters larger than 1 mm [3]. These numbers are derived from sophisticated space debris source models within MASTER combined with a validation procedure that incorporates all available observation data (direct or indirect). The population that consists of objects with a diameter $d \geq 1$ cm is referred to as "Large Object Population". The so called "Small Object Population" consists of object with diameters $1\,\mu m \leq d < 1$ cm. The reason for this discretization are the different validation mechanisms. For the validation of the small object population, impact data from returned surfaces of different space missions are considered (indirect). The large object population is validated against dedicated space debris observation

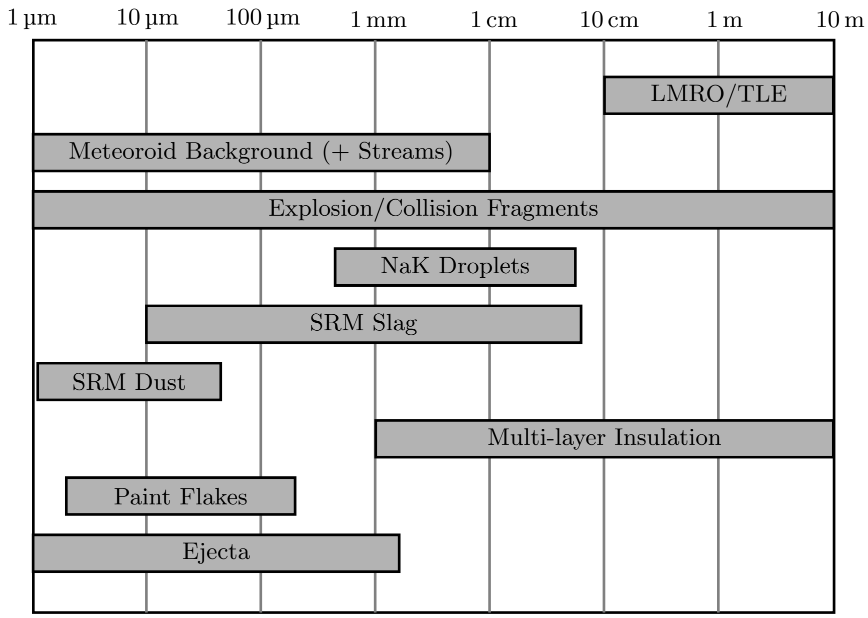


Fig. 1.1. ESA MASTER-2009 source and diameter coverage

campaigns in form of radar- and telescope campaigns (direct). An overview of all available validation data can be found in Tab. 2.1. Due to the source-whise modeling approach of the MASTER population, the expected simulated observations evaluate all different sources shown in Fig. 1.1 (cf. Sec. 2). Consequently, MASTER is not only able to quantify the space debris population in terms of spatial object density and expected flux on a target orbit, it also can discriminate between the contribution of different sources during the campaigns. This paper will cover parts of the large object population, hence the population of objects with diameters $d \geq 1\,\mathrm{cm}$. Since the 1 cm population is dominated by objects originating from on-orbit fragmentations such as explosions and collisions (cf. Tab. 1.1), it focuses on fragmentations events and their contribution to the space debris environment.

Table 1.1. Object number share with $d \geq 1\,\mathrm{cm}$ in Low Earth Orbit (LEO) [3]

Source	**Share**
Launch and Mission Related Objects (LMRO)	1.2 %
Explosions fragments	62.4 %
Collisions fragments	26.4 %
Sodium Potassium (NaK) droplets	6.8 %
Solid Rocket Motor (SRM) slag	2.5 %
Multi-layer Insulation (MLI) fragments	0.7 %

In this paper, the following three questions will be answered:

1. How is the MASTER population calibrated against observation results?
2. Do recent fragmentation events affect the validation phase?
3. Does the space debris model represent reality sufficiently?

To approach these, the MASTER population is processed with PROOF-2009 to compare model data and measurements. One important aspect during this validation is that observation campaigns can be susceptible to recent fragmentation events due to the sensors' detection sensitivity. This is shown by comparing LEO radar observations, which were performed shortly after a fragmentation event, and a state-of-the-art MASTER population snapshot at the same epoch. Evaluations are based on the deliberate fragmentation of the Chinese weather satellite Fengyun-1C during an anti-satellite test in 2007 and the contemporary radar observations [8, 12, 16].

2 POPULATION VALIDATION CYCLE

2.1 AVAILABLE VALIDATION DATA

All on-orbit fragments are modeled event-based. Hence, one of the main calibration parameters for each fragmentation is the number of objects that are tracked by the Space Surveillance Network (SSN). However, to further calibrate the LEO population, radar surveys such as the Tracking and Imaging Radar (TIRA) beampark experiments (Fraunhofer Institute/FHR, Germany) and European Incoherent SCATter Radar systems (EISCAT) observations (three radar systems in northern Scandinavia) are performed within dedicated observation campaigns. These space debris observation campaigns can detect objects in LEO down to $d \approx 1\,\mathrm{cm}$. GEO observation campaigns are conducted by the Astronomical Institute of the University of Bern (AIUB) using telescopes. The small object validation in contrast relies on analyses of returned surfaces such as Long Duration Exposure Facility (LDEF) experiment, Hubble Space Telescope (HST) and European Retrievable Carrier (EuReCa) solar arrays. An overview of all available validation data for the history of MASTER releases is shown in Tab. 2.1. In the following, measurements from EISCAT observation

Table 2.1. Available validation data for past and current MASTER model releases

	MASTER'95	MASTER'97	MASTER'99	MASTER-2001	MASTER-2005	MASTER-2009
Diameter range	$\geq 100\,\mu\mathrm{m}$	$\geq 100\,\mu\mathrm{m}$	$\geq 1\,\mu\mathrm{m}$	$\geq 1\,\mu\mathrm{m}$	$\geq 1\,\mu\mathrm{m}$	$\geq 1\,\mu\mathrm{m}$
Validation data	LDEF	LDEF	LDEF, HST-SM1, EuReCa	LDEF, HST(SM1), EuReCa *PROOF:* TIRA, EISCAT, ESA-SDT	LDEF, HST(SM1,SM3B), EuReCa *PROOF:* TIRA, EISCAT, ESA-SDT	LDEF, HST(SM1,SM3B), EuReCa *PROOF:* TIRA, EISCAT, ESA-SDT

campaigns are used. The data was produced by the Svalbard radar at 78.153° latitude and 16.029° longitude (Fig. 2.1). Over a time span of nearly two years (13.03.2007 - 10.02.2009) the system has detected a large number of objects during 2467 hours of observation during 105 days. The measurements provide detailed information on the number of detections covering e.g. range-rate, Radar Cross Section (RCS) and diameter down to 1 cm.

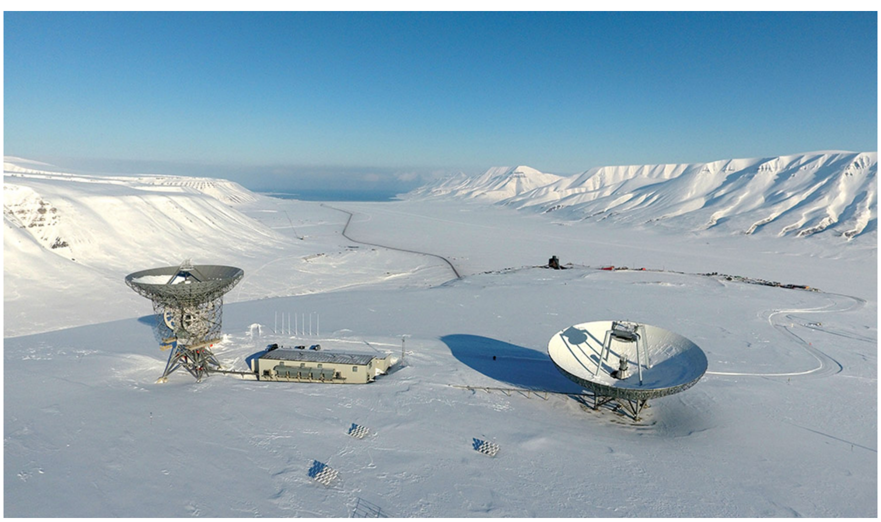


Fig. 2.1. The EISCAT Svalbard Radar site at Longyearbyen: The 32 m antenna (left) and the 42 m magnetic field aligned antenna (right) [www.esa.int]. Photo by Craig Heinselman.

2.2 PROCESSING LARGE OBJECT MEASUREMENT DATA

The diameter spectrum of the observations represents one of the most important validation data since it allows to compare the individual fragmentation modeling approach implemented in MASTER. In order to compare the raw measurements to the PROOF-2009 output, it has to be converted into a compatible form. A common way to visualise the data is to derive a differential histogram covering the desired output spectrum. Since the derived histograms are differential spectra, a comparison is only possible, if both histograms (PROOF-2009 and the raw measurement output) have the exact same class-width and number of classes. Otherwise the results would seem to diverge although they show the same numbers (cf. Fig. 2.2). For both spectra, cumulating all classes from the highest diameter class down to the smallest diameter class will result in the same number which represent the total amount of detected objects.

2.3 PROCESSING POPULATION MODEL DATA

For the large object validation, the observation campaigns are simulated with PROOF-2009 using the MASTER population. PROOF-2009 is designed to simulate and design radar and telescope systems with respect to all performance parameters and can be used for the following purposes:

- Validation of space debris models,
- Analysis of measurement data,
- Planning of observation campaigns.

The validation of space debris models is achieved by comparing measurement data of specific observation ground systems with the virtual observation performed by PROOF-2009 on the underlying MASTER population. This can be based e.g. on detection rates or discrete object observations in the local horizon coordinate system. The interpretation of measurement data can be supported by correlating different debris sources to the observations. This is especially useful for designing and planning of observation campaigns.

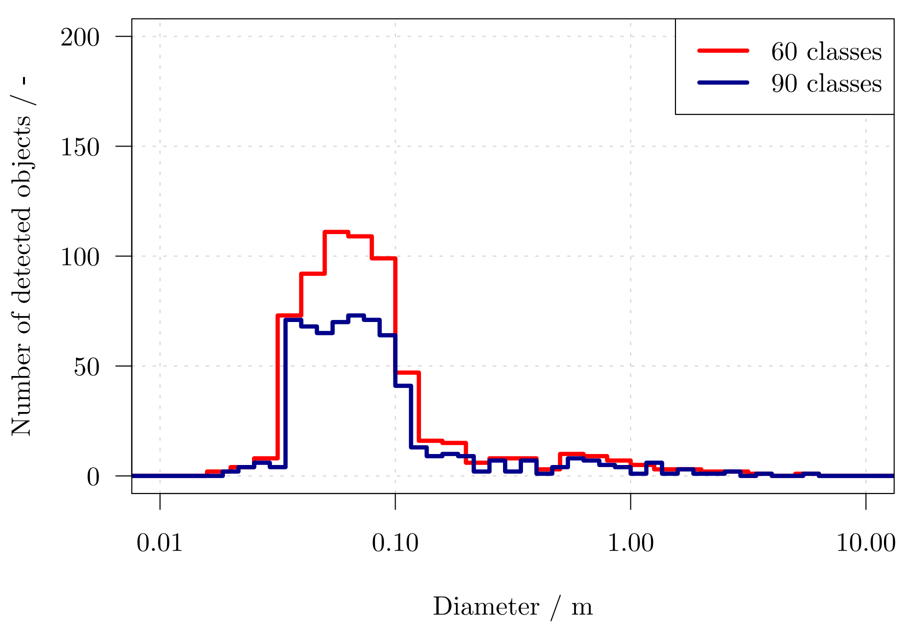


Fig. 2.2. EISCAT data evaluation in histogram format (13th March, 2007).

Since detection rates and Field of View (FoV) passes can be predicted, the instrument parameters as well as viewing direction, sensor position or orbit-based systems can be optimized. Therein, a discretization between crossing objects and detected objects is made. Crossing objects are all objects that entered the FoV regardless of detection thresholds like size or reflectivity (cf. Fig. 2.3). Detections are filtered objects based on the

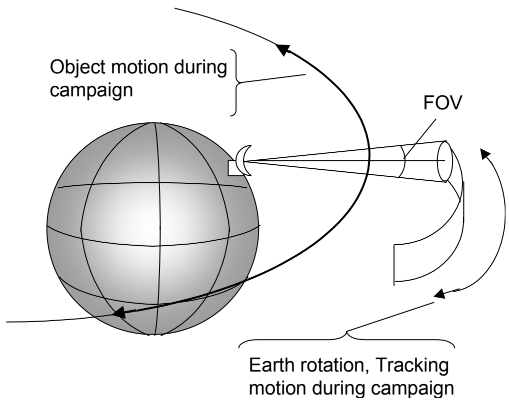


Fig. 2.3. Visualization of FoV and crossing object relationship [4]

crossing objects that fall above a sensor specific minimum threshold detection criteria. In order to compare the results to the actual measurement data, the radar sensor has to be described by detection parameters within PROOF-2009. This is done with a number of input files that describe all performance parameters of the sensor. Since the EISCAT sensor is a radar system, a group of radar specific parameters have to be set along with the observation epoch: antenna pattern description, radar system description, ground based scenario description and job sequence definition. More details on required inputs for PROOF-2009 can be found in [5].
In the antenna pattern description file, the 1-way intensity distribution of the beam pattern is described in form of Taylor coefficients. The Taylor series represents the 2-dimensional projection of the beam pattern (cf. Fig. 2.4). It gives the relative gain of the antenna over the radial offset of the beam pattern. Therefore,

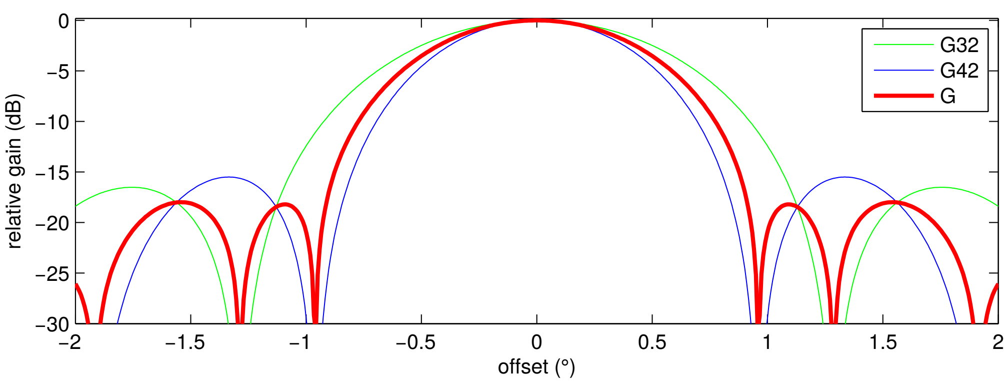


Fig. 2.4. 2D-projection of a circular symmetric antenna gain pattern (beam pattern) for the EISCAT radar (courtesy of EISCAT)

the gain is highest in the center of the beam and decreases with increased radial distance. Fig. 2.4 contains 2 individual beam patterns that describe the gain for the 32 m antenna (G32) and for the 42 m antenna (G42) that are available for the EISCAT Svalbard radar in Longyearbyen. These can operate on their own (monostatic) or in combination (bi-static). The resulting gain pattern for the bi-static mode is shown as the red line (G).
The PROOF-2009 radar system description sets parameters such as antenna constant, wavelength, transmitter power, number and duration of pulses and other sensor characteristic parameters. The ground based scenario description gives the location of the sensor along with the coordinates of the FoV in the local hori-

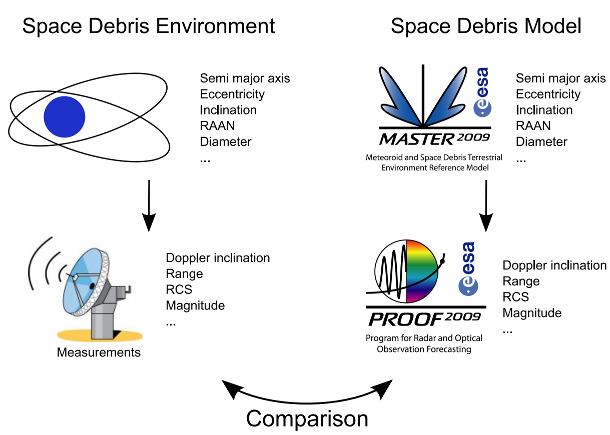
zontal coordinate system, as well as minimum and maximum detection range of the sensor. The job sequence definition is required to temporarily change certain radar parameters during the observation campaign. This is especially useful when runing PROOF-2009 in batch mode, or if certain parameters changed during on ongoing campaign. During the MASTER validation procedure, the complete EISCAT-specific PROOF-2009 description files are provided by the EISCAT operators through ESA.

2.4 CALIBRATION OF POPULATION MODEL DATA

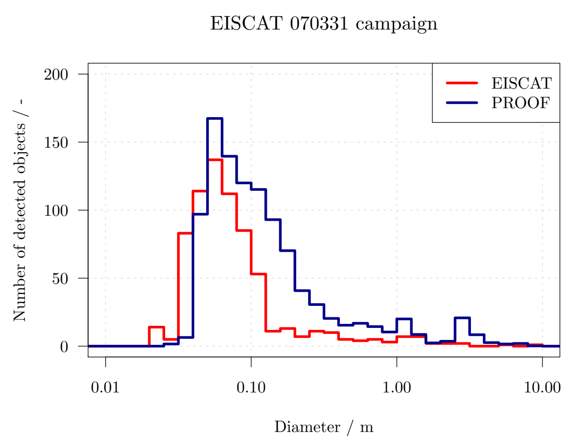
Since processing of the measurement and the population model data (cf. Sec. 2.2 and Sec. 2.3) is performed almost automatically and with the help of sophisticated algorithms, the actual calibration of the MASTER population to represent the observations sufficiently is an engineers task. The comparison between the space debris environment and the space debris model, and the fine tuning of the population are part of the population validation procedure (cp. Fig. 2.5a). The complete population iteration cycle can be described as:

1. Correlation of fragments with objects part of the Two Line Elements (TLE) catalogue
2. Virtual observation campaign of the MASTER population using PROOF-2009
3. Updating model parameters where necessary
4. Iterative re-generation of fragmentation clouds

During this procedure, the measurements are constant data, whereas model output varies during the validation cycle. Since all fragments are initially modeled event-based, duplicates in the TLE catalog have to be filtered out. Therefore, the simulated trackable part of the fragments (usually objects with approximately $d \geq 10\,\mathrm{cm}$) are correlated with the objects currently tracked by the SSN (1.). During the MASTER development, the TLE-correlation procedure was successful for over 93 % of the simulated objects. For a selected EISCAT campaign, a diameter spectrum as part of an initial validation step is shown in Fig. 2.5b. At this



(a) Validation scheme [4]



(b) EISCAT initial validation data for 31st March, 2007, 24 h observation campaign, azimuth 182°, elevation 82°

Fig. 2.5. Comparing measurement data with the MASTER population

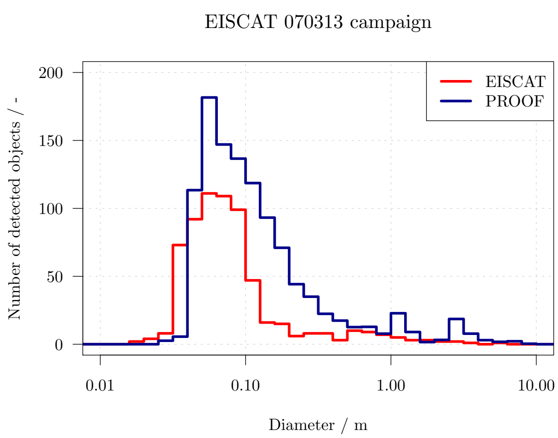
step of the population iteration cycle (2.) the results are investigated in detail for every single validation campaign. Deviations that are out of explainable margins are re-evaluated. Therefore, fragmentation parameters of individual events (e.g. the number of detected objects) are altered to isolate the sensitivity of the validation quality to these events (3.). Sufficient results are generated by re-generation of the complete fragmentation history (4.). Final results on the most recent validation of the MASTER population are currently work in progress under ESA contract. Remaining deviations are expected due to the modeling approach.

However, since raw measurement data have an adequate but limited sensitivity on detections (source?), their conclusions must not be taken as absolutely accurate. Consequences of these effects, partially due to radar sensitivity or a limited number of observation campaigns, have a direct influence on the validation phase and might delude the picture of the “actual” space debris population. The following section describes two important aspects that have to be considered when interpreting validation results. These are illustrated by evaluating the Fengyun-1C fragmentation cloud.

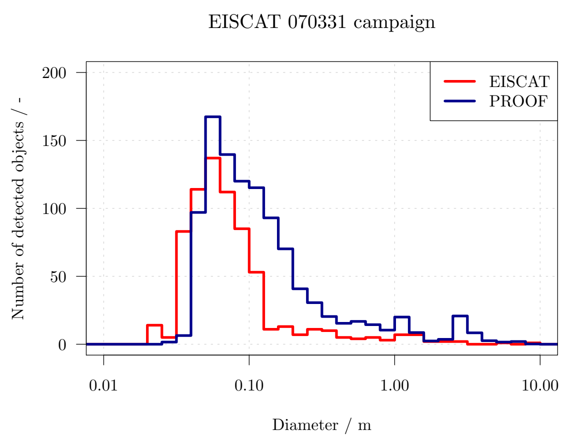
3 INFLUENCES ON THE VALIDATION PHASE

3.1 RADAR DETECTION SENSITIVITY

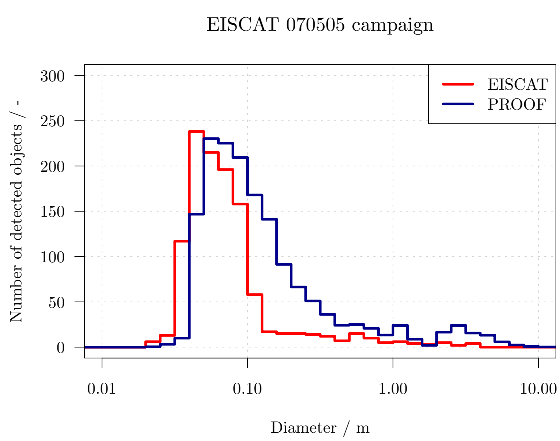
When relying on radar data (or any other observation data) during a MASTER validation, several aspects regarding the data interpretation have to be considered. One important aspect is the radar sensitivity to the cloud spreading. This is demonstrated by analyzing observation campaigns after the Fengyun-1C event, shown in Fig. 3.1 (first population iteration from January 2017 and currently work in progress). The event took place on 11th January, 2007 at 22:26 UTC north east of the city Xichang at an altitude of approximately 860 km [8]. The first available observation campaign from the EISCAT radar after the event is on 13th March,



(a) 13th March, 2007 (event epoch +2 months)



(b) 31st March, 2007 (event epoch +3 months)

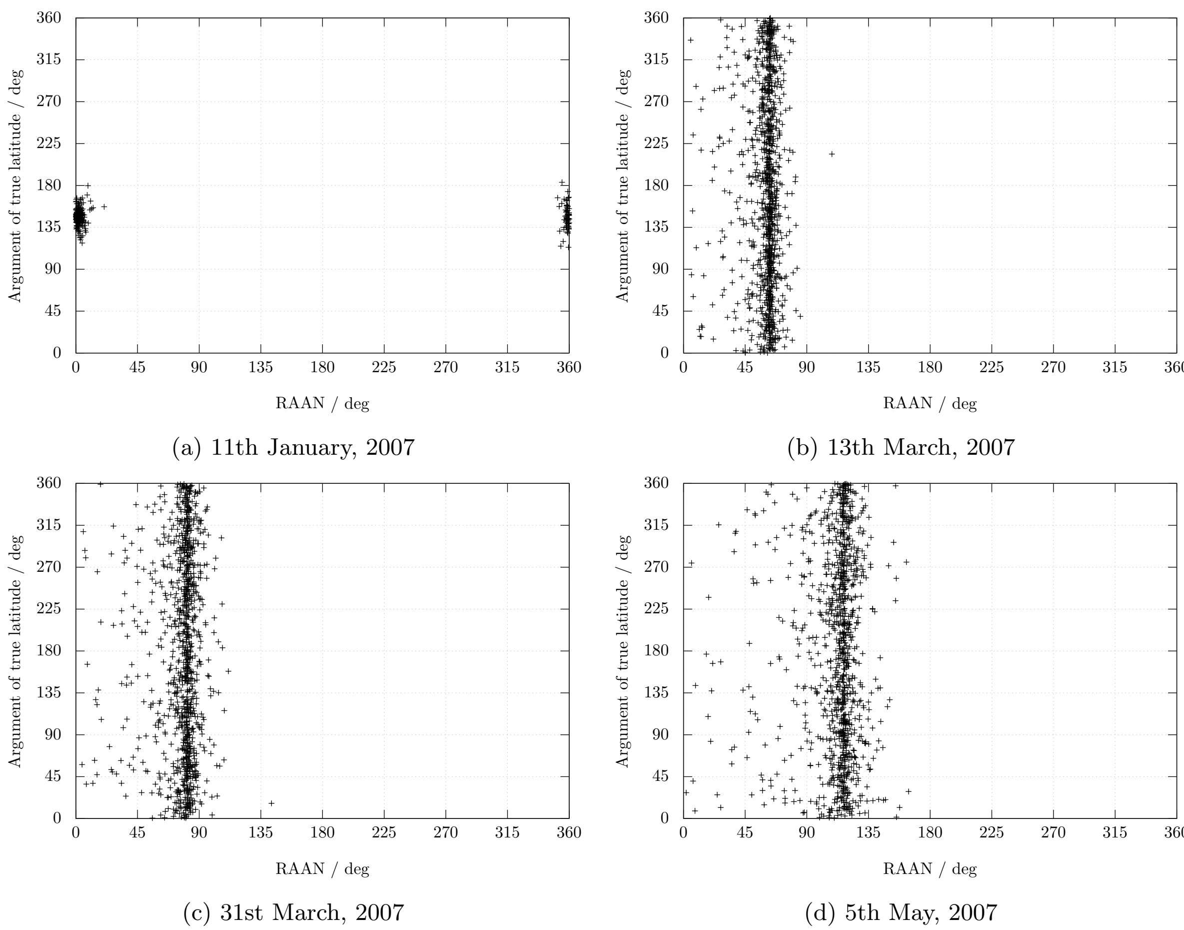


(c) 5th May, 2007 (event epoch +5 months)

Fig. 3.1. Comparing different EISCAT campaigns with PROOF-2009 after the Fengyun-1C fragmentation event, 24 h observation campaigns, azimuth 182°, elevation 82°

2007, approximately 2 months after the event (Fig. 3.1a). The red line shows the derived histogram from the raw measurement data, whereas the blue line shows the PROOF-2009 output of an initial MASTER population. Since the reflection coefficient of an object depends not only on the size but also on its optical and geometric properties, some objects are not detected by real radars. The inherent reflection coefficient of a target depends on the surface roughness, dialectic properties of the surface and and the grazing angle of the radar beam [17]. The detection of complex fragments therefore is impaired by these properties. In addition, for detecting plate-like shapes, the RCS for these objects depends on the transmitter frequency of the radar, whereas spheres provide a RCS independent of the frequency [1]. Continuous observations increase the chance of detections for individual fragments due to the increased detection probability. This effect can be seen in Fig. 3.1b and Fig. 3.1c. Although no additional fragmentations happened in between both epochs, the radar detections converge slowly towards the prediction made by the MASTER population. Although the FoV remained unchanged, the radar observations showed more detections than a month before. This trend continues over time and showing sufficient correlation for the peak values while also showing similar shape.

Considering the Fengyun-1C fragmentation cloud, the internal cloud spreading can also have an effect on the detection due to the increased scattering of beams and increased noise generation of radar echos. Initially, the cloud-density is high since the fragments are not spread out very far. However, over time the mean distance between the fragments increases, the orientation changes and therefore the chance of detecting even complex fragments increases. A visualization of the clouds evolution over time for the considered EISCAT campaigns is shown in Fig. 3.2. All plots show the cloud distribution of objects larger than 1 cm with regard to argument of true latitude over Right Ascension of the Ascending Node (RAAN). From the fragmentation



(a) 11th January, 2007

(b) 13th March, 2007

(c) 31st March, 2007

(d) 5th May, 2007

Fig. 3.2. Fengyun-1C cloud evolution for objects $d \geq 1\,\mathrm{cm}$

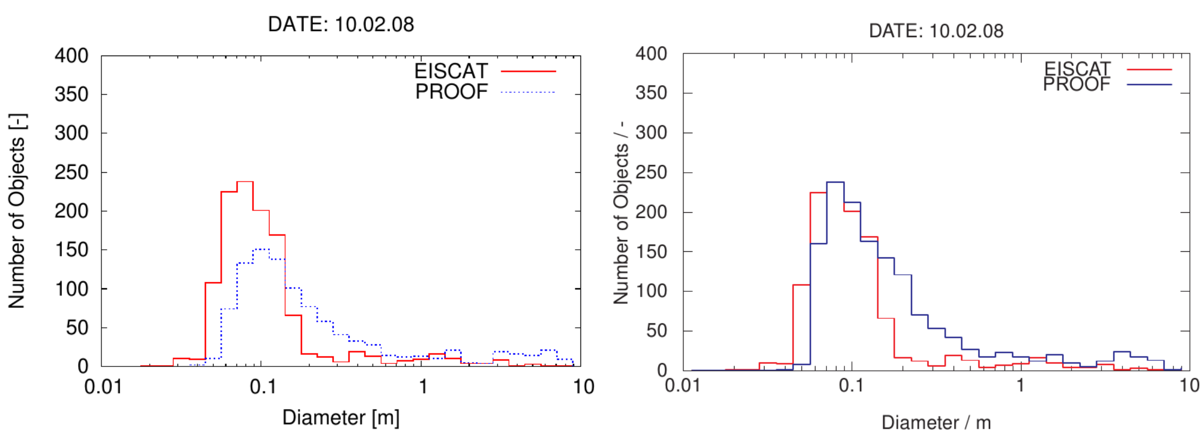
event epoch until five months later, the mean distance of the fragments increase which is best shown by a wider distribution along the RAAN.
The over-prediction of detections for diameters above 10 cm is not generally a modeling issue. During the population generation, optical and geometric properties remain constant. In reality, it is not guaranteed that the radar can detect all fragments at this size, as explained before. Orientation as well as reflectivity can change over time and can affect the detection performance of any radar. Further, during the EISCAT campaign, the diameter is computed based on the radar cross section with a simplified cross section model which joins the Rayleigh and optical regions, not considering the resonance region [10, 13, 14]. In addition, the conversion from RCS to diameter is not valid for every single detection. Focused or scattered radar beams combined with a random orientation can alter the conversion result [17].
Consequently, since in PROOF-2009, objects are represented as spheres, it can be used to calibrate observation campaigns by predicting what the radar could see. Therefore, during the population validation phase of MASTER, recent observation campaigns always have to be evaluated more carefully than older observations. Especially the validation results soon after recent fragmentation events have to be evaluated with caution. Further, long observation campaigns with more detections are more representative for the space debris environment than shorter campaigns.

3.2 CONTINUOUS OBSERVATION CAMPAIGNS

The second important aspect during the interpretation of the validation results are the temporal coverage of scheduled observation campaigns and the continuous maintenance of fragmentation parameters. When modeling orbital fragmentations, the debris size distribution follows the NASA break model while also considering the number of observed debris as a calibration parameter. The number of observed debris directly influences the numbers for objects with smaller diameters, i.e. down to 1 cm in diameter which is shown in Equ. 1

$$N_f(> d) = \begin{cases} 6s\hat{d}^{-1.6} & \text{for explosions} \\ 0.1\hat{m}_e^{0.75} \cdot \hat{d}^{-1.71} & \text{for collisions} \end{cases} \tag{1}$$

with $\hat{d}$ being the object diameter in meters, s is a dimensionless calibration parameter for the considered object type and $\hat{m}_e$ the mass involved in the collision. Therefore, as soon as the number of objects with e.g. $d \geq 10$ cm is set, the cumulative number distribution for the complete diameter spectrum is set as well. More detailed parameter descriptions and graphical evaluations of this power law can be found in [7, 11]. Since it is difficult to assess the actual number of fragments above certain threshold diameter (even for larger pieces of $d \geq 10$ cm), the 1 cm population is also sensitive to the observation of large fragments. An example is shown in Fig. 3.3. During the validation of MASTER-2009, the modeled population was



(a) Validation in 2009 (b) Validation in 2016

Fig. 3.3. Comparison of MASTER validation results for the same EISCAT campaigns in different validation phases, 24 h observation campaign, azimuth 182°, elevation 82°

underestimating the diameter spectrum for the EISCAT campaign of 10th February, 2008. Validating with these information yield the results shown in Fig. 3.3a. At this point in time, the origin of the additional detections remained unknown. Although the incompleteness of the TLE catalog was considered by a perigee altitude dependent factor of certain fragmentation events, the modeled population was still underestimating the observation campaigns. However, years later, and currently still under detailed investigation, the first population iteration considers important updates on numerous event characteristics, so that the validation results yield a much better agreement between past observation and population model output (cf. Fig. 3.3b). The most influencing parameter was the significant increase in the number of detected debris originating from the Fengyun-1C event. Its number went from 1000 fragments in 2009 up to over 3430 fragments in 2016 [6]. The remaining underrepresentation of objects around 5 cm is currently under investigation. Goal of the all validation cycles including the most recent one, is modeling all fragmentation events so that the PROOF-2009 outputs represent the raw measurement data without any non-explainable deviation.
This shows the importance of observation campaigns. More information on fragmentation events usually yield better match between observation and the MASTER model. Therefore, it is necessary and mandatory to operate space debris observations on a regular basis in order to assess the debris environment sufficiently.

4 CONCLUSIONS AND OUTLOOK

In this paper, the validation method for the 1 cm population in LEO was presented. Due to the available validation data in form of radar and telescope observation campaigns, MASTER provides sophisticated evaluations for any Earth bound satellite mission. In order to always provide the most accurate space debris model as possible, the MASTER model incorporates over 4200 hours of direct observation data (cf. Fig. 2.1) covering the LEO and GEO regime. For the LEO regime, more than 2920 hours are incorporated into the validation cycle. Maintaining and updating all individual events is done on a regular basis which directly gives an estimation of the model accuracy. Regarding the validation data, a certain number of detections is needed in order to make statistically relevant conclusions on the MASTER model. To benefit collision risk estimations and global mission safety, international cooperation and information exchange is successfully carried out and has to be continued. This involves space debris model comparisons, exchange of observation data, communication between all agencies and a pursued approach on providing valid informations on the space debris environment. Based on all available validation results, the future MASTER release will provide uncertainties for flux and spatial density spectra [6].
To summarize the answers to the three questions from Sec. 1: the MASTER population is calibrated against observation results by using PROOF-2009. The corresponding observation campaign is simulated by observing the underlying MASTER population. Both observation results are evaluated and compared to each other. During the validation phase, fragmentations shortly before or during the observation campaign have to be interpreted carefully by considering performance and detection thresholds of the sensor. The remaining deviations have to be explainable e.g. because of the sensor limitations. Consequently, all validation data give valuable input for the MASTER population calibration and help to provide a highly accurate space debris model. This ensures an accurate model for the space debris environment that represents the number and distributions of objects in space.

5 ACKNOWLEDGEMENTS

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