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Interactive comment on "Ducting of incoherent scatter radar waves by field-aligned irregularities" *by* Michael T. Rietveld and Andrew Senior

Michael T. Rietveld and Andrew Senior

mike.rietveld@eiscat.uit.no

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We thank both referees for their positive and constructive comments. Before responding to their specific comments we point out an error in the results in the submitted manuscript. In checking and extending the raytracing after submission, we realised that the cone of rays transmitted from the antenna was narrower than the 0.6° implied in the paper ('approximately inversely proportional to...'). A repeat of the raytracing results with the corrected launch cone gives essentially similar patterns to those in Figures 6-9 but with lower enhancements at the longer wavelengths. We also extended the modelling to longer wavelength irregularities (535m instead of 444m) to show that the enhancements from 600 km had mostly peaked around or slightly below this longest wavelength. Figures 6-9 have been updated with the corrected modelling results.

In response to specific points below we have modified all the other figures in the paper as well. Line numbers (e.g. L83) refer to those in the originally submitted MS unless otherwise specified. We believe that we fixed all the technical and grammatical errors in the manuscript pointed out by both referees.

Both referees commented that the residual value seems nearer two rather than one. It is indeed a feature we cannot fully explain, but is most likely related to how the expected errors (variance) of the autocorrelation functions are calculated. The residual is the difference between theoretical autocorrelation function and measured values/expected_difference. So, if the variance of the points is correctly calculated and the theory correct it should be 1. One needs to weight against the number of free parameters as well. The residuals in Fig.1 used the variance of the measured points as the expected difference. Our expert in EISCAT says "Normally (always) we calculate the variance from the variation between dumps, and there is a minimum value of 6 estimates for each point to get a good variance. 6 is a rather arbitrary/practical value. When we have less than 6, we look at the variance along the profile as well, until we get at least 6 estimates along time or range." In the data shown here the dump time is 5s, so that 6 estimates were used. He suggests that we should use purely theoretical variances, but this was too slow in the past. During the corona virus period he sped up the calculation such that it takes only a fraction of the fitting time. The residual based on this theoretical variance is shown in the revised fig.1. The main feature relevant to this paper is that it is near 1 for the height range of interest, but higher values are now seen between about 150 and 200 km. This is presumably because the theory is non-linear and one assumes homogeneous volumes in the theoretical variance calculation so that any gradient of the parameters, such as in the bottomside ionosphere, and the change in the ion composition in this region, makes the residual increase. Results where the residual was greater than ten are shown as white spaces. We have added most of these details in the text (lines 90-97, revised version) as well as in the figure caption.

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Responses to referee#1: L83: A sentence has been added mentioning other gyro-harmonic effects and several references to them. L86: Answered above. L154: The sentence has been expanded so that it should be clear now. L184: It should be “and”. The sentence is expanded to explain why both were used: Octave was used initially and later MATLAB to speed things up. Figs. 6-9: The wiggles in the plots may not be real. In the revised figs. 6-9 we join the modelled points with straight lines rather than a smoothed curve. To better show the significance of the modelled points we show three points with error bars in new Figs. 6-9 for the case of A=1x10-6. These error bars are the spread in the results after repeating the raytracing 6 times. As stated in the text, the 30 backscattered rays are launched with a random spacing between ± 0.32° so that there will be a different spread in the rays arriving at the antenna on each recalculation. We have added a paragraph explaining these ‘error’ bars in lines 306-310 in the revised text. L286: The sentence has been re-phrased. L340: Corrected and expanded as suggested.

Responses to referee#2: L86: see above L96: A reference to Bryers et al. 2013 has been added and the sentence expanded to compare with resonant heating by O-mode waves. Figure 1. The red lines indicating HF on times have been converted to red bars and moved between the first and second panels nearer the time ticks and labels. L145-179: We agree that a schematic diagram illustrating the raytracing geometry would be very helpful. We have modified Figs. 2 and 3 in orientation (swapped x and y variables) and added shading to show the irregularity region and their parameters. A new Fig.4 shows a sketch of the geometry and two representative rays for the cases without and with irregularities, together with histograms at the top showing the distribution of rays from the transmitter arriving at 600 km. More details of the irregularity modelling are also added in the text (lines 197-207), including the equation describing the irregularities (new Eq.1). A new Fig.5 shows the merged old Figs.4 and 5 of the final distribution of rays arriving at the ground from the 600 km level for the two cases without and with irregularities. L158-160: Actually, the assumed 100 m spacing is unnecessary and has been changed to tens of meters. For the ray-tracing it is just necessary that it is much longer than the radar wavelength The assumed value of the density depletion is in line with rocket measurements made at Arecibo and a reference has been added here to Kelley et al., 1995 as well as in the subsequent discussion in section 6.

Revised Figs. are attached here

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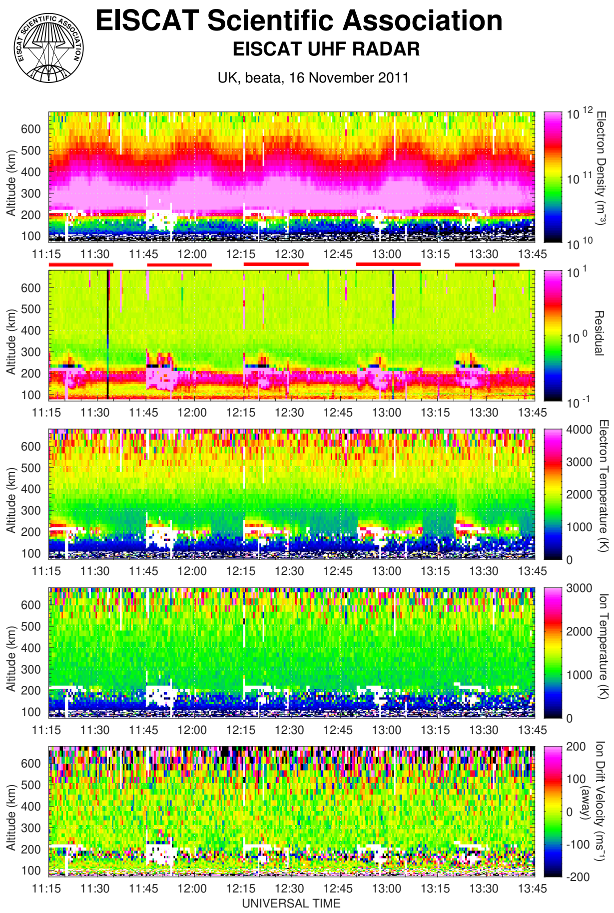

Fig. 1. An example of wide altitude ion line enhancements (WAILE). The top panel shows the enhancements interpreted by the analysis as an electron density increase between about 200 km and 600 km. The HF on t

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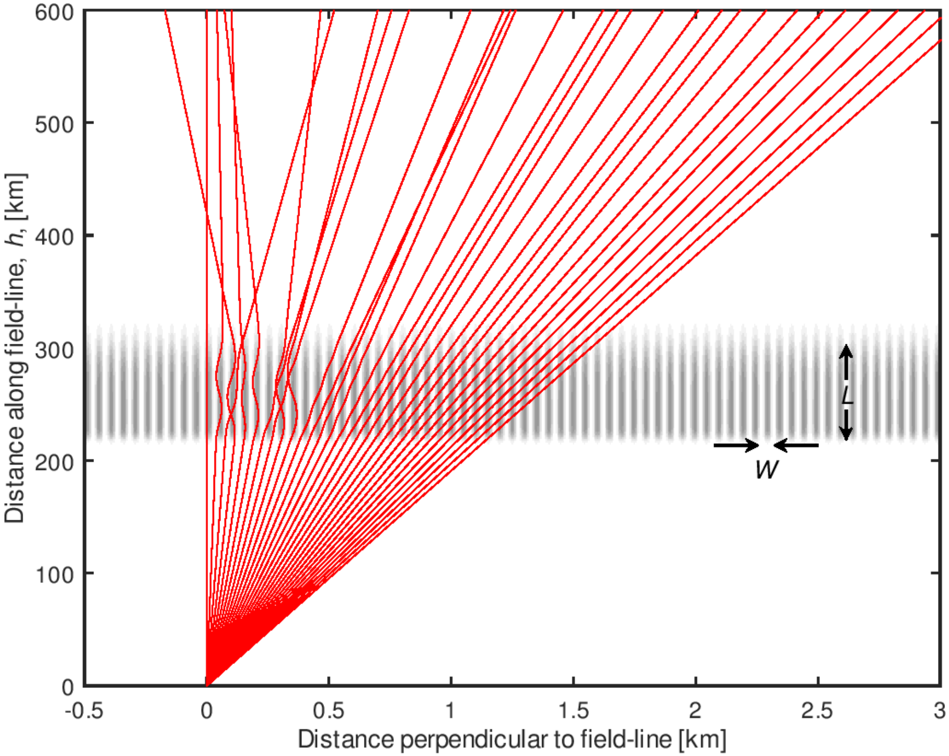

Fig. 2. Ray paths of a set of 30 up-going 933 MHz waves from the transmitter at (0,0) with launch zenith angles evenly spaced between 0 and 0.3° passing through a region of vertically aligned irregularities,

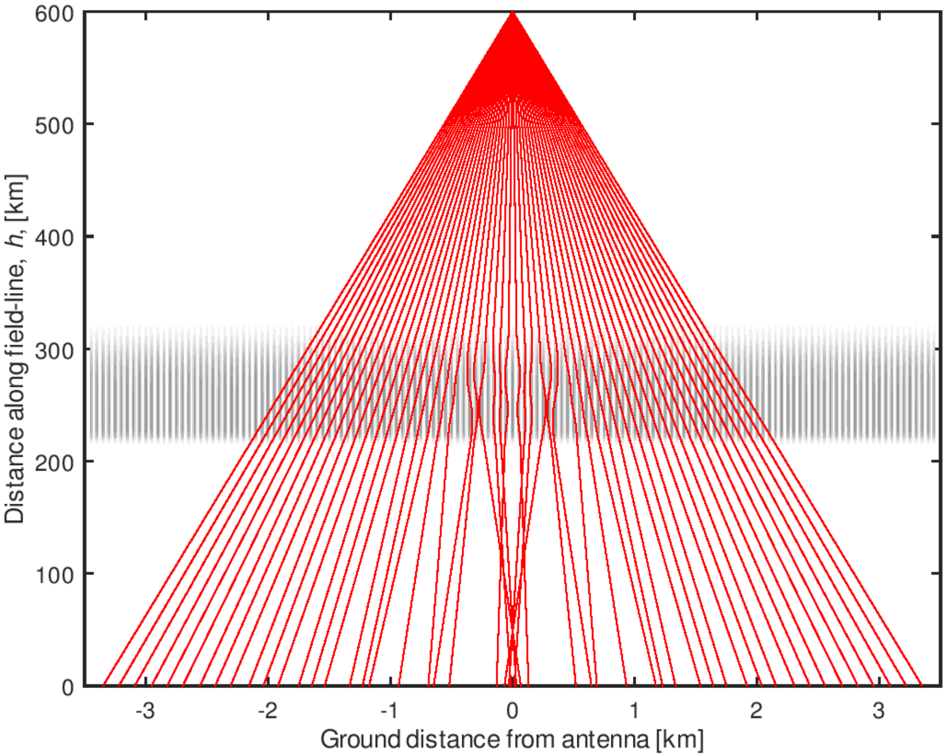

Fig. 3. Backscattered down-going 933 MHz rays from one up-going ray which arrived at 600 km. The 51 rays pass through the same region of irregularities as in Fig. 2 with A = 1 x 10-6, W = 50 m and L = 80 km b

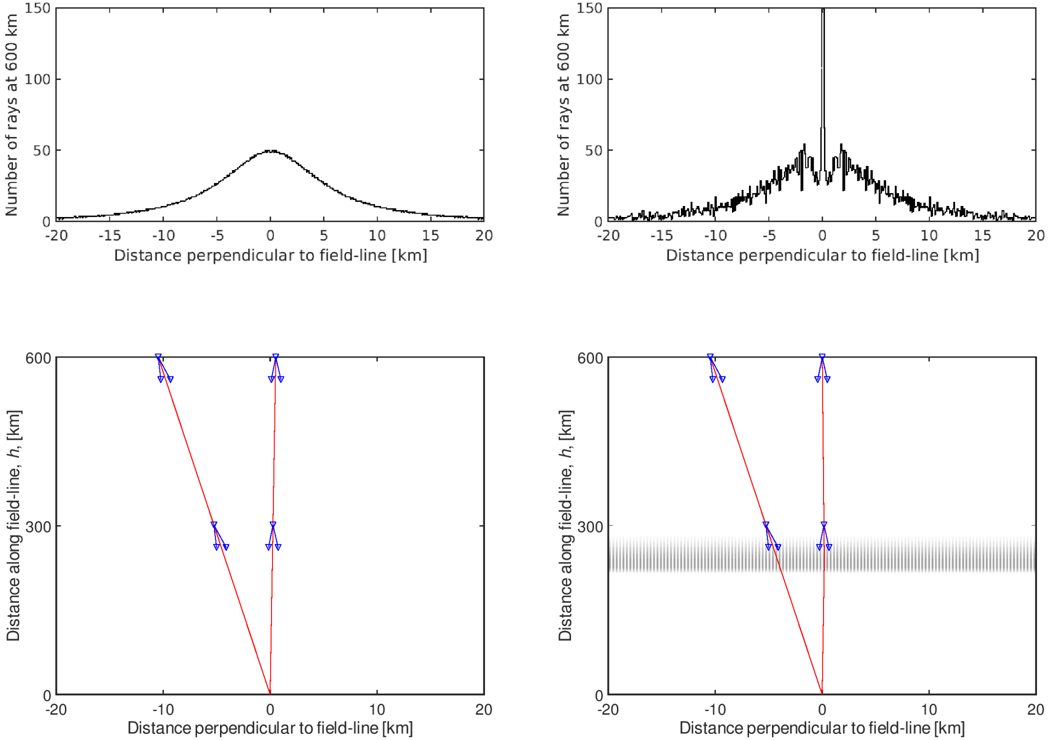

Fig. 4. Schematic diagram of the model showing (in red) two out of thousands of rays launched from the transmitter at (0,0), for the free-space case on the left and with irregularities (in grey) on the right.

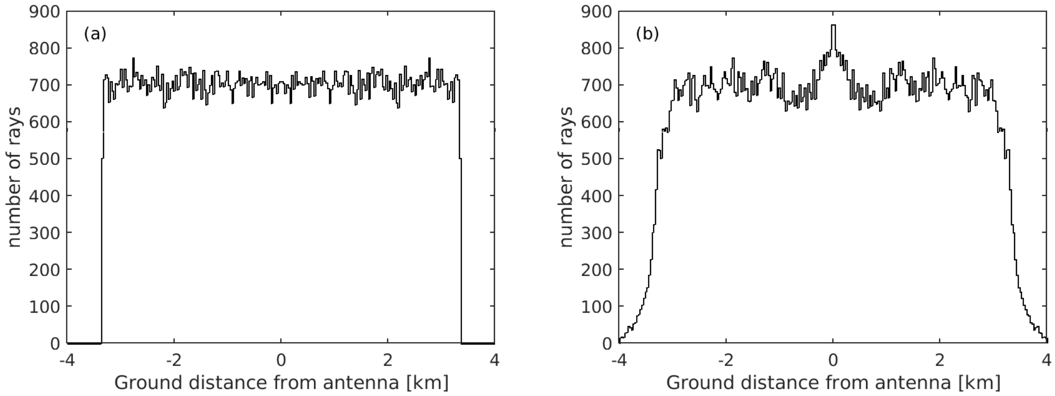

Fig. 5. Histograms of the number of rays arriving on the ground from 600 km, for (a) when no irregularities are present and (b) after propagating through irregularities having parameters A = 1 x 10-6, W = 50

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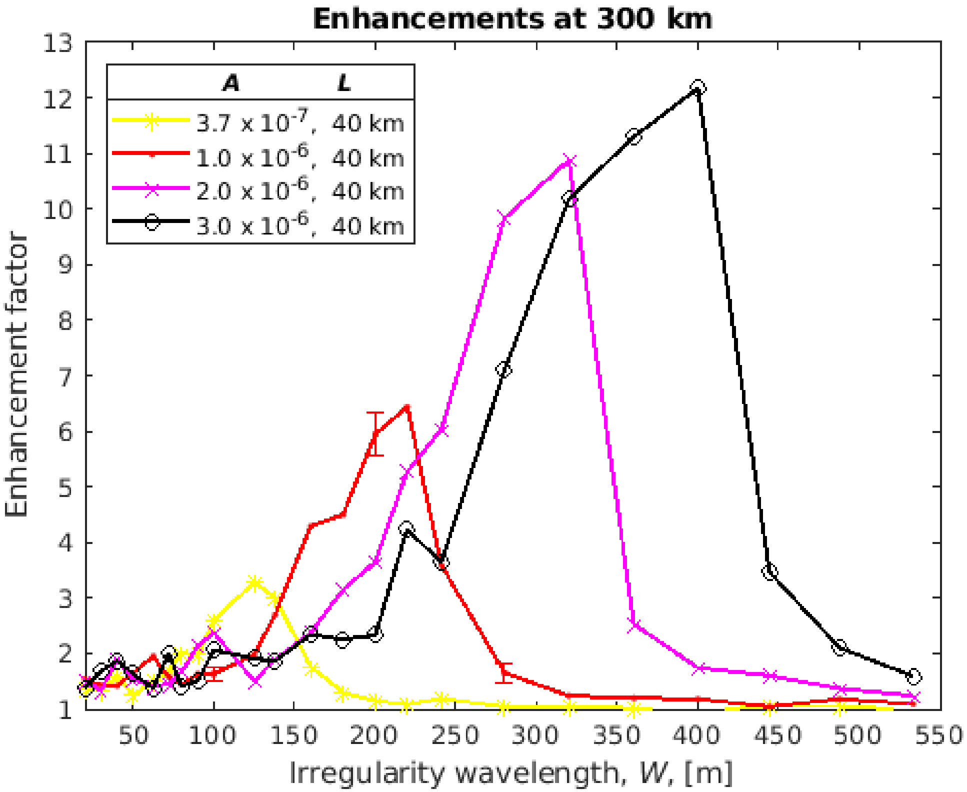

Fig. 6. Enhancement factors for 933 MHz backscatter from 300 km calculated from the density of rays entering the antenna beam compared to the case of free space propagation, for various depths of irregularity

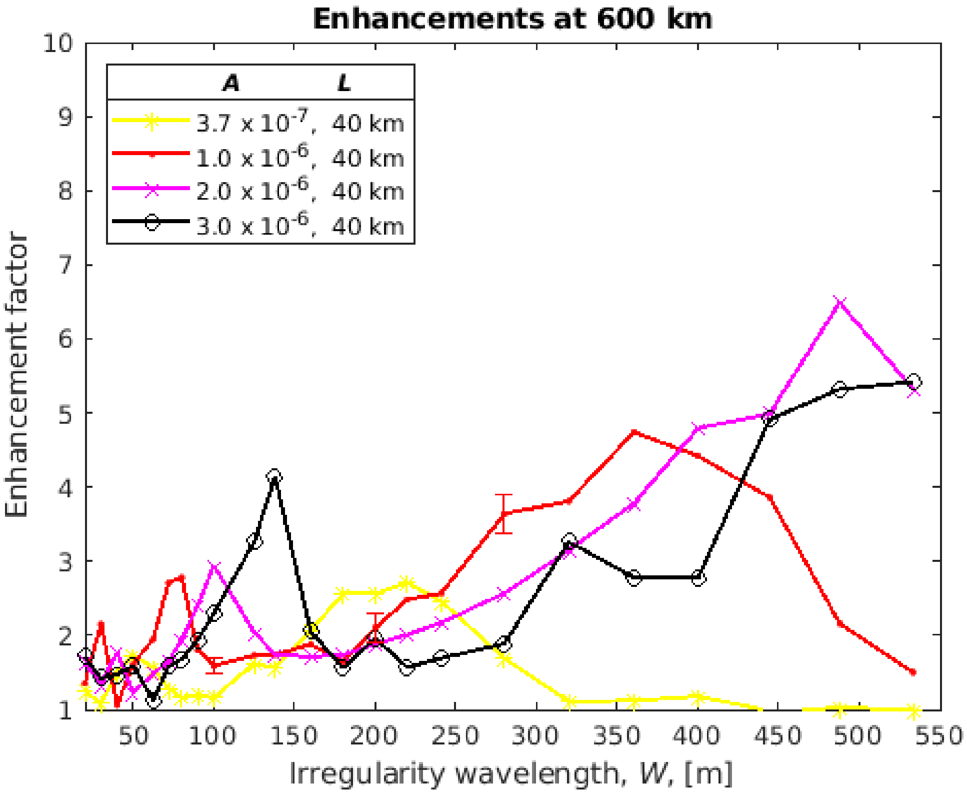

Fig. 7. Enhancement factors for 933 MHz backscatter from 600 km calculated from the density of rays entering the antenna beam compared to the case of free space propagation, for various depths of irregularity

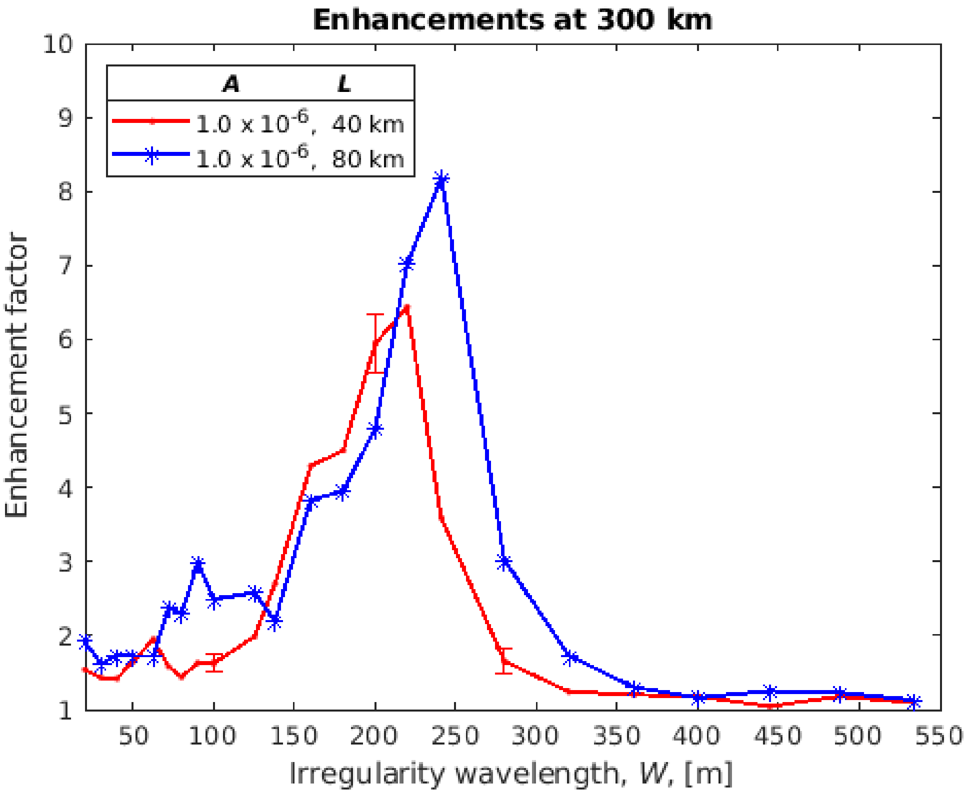

Fig. 8. Enhancement factors for 933 MHz backscatter from 600 km for two lengths of the irregularity, L, along the field line for a fixed irregularity depth, A.

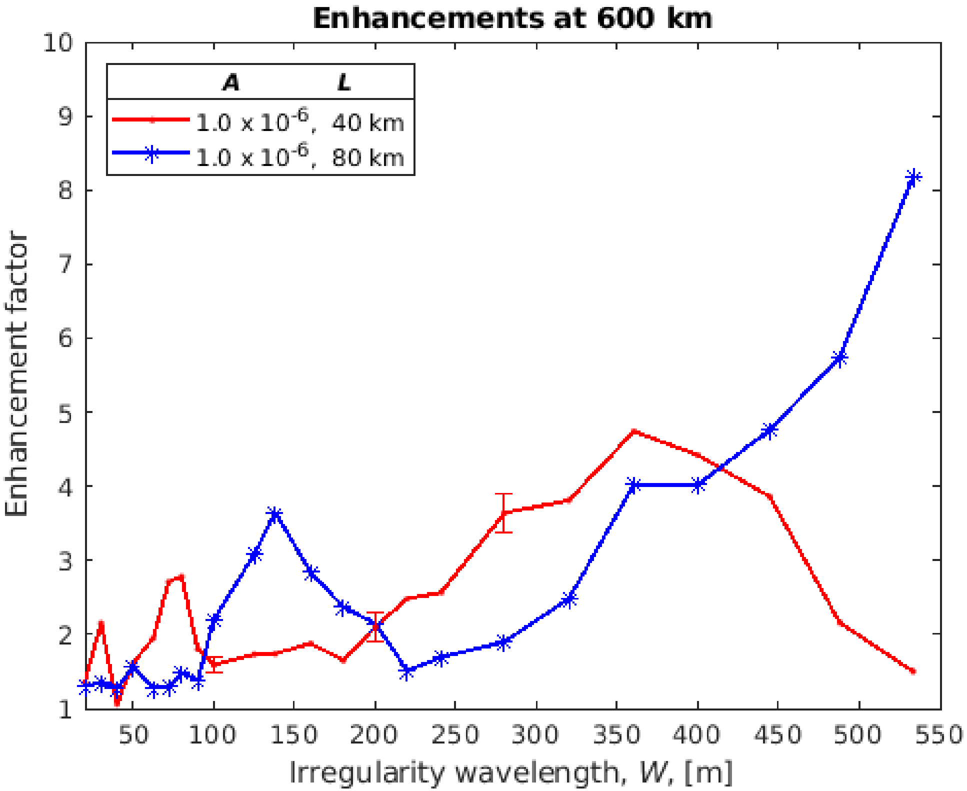

Fig. 9. Enhancement factors for 933 MHz backscatter from 600 km for two lengths of the irregularity, L, along the field line for a fixed irregularity depth, A.

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