MODEL POPULATION UPGRADES BASED ON RECENT OBSERVATIONS

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ABSTRACT

The ESA MASTER model predicts the object flux on an arbitrary object in space by simulating all source terms contributing to the Earth environment in a semi-deterministic way. One of the main problems in the past was the incompatibility of flux predictions returned by the model with detection rates achieved by radar or optical observation campaigns. The ESA PROOF tool lately closed this gap by providing a set of filter mechanisms to simulate the observation campaigns in detail from geometrical crossing up to detection by individual devices. For the first time, this tool allowed a detailed comparison of model predictions with observation data. First evaluations have been made using data from the German TIRA radar system as well as data from the US Haystack radar and the ESA Space Debris Telescope. Although attesting a good conformance in general, the results indicate overestimation of some object families on one hand and a complete neglect of some other population fractions on the other. This paper evaluates modifications of the standard MASTER reference population e.g. by introduction of complementary populations, aiming for a better agreement of the MASTER model with the measurement results. The induced effects of the modifications on detection rates are iteratively analysed with PROOF and possibilities for a future improvement of the debris model are pointed out.

1. COMPARISON OF MODELLED OBJECT POPULATIONS WITH OBSERVATION DATA

Space debris models incorporate plenty of different assumptions concerning the generation mechanisms of the distinct source terms, ranging from sub-models on mass- or diameter distribution up to functional expressions describing impressed additional velocities. Hence, the error margin of the entire space debris model is determined by the product of the error margins of the underlying sub-models. This fact outlines the need for validation of the models based on observation data from radar devices or optical telescopes. In this context, one of the main problems in the past was the incomparability of space debris model flux or spatial density predictions with detection rates resulting from observation campaigns. This problem can be solved by using a dedicated filter algorithm like the recently released ESA PROOF tool, which simulates the observation campaign sophisticatedly (see Fig. 1). Thus, the user is provided with detection rates, which in turn can be directly compared to observation results.

1.1 <u>Available observation data</u>

One major example for recent radar observation campaign is the Beam-Park Experiment (BPE), which has been conducted twice in 1999 (BPE-1/99 on February 2nd and BPE-2/99 on April 11th), also known as Beam-Park I, and once again on October 27th, 2000, also designated as Beam-Park II. The typical observation scenario was a synchronous staring mode operation of the German FGAN/TIRA radar and the US Haystack device. The geographic position of the detectors limits observation to orbits with inclinations $> \approx 40°$. The investigated altitude regime covered up to 1300 km in Beam-Park I and up to 2000 km in Beam-Park II.
Optical space debris observations are mainly dedicated to the environment of the geostationary ring (GEO), as for example those performed by the ESA Space Debris Telescope (SDT).

This study will in the following concentrate on radar observation results of the BP-I campaign, especially BPE-1/99, and build-up on considerations in [1].

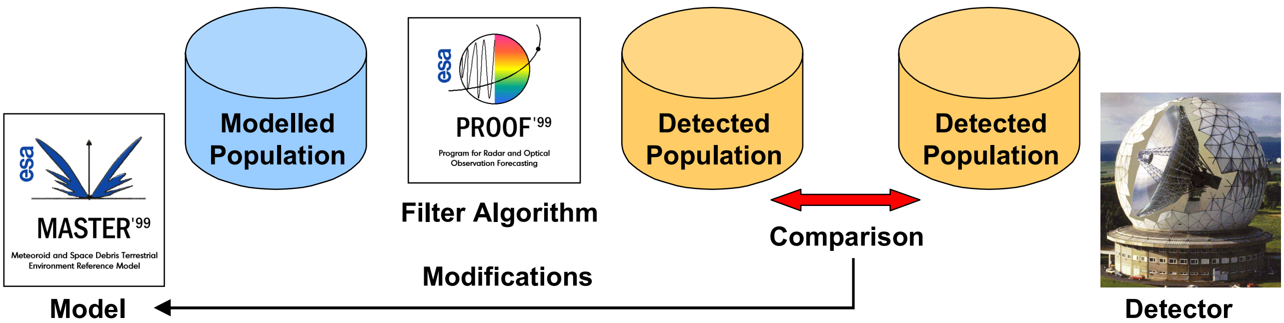

Fig. 1. Processing scheme for comparisons between space debris models and detector results

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2. RESULTS FROM THE TWO BEAM-PARK EXPERIMENTS OF 1999

The comparison of BPE-1/99 data with the PROOF forecasts for the same campaign, based on the MASTER'99 population, shows that, in general, the model underpredicts the number of detected objects (see Fig. 2–Fig. 4). While the 65° inclination peak obviously is overestimated by MASTER (Fig. 2), there seems to be a lack of objects at 70° inclination. More than this, the very broad peak at 80° inclination is met in height, but not in extension. Apparently, it is this underestimation of the integral number of objects in the 80° regime, which is mainly responsible for the general lack of object detections observed. Compared to this clear deficiency, the modelling in the 100° range matches the observation results quite well.

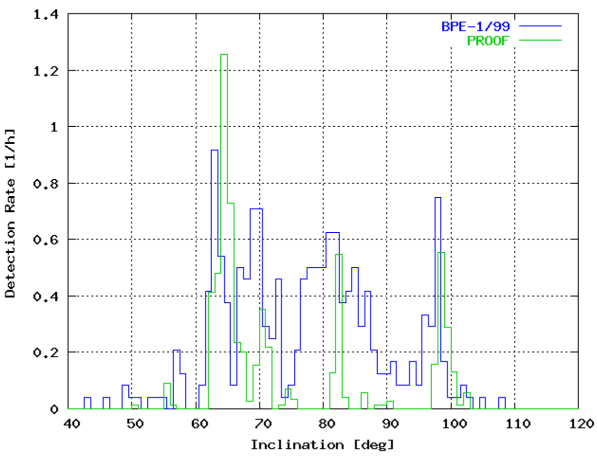

Fig. 2. Inclination Spectrum of the BPE-1/99 experiment compared to PROOF prediction

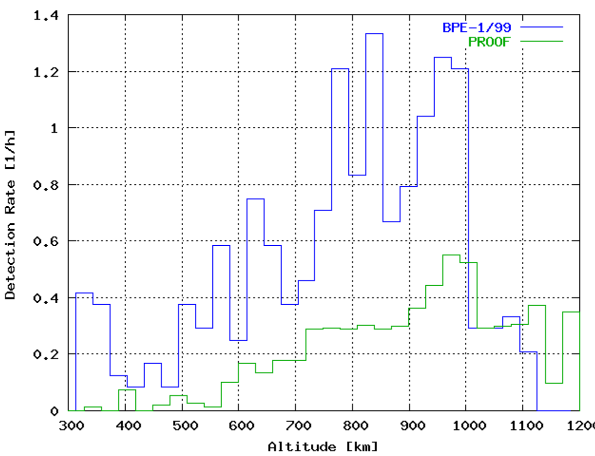

Fig. 3. Altitude Spectrum of the BPE-1/99 experiment compared to PROOF prediction

The above mentioned shortcoming are similarly reflected by the altitude distribution (see Fig. 3). Again, the model underpredicts the number of detected objects. The peak at 950 km is not as pronounced in the PROOF prediction as it is in the radar data. Additionally, the model does not account for several other object accumulations at 350 km, around 600 km and at 800 km.

2.1 Conclusions from the comparison of inclination and altitude spectra

Obviously, in the MASTER model population there are too few objects > 1–2 cm in diameter, especially around 80° inclination. This evokes the question for the reason of this shortcoming. Basically, there are three options:

1. Some documented events in the inclination bands in question were modelled inadequately
2. Some undocumented events of known type occurred and have not been considered at all
3. There exists a space debris source still not considered by MASTER

On the other hand, there is no doubt that too many objects in the radar relevant diameter range are attributed to events around 65° inclination. Here, the only reasonable conclusion is that some documented events near this inclination were modelled inadequately.

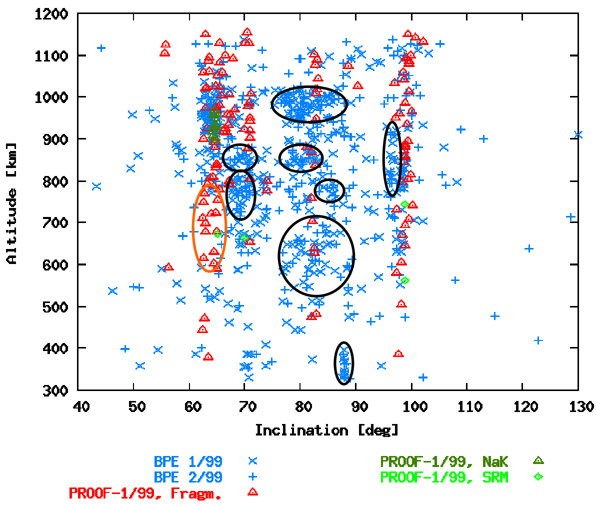

Fig. 4. Identification of problematic areas in the altitude/inclination scatter plot (PROOF BPE-1/99 forecast plotted against combined (!) BPE1/99-BPE-2/99 results)

A better impression of model deficiencies can be drawn from the cross correlation of inclination and altitude as it is offered by a scatter plot as given in Fig. 4. In this diagram, the number of samples was increased by overlaying BPE-1/99 and BPE-2/99 data in order to improve the statistical relevance of the radar data. Hence, it has to be kept in mind that the number of detected objects is doubled artificially by this measure, which is not the case for the displayed PROOF data based on BPE-1/99 only. However, the identification of critical inclination/altitude regions is facilitated this way.

One area at 65° inclination can be identified, where MASTER predicts objects, but none have been measured by the radar. Hence, objects from this altitude/inclination regime are good candidates for being a major driver for the observed overprediction in this inclination band. In addition, several further areas with missing object populations can be identified, mainly in the 80° inclination regime (compare the oval marks in Fig. 4).

3. POSSIBLE SOLUTIONS

As a first measure, it has to be clarified if the first of the above mentioned three options applies, or, in other words, if the identified object clouds can be attributed to events yet documented. Since only 4 of the PROOF predicted detections were SRM slag, SRM firing events can be excluded from further considerations, leaving only fragmentation events as possible candidates since NaK releases are definitely restricted to a very narrow region near 65° inclination and 900 km altitude. The location of all known fragmentation events in relation to the observed object clouds is displayed in Fig. 5.

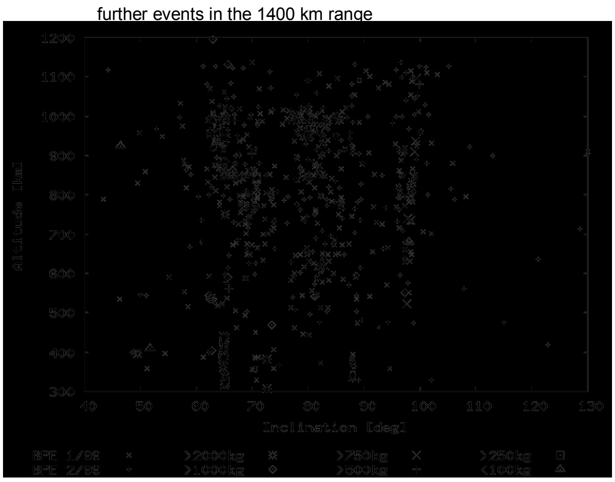

Fig. 5. Correlation with known events

3.1 The surplus objects near 65° inclination

Analysis of the PROOF resolved object IDs showed that 18 different events contribute to the surplus objects below 65° inclination, 8 of them significantly. All of the latter major events are classified as 'High Intensity' explosions in the MASTER fragmentation event data base. This indicates that a re-classification to 'Low Intensity' might be an appropriate mean to reduce the number of modelled objects in this regime.

3.2 The Pegasus/HAPS event

The Pegasus/HAPS fragmentation of 1996 seems to be correlated to the widely spread low altitude population around 80°. Obviously, the broad spread in altitude and inclination is not adequately reflected by the model.

On June, 3rd 1996 the HAPS (Hydrazine Auxiliary Propulsion System) upper stage of a Pegasus launch vehicle exploded 2 years after launch due to overpressurization of the propellant tank. The event at 625 km altitude and 82° inclination created more than 700 trackable objects, making it the worst space debris related event ever, although the stage had a mass of 97 kg only. Radar signatures from Haystack and HAX indicate that those fragments resulting from the rupture of the graphite epoxy over-wrapped aluminium tank are of a filamentous shape and, hence, dipole-like [2]. Since they show a large area-to-mass ratio, even objects of low mass are visible to the radar. The difference velocities of these low-mass objects are unusually high for objects visible to radar facilities (up to ≈ 450 m/s), which results in a theoretical inclination spread of ± 3.5°. This is confirmed by the observation. An additional range can be attributed to uncertainties in the determination of the Doppler inclination on the basis of range rates as it is done for statistical observations in staring mode operation.

While this clearly bears out that the observed broadly spread cloud at 400 – 800 km altitude and 78° – 86° inclination corresponds to the HAPS event, the question remains why this event is not adequately reflected by the PROOF prediction. MASTER currently handles the HAPS event via its standard break-up model, thus assuming the resulting objects as spheres. This procedure conserves mass balance, but assigns too small diameters to a large share of HAPS objects. Consequently, PROOF classifies these objects as not detectable by the radar. In addition, too few objects are generated by the standard break-up model, thus further decreasing the detection probability for HAPS objects. Those objects detected by PROOF have a comparatively large mass and, thus, gain only low additional velocity. This explains why the inclination range predicted by PROOF is very narrow even for this special event. This indicates that the MASTER break-up model will have to be modified in order to be able to simulate the HAPS event in an appropriate way.

3.3 Other object accumulations

For the remaining clouds observed, no direct connection to documented fragmentation events seems obvious. Hence, the assumption of additional events not yet included in the event data base seems reasonable.

4. INTRODUCTION OF ADDITIONAL FRAGMENTATION EVENTS

A remarkable characteristic of the radar observed clouds is their comparatively sharp edge in altitude direction and their spreading over several degrees of inclination (while the latter feature might again be explained by Doppler-inclination errors).

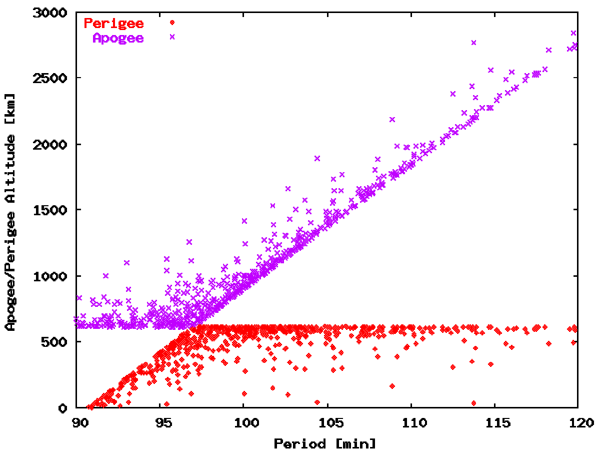

Fig. 6. Gabbard diagram of the fresh HAPS cloud

Following a normal explosion event, the object cloud covers a wide range of altitudes due to the additional velocity imparted to the fragments in the moment of break-up (see Fig. 6 displaying the fresh HAPS cloud as an example). The range of the inclination shift depends on the position of the explosion relative to the line of nodes. But even for events directly at the node, the inclination range normally remains narrow, since orbit rotation is very energy consuming.

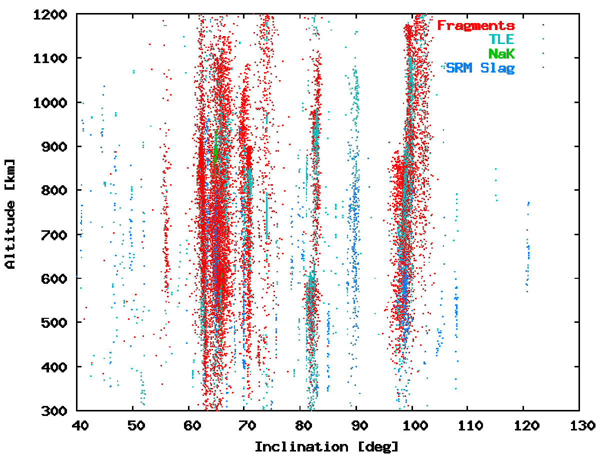

Fig. 7. Wide altitude spreading as exposed by the MASTER population visible to the radar

Since a large fraction of the MASTER population is based on explosion events, the total population exposes a behaviour of stretching in altitude but remaining very close to the parent object in terms of orbit inclination (compare Fig. 7).

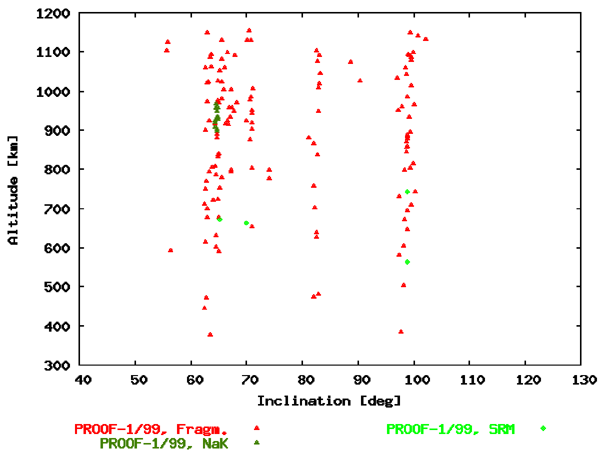

Fig. 8. Resulting narrow inclination bands in PROOF forecasts

This is in turn reflected by the PROOF predictions (see Fig. 8). Using the current break-up model, it is difficult to generate object clouds exposing sharp edged altitude characteristics. This might point to deficiencies in the underlying mass and/or additional velocity distribution, what will be further investigated in the short-term.

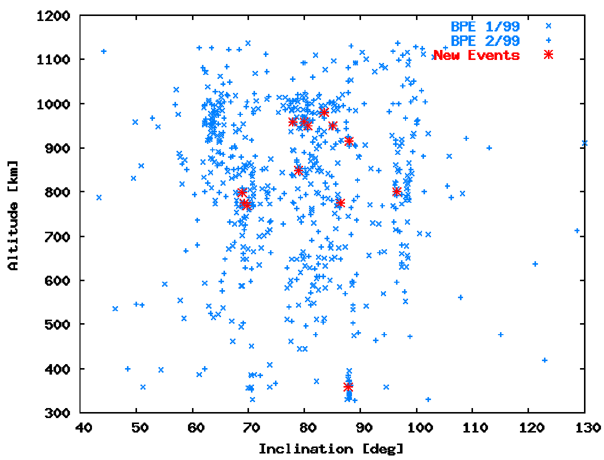

Fig. 9. Position of the added virtual events in altitude and inclination

13 additional fragmentation events as displayed in Fig. 9 have been assumed for this study in order to evaluate to which extent the identified gaps can be closed by such a provisional measure. The broad extension in inclination of the 1000 km cloud near 80° could only be matched by multiple events due to the above mentioned narrow inclination band covered by normal fragmentations.

Investigations showed that this cloud below 1000 km altitude might be related to about 160 Russian Tsiklon/Parus military navigation satellites operating in this region, not counted the related 160 Cosmos (SL-8) rocket upper stages.

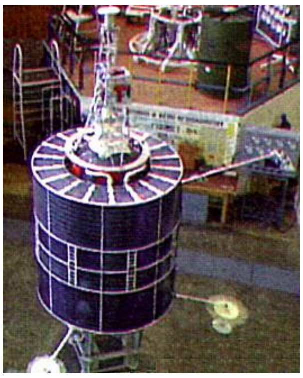

Fig. 10. Parus navigation satellite
(800 kg)

Following the current break-up model, a total additional mass of 33.5 t was fragmented in the context of this study.

5. RESULTS

The population resulting from the additional events was iteratively processed using the PROOF tool to come to predicted detections or detection rates, respectively.

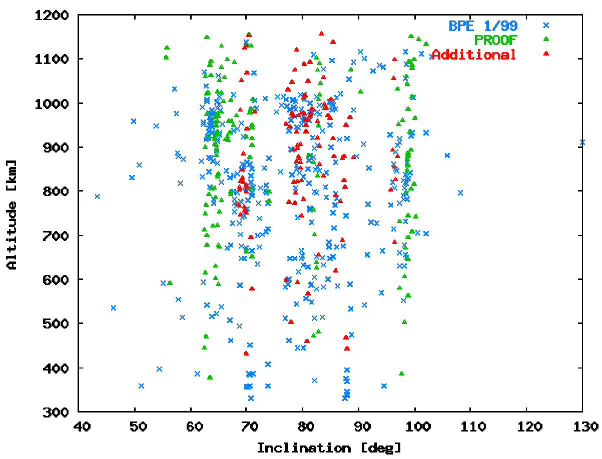

Fig. 11. Additional detections introduced by the virtual new events

The resulting scatter plot (Fig. 11) matches the observation data significantly better, even if the clouds are spread beyond the pronounced 1000 km altitude boundary due to the mentioned problem restricting explosion clouds to certain altitude regimes.

The Pegasus/HAPS event was not re-modelled during this study due to the need for significant changes in the underlying models. Hence, the predictions in the 625 km range show no obvious changes.

The improvement yet indicated by the scatter plot can also be observed in the related altitude and inclination spectra (see Fig. 12 and Fig. 13, respectively).

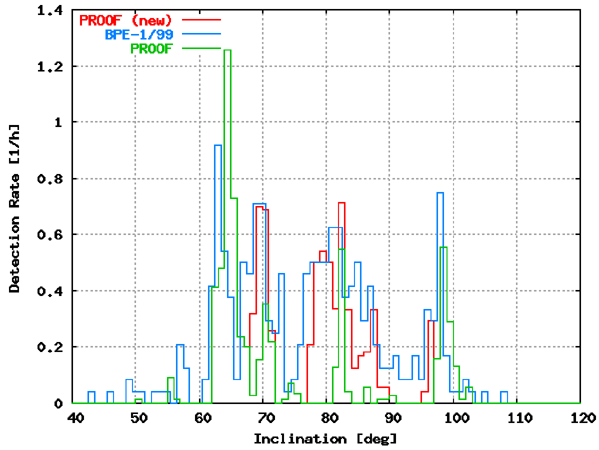

Fig. 12.Inclination spectrum resulting from the introduction of additional events

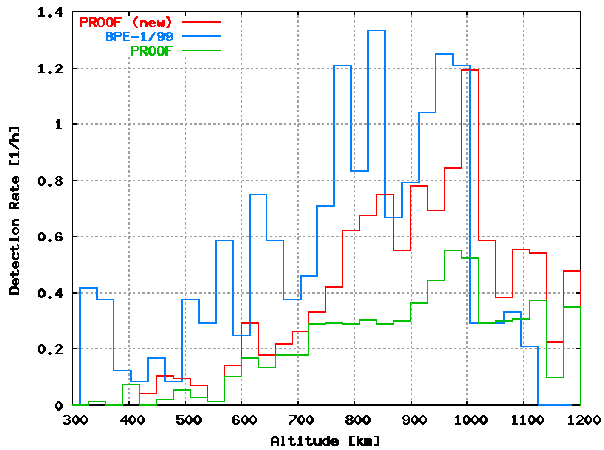

Fig. 13. Altitude spectrum resulting from the introduction of additional events

6. CONCLUSIONS

The generation of new object clouds by modelling additional, not documented fragmentation events can significantly improve the MASTER model conformance with radar observation data. This is understood to be a comparatively rough approach, but it appears justified in absence of a better understanding of the origin of these objects. Particularly, it does not rule out that other generation mechanisms than ‘standard’ fragmentation might be responsible for the observed additional objects. The narrow altitude spreading of many of the observed clouds could indicate deficiencies in the break-up model’s mass and/or additional velocity distribution underlying MASTER, which will be reviewed in advance of the next model release.

The Pegasus/HAPS event will have to be treated more sophisticatedly in future MASTER populations in order to match the observed cloud characteristics, which will help to further narrow the gap around 80° inclination.

7. REFERENCES

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