

Emission: a simple new technique to correct rainfall estimates from attenuation due to both the radome and heavy rainfall.

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Abstract We present a new technique for correcting errors in radar estimates of rainfall due to attenuation, which is based on the fact that any attenuating target will itself emit and that this emission can be detected by the increased noise level in the radar receiver. The technique is being installed on the UK operational network, and allows, for the first time, radome attenuation to be monitored using the increased noise at the higher beam elevations. This attenuation has a large azimuthal dependence but for an old radome can be up to 4dB for rainfall rates of just 2-4 mm/hr. This effect has been neglected in the past, but may be responsible for significant errors in rainfall estimates and in radar calibrations using gauges. The extra noise at low radar elevations provides an estimate of the total path integrated attenuation of nearby storms; this total attenuation can then be used as a constraint for gate-by-gate or polarimetric correction algorithms.

INTRODUCTION.

Attenuation is a severe problem for C-band radars, especially in the very storms where the rain is heaviest and accurate rainfall rates are needed for improved flood predictions. Gate by gate correction schemes are notoriously unstable (Hildebrand, 1978) because any small initial calibration error at the first gate is increasingly magnified as subsequent gates are corrected. Polarisation techniques using, for example, the differential phase shift between the horizontally and vertically polarised returns are very powerful, but the coefficient linking the phase shift to the attenuation is uncertain and variable (Bringi and Chandrasekar, 2001). Phase shifts of up to 300° were observed in the storms producing the floods in London on 20 July 2007, but correction was difficult due to the uncertainty of up to a factor of two in this coefficient (Tabary et al, 2008). Recent experiments with artificial rain on radomes indicate an attenuation of 3 dB can occur in rainfall of 15mm/hr (e.g. Kurri and Huuskonen, 2008, and references therein). However, operationally there has been no way of monitoring this radome attenuation so it has always been ignored. In this paper we will revive the suggestion, made by Fabry (2001) in a short note, that attenuation due to storms can be corrected using the microwave emissions from the attenuating targets. The operational system has been functioning since November 2010. We report the first measurements made with an operational radar of attenuation by a wet radome. Attenuation from storms is rare in the winter, but we will describe one case where path attenuation of 2dB was inferred for a heavy shower.

THE EMISSION TECHNIQUE.

Attenuation can be detected by the increased noise in the radar receiver as a consequence of the emission from any attenuating target. The effect of an attenuating storm with a physical temperature, T_p , and a one way optical thickness at radar frequencies of τ , will be an increase in the brightness temperature, ΔT_b , detected by the receiver, given by:

$$\Delta T_b = (T_p - T_g) (1 - \exp(-\tau)) \quad (1)$$

where T_g is the brightness temperature due to gaseous emission from the atmosphere in the absence of any attenuating radar targets. Suppose the target has a physical temperature, T_p , of 280K and the gaseous emission has a T_g of 30K, so that $T_p - T_g$ is 250K; the equation is approximately linear for two-way attenuations of up to 6dB, or 75% loss of signal, with a gradient of 1dB two way loss for each ΔT_b of 20K. If we wish, initially, to estimate the two way attenuation

to 10% (in dB), then this implies $T_p - T_g$ must be known to 25K. This is easily achieved because the temperature of the attenuating water on the radome or in the storm (remembering that the beam elevation will only be at a height of 1-2km) is usually known to about 5K; and the gaseous attenuation can be estimated to this accuracy from sonde ascents or the forecast model. In the mid-latitudes 75% of the gaseous attenuation is due to oxygen which depends on the pressure, only about 25% is due to the variable water vapour. For much larger attenuations the emission will saturate as τ increases, so for an attenuation of 16dB (97.5% loss of signal) ΔT_b must be known to within $\pm 5K$ if the attenuation is to be estimated to within 1.3dB.

A large number of samples is needed to detect the increased noise level when emission is occurring. For example, the equivalent T_b for the receivers in the UK network is about 1000K. If this is to be known to 10K so that the attenuation can be estimated to 0.5dB, then 10,000 independent estimates of the noise are needed. The weather radars in the UK use a low prf of about 300Hz, giving them a maximum range of nearly 500km. Twenty one pulses are transmitted for each one degree of azimuth of the higher elevation beams. Beyond a range of about 350km the noise from 1453 gates, extending over a distance of 108km, is sampled, giving 30,513 independent estimates of the noise, or a temperature accuracy of about 6K if the receiver noise temperature is around 1000K. The two lower elevation beams scan more slowly with 44 pulses per degree, so the temperature should be known to about 4K. Remembering that a ΔT of 10K is equivalent to 0.5dB two way attenuation, this accuracy should be acceptable. By sampling the noise for gates beyond 350km problems with spurious returns from precipitation or ground echoes should be minimised.

DATA QUALITY AND CALIBRATION.

Discrete targets such as aircraft appear in a single gate and are efficiently removed by a speckle filter. Sunrise and sunset are predictable and give much larger signals than are possible from attenuating targets and thus can be recognised and removed. To recognise any anomalous rays remaining where a few gates are still affected by targets, the mean noise signal averaged for the 1453 gates for each degree of azimuth (a 'ray') is recorded along with the standard deviation of these estimates; occasional rays with a higher standard deviation can then be identified and rejected.

Absolute calibration is achieved by injecting a known (1165K) noise source for five gates just before the 1453 empty distant gates. Calibration from day to day is found to be remarkably stable providing dry days are used. The calibration of neighbouring radars can differ by almost a factor of two. The reason for this is unclear, so a cross check of the relative values of the calibration of neighbouring radars has been carried out on dry days. By comparing the values of T_g as the elevation angles increases and the path through the atmosphere is less, the relative calibrations of the radars were found to be consistent with those derived from the noise source.

WET RADOME ATTENUATION.

The analysis has concentrated on two radars. Predannack, on the Cornish coast close to the sea where a new 'orange-peel' radome was installed in the summer 2010, and Cobbacombe, Devon with a 15 year old 'faceted' radome. Both radars have a five minute scan sequence in which time five PPIs are executed at four elevation angles. Tests on dry days at Cobbacombe with the upper two beams at 4° and 2° confirmed that the changes of noise with azimuth were very small and equivalent to less than 3K change in T_b , or less than 0.15dB change in two way attenuation.

Figure one shows the two way attenuation at Cobbacombe inferred from the increase in noise level as a function of the azimuth angle for the upper two elevation angles of 4° and 2° for the 576 scans during a two day period starting at midnight on 16 November 2010. The difference in the attenuation between these two elevations is plotted in the third panel and is effectively zero.

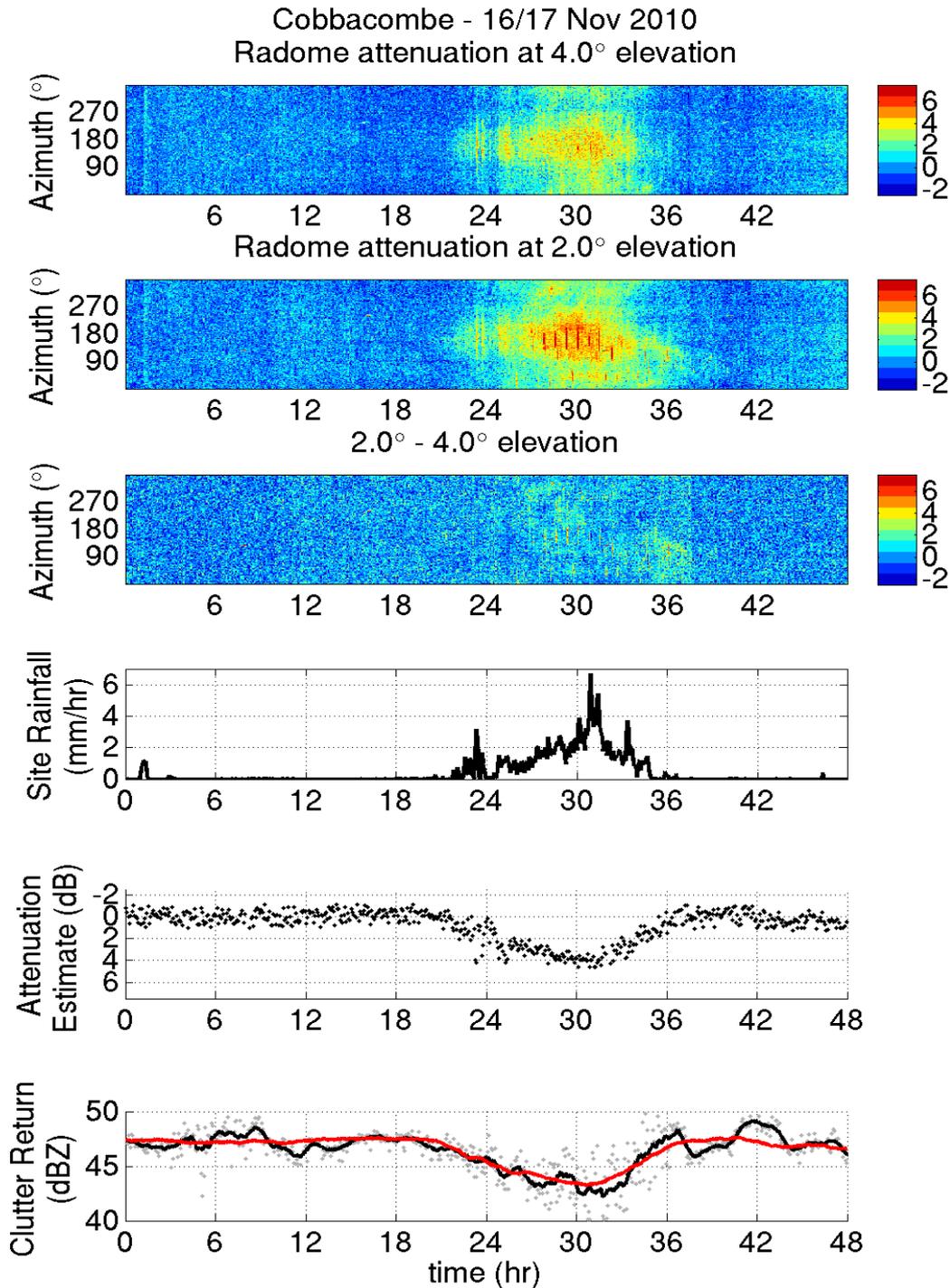


Fig. 1 The two-way attenuation inferred from the increased noise as a function of azimuth for the 48 hours starting at 0000h on 16 November 2010. Upper two panels, for the 4° and 2° beams, and (third panel) the difference between these two beams. The fourth panel is the rainfall rate at the radar site. The fifth panel is the attenuation from the emission for each scan averaged over nine neighbouring azimuths centred on the 130° azimuth (standard deviation about the running mean 0.6dB). Sixth panel: gray points – return from the clutter target on the 130° azimuth for each scan, black line - clutter return averaged over one hour; red line - attenuation from the emission averaged over one hour.

This confirms the suggestion that the upper beams are detecting the same radome attenuation. The fourth panel shows the rainfall intensity at the radar site. Because no automatic gauge is available, the rainfall is derived by averaging the composite radar rainrates over a 5 x 5km square centred on the radar. The attenuation along the 130° azimuth averaged over nine neighbouring azimuths inferred from the emission is displayed in the fifth pane, and then in the bottom panel is compared with the changes in apparent reflectivity of a strong ground clutter target on the same 130° azimuth using the lowest (0°) elevation radar beam. The other elevations are 0.5 and 1°. The following features are evident from Figure one:

- a) Attenuation coincides with the rainfall over the radar site. Studies of many days for the upper two beams at the two radars during November 2010 and January 2011 confirm that when it rains at the radar site there is always an increase in the noise.
- b) At Cobbacombe the radome attenuation exceeds 4dB for periods when the rain rate is only 2mm/hr. We find such high attenuation with all light rainfall events.
- c) The difference in attenuation at the two beams is small, suggesting that the layer of water on the radome is uniform for small vertical displacements just above the equator.
- d) The radome attenuation is highly dependent upon the azimuth; the 4dB maximum value extends over 100°, whereas at other angles it can be as low as 1 or 2dB. As a result it is difficult to predict the attenuation from the rainfall rate.
- e) The structure of the patterns in the figure is predominantly vertical, indicating that, at Cobbacombe, the whole radome gets wet at the same time.
- f) The short vertical red lines for the 2° elevation data, indicate enhanced emission for individual scans extending over about 100° in azimuth. These events can be identified by the anomalously high standard deviation of the noise from the gates and so could be removed. These spurious signals are only found when it rains; we believe there must be some subtle intermittent coupling of radio frequency interference via the wet radome or perhaps they are caused by streams of water on the radome.
- g) The change in the apparent reflectivity of the strong clutter echo on azimuth 130° tracks the attenuation inferred from the emission almost perfectly, thus providing independent validation of the technique.

EMISSION FROM DISTANT ATTENUATING STORMS.

In theory, the technique for detecting radome emissions from the upper beams can be applied to the lower beams, where any additional signal should be due to emission from distant storms. We have not had opportunity to fully evaluate this approach, because attenuating storms are rare in the UK during the winter time. We do find that lower beams are affected by ‘glowing’ clutter which is detected via the sidelobes and increases the noise at all gates. This ‘glowing clutter’ can be recognised by an azimuthal variations in brightness temperature of up to 60K, but on dry days the pattern of the azimuthal variation is very constant and reproducible to within 6K. This suggests that it should be possible to identify the emission from storms by a positive excursion of the noise over a few degrees of azimuth. However, observations of the noise in the lower beams on wet days, when no attenuation by heavy rain is expected, are less encouraging; the clear signal from the upper beams in figure one is lost, and superposed is a complex and irregular increase in noise at many azimuths. This warrants further examination, but we think it may be due to water gathering in drops at the equator of the radome where it then forms drips which fall to ground.

Figure two is an example from the Predannack radar where emission can be identified from the upper two beams. The figure reveals an additional emission signal for the 2.4° elevation beam between 1200h and 1330h which is not apparent in the 4° elevation beam. A series of radar images from the Predannack radar of the movement of an intense radar echo to the E and NE of the radar is also displayed in the figure.

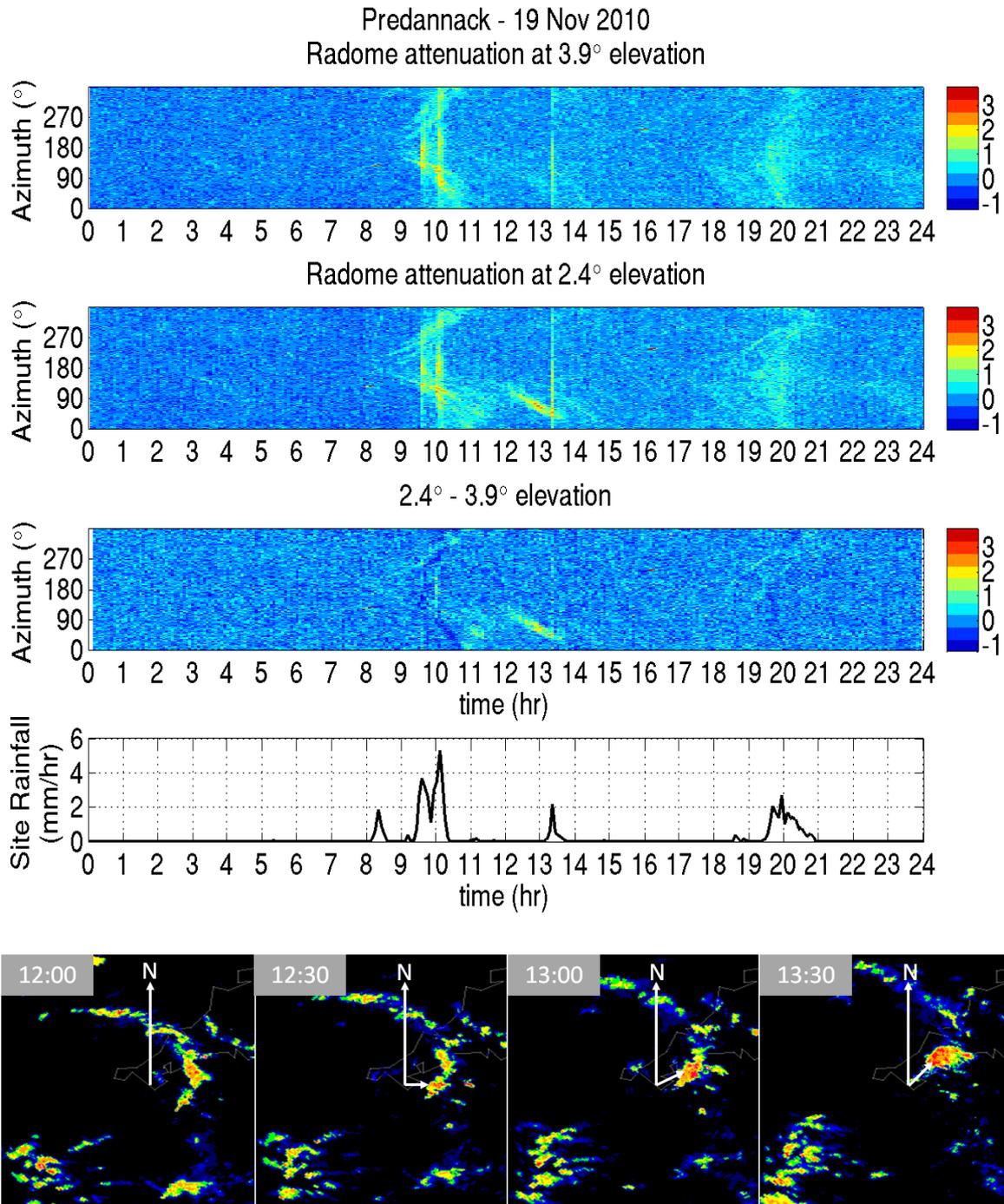


Fig. 2 Attenuation inferred from the Predannack radar on 19 November 2010. The upper four panels are as for Figure 1, showing the two way attenuation in dB as a function of azimuth, firstly for the 4° beam, then the 2° beam then the difference between the two beams, and finally the rainfall rate at the radar site. Note the streak of attenuation between 1200h and 1330hours in the third panel during which the azimuth direction changes from E to NE. The final row of images are the radar composites between 1200 and 1330h over a region of about 250 by 250km with the arrows indicating the azimuth of the intensifying cell to the E and then the NE of the radar site. The position of this cell is consistent with the extra emission in the 2° beam, indicating that the total path attenuation through this cell is reaching 2dB (two-way).

In summary the figure shows:

- a) The attenuation for this new radome is less than at Cobbacombe, but it is still significant; at 1330h a two way attenuation of 2dB coincides with 2-4mm/hr rainfall. .
- b) There is also evidence of an azimuthal wetting which varies in time; at 0900h the side of the radome between 120° and 250° azimuth appears to attenuate before the rest of the radome. This feature is common at Predannack and in heavier rain is much clearer than this example. We suspect the increased wind at the exposed radar site is responsible for differential wetting of the radome.
- c) Emission from a distant storm is evident between 1200h and 1330 hours, starting on an Easterly azimuth and gradually increasing to be equivalent to an attenuation of about 2dB (two-way) as it moves to the North-East. The sequence of composite images in the figure confirms this interpretation; an intensifying echo can be clearly seen moving in the direction inferred from the emission observations.

CONCLUSION AND DISCUSSION.

An operational system for monitoring attenuation both due to the wet radome and to more distant storms has been installed on the operational radar network in the UK. First results are encouraging and indicate that the technique is viable. The two-way radome attenuation can be inferred by monitoring the increased brightness temperature for beams at 2° and 4° with an accuracy of 0.25dB (5K). Increased emission can be detected even in the lightest rain. For the 15 year old Cobbacombe radome the attenuation is 3-4dB for rainfall rates of only 1-2mm/hr; these values have been independently confirmed by monitoring changes in the reflectivity of a strong and constant clutter target. For the new Predannack radome, attenuation is less but can be significant at 1-2dB for 2mm/hr. The attenuation varies markedly with azimuth, so that it is difficult to predict from a knowledge of the rain rate. If such changes are at all typical then they may be affecting radar calibrations using close in gauges, and they may be the source of the rather disappointing reports of disagreement of $\pm 60\%$ when hourly or daily gauge totals are compared with those inferred from radar in Switzerland (Germann et al, 2006) and France (Tabary et al, 2008).

We report one case where emission was higher on the 2° elevation beam than the 4° beam, equivalent to an additional two-way attenuation of 2dB, and show that the azimuths over which this occurs track a developing intense radar echo. More observations are needed during the summer time to evaluate the accuracy with which the total path integrated attenuation through attenuating radar echoes can be derived from the increased noise level of the lower elevation beams. The advantage of this technique is that it works equally well for heavy rain and wet hail and no assumption is made about the microphysics of the attenuating storm. Total path attenuation of up to nearly 20dB can, in theory, be accurately estimated, and then used as a constraint for the total attenuation computed using gate-by-gate or polarimetric correction algorithms.

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