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Techniques for improving ground clutter identification

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Abstract Several radar parameters quantifying signal variability in single-polarisation radar measurements (Power Ratio, PR; Clutter Phase Alignment, CPA; and Absolute Power Difference, APD) are evaluated using Bayes' theorem in terms of the separation between the returns from ground clutter and precipitation. As these parameters are not independent, the intention is to identify the parameter providing the best separation. It is shown that either PR or CPA, in combination with a radial measure of texture of reflectivity (in dBZ), provides excellent separation of ground clutter and precipitation returns on a gate-by-gate basis. The demonstrated skill in clutter identification is comparable to that only previously reported using dual-polarisation measurements. This approach is well-suited for anomalous propagation as clutter maps are not used. The findings suggest that ground clutter identification is likely to benefit from measurements of PR or CPA even when dual-polarisation parameters are available.

Key words weather radar; ground clutter; precipitation; Bayes classifier

INTRODUCTION

Ground clutter returns are a well-known problem affecting quantitative weather radar applications. Radar data quality control is increasingly important as the assimilation of this data in NWP models becomes more common. The UK Met Office has recently developed its own in-house digital radar receivers, allowing processing of the in-phase and quadrature samples. The collection and evaluation of two new parameters capturing pulse-to-pulse signal variability has recently begun. This work is a preliminary investigation of the identification of ground clutter returns for operational, single-polarisation weather radar. A Bayes classifier is used to estimate the class of scatterer (clutter or precipitation) on a gate-by-gate basis, using likelihood functions of signal variability and reflectivity texture parameters established for clutter and precipitation from calibration data sets. Independent data sets are used for evaluation. The approach employed here only uses real-time measurements and does not rely on previously established clutter maps. This approach provides greater potential for clutter identification during anomalous propagation (AP) conditions, when atypical patterns of ground clutter coverage occur. However, clutter identification in standard and AP conditions have yet to be determined separately due to the limited number of AP cases currently available. Future improvements in clutter identification may come through spectral techniques (e.g. Warde and Torres, 2009), though these have yet to be demonstrated and evaluated on operational weather radars.

RADAR SPECIFICATIONS

This work involves the evaluation of ground clutter identification for radars of the UK operational weather radar network. Recent modifications allow the collection of extra radar parameters capturing the pulse-to-pulse variability of the returned signal. The network radars operate at C-band (5-cm) wavelengths and are generally only capable of single-polarisation measurements. These systems are to be upgraded for dual-polarisation measurements, so any clutter identification algorithm needs to easily accommodate dual-polarisation data when available. The data considered here have been collected by two of the operational radars (Cobbacombe and Chenies) in southern England since 13/01/2011. Data have been available for the lowest elevation PPIs at these sites (0° and 0.4° respectively), which are repeated every 5 minutes. The radar specifications for these PPIs are; pulse duration = 2 μs, beamwidth = 1°, PRF = 300 Hz, scan rate = 1.2 rpm and max. range = 255 km. The integration and spacing of data is 1° in azimuth and 600 m in range.

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GROUND CLUTTER IDENTIFICATION

In this work, a Bayes classifier is used to determine the likelihood that a given radar measurement is due to ground clutter rather than precipitation. Parameters that are used for this purpose should provide good separation between ground clutter and precipitation echoes. Ground clutter echoes may be characterized as having zero-velocity and low spectral widths compared to weather echoes (Doviak and Zrnic, 1993). However, precipitation echoes may also have near-zero radial velocity and low spectral widths. Spectral width estimates are also not very accurate, particularly at low spectral widths and low signal-to-noise ratios. Another distinguishing characteristic of ground clutter echoes is that the reflectivity fields are characteristically much more textured than they are for precipitation. We therefore consider these two characteristics for the separation of clutter and precipitation; signal variability and texture of reflectivity.

Signal variability parameters

Three signal variability parameters are considered for the identification of clutter echoes. These parameters are independent of echo intensity and hence the overall calibration of the radar system. First-of-all, PR is defined as “power of the mean complex signal divided by the mean complex signal power”. In terms of power spectra, PR is the ratio of the power at zero-frequency to the total power (over all frequencies). PR can only take values between 0 and 1 inclusive. PR=1 corresponds to a completely constant signal in both power and phase. Variability in either power or phase will reduce this value. The expected value of a completely incoherent signal is equal to 1/N, where N is the number of pulses. Secondly, CPA, from Hubbert et al. (2009a), is equivalent to PR except that it is calculated in terms of signal amplitude (A) rather than power ($P=A^2$). They found that CPA outperformed PR when tested on NEXRAD radars in the USA and it is now part of the operational ground clutter mitigation scheme. As CPA is amplitude- rather than power-weighted, the improvement in performance was attributed to the fact that CPA is less affected by dramatic changes in signal strength as the radar beam scans past strongly backscattering ground clutter targets. Like PR, CPA can only take values between 0 and 1 inclusive. Finally, APD is the mean absolute power difference (in dBZ) using a specified lag between pulses. For the operational weather radars in the UK, a 2-pulse lag is employed (delay of 6.66 ms). This measure is currently used in the operational ground clutter identification scheme in the UK (Sugier et al., 2002), referred to therein as the Clutter indicator (*Ci*). Values of APD vary from 0 dB (signal has constant power) to about 6 dB (incoherent signal). APD has also been shown to provide accurate estimates of low spectral widths (Melnikov et al, 2002), which suggests it may provide good clutter identification. While the first two parameters are influenced by the mean radial velocity of the target, APD is completely independent of velocity though closely related to spectral width.

Texture parameters

Two parameters capturing the spatial variability of reflectivity are considered. Firstly, Texture (TEX) is simply defined as the standard deviation of reflectivity (in dBZ) over an *n*x*n* window (i.e. *n* rays by *n* gates). Texture calculated in this manner has been widely used in clutter schemes (e.g. Gourley et al., 2007; Hubbert et al., 2009b). In contrast, Radial Texture (RTX) is the mean squared difference of reflectivity (in dBZ) only between adjacent gates in range, within an *n*x*n* window. For example, a 3x3 window consists of six pairs of adjacent range-gates, hence RTX would be calculated from these six differences at a given location. RTX is expected to be a better indicator of the texture of the underlying field given that the radar beam typically smoothes much more in azimuth than in range relative to the typical sampling and averaging of the received signal.

Bayes classifier

The use of a Bayes classifier has previously been proposed for the identification of ground clutter (e.g. Moskowicz et al. (1994); Rico-Ramirez and Cluckie (2008)). This approach is now briefly summarised. The posterior probability $P(C|x)$ represents the probability of the occurrence of ground clutter (C) given the observation of parameter x. It is assumed here that all observations are either due to ground clutter or precipitation (*R*), i.e. P(*C*)+P(*R*)=1. The posterior probability or Probability of Clutter (POC) may be expressed using Bayes' theorem as,

$$P(C|x) = \frac{P(x|C)P(C)}{P(x|C)P(C)+P(x|R)P(R)} = \frac{P(x|C)P(C)}{P(x|C)P(C)+P(x|R)(1-P(C))} \quad (1)$$

POC depends on the likelihood functions for ground clutter P(*x*|*C*) and precipitation P(*x*|*R*) which may be empirically determined, making the separation between clutter and precipitation using calibration data sets. The prior probabilities (P(*C*) and P(*R*)) represent the expected probabilities of *C* and *R*. We assume that these quantities are unknown for any given observation, so we are equally likely to expect clutter or precipitation, e.g. P(*C*)=P(*R*)=0.5. This is known as a naïve Bayes classifier and may be written as

$$P(C|x) = \frac{P(x|C)}{P(x|C)+P(x|R)} \quad (2)$$

for a single input parameter, or extended to two parameters, *x* and *y*, (e.g. PR & RTX) as

$$P(C|x,y) = \frac{P(x|C)P(y|C)}{P(x|C)P(y|C)+P(x|R)P(y|R)} \quad (3)$$

EVALUATION OF GROUND CLUTTER IDENTIFICATION

The first step in the application of a Bayes classifier for ground clutter detection is to define both 'cluttered' and 'clutter-free' regions, which are to be used for calibration. The following steps were taken to define these regions. Initially, a dry period was objectively identified using a combination of radar and satellite observations. The frequency of occurrence (FOD) for significant radar returns (>15 dBZ) was then calculated during this 24-hour period (19/01/2011) at both radar sites, each based on 288 PPIs. For our purposes, returns have been broadly categorized as 'clutter-free' (FOD<1%), 'intermittent' (1%<=FOD<=90%) and 'cluttered' (FOD>90%). Thus, the clutter-free regions exhibited no more than one significant return (>15 dBZ) from the 288 PPIs considered. Cluttered regions covered an area of about 6% and 3% of the entire radar domain at Cobbacombe and Chenies respectively. Intermittent echoes covered about 3% and 2% of the entire domain at these two sites. However, due to the fact that these intermittent echoes occur infrequently, returns from cluttered regions comprised over 80% of all significant returns during the calibration period. It is not necessary to include all possible observations in the calibration set to accurately characterize clutter returns. Sensitivity tests have shown that the FOD threshold for cluttered regions can vary between 50% and 99% without significantly affecting the results presented later in this work.

The next step is to establish the likelihood functions for clutter and precipitation. The likelihood functions for ground clutter, P(*x*|*C*), have been estimated from returns from the previously defined cluttered regions during the same dry 24-hour period (19/01/2011). Likelihood functions have been derived for the three signal variability parameters (PR, CPA & APD) and the two texture parameters (TEX & RTX). The texture parameters have been calculated using a 3x3 window. To assess the benefits of smoothing the signal variability parameters, likelihood functions have been determined for these parameters averaged over a 3x3 window (denoted PR3, CPA3 & APD3), in addition to the raw measurements. The likelihood functions for precipitation, P(*x*|*R*), have been established during a 24-hour period (13/01/2011) from the clutter-free regions for each radar. This day was characterized by widespread and prolonged rain across southern England, exhibiting a mixture of rainfall from frontal and convective origins. It is implicitly assumed using the approach employed here, that the characteristics of returns from ground clutter mixed with precipitation will tend towards those of the dominant component.

These likelihood functions (given the occurrence of ground clutter (*C*) or precipitation (*R*)) have been used to derive the POC as a function of each of the parameters considered using Bayes' theorem. The likelihood functions for precipitation (blue) and clutter (red) are shown in figs. 1a, 1b and 1c for PR, CPA and APD respectively, all smoothed using a 3x3 window. One may observe the excellent separation and small overlap between these two distributions for PR and CPA. The corresponding cumulative likelihood functions along with the POCs (green) are shown in figs. 1d, 1e and 1f, respectively. When POC=0.5, returns have an equal likelihood of originating from clutter as they do from precipitation. This determines the threshold above which returns are more likely to be due to ground clutter than they are to be from precipitation. If returns with POC>=0.5 are identified as clutter, both the fraction of clutter which is successfully identified (probability of detection-POD) and the fraction of precipitation echoes which is falsely identified (false alarm rate-FAR) may be determined. The Critical Success Index, CSI=POD/(1+FAR), combines the performance in clutter and precipitation as a single quantity.

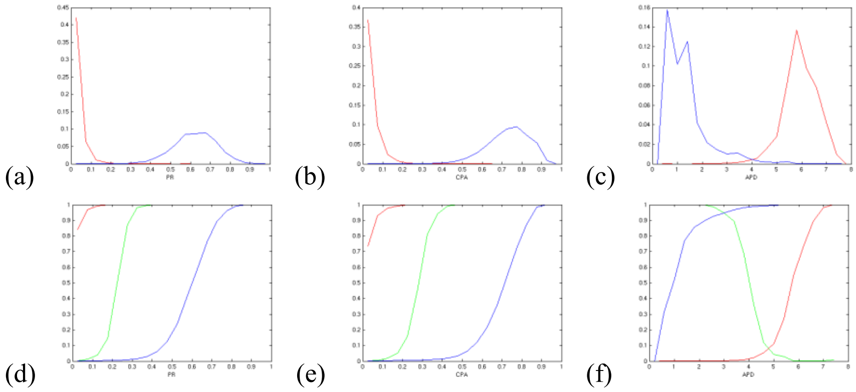
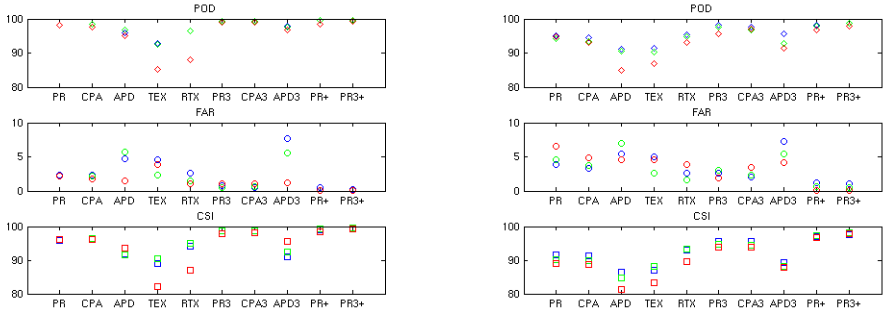


Fig. 1 Likelihood functions for ground clutter (blue) and precipitation (red) for signal variability parameters; (a) PR3 (PR averaged using 3x3 window), (b) CPA3 and (c) APD3. Cumulative likelihood functions (blue & red) and posterior probability or Probability of Clutter (green) for signal variability parameters; (d) PR3, (e) CPA3 and (f) APD3. (minimum reflectivity threshold = 15 dBZ).

To assess and validate the identification of ground clutter, 'dry' and 'wet' validation data sets have been developed. The 'dry' data sets correspond to 48-hour periods with no precipitation over the entire radar domain at Cobbacombe (30/01/2011-31/01/2011) and Chenies (28/01/2011-29/01/2011). The 'wet' data sets correspond to the same 4-day period (14/01/2011-17/01/2011) with widespread and prolonged rain over the majority of southern England, again exhibiting a mixture of frontal and convective rainfall. Evaluation statistics have been determined from these data sets as follows. POD (clutter identified as clutter) is calculated over the entire radar domain during the 'dry' period, essentially assuming that all returns are due to clutter. FAR (precipitation identified as clutter) is calculated only from the 'clutter-free' regions throughout the 'wet' period. We assume that any significant returns in regions previously deemed to be free of clutter in the FOD maps are due to precipitation. The results (POD, FAR & CSI) from this preliminary analysis are shown in fig. 2 (a) and (b) for Cobbacombe and Chenies respectively, using various minimum thresholds (15, 25 & 35 dBZ) which broadly represent the lower bounds for light, moderate and heavy rainfall (0.3, 1.3 & 5.6 mm/hr).

In addition to the unsmoothed (PR, CPA & APD) and smoothed (PR3, CPA3 & APD3) signal variability parameters and the texture parameters (TEX & RTX), statistics have also been derived for the combination of parameters (eqtn. 3), PR and RTX, both with (PR3+) and without (PR+) smoothing. In terms of the signal variability parameters, improved separation between clutter and precipitation on a gate-by-gate basis is achieved by smoothing using a 3x3 window. Inferior results (not presented here) were obtained using smoothing and texture calculations with windows larger than 3x3, indicating the trade-off between accuracy and resolution. Overall, the performance of PR and CPA is practically identical and both of these parameters outperform APD. CSI values from

PR3 and CPA3 were typically higher than those using APD by about 0.06 (6%). Low values of APD, typical of clutter, correspond to narrow spectral widths. High values of PR and CPA, also typical of clutter, require both near-zero velocities and narrow spectral widths. It is believed that this explains the improved separation of clutter and precipitation using either of these parameters relative to APD. Regarding the texture parameters, the radial texture (RTX) provides significantly better separation than the isotropic texture (TEX). In terms of CSI, RTX is consistently about 0.05 (5%) higher than TEX at both radar sites. It is believed that the effective smoothing of the beam in azimuth leads to a higher degree of correlation between adjacent rays than adjacent range-gates. This reduces the variability in intensity of clutter returns in azimuth. Hence, RTX is better than TEX at capturing the 'point' target-like nature of the underlying clutter field.



(a) (b)

Fig. 2 (a) Clutter identification POD, FAR and CSI for the radar at Cobbacombe for various signal variability and texture parameters. Minimum reflectivity thresholds (15, 25 & 35 dBZ), which broadly represent the lower bounds for light (blue), moderate (green) and heavy (red) rainfall respectively, have been employed. (b) Same for the radar at Chenies.

The overall performance using PR3 and RTX at Cobbacombe is exceptional. CSI values of 0.993, 0.996 and 0.993 were obtained for the minimum thresholds of 15, 25 and 35 dBZ respectively. These correspond to PODs greater than 99.2% with FARs less than 0.3% in all three classes. The performance using PR3 and RTX at Chenies was also very good. CSI values of 0.977, 0.978 and 0.982 for the same thresholds were obtained with PODs close to 99% and FARs less than 1 %. The poorer performance at Chenies may be related to other forms of interference and clutter due to the proximity to London and Heathrow airport (~30 km from radar) in particular. These results compare favourably with those previously reported using dual-polarisation measurements from a radar at Thurnham in the UK (Rico-Ramirez and Cluckie, 2008). They found CSI values of around 96% using single-polarisation measurements and the highest CSI value using an optimally-weighted combination of available dual-polarisation observations was 98.2%. Their scheme also used clutter frequency maps (based on the prior probability of occurrence) and textures were calculated using a 5x5 window. Similar performance has been obtained here for the radar at Chenies and even better performance at Cobbacombe using just two single-polarisation input parameters, PR and the radial texture of reflectivity.

EXAMPLES

Here, we provide two examples of clutter identification in special circumstances; AP and concurrent returns from clutter and precipitation. A dry-weather AP episode is shown in fig. 3a (reflectivity) for the radar at Cobbacombe at 2100 UTC, 31/01/2011. The echoes beyond 100km (~15-25 dBZ) are due to AP. Figs. 3b-d show POC based on APD3, PR3 and PR3+ respectively. POC>=0.5 indicates ground clutter. While APD3 is only partially successful at identifying the AP returns, improved identification is found using PR3 and excellent (PR3+) detection achieved using PR3+. The second example, shown in fig. 4a (reflectivity), shows a widespread region of precipitation around the radar at Chenies. POC using PR3+ is shown in fig. 4b. The detected regions correspond very well with the standard day-weather clutter map even in the presence of rain. Bright band effects may be observed to the west of the radar, indicating the presence of rain and ice within the radar domain. It may be inferred that partial beam-filling and beam blocking effects do not seem to degrade the separation of clutter and precipitation.

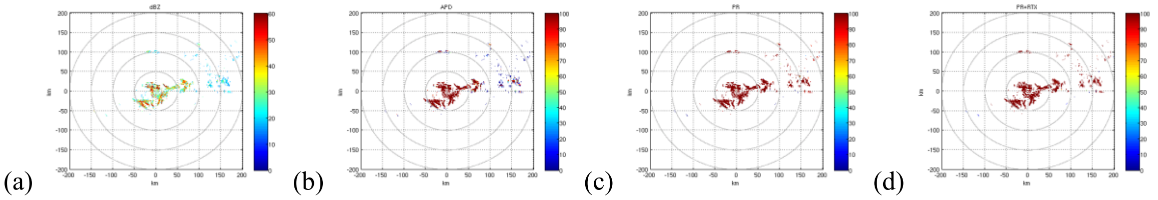


Fig. 3 Images of (a) reflectivity (in dBZ) and the Probability of Clutter (POC) using (b) APD3, (c) PR3 and (d) PR3+ during an AP episode (21:00 31/01/2011) for the radar at Cobbacombe. Clutter is detected when POC>=0.5. The echoes beyond about 100 km (~15-25 dBZ) are due to AP.

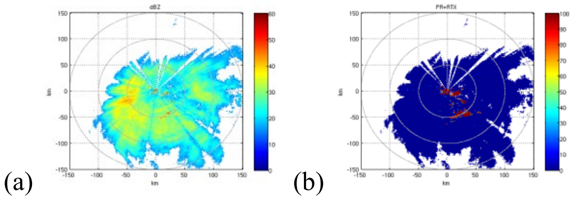


Fig. 4 Images of (a) reflectivity (in dBZ) and (b) Probability of Clutter for the radar at Chenies using PR3+ at 06:45 17/01/2011, demonstrating ground clutter identification in the presence of rain.

CONCLUSIONS

We have presented some preliminary findings on ground clutter identification using signal variability parameters on two radars of the UK operational weather radar network. This has involved the use of a naïve Bayes classifier on various parameters capturing signal variability and the texture of reflectivity. The two new parameters considered (PR & CPA) provide a significant improvement over that currently used in the operational ground clutter scheme (APD). No significant improvement was found using CPA over PR, in contrast to the findings in Hubbert et al. (2009a) using NEXRAD radars in the USA. It is believed that the difference is due to the slower operational scan rates employed at low elevations in the UK (7.2°/s). Radial texture was also found to significantly outperform an isotropic measure of the texture of reflectivity. In combination, PR3 (PR averaged using a 3x3 window) and RTX seem to provide excellent discrimination between clutter and precipitation with results comparable to those obtained from dual-polarisation measurements. Inferior results were obtained using larger windows (e.g. 5x5,…). Examples illustrating good performance for dry-weather AP and when clutter and precipitation co-exist have been presented. The findings suggest that PR or CPA would likely improve ground clutter identification even when dual-polarisation measurements are available.

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