COMPARISON OF EISCAT RADAR DATA ON SPACE DEBRIS WITH MODEL PREDICTIONS BY THE MASTER MODEL OF ESA

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ABSTRACT

In the effort to obtain low cost routine space debris observations in low Earth orbit, ESA plans to utilise the radar facilities of the European Incoherent Scatter Scientific Association. First demonstration measurements were performed from 11 to 23 February 2001. In total 16 hours of radar signals were collected. Here we compare these initial measurements with the predictions of the ESA MASTER/PROOF’99 model in order to assess the sensitivity as well as the reliability of the data. We find that while the determination of object size needs to be reviewed, the altitude distribution provides a good fit to the model prediction. The absolute number of objects detected in the various altitude bins indicates that the coherent integration method indeed increases the detection sensitivity when compared to incoherent integration. In the data presented here integration times from 0.1 to 0.3 s were used. As expected, orbit information cannot be obtained from the measurements if they are linked to ionospheric measurements as planned. In addition routine space debris observations provide also useful information for the validation of large-object catalogues.

INTRODUCTION

Currently ESA monitors the space debris population in low Earth orbit (LEO) in irregular intervals (Mehrholz et al., 2002). This is done in the frame of 24 hour radar beam-park experiments. The data from these measurements are taken in order to constrain models of the population evolution of space debris in orbit (Klinkrad et al., 2001). The most prominent of the European space debris models is MASTER/PROOF’99, which allows spacecraft operators to assess the risk of a debris impact for their mission. As the 24 hour experiments only provide a snapshot of the environment, the temporal behaviour of the space debris population is difficult to determine. Routine monitoring of LEO is required in order to better constrain the debris models. The most suitable technique for monitoring LEO is radar detection by high-power, large aperture facilities.

In order to obtain inexpensive access to such observations, ESA started in 2000 a study with the Sodankylä Geophysical Observatory (SGO) to use the radar facilities of the European Incoherent SCATter (EISCAT) scientific association. These facilities operate up to 2000 hours per year for ionospheric research purposes. In the study, the SGO team was able to demonstrate the exploitation of ionospheric measurements for space debris observations. A comparison of the retrieved, still preliminary, data with the ESA MASTER/PROOF’99 model is presented here.

THE EISCAT FACILITY AT TROMSØ

The space debris measurements were performed in the frame of a demonstration campaign in February 2001. A radar facility located at 69°35' N and 19°14' E near Tromsø, Norway, was used. The UHF radar at Tromsø operates at a frequency of 931 MHz with a pulse repetition frequency of 200 kHz. The transmitter can transmit peak powers up to 1.5 MW through the main antenna, but it was restricted to just below 1 MW during the measurement campaign. The 35 m antenna was pointed parallel to the field lines of the local geo-magnetic field, azimuth 183° 18' and elevation 77° 6'. During the test campaign two different phase codes called TAU2 and CP1LT were transmitted. Of the TAU2
data 1.2 hours have been analysed as well as 2.8 hours of the CP1LT data. For both experiments the pulse length was about 0.5 ms. The range window of the CP1LT experiment covered ranges from 400 to 1,400 km with a gap between 700 and 800 km, and TAU covered ranges from 500 to 1,800 km with a gap between 800 and 1,100 km.

CATALOGUED OBJECT

The strongest of the high-altitude TAU2 events during the test campaign began at 22:19:06 UTC, 20 February 2001. We identified the target as a large catalogued object, a Tsyklon upper stage with the COSPAR designator 1994-11G. According to the catalogue the object has a total mass of 1,390 kg and is cylindrical in shape, with a diameter of 2.7 m, a height of 2.2 m, and a radar cross section of 8.3 m². The orbital information in the TLE catalogue, with TLE epoch one day before the experiment epoch, lets us predict that it should have passed the radar beam at the off-axis angular distance of 1°16'. Figure 1 shows the analysis summary plot of the event. The analysis was done using 0.27 s coherent integration.

Fig. 1. Event at 22:19:06, 20 February 2001, compared against the catalogue. The top panel shows a quantity proportional to the signal to noise power ratio. The middle panel shows the measured slant range (small circles), a parabolic fit, and the catalogue prediction (large circles). The bottom panel shows the measured Doppler velocity (small circles), a linear fit, and the catalogue prediction for the range rate (large circles).

The top panel of Figure 1 shows a quantity proportional to the signal to noise power ratio during the beam transit.
The antenna side-lobe structure is clearly visible. Markers indicate those scans where the ratio was larger than the detection threshold of 4.5. The off-centre angular distance of the pass was fit to the data (Markkanen et al., 2002). The best fit was achieved by assuming that the transit occurred 31' off-axis. It seems difficult to reconcile the predicted offset 1°16' with the inferred value of 31'.

The middle and bottom panels of Figure 1 show the measured slant range and Doppler velocity. The solid dark curves represent quadratic and linear fits to the data points. The large dots represent the predicted values. The measured range is about 7 km larger than predicted. The slope of the velocity curve is as predicted, but there is a discrepancy of about 0.1 km s⁻¹ in the actual velocity values. The circular-orbit, vertical-beam acceleration is 27.5 m s⁻², which is consistent with the value 27.1 m s⁻² from the velocity fit. The timing accuracy for the catalogued objects is of the order of 10 s, while we believe the measured timing to be accurate to within about 0.1 s. However, the range and velocity discrepancies cannot be removed simply by adjusting the relative timing, because the required correction would be about six seconds for the range data, but only about three seconds for the Doppler data. A small misalignment of the antenna can, however, explain the observed deviation.

This example of the detection of a large catalogued object by the EISCAT radar demonstrates the usefulness of routine space debris observations for the validation of large-object catalogues.

SMALL-SIZE DEBRIS

While collisions of operational spacecraft with large catalogued objects like the upper stage discussed above can be avoided by manoeuvring the spacecraft, objects smaller than 10 cm, that normally are not found in the catalogue, pose a serious threat to manned and unmanned spacecraft. Complex spacecraft like the International Space Station Alpha are shielded from impacts of objects smaller than about 1 cm. Thus, the population in the size range between 1 and 10 cm is particularly important to observe.

In the demonstration campaign performed by SGO, 56 objects in the size range above 1 cm were detected within the 3 hours of analysed data. The measured distribution in size and altitude distributions discussed below are compared to the prediction by the ESA MASTER/PROOF’99 model. Due to the pointing of the radar beam along the local geomagnetic field line, orbital parameters could not be determined from the measurements. The predicted distribution of orbital elements is discussed below anyhow.

Size Distribution

Figure 2 shows the distribution of object diameter, as determined by the analysis of the reflected signal amplitude, as well as the prediction by the MASTER/PROOF’99 model. Only objects detected in the range window from 800 to 1,400 km have been considered.

![Size Distribution Graph](image)

Fig. 2. Distribution of object sizes. The prediction of the absolute number of beam-crossing objects as a function of object size by the MASTER/PROOF’99 model is shown as the dark gray histogram, the light gray histogram shows the detectable objects, according to the model, and the distribution of sizes of actually detected objects is shown as the diamond symbols.

Under the assumption of incoherent integration, objects larger than about 7 cm are detectable reliably in the range window between 800 and 1,400 km. While the majority of the objects predicted to cross the beam are smaller...
than 2 cm, sizes of 2 to 3 cm have been derived for the objects actually detected in the experiment. From the figure it is evident that while no object with a derived size larger than 6 cm has been detected, more than 20 of those large objects should have crossed the beam according to the prediction by MASTER/PROOF’99. Also, the number of 3 cm objects is three times higher than predicted, while the total number of detected objects is in agreement. Apparently, the sizes derived for the objects larger than 10 cm have been underestimated. Because it is unknown where the objects cross the beam pattern, the EISCAT radars can only give a lower bound for the radar cross section. Consequently, the translation of the measured radar cross section to object diameter systematically underestimates the object size.

**Altitude Distribution**

The distribution of orbital altitudes of detected objects is shown in Figure 3. At the altitudes of maximum debris density between 850 and 950 km, 12 objects were detected. According to the MASTER/PROOF’99 model, the predicted number of objects detectable in this altitude bin by incoherent integration is below 8, significantly less than actually detected. This is also true for all but the altitude bin around 1,200 km. The sensitivity of the radar appears to be higher than for the standard incoherent detection method. This can be explained by the fact that the detection algorithm exploits the phase information by coherently integrating the detected signal over 0.1 s. MASTER/PROOF’99 can only simulate radar detection with incoherent integration. Since the detection algorithm used by the EISCAT team is based on a coherent integration technique, the predicted number of objects is lower than the EISCAT data.

![Fig. 3. Distribution of orbital altitudes. The prediction of the absolute object number as a function of orbital altitude by the MASTER/PROOF’99 model is shown as the gray histogram. The light gray bars give the number of objects that would be detectable by the Tromsø radar if an incoherent detection method was used. The dark gray part of each bar indicates the predicted number of objects undetectable by this method. The distribution of orbital altitudes of detected space debris object is shown by the diamond symbols.](image)

**Inclination Distribution**

Assuming circular orbits, the inclination of an object’s orbit can in theory be derived from the Doppler velocity measured by the radar. However, the functional dependence of the Doppler velocity on the orbit inclination varies with the orientation of the radar beam. As can be seen in Figures 4 and 5, the mapping from Doppler velocity to orbit inclination is ambiguous for an antenna azimuth around 180° (South). An easterly pointing (antenna azimuth 90°) will provide an unambiguous relationship between the measured Doppler velocity and orbit inclination.

As the EISCAT transmitter at Tromsø was pointed parallel to the geo-magnetic field lines, which follow the north-south direction, orbit inclinations can not be derived from the data obtained during the measurement campaign. Using the PROOF application of the MASTER/PROOF’99 model, we can however predict the inclination distribution expected for the measurement campaign. The prediction is shown in Figure 6. It can be seen that inclinations from 60° to 110° are covered by beam-park experiments with the transmitter at Tromsø. This covers debris created in classical Sun-synchronous orbits as well as debris created by most launches from Plesetsk.
CONCLUSION AND OUTLOOK

The test campaign performed by SGO resulted in raw data on one large space debris object as well as in the size and altitude distribution of 55 small space debris objects. The comparison with the ESA MASTER/PROOF’99 model shows that the conversion from signal amplitudes to object sizes has to be reviewed. The more straightforward measurement of the objects’ altitude provides a distribution that is well in accord with the prediction by the model. As the model is regularly checked against results from other beam-park experiments, we can conclude that the demonstration measurements with the EISCAT transmitter at Tromsø provides reliable measurements. The absolute number of detections is significantly larger than the predicted number when assuming incoherent integration as a detection technique. Thus, the coherent integration of the received signal indeed increases the detection sensitivity.

As expected, we find that, when linked to ionospheric measurements, we will not obtain orbital information using the EISCAT radars. This restriction can, however, easily be removed if dedicated observation time is acquired. In this case an optimum antenna pointing will allow us to determine at least Doppler inclinations, which are identical to true orbit inclinations for circular orbits. As the PROOF tool of the new MASTER/PROOF-2001 model allows to predict the distribution of Doppler inclinations, this would allow us to constrain the statistical orbit properties of the small-size LEO space debris population.

In summary we find that the measurements performed during the demonstration campaign in February 2001 prove the value of space debris data obtained by exploiting ionospheric measurements. The mere amount of data, that
will be available in case simultaneous operations with ionospheric measurements in the order of 1000 hours per year can be performed, provides an important contribution to the understanding of the evolution of LEO space debris.

In order to realise measurements that operate simultaneously with the ionospheric investigations, a real-time detection method has to be developed, because the volume of data that would be needed to record the raw signal from the radar for 1000 hours per year is prohibitive. With real-time detection only the object parameters as well as the signal of the passage will be recorded. A study to develop real-time measurements will be started by the end of 2002.

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