High Power Large Aperture Radar Observations of the Iridium-Cosmos collision

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Abstract

We present results from two recent beam park radar experiments conducted with the EISCAT UHF radars in February and May 2009 to survey the debris produced by the Iridium-Cosmos satellite collision. The resulting debris is clearly visible in the measurements. The results are compared to a simulated observation produced with the ESA PROOF model. The measurements are found to agree to some extent with the model, but there are still discrepancies between the measurement and the simulation, mainly in the shape of the debris cloud and the total amount of observed debris.

1 Introduction

The European Incoherent Scatter radar facility (EISCAT) currently consists of three high power large aperture radar systems: the mainland VHF (225 MHz) and UHF (930 MHz) radars with transmitters in Tromsø, Norway, and the 500 MHz EISCAT Svalbard radar (ESR). The mainland UHF system is tri-static, with additional receivers located in Kiruna, Sweden and Sodankylä, Finland. The radars are primarily used for ionospheric studies, but since 2000 [6, 5], there has existed the capability to analyze the measurements also for space debris. For this purpose, a separate digital receiver, which we will here refer as the space debris receiver, is operated in parallel with the standard EISCAT receiver. Since 2000, the EISCAT facilities have been used several times for statistical space debris studies with co-operation with the European Space Agency.

In situ measurements of debris can be used to statistically measure < 1 cm scale debris [2]. Existing space surveillance radars can be used to track > 10 cm scale objects. Debris between 1 and 10 cm can be measured with megawatt-scale high power large aperture radars. There are two such facilities in Europe: EISCAT and TIRA [1].

After the collision of the Iridium and Cosmos satellites on 10 February 2009, we have conducted two dedicated beam-park experiments to study the debris cloud produced by the collision, one on 14 February 2009 and another on 14 May 2009. Both were conducted with the Tromsø UHF radar. In addition to this, we have recorded with the space debris receivers several standard ionospheric measurements, both before and after the collision. All our post-collision measurements show clear increase of event count at the times and altitudes when the radar beam is predicted to cross the two debris rings.

2 Analysis methods

The measurement analysis is based on a coherent integration of signals scattered from point targets. The detection algorithm is a new version of the fast generalized match function algorithm previously used at EISCAT [6, 7]. Instead of assuming that the signal is fully coherent, the new version allows slight broadening of the backscatter spectrum due to, e.g., object rotation or insufficiently modeled acceleration.

In the detection phase our complex baseband signal model, in discretized form, is

$$m_t = \epsilon_{t-r} \sum_{k=\lfloor -(N-1)/2 \rfloor}^{\lfloor (N-1)/2 \rfloor} a_k \exp\{i(\omega + k\Delta\omega)t\} + \xi_t, \quad (1)$$

where ϵ_t is the transmission envelope, r is the target range gate, N is the number of adjacent frequency components with corresponding complex coefficients a_k, and ω is the central frequency. The term ξ_t corresponds to measurement noise, which is assumed to be complex Gaussian independent and identically distributed noise with power $\mathrm{E}\xi_t\overline{\xi_{t'}} = \delta_{t,t'}kTB$.

Our debris observations are formed by searching for the maximum likelihood estimates of parameters r, ω and a_k. This is done using a FFT-based grid search. The results of these coherent integration blocks are then combined into events, which provide an estimate of the target radial trajectory and radar cross-section. However, as the EISCAT radars are not equiped with a monopulse feed, we cannot produce an accurate radar cross-section estimate if the detection is not tri-static. Thus, the radar cross-section estimate obtained by taking the peak target signal to noise ratio along the trajectory is usually a lower bound for the true value, as the target doesn't necessarily pass through the center of the beam.

3 Radar experiments

For performing our beam-park measurements, we have used standard EISCAT ionospheric radar experiments called *beata* and *steffe*, and a newly developed space debris program called *spade* [9]. Even though the EISCAT ionospheric experiments are able to provide the unambiguous range coverage that one needs for low earth orbit space debris surveys, they have problematic gaps in range, caused by the high (10-25%) transmission duty cycle and uniform interpulse intervals. The *spade* experiment also has a high duty-cycle, but avoids the gaps in range (up to $16 \cdot 10^3$ km) by using non-uniform interpulse periods. Table 1. lists our measurements related to the Iridium-Cosmos collision.

3.1 Tri-static observations

The 14 May 2009 measurement was the first-ever tri-static space debris measurement with the EISCAT UHF system. In this case, the Tromsø transmitter was pointed eastward, above Ivalo, Finland, at 780 km height. The two 32 m receive-only antennas were also pointed to the same point. The geometry is shown in Fig. 1. This pointing direction is more beneficial than the magnetic field align direction that is normally used by EISCAT, as it gives better Doppler-inclination information. Also, multi-static detections are expected to give some information about the orbital elements as well.

We managed to get surprisingly many bi-static events with the Kiruna (16 per hour) and Sodankylä (12 per hour) systems. Some of the detections were also tri-static. This is perhaps due to the transmitter main lobe, receiver sidelobe combination, which is only about -20 dB at the first side lobe of the receiving antenna.

We also noticed that the remote receiver data quality was better than the receiver located at the transmitter, making it possible to use a smaller detection thresholds at the remotes. This can be attributed to many things: there are no missing echos because the remote sites don't transmit; there is significantly less ionospheric clutter at the remotes; and the receiver noise temperature at the remotes is lower.

4 Results

We show here only results from the two *spade*-experiments. Figs. 2. and 3. show results from the 14-15 February 2009 run, and Figs. 4. and 5. show the run on 14-15 May 2009. Simulated measurements produced with the ESA PROOF model [4] are shown alongside the real measurements.

The detection rate for the field align measurement in February was about 24 detections per hour. For the eastward, slightly lower elevation, pointing direction in May, it was about 30 detections per hour. A previous March 2006 field aligned pointing direction measurement resulted in about 17 detections per hour [8], so there is a nearly 40% increase

Date	Experiment	Radar	Pointing
14:00 14.2.2009 – 11:00 15.2.2009	spade	UHF	FA
12:00 19.2.2009 – 12:00 20.2.2009	steffe	ESR	FA
08:00 12.5.2009 – 14:00 14.5.2009	beata	UHF	FA
14:00 14.5.2009 – 15:00 15.5.2009	spade	UHF	SD

Table 1: List of beam-park experiments conducted after the Iridium-Cosmos collision. The UHF radar refers to the Tromsø 930 MHz radar and ESR refers to the Svalbard 500 MHz radar. The *beata*- and *steffe*-experiments are ionospheric experiments, which can be analyzed for space debris, although there are gaps in the range coverage. The *spade*-experiment is a new space debris radar program that gives gapless range coverage with full radar duty-cycle. The pointing direction FA means magnetic field aligned at approximately 300 km. In Tromsø, this corresponds to a pointing direction of azimuth 185.8° and elevation 77.4°. The pointing labeled SD is an eastward pointing direction shown in Fig. 1., which gives more Doppler inclination information. This corresponds to a pointing direction of azimuth 86.5° and elevation 67.3°.

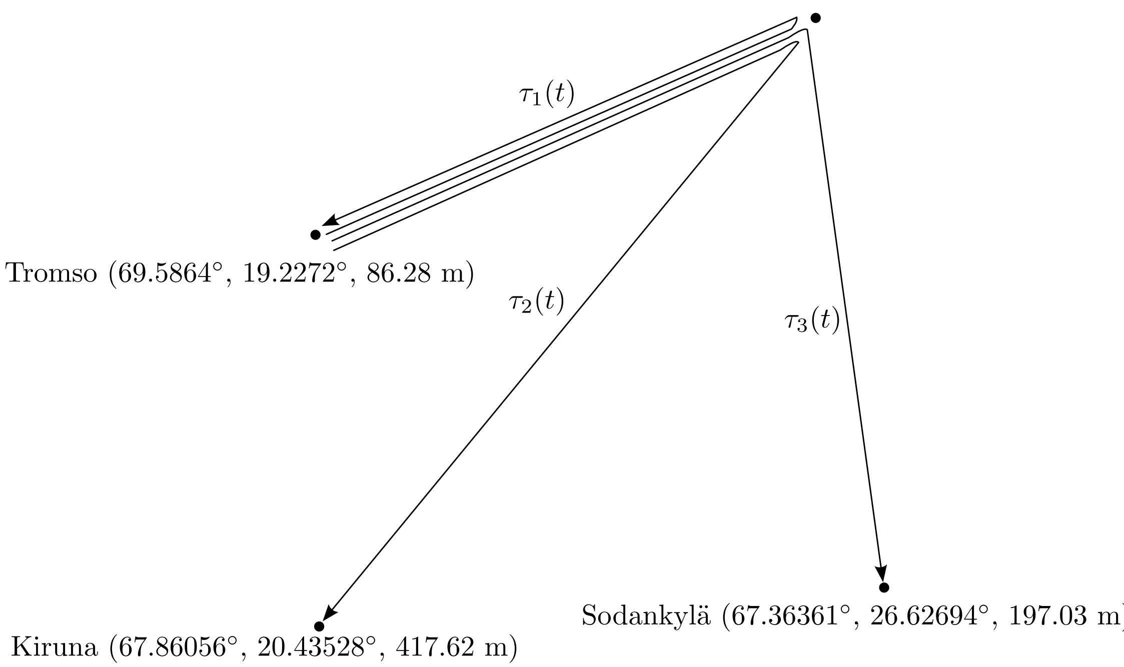

Figure 1: The geometry of the tri-static space debris experiment. All three antennas are pointed above Ivalo (69.5864°, 26.6269°) at the height of 780 km.

as a result of the Chinese anti-satellite experiment and the Iridium-Cosmos collision. However, these number are not completely comparable, as a different radar experiment, different detection algorithms and different receiver hardware were used in these two measurements.

A quick visual inspection of the results shows that the Cosmos cloud is over twice the size of the Iridium debris cloud. Also, the Cosmos cloud appears to be more spread out in range, about 100 km in February and about 500 km in May. The Iridium cloud is initially spread out to a 100 km range in February and 200 km May. The Cosmos cloud causes approximately an increase of 200-300 % compared to the background level during one 15 minute histogram bin. The Iridium cloud causes a smaller, perhaps 100-200 % increase during a 15-minute histogram bin.

When comparing the results to the simulation, the measured debris cloud is much more clumped together, both in range and time of day. The simulation also shows all in all about twice the number of detections compared to the real measurement. The model also seems to over-predict the size of the Iridium and Cosmos debris clouds. The overall of tilt and Doppler of the clouds are modeled to some extent correctly, although the shape of the clouds is quite different in the real measurement.

The reason for these discrepancies is not yet clear. One problem with the analysis is that it can only detect one target at a time. This can result in some undetected events. The mean time between detections is about 120 s, so this shouldn't cause 50% loss of data. It is more probable that there is some as-yet unidentified inconsistency in how PROOF models our new experiments.

5 Conclusions

We have performed several measurements of > 1 cm scale debris with the EISCAT radars after the Iridium-Cosmos collision to assess the shape of the produced debris cloud. All measurements detect a clear increase in debris during the two passes of the debris rings.

The measurements agree to some extent with PROOF model simulations, although there are also certain differences. The measured debris cloud is more clumped together than the model suggests. Also, the amount of detected debris in the real measurement (about 24-30 events per hour) is approximately 50% of that in the simulation. This can be partially explained by insufficient sensor modeling, which assumes a wider beam than actually used. Another possibility is unoptimal analysis, which fails to detect weaker events. However, the magnetic field aligned detection rate of 24 events per hour in the February 2009 measurement is more in line with previous measurements made in 2006 with the same radar [8], which suggests that the new analysis and radar experiment are consistent with previous ones.

6 Future Work

We plan to continue observing the time evolution of the Iridium-Cosmos debris cloud with EISCAT by analyzing all ≥ 24 h routine ionospheric measurements for space debris, and possibly performing dedicated space debris beam park observations.

In terms of data analysis, there is still work to be done, especially with the post-integration processing of detections. Currently, only one target is allowed to be observed at a time, which causes some simultaneous events to go undetected. A better post-integration algorithm is also likely to improve the sensitivity of the analysis.

The tri-static beam-park campaign is still being processed. One goal is to produce estimates for orbital elements of the multi-static detections that were found. Similar work has already been done at EISCAT for determining micrometeor orbits from tri-static measurements [3]. We have also attempted a tracking experiment for the Envisat-satellite, using low quality TLE to point the UHF antenna. The goal of this experiment was to see if EISCAT can be used for obtaining precise orbital elements.

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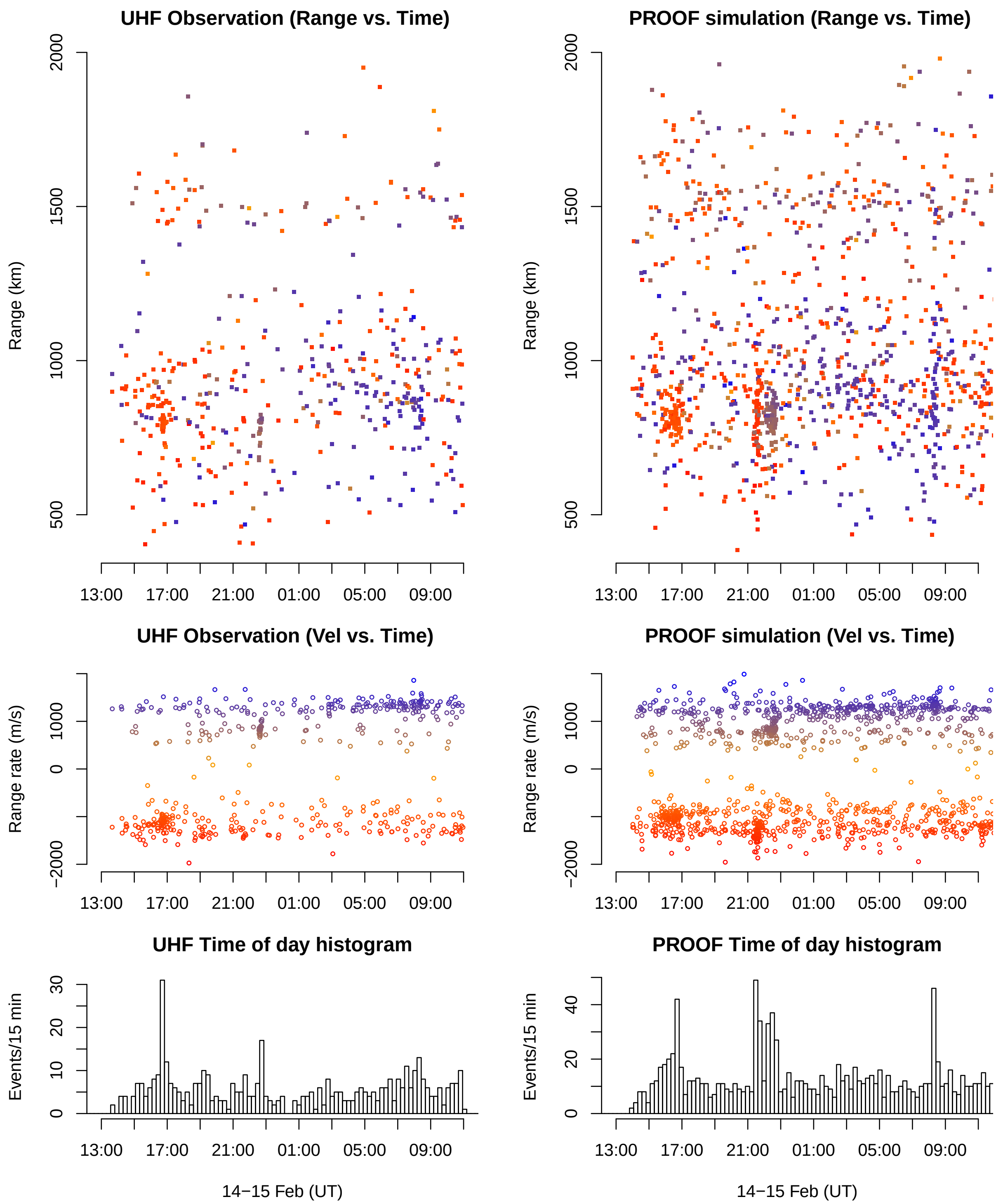

Figure 2: Detections from the 14-15 February 2009 21 h beam-park experiment. The left-hand side shows the monostatic measurement made with the Tromsø radar. The right-hand side shows the simulations produced with the PROOF tool. Doppler shifts are color-coded with colors indicated by the middle panel. The Iridium cloud passes at ≈ 08:30 and 22:00, and the Cosmos cloud passes at ≈ 16:45 and 22:45.

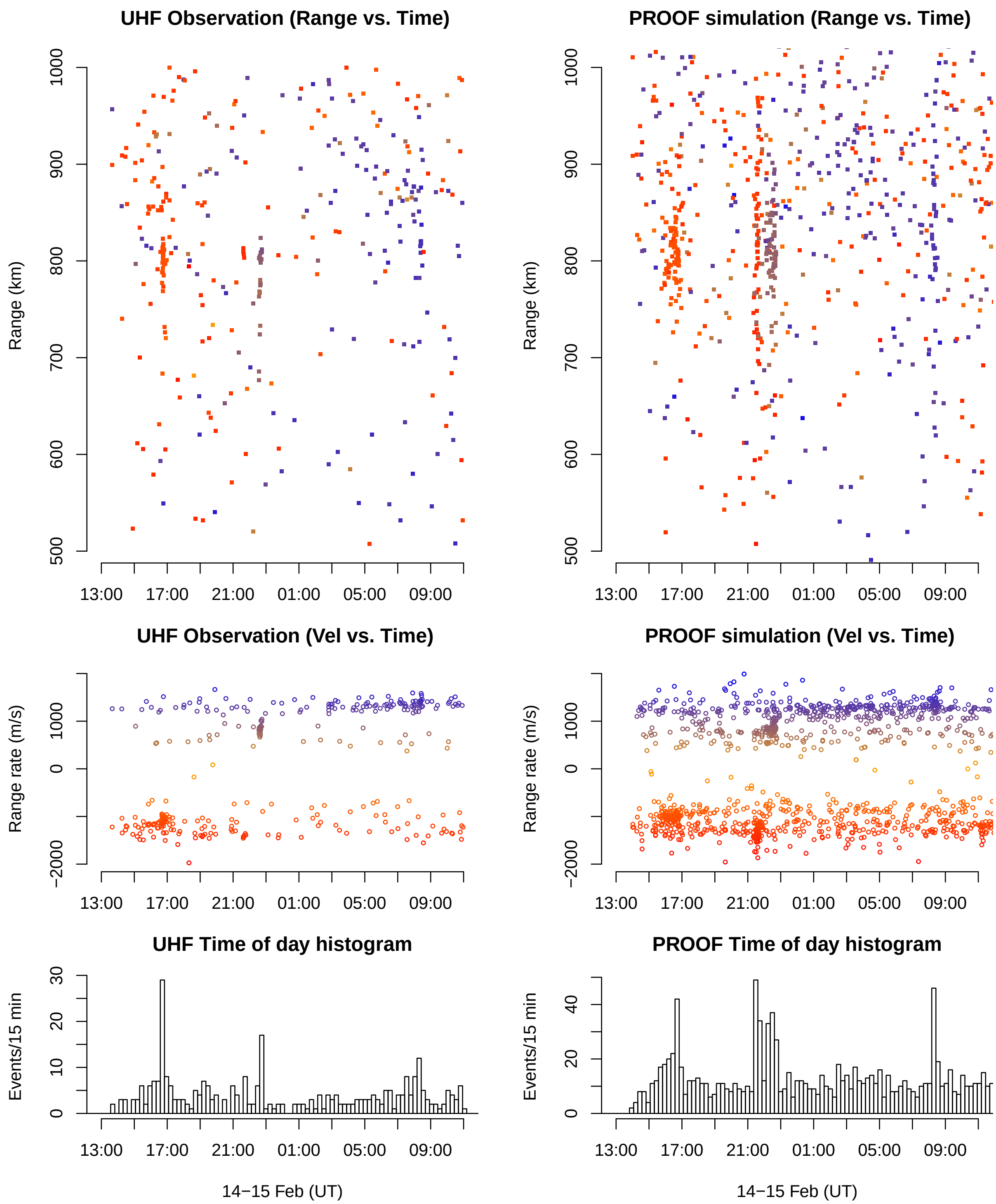

Figure 3: The same as Fig. 2., but ranges restricted to between 500 and 1000 km.

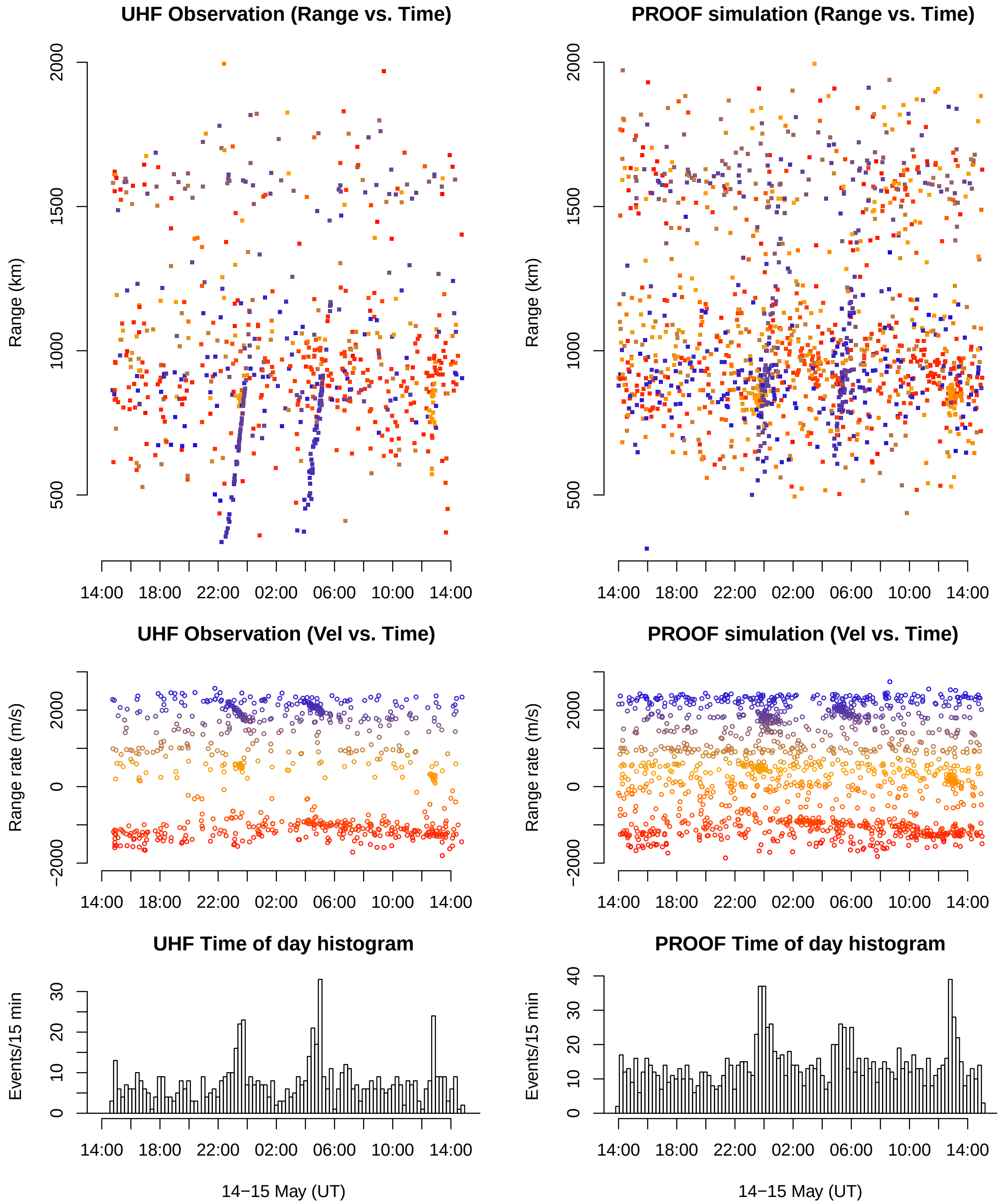

Figure 4: Detections from the 14-15 May 2009 beam-park experiment. The left-hand side shows the real monostatic measurement made with the Tromsø radar. The right-hand side shows the simulations produced with the PROOF model. The Iridium cloud passes at ≈ 00:00 and 13:00, and the Cosmos cloud passes at ≈ 00:00 and 06:00.

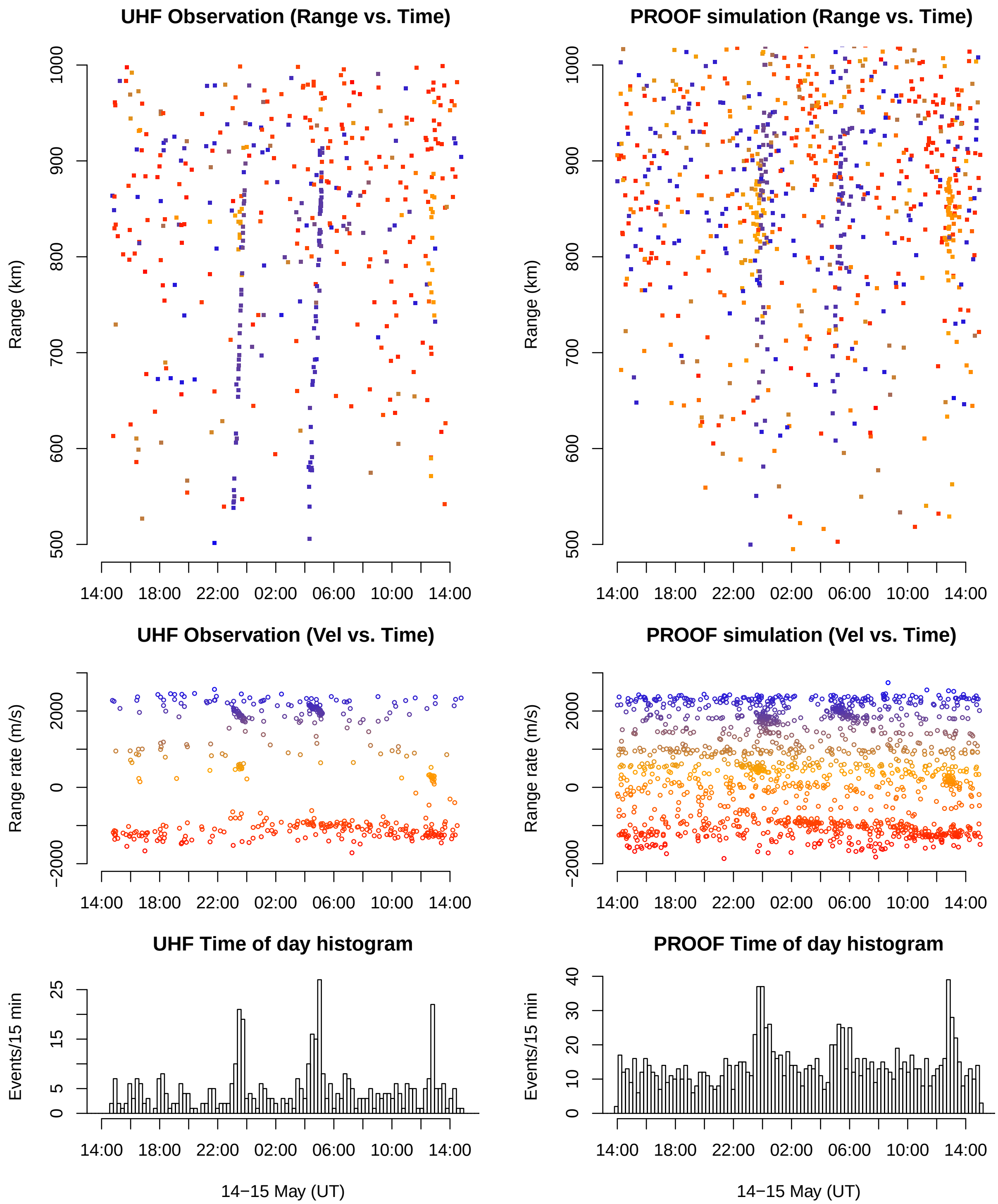

Figure 5: The same as Fig. 4., but ranges restricted to between 500 and 1000 km.

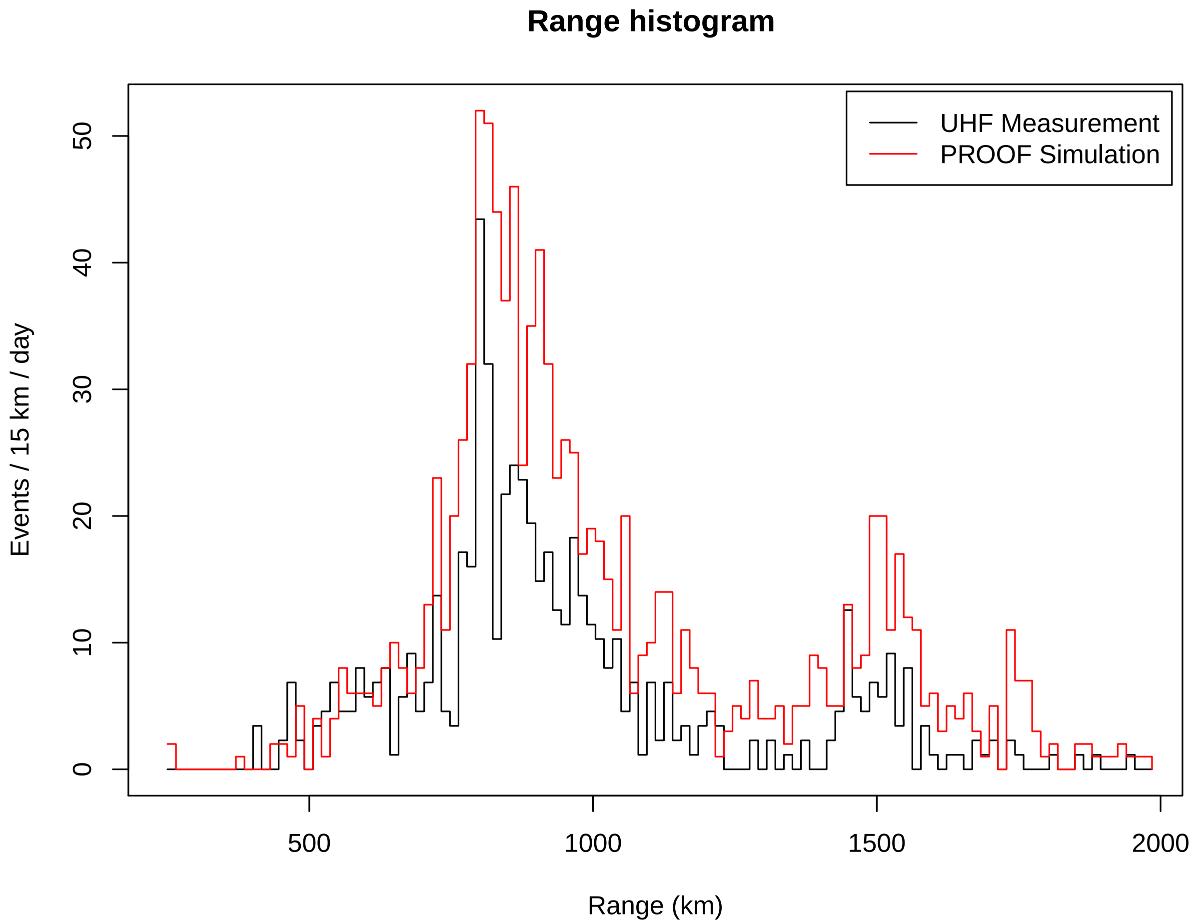

Figure 6: Range histograms for the PROOF simulation and the measured data for the 14-15 February 2009 measurement. The general shape of the measurement agrees with the simulation, although the simulation predicts significantly more detections.

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