The Effect of Precipitation on Wind-Profiler Clear Air Returns

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Abstract

A small number of recent studies have indicated that reductions in the signal strength of clear air returns can be observed at low altitudes in regions of precipitation. This study uses data from the NERC MST radar facility in Aberystwyth (52.4°N, 4.1°W) and co-located tipping bucket rain gauge data to determine whether this effect can be observed for all periods where high rainfall rates were observed at the ground. The period selected for examination includes all of the days where a peak rainfall rate of 1 mm h^{-1} was exceeded in 2001. A statistical examination of VHF radar signal power during periods with and without surface rainfall suggests that the returned power is reduced by the presence of precipitating clouds. The corrected spectral width of the Doppler spectra is also significantly wider during periods of precipitation. The process which causes the decrease in the VHF signal power seems to be associated with a reduction in Fresnel reflection within precipitating clouds. This in turn may be due to a reduction of humidity gradients in clouds. Use is also made of UHF wind profiler data to determine whether there is a relationship between enhanced UHF returns (signifying precipitation) and reduced VHF returns. To clarify the processes and effects observed we examine two case studies which show typical relationships between the VHF signal power and surface rainfall or enhanced UHF signal to noise ratios. The effect of precipitation on the signal processing scheme's derivation of signal power and spectral width is explored using individual Doppler spectra.

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1 Introduction

Wind profiler radars operating at very high and ultra high frequencies (VHF and UHF, respectively) are sensitive to both clear air returns, from radio refractive index irregularities, and Rayleigh scattering, from distributed targets such as hydrometeors. The dependence of both mechanisms on wavelength means that UHF and VHF radars have very different sensitivities to these processes. A largely theoretical study described in Ralph (1995) reveals that only under conditions of heavy rain ($>$8.4 mm h^{-1}) is the Rayleigh scattered signal expected to exceed the clear air radar return at VHF. At UHF wavelengths, however, rainfall rates characteristic of light rain or drizzle are sufficient for the Rayleigh scatter to dominate the clear air returns. These conclusions are consistent with the results described in Currier et al. (1992) which indicate that two radars which operate at 915 MHz (UHF) and at 50 MHz (VHF) displayed very different sensitivities to clear air and precipitation returns. Specifically the 50 MHz radar provided primarily Doppler information on the non-precipitating background atmosphere, while the 915 MHz radar provided precipitation information, with minimal clear air information even during weak precipitation periods. However, it should be noted that a number of studies have also indicated that VHF radar data can be used to observe precipitation echoes at much lower rain rates (Wakasugi et al., 1986).

The benefits of simultaneously observing precipitation and clear air turbulent activity using a combination of UHF and VHF radar has been recognized by the scientific community for several years. The sensitivity of these profilers to motions of hydrometeors has enabled studies of the vertical structure of precipitating clouds to be made. This vertical structure is important in understanding how the distribution of latent heating affects the atmospheric circulation and how to better parameterize precipitating clouds in numerical models. In addition this capability has allowed many precipitation related parameters and features incapable of being obtained from conventional microwave radar, including the terminal velocity of hydrometeors, drop-size distribution, and the three-dimensional wind-field in a raincloud, to be observed accurately. In particular a great deal of attention has been paid to accurately determining the drop size distribution of hydrometeors. The latter is inferred from the the spectrum of raindrop terminal fall speeds. However, a correction must be made for the vertical air velocity which offsets the whole spectrum (Atlas et al., 1973). The accuracy of distributions derived from microwave radar observations is therefore limited by the fact that these radars are primarily sensitive to hydrometeor returns. The value of the vertical air velocity must therefore be assumed. Thus, under many conditions combined UHF and VHF radar data is necessary to evaluate precipitation information accurately.

Chu and Song (1998) analyzed VHF radar returns from hydrometeors and refractivity fluctuations associated with a cold front. A composite analysis of the precipitation echo intensity and the vertical air velocity indicated that the latter plays a vital role in the formation of the bright band. VHF radar reflectivity from precipitation at the height around the melting layer may be enhanced for weak vertical air velocity, while the bright band may be disrupted if the upward vertical air speed is large. These updrafts may also diminish the echo intensity from refractivity fluctuations through the mechanism of turbulent mixing. They postulate that a plausible mechanism for the depletion of the precipitation echo accompanying an intense updraft in the height range of the melting layer is the process of turbulent mixing. Their study also suggested that the depletion of the clear air echo power can be attributed to the turbulent mixing between warm and humid in-cloud air and cool and dry ambient air entrained into the cloud following a strong updraft.

Vaughan and Worthington (2000) investigated the variation in power of VHF radar vertical echoes as a function of atmospheric humidity. Their work indicated that the observed echoes are greatest in air of moderate humidity, and least in very dry or near-saturated air. The standard Fresnel scattering model for relating clear air echo power to the mean vertical gradient of generalised potential refractive index thus seems to overpredict echo power at high relative humidities (Ottersten, 1969). Their study proposes that this is due to the effect of precipitation in supressing small-scale humidity gradients. Their study also suggests that the echoes are more isotropic, and their spectra are broader, at high humidity, indicating a greater contribution from turbulent scatter than Fresnel scatter. The present study aims to examine the effects of precipitation on clear air returns using a combination of surface rainfall measurements and co-located VHF and UHF radar observations.

2 Instruments and Measurement Strategy

The NERC MST radar at Aberystwyth (52.4°N, 4.1°W) operates at a frequency of 46.5 MHz and has a peak transmitted power of 160 kW. The antenna consists of a 20 by 20 array of four element Yagi aerials covering an area of 110 m by 110 m. The radar beam has a one-way half power width of 1.5 degrees and can be directed in sixteen possible directions, these directions being vertical and at angles of 4.2, 6, 8.5 and 12 degrees off-vertical.

Several recent studies have described methods used to derive parameters from Doppler spectra. Normally these processing schemes aim to determine the returned signal power, Doppler shift and spectral width associated with the clear air returns observed at VHF frequencies. Studies which discuss this type of analysis include Barth et al. (1994), Hocking (1997), Hooper (1999), and May and Strauch (1998). More complicated processing schemes can also be used to attempt to separate the characteristics of any precipitation signal from the clear air signal (Wakasugi et al., 1986; Rajopadhyaya et al., 1994). In this study, the standard processing scheme used by the NERC MST radar, described in Slater et al. (1991), is used in a statistical examination of the data. A more complicated scheme, similar to that described in Rajopadhyaya et al. (1994), is also used to identify the precipitation and clear air signals in a case study to show the difficulty in separating these signals at low rainfall rates.

The surface rainfall rate used in this study is measured by an ARG100 raingauge. The amount of rain collected is measured by the well-proven tipping bucket method. A contact closure at each tip is recorded by a datalogger and the number of tips during a 10 minute interval is recorded. Thus, the rain gauge measures the integrated rainfall for a given time interval. In addition use is made of data from a (UK) Met Office 915 MHz (UHF) boundary-layer wind-profiler which was co-located with the NERC MST radar between 17th November 1999 and 11th March 2002. The useful altitude coverage of the UHF profiler varies with the measurement mode utilised and atmospheric conditions and generally only extends significantly above 2 km when precipitation is present. Although the cycle time for observations is of the order of a few minutes, the available data represents a consensus average over 30 minutes.

3 Results

This study uses data from the NERC MST Radar facility at Aberystwyth in mid-Wales. Examples of the effect of precipitation on the observed signal power are shown after a statistical analysis of the effect of precipitation on VHF returns. To examine the role of precipitation on clear air returns statistically a number of days associated with high rainfall rates at the surface were selected. High rainfall days were defined in this study as days where the surface rainfall rate was greater than 1 mm h^{-1} for a continuous period greater than 10 minutes. A total of 33 days during the calendar year 2001 were selected using this criterion. Later in the statistical analysis co-located UHF wind-profiler measurements are used to examine the statistical relationship between precipitating cloud regions (associated with large signal to noise ratios in the UHF signal at high altitudes) and the VHF returns. A subset of 17 days from the 33 days previously selected is used in this analysis because of a lack of simultaneous UHF data during many days.

3.1 Statistical Analysis

Table 1 shows the mean signal power, for three altitude regions, associated with surface precipitation and non-precipitation conditions. As a check, two different threshold rainfall rates (0 mm h^{-1} and 0.5 mm h^{-1}) are used to distinguish precipitation conditions from non-precipitation ones. When the mean signal power is calculated from VHF data between 2 and 4 km using a rainfall threshold of 0 mm h^{-1} (rain and no rain periods) a clear decrease of roughly 3 dB is observed during rainfall. Between 4 and 6 km this difference decreases to 0.4 dB and at 16 – 18 km is only 0.1 dB. This decrease indicates that this change is not associated with increased noise levels at all altitudes caused by rain static. The observed altitude dependence also seems to suggest that precipitation between 2 and 4 km causes this change. When the rainfall threshold is increased to 0.5 mm h^{-1} the difference between the signal powers remains approximately the same for measurements between 2 and 4 km. However, seperating VHF signal power data into periods of heavier (rate greater than 0.5 mm h^{-1}) and lighter (rate less than 0.5 mm h^{-1}) surface rainfall changes the results for the 4 – 6 km altitude region giving rise to a difference of 1 dB. It is suggested that this is caused by the larger vertical extent of convective precipitation which is generally responsible for the highest rainfall rates at this location. Table 1 also shows the number of events where the variation in the mean changes significantly at the 95% level. Examination shows that over half the events display a significant decrease in signal power during rainfall for averages derived from data between 2 and 4 km.

Examination of Table 2 shows that the vertical spectral width, which is corrected for the effect of beam broadening, observed during periods above the surface rainfall threshold is larger than that during periods when the surface rainfall threshold is not exceeded. Table 2 also shows the number of events when the spectral width increase during rainfall is significant. It is interesting to note that this effect is much more pronounced than the signal power decrease with nearly all days (25 out of 33) showing a significant increase in spectral width. This statistical increase either suggests that a combination of clear air and precipitation returns is observed by the standard signal processing scheme used by the VHF radar or that a large contribution is observed from turbulent scatter inside precipitating clouds. If this increase in the spectral width during periods of rainfall is associated with a combination of clear air and precipitation returns it is highly significant; this is because it indicates that the signal power observed is also a combination of both precipitation and clear air returns suggesting that the true reduction of the clear air return must be even larger than indicated since some part of the observed signal power will be associated with the precipitation return.

A closer examination into whether the change in the VHF signal return is associated with precipitation measurements is achieved using the signal to noise ratio (SNR) between 2 and 4 km of a UHF wind profiler. Table 3 displays the mean VHF signal power averaged over the 2 to 4 km range during periods where the mean UHF SNR averaged between 2 and 4 km is greater or less than a threshold value. During the periods where the mean SNR of the UHF signal is greater than 0 dB the signal observed by the VHF radar is 3.6 dB smaller than during the other periods. It should be noted at this point that if the subset of data used for the UHF data comparison is processed using a rainfall threshold the difference is only 2.8 dB. Thus, regions of precipitation identified by the UHF profiler seem to clearly correspond to regions of low signal power in the VHF return. This supports the conclusion that the clear air return is reduced in periods of precipitation. To clarify the processes and effects observed we examine two different case studies.

3.2 Case study 1: 17th May 2001

Figure 1 displays time-height contour plots of the vertical signal power and corrected spectral width observed by the VHF radar and the corresponding surface rainfall rate measured by a tipping bucket rain gauge. The negative correlation between VHF signal power and surface rainfall rate expected from the statistical study is clearly evident at the low altitudes. The positive correlation expected between beam-broadening corrected spectral width and surface rainfall rate is also apparent but not as clearly.

Examination of the UHF signal to noise ratio during this day (shown in Figure 1(c)) displays enhancements between 2 and 3 km during the period of intense rainfall. This indicates that hydrometeors are present in the range where the VHF signal power is reduced which again implies that the signal is affected by precipitation or some process associated with the precipitating clouds.

Examination of the UHF signal to noise ratio profiles during the period of rainfall (not shown) indicates the presence of a bright band during most periods. Previously, Williams et al. (1995) used the presence or absence of a bright band in the UHF signal profile in an automated algorithm to distinguish between convective or stratiform precipitating rain clouds. Thus, this data suggests that during stratiform rain a clear VHF signal power reduction can be observed. This is not as clear in rainfall periods associated with convection where signal power can sometimes increase during rainfall. However, an examination based on different precipitating cloud types is outside of the scope of the present study because of the relatively small data sample (only 33 days).

VHF radar Doppler spectra at 07:24 UT on the 17th May 2001 (close to the peak in the surface rainfall rate) are shown in Figure 2. Examination of these spectra shows clear indication of a secondary peak associated with a precipitation echo in nearly all the spectra displayed, the clearest secondary peaks being observed at lower altitudes. In addition, the width of the echoes is large at higher altitudes which is likely to indicate that the signal is associated with a combination of the clear air and precipitation return. It should be reiterated that if this is the case the decrease in clear air returns during precipitation will be larger than indicated since some part of the observed signal power would be associated with the precipitation return. This possibility has previously been indicated by the statistical increase in the spectral width observed during rainfall. Figure 2 also shows fits to possible clear air and Rayleigh scattering peaks using a technique similar to that described in Rajopadhyaya et al. (1994). It should be noted that examination of these fits and their residuals (not shown) displays the difficulty in trying to separate the observed data into these two signals, particularly at higher altitudes.

3.3 Case study 2: 5th October 2001

Figure 3 displays time-height contour plots of the vertical signal power and corrected spectral width observed by the VHF radar and the corresponding surface rainfall rate measured by a tipping bucket rain gauge measured on the 5th October 2001. Comparison of the vertical signal power and the surface rainfall in this case shows a less clear negative relationship than observed in Figure 1. Examination also indicates that on this day a clear relationship between the corrected spectral width and surface rainfall exists.

Examination of the UHF SNR during this day (shown in Figure 3(c)) displays enhancements between 2 and 6 km during periods of intense rainfall. This indicates that hydrometeors are present in the range where the VHF signal power is reduced which implies that the signal is affected by precipitation. It is particularly interesting to note in this case that a region which displays a decrease in the signal power observed by the VHF radar at approximately 15:00 UT does not correspond to surface rainfall. But does match well with a period of enhanced SNR observed by the UHF wind profiler at roughly 15:00 UT. This suggests that a signal associated with precipitating cloud is observed by both radars, but that the precipitation does not reach the surface.

4 Discussion

Chu and Song (1998) suggests that the depletion of the clear air echo power can be attributed to the turbulent mixing between warm and humid in-cloud air and cool and dry ambient air entrained into the cloud following a strong updraft. This conclusion can be tested by examining the vertical velocity field for the two days previously examined relative to the regions associated with depletion of the clear air returns. Assessment of the vertical velocity data on 17th May 2001 does not indicate any strong updrafts associated with the reduction in the clear air returns. However, the presence of strong turbulent mixing can not be ruled out. To further examine this possibility the signal power measured in the vertical beam relative to that measured by a six-degree off-vertical beam is assessed. Figure 4 shows the mean power imbalance between the vertical and the six degree beams signal power for averages taken between 2 and 4 km on the 17th May 2001. Comparison of Figure 1(a) and Figure 4 indicates that the signals observed are more isotropic during precipitation events. This change indicates that the type of scattering inside precipitating regions may be associated with turbulent scatter rather than Fresnel reflection which would lead to more anisotropic scatter. This result has previously been indicated by Vaughan and Worthington (2000) and suggests that Fresnel reflection might be reduced in precipitating clouds. However, both their study and the current work can not determine whether this is a result of a reduction in the small-scale humidity gradients in the clouds or some other process due to the limitations of the available data.

It is interesting to note that the Doppler spectra displayed in Figure 3 clearly indicate the presence of signals associated with both clear air and precipitation returns. The rainfall rate at this period is less than 5.0 mm h^{-1} and thus should not be observable according to the work detailed in Ralph (1995).In addition, the spectral width determined by the standard signal processing scheme, described in Slater et al. (1991), represents the signal from a combination of both precipitation and clear air returns at a number of heights. This is noteworthy because this implies that the reduction in the VHF signal power associated with clear air returns must be larger than indicated because the signal power determined is a combination of both the clear air and precipitation return. It should also be noted that this study suggests that VHF radar may be of considerably more use in precipitation studies than the theoretical study by Ralph (1995) indicates since the clear air return will be reduced and therefore not mask the precipitation return.

5 Conclusions

A statistical examination of VHF radar signal power during periods with and without surface rainfall suggests that the returned power is reduced by the presence of precipitating clouds. The process which causes this effect seems to be associated with a reduction in Fresnel refelction within precipitating clouds. This in turn may be due to a reduction of humidity gradients in clouds. However, the available data does not allow a clear conclusion to be drawn about the reduced Fresnel reflection observed.

The corrected spectral width of the Doppler spectra is also significantly wider during periods of precipitation. This may be associated with the difficultly in separating precipitation and Bragg scatter echoes or increased turbulence inside precipitating clouds. If the enhanced spectral width observed during rainfall is associated with a contribution from Rayleigh scatter, then the effect on the clear air return is more substantial than suggested since at least some proportion of the signal measured will be associated with precipitation returns.

When UHF wind profiler measurements are compared with the signal power observed by the VHF radar a clear relationship between enhanced signal to noise ratios in the UHF wind profiler data (which are very likely to be associated with Rayleigh scattering from hydrometeors) and reductions in the VHF signal are also observed.

Two case studies also display the clear relationship between reduced VHF signal power and surface rainfall or enhanced UHF radar returns. Typical Doppler spectra taken from the 17th May 2001 clearly indicate the possibility of echoes associated with a combination of the clear air and precipitation returns. Thus, suggesting that the standard signal processing scheme may reduce the impact of the observed effect.

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Tables

Height range (km)	Surface rainfall threshold (mm h^{-1})	Mean VHF signal power during periods when the surface rainfall threshold was exceeded (dB)	Mean VHF signal power during periods when the surface rainfall threshold was NOT exceeded (dB)	Values (positive/negative)	Significant decreases/Total
2-4	0.0	72.6	75.6	3/30	18/33
4-6	0.0	66.2	66.6	13/20	10/33
16-18	0.5	40.0	39.9	13/20	6/33
2-4	0.5	72.2	75.1	7/26	13/33
4-6	0.5	65.6	66.6	14/19	7/33
16-18	0.5	40.0	39.9	13/20	6/33

Table 1. The mean VHF signal power averaged over the height range indicated during periods where the indicated rainfall threshold was and was not exceeded is shown. In addition the number of positive and negative changes in the mean signal power associated with rainfall and the number of significant decreases in the signal power associated with periods of surface rainfall above the indicated threshold are shown. The surface rainfall is observed by a tipping bucket rain gauge co-located with the VHF radar.

Height range (km)	Surface rainfall threshold (mm h^{-1})	Mean VHF spectral width during periods when the surface rainfall threshold was exceeded (m s^{-1})	Mean VHF spectral width during periods when the surface rainfall threshold was NOT exceeded (m s^{-1})	Values (positive/negative)	Significant increases/Total
2-4	0.0	0.31	0.22	30/3	25/33
4-6	0.0	0.21	0.17	29/4	16/33
16-18	0.0	0.08	0.10	14/19	1/33
2-4	0.5	0.36	0.23	31/2	22/33
4-6	0.5	0.23	0.18	28/5	12/33
16-18	0.5	0.08	0.10	13/20	1/33

Table 2. The mean VHF spectral width averaged over the height range indicated during periods where the indicated rainfall threshold was and was not exceeded is shown. In addition the number of positive and negative changes in the spectral width and the number of significant increases in the spectral width associated with periods of surface rainfall above the indicated threshold are shown. The surface rainfall is observed by a tipping bucket rain gauge co-located with the VHF radar.

UHF SNR between 2 and 4 km (dB)	Mean VHF signal power during periods when the UHF SNR threshold is exceeded (dB)	Mean VHF signal power during periods when the UHF SNR threshold is NOT exceeded (dB)	Values (positive/negative)	Significant increases/Total
0.0	72.2	75.9	3/14	13/17
5.0	71.5	75.4	2/16	9/17

Table 3. The mean VHF signal power averaged over the 2 to 4 km height range during periods where the UHF signal to noise ratio was greater or less than the thresholds indicated are shown. The number of positive and negative changes in the VHF signal power and the number of days where a significant decrease in signal power was associated with large UHF signal to noise ratios are also shown.

Figure Captions

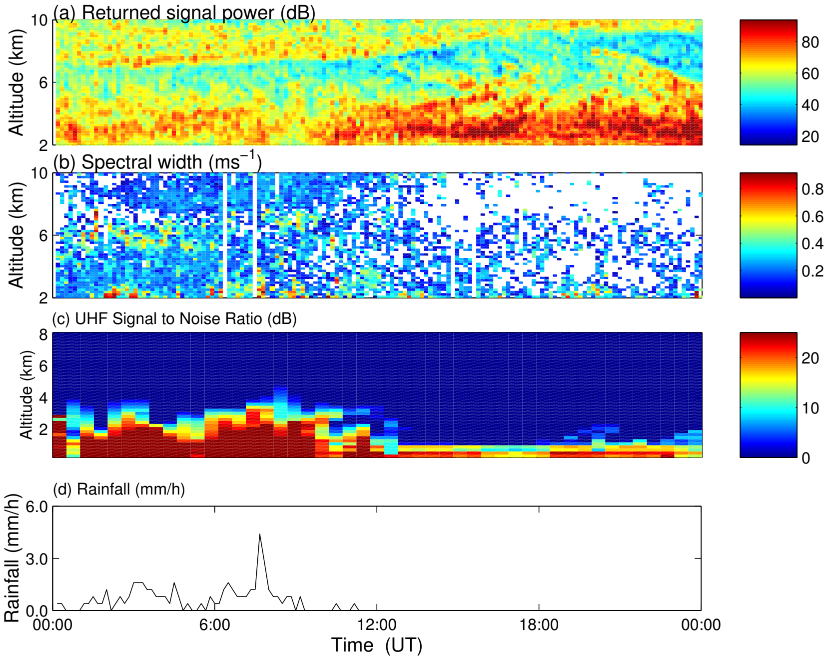
Fig. 1. Time-height contour plots of (a) vertical signal power (dB), (b) vertical corrected spectral width (m s^{-1}) observed by the VHF radar, (c) the vertical signal to noise ratio measured by a co-located UHF wind profiler (dB) and (d) the variation of surface rainfall observed by a tipping bucket rain gauge on 17th May 2001.

Fig. 2. VHF Doppler spectra taken at 07:24 UT on the 17th May 2001, the observation altitude being shown for each spectrum. The black line represents the raw data and the dotted and dashed lines show fits to any possible Rayleigh or clear air echoes using a technique similar to that described in Rajopadhyaya et al. (1994).

Fig. 3. Time-height contour plots of (a) vertical signal power (dB), (b) vertical corrected spectral width (m s^{-1}) observed by the VHF radar, (c) the vertical signal to noise ratio measured by a co-located UHF wind profiler (dB) and (d) the variation of surface rainfall observed by a tipping bucket rain gauge on 5th October 2001.

Fig. 4. The mean power imbalance observed by the VHF radar between the vertical and the six degree off-vertical beams averaged over the region 2 to 4 km for observations made on the 17th May 2001.

Figures



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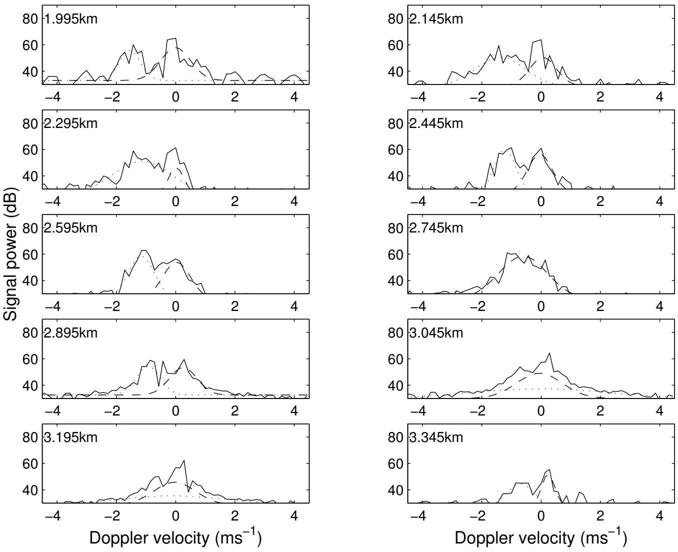

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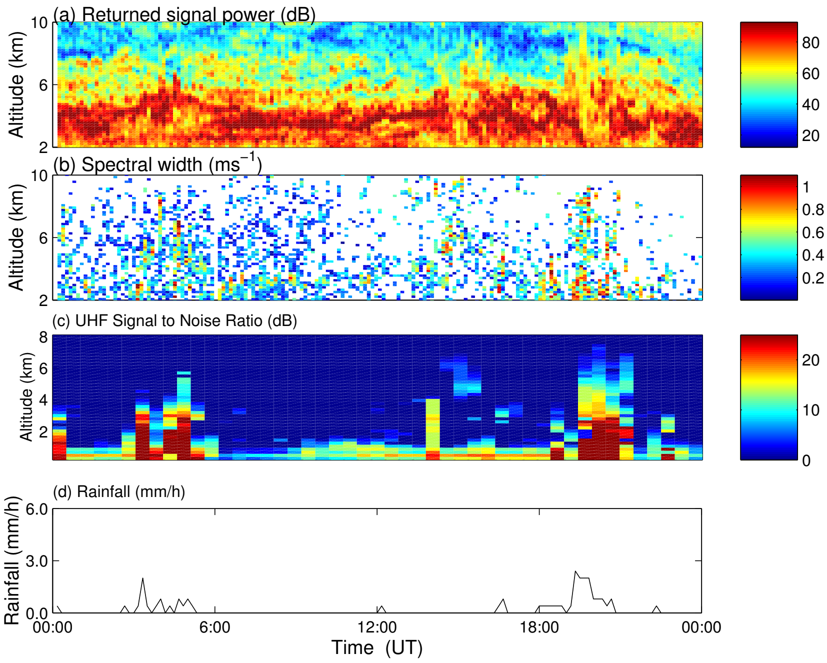

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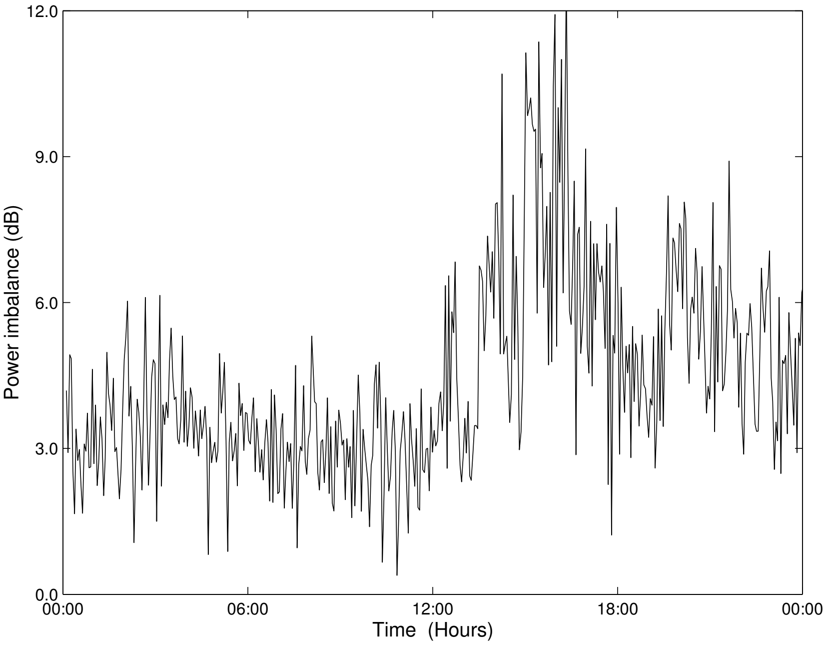

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