Operational Radar Refractivity Retrieval for Numerical Weather Prediction

J. C. NICOL[1]**, K. BARTHOLEMEW**[1]**, T. DARLINGTON**[2]**, A. J. ILLINGWORTH**[1]**, & M. KITCHEN**[2]

1 *University of Reading, Reading, UK.*
j.c.nicol@reading.ac.uk
2 *UK Met Office, Exeter, UK*

Abstract This work describes the application of radar refractivity retrieval to the C-band radars of the UK operational weather radar network. Radar refractivity retrieval allows humidity changes near the surface to be inferred from the phase of stationary ground clutter targets. Previously, this technique had only been demonstrated for radars with klystron transmitters, for which the frequency of the transmitted signal is essentially constant. Radars of the UK operational network use magnetron transmitters which are prone to drift in frequency. The original technique has been modified to take these frequency changes into account and reliable retrievals of hourly refractivity changes have been achieved. Good correspondence has been found with surface observations of refractivity. Comparison with output of the Met Office Unified Model (UM) at 4-km resolution indicate closer agreement between the surface observations and radar-derived refractivity changes than those represented in the UM. These findings suggest that the assimilation of radar–derived refractivity changes in Numerical Weather Prediction models could help improve the representation of near-surface humidity.

Key words radar refractivity; humidity; NWP

INTRODUCTION

In this paper, we describe the implementation and evaluation of radar refractivity retrieval on one of the radars of the UK operational weather radar network. Particular considerations regarding the implementation of refractivity retrieval on these radars are discussed. The retrieval of hourly changes compare well with surface observations of refractivity as measured at two sites within the domain of ground clutter coverage. The representation of refractivity, as a proxy for humidity, in the Met Office Unified Model is also investigated.

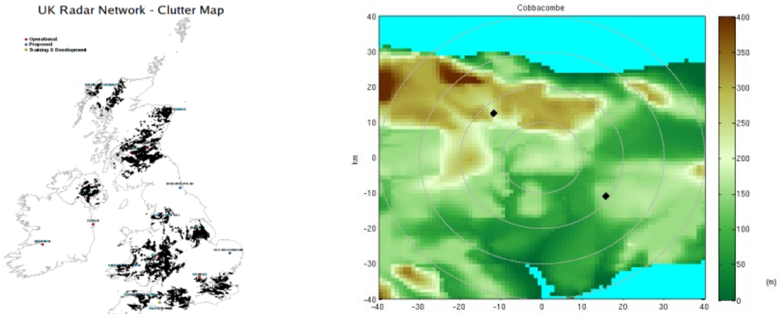
BACKGROUND

Radar refractivity retrieval is a relatively new application of weather radar measurements requiring the measurement of the phase of ground clutter returns, originally presented in Fabry et al. (1997). Refractivity (N) is a convenient measure of the refractive index (n) of air, where $N=(n-1)\mathrm{x}10^6$ in parts per million (ppm) This technique utilises the phase change between two times of returns from stationary ground clutter targets. The refractivity change between these two times will produce a particular phase change as a function of range. By measuring the gradient of the phase change with respect to range over short distances, spatial maps of near-surface refractivity changes may be derived in regions with sufficiently stationary ground clutter. At C-band wavelengths, a refractivity change of 1 ppm results in a phase change gradient of 13˚/km with respect to range. As radar refractivity is closely related to humidity (1 ppm ≈ 1% RH @ 20˚C), it is anticipated that such measurements will provide valuable insights into the dynamic variability of water vapour and may be a valuable new data source for assimilation into Numerical Weather Prediction models, particularly with respect to the initiation of convection.

The refractivity technique has previously been demonstrated for radars with klystron transmitters. Klystron transmitters are very stable in terms of frequency. Weather radars in the UK use magnetron transmitters, for which the transmitted frequency is prone to drift. These frequency drifts are primarily caused by changes in the ambient temperature (Skolnik, 1990) and changes in the average input power (e.g. change in pulse duration or PRF). Changes in the transmitted frequency (experienced by radars with magnetron transmitters) during the time taken for Doppler radar measurements are negligibly small, however they become significant when considering phase measurements made at considerably different times and therefore must be treated for radar refractivity retrieval using magnetron transmitters. The role of the transmitted frequency on absolute phase measurements has not been well-understood. It was originally maintained that in order to apply radar refractivity retrieval to magnetron radars, the transmitted frequency would be needed to be measured in real-time with an accuracy of at least 1 ppm (Fabry et al., 1997). It has since been proposed (Parent du Chatelet and Boudjabi, 2008) that phase changes primarily occur due to STALO frequency changes, rather than transmitted frequency changes. Indeed, phase changes must be corrected for any changes in the frequency of local oscillators (Nicol et al., 2011), with an accuracy of at least 1ppm (i.e. 5.6 kHz at C-band). However, it was also shown that transmitted frequency changes can be a limiting factor in refractivity retrievals when a long pulse length is used.

UK OPERATIONAL RADAR NETWORK

The UK operational weather radar network currently comprises 16 magnetron-based C-band (5-cm wavelength) radars. The coverage of ground clutter throughout the UK is indicated in fig. 1a. This represents the possible coverage of refractivity retrievals from the entire network. The testing and development of refractivity retrievals on the operational radars has focused on an operational radar at Cobbacombe in south-west England. The topography surrounding Cobbacombe from a digital terrain model is shown in fig. 1b.



(a) (b)

Fig. 1 (a) Possible coverage of radar refractivity retrievals from the existing UK operational weather radar network, **(b)** Topography surrounding the radar at Cobbacombe, indicating the surface-observation stations at Liscombe (NW of radar) and Dunkeswell (SE of radar)

Phase and phase variability data are collected at each gate along with the LO frequency for each PPI at the lowest operational elevation angle (0˚), which are repeated every 5 minutes. A relatively long pulse is employed for low-elevation scans (2 μs, 300 m). The radar transmits with a pulse repetition frequency (PRF) of 300 Hz and scans at 1.2 rpm or 7.2˚/s.

CONSIDERATIONS FOR REFRACTIVITY RETRIEVAL

Frequency-dependence of phase measurements

Transmitted and local oscillator frequency changes must be considered independently regarding phase change measurements at two significantly different times (Nicol et al., 2011). The two effects described below combine additively. The local oscillators (LO) frequency is considered to be the sum of the local oscillator frequencies (e.g. STALO + COHO or STALO + Numerically-Controlled Oscillator for analogue and digital radar receivers respectively). LO frequency changes cause a phase change error which is proportional to the time between transmission (Tx) and sampling of the received signal (Rx). This is equivalent to the distance from the radar to the centre of a particular range-gate. This steady phase change with range results in an additive refractivity error in retrievals, if uncorrected. Represented graphically in fig. 2, the LO frequency at two times (red and black waves) are depicted relative to the transmission and reception of a finite pulse. The contribution to the phase change from changes in the LO frequency depends only on the time between Tx to Rx and the change in LO frequency between the two times.

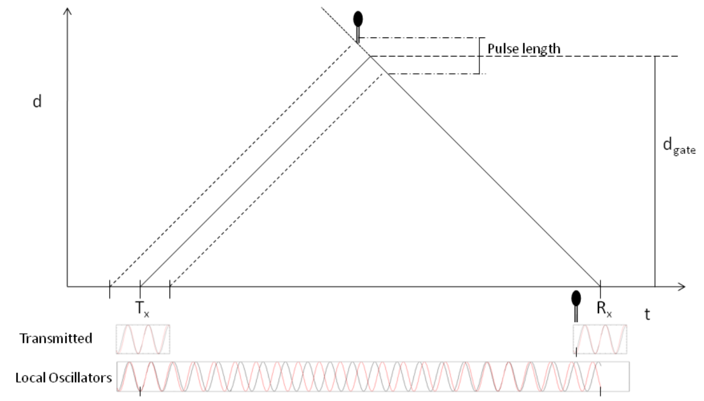


Fig. 2 Illustration of the dependence of phase measurements from stationary targets on the transmitted and local oscillator frequencies at two times (red and black waves).

In contrast, transmitted frequency changes cause a phase change which is proportional to the target distance from the centre of the range-gate. In fig. 2, upon transmission the radar pulse propagates away from the radar, is reflected back from a target and the returned signal is sampled at Rx. One may infer that the phase of the received signal depends on the transmitted frequency and path difference relative to the centre of the pulse (2 x distance of the target from the centre of the range-gate). Thus, the phase change between two times (red and black waves) depends on the transmitted frequency change and the distance of the target from the centre of the range-gate. This results in an additive phase change error depending on the exact target locations relative to the range-gate centre and not a refractivity bias. If we assume that targets are uniformly-distributed across each range-gate, a transmitted frequency change of 100 kHz would result in phase change errors of about 20° with a 300 m pulse length. Similar errors would occur for refractivity changes of about 20 N due to the uncertainty of the exact ground clutter target location (Nicol et al., 2011).

Particularly with long pulses at shorter weather radar wavelengths, these effects combined with other sources of phase change error, such as target motion, can prevent reliable refractivity retrievals. The use of a relatively long pulse (300m in range) for refractivity retrieval implies that performance will be degraded when either large transmitted frequency or refractivity changes occur. For these reasons, refractivity changes can only be reliably extracted over limited periods of time. For the current radar configuration, we consider hourly refractivity changes as a candidate for data assimilation in NWP.

Spreading targets

Refractivity retrieval requires returns from many independent targets, however, some very strong backscattering ground clutter targets may dominate over many successive range-gates. After correction for LO frequency changes, the phase change from these targets is proportional to the transmitted frequency change and not the refractivity change. Unless excluded from refractivity retrievals, such targets will bias refractivity retrievals for both magnetron and klystron radars towards the fractional change in transmitted frequency and towards zero, respectively. For the operational weather radars in the UK, the LO frequency is set to match the transmitted frequency (measured in real-time from the transmit pulse) immediately prior to each PPI. It has been shown that returns from spreading targets may be used to check the accuracy with which transmitted and LO frequency changes are measured and recorded (Nicol et al., 2011). This has confirmed that LO frequency changes are known to better than 1 kHz, or equivalently, resulting refractivity errors will be less than 0.2 N and may be neglected.

IMPLEMENTATION AND VALIDATION

It has been shown that both refractivity and transmitted frequency changes may result in large phase change errors when a long pulse length is used (Nicol et al., 2011). In addition, large refractivity changes can lead to phase change aliasing and problems arising from smoothing the phase change field. These problems are most pronounced using long pulses at short wavelengths. Therefore, the use of a reference phase map to estimate refractivity (Fabry et al., 1997), rather than refractivity changes, is not achievable for the radar specifications considered. To maintain reliable retrievals, the time between PPIs needs to be limited (e.g. hourly changes).

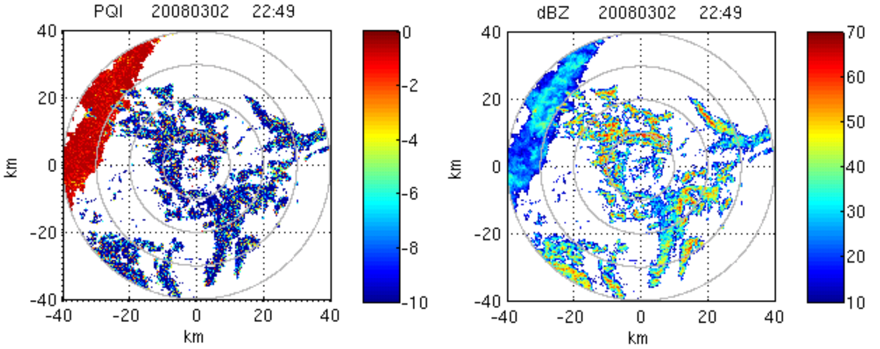


Fig. 3 Phase Quality Indicator (a) and reflectivity (b) 2250 UTC 02/03/2011 clearly depicting the ground clutter field within 40 km of the radar and a narrow band of precipitation to the NW.

A measurement of pulse-to-pulse phase variability (PQI; Nicol et al., 2009) allows stationary targets to be identified in real-time. An example of a PQI field and the corresponding dBZ image are shown in figs. 3a and b respectively. A PQI threshold of -5 dB is used to eliminate poor quality targets such as non-stationary clutter and precipitation. Spreading targets may be identified by examining the phase change correlation across adjacent range-gates between times when significant refractivity and frequency changes have occurred (Nicol et al., 2011). They may then also be excluded from retrievals. For the remaining targets, a phase change correction for LO frequency changes (Δf_{LO}) must be added to the raw phase change measurements using eqtn. 1. This correction is proportional to the range-gate distance (d_{gate}).

$$\Phi(d_{gate}) = -\frac{4\pi d_{gate}\Delta f_{LO}}{c} \qquad (1)$$

Apart from this correction, the formulation of radar refractivity measurements is essentially the same as the original formulation for which both the transmitted and LO frequencies are constant in time (i.e. eqtn. 2 from Fabry (1997)). Strictly speaking, one must correct for LO rather than transmitted frequency changes, contrary to the implication in Fabry (1997). Although the LO frequency is typically adjusted to track the transmitted frequency in magnetron-based radar systems, this is a subtle though important distinction to make when considering radar refractivity retrievals (Nicol et al., 2011). A 2D-Gaussian function (truncated at 3 x std. dev.) is used to spatially-average the corrected phase changes on a gate-by-gate basis (std. dev. (range) = 375 m; std. dev. (azimuth) = 750 m). To estimate refractivity changes, phase change gradients with respect to range (over 3 range-gates = 900 m) are also averaged using a 2D-Gaussian function (std. dev. = 1.5 km). Thus, the resulting maps of hourly refractivity changes have a resolution of about 3 km. Refractivity errors are estimated from the standard deviation of these phase change gradients within regions covered by the truncated 2D-Gaussian function. Examples of the refractivity change (between 1250 and 1350 UTC 07/03/2008) and corresponding error estimate are shown in figs. 4a and b, respectively.

Radar refractivity retrievals have been validated using surface observations of temperature, pressure and RH. Data from two stations shown in fig. 1b (Liscombe and Dunkeswell) were available for comparisons from March to August 2008. Comparisons suggest that eliminating measurements with error estimates greater than 1.5 N largely excludes poor quality retrievals. Although refractivity changes are not necessarily available at all times at a given location due to the elimination of poor quality targets, the accumulated hourly refractivity retrievals at times show excellent agreement with surface observations. Figs. 5a and b show the refractivity change relative to the beginning of the period (09/07/2008-16/07/2008) from surface observations (black lines) at Liscombe and Dunkeswell respectively. Also shown is the corresponding radar-derived refractivity change (red lines), obtained by accumulating the individual hourly changes throughout the 7-day period (made up of 168 hourly changes). Hourly radar refractivity changes have a correlation of about 0.6 with respect to surface observations during the study period.

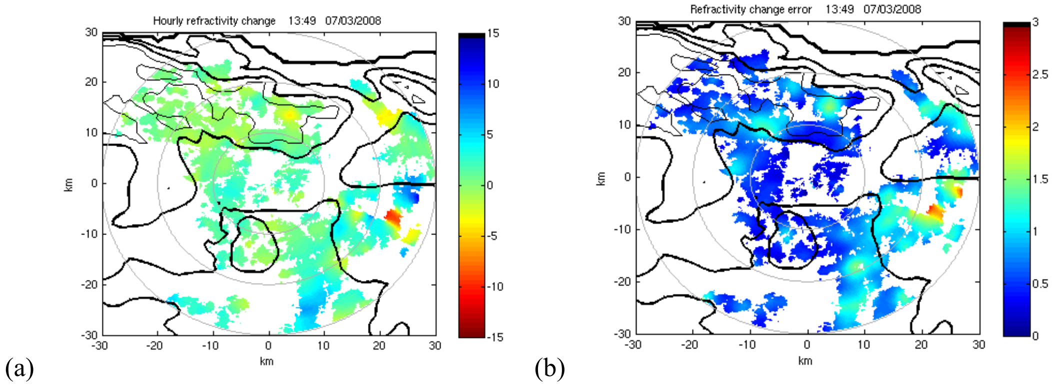


Fig. 4 An example of the refractivity change (a) between 1250 UTC and 1350 UTC 07/07/2008 with corresponding error estimate (b). Height contours at 0, 50, 150, 250 and 350m.

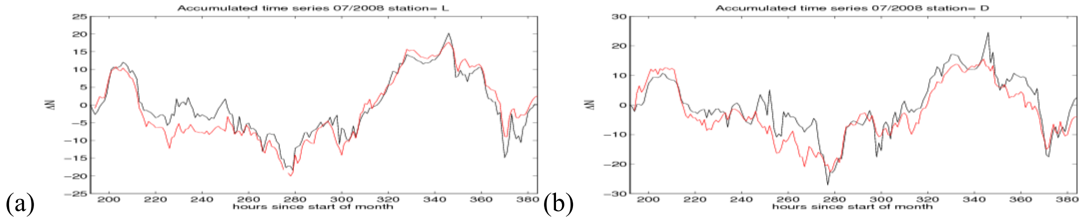


Fig. 5 Refractivity change relative to the beginning of the period (09/07/2008-16/07/2008) from surface observations (black lines) at Liscombe (a) and Dunkeswell (b). The corresponding radar-derived refractivity change (red lines), obtained by accumulating the individual hourly changes (168 at each site) throughout the period

REFRACTIVITY IN NUMERICAL WEATHER PREDICTION

The Unified Model (UM) of the UK Met Office is moving to higher spatial resolution. The horizontal resolution is currently at 4-km and soon to move to 1.5-km. Output from the UM (4-km) for a 10-day period (25/07/2008-03/08/2008) has been selected to analyse the representation of refractivity (humidity) in the UM under a variety of synoptic conditions. An example of a refractivity field calculated from model variables (T, RH, p) is shown in fig.6a. Hourly changes have been calculated throughout this period, an example of which is shown in fig. 6b. Both UM and radar-derived hourly refractivity changes have been compared with surface observations made at Liscombe and Dunkeswell. The daily correlations of hourly refractivity changes with surface observations indicate that the radar refractivity retrievals consistently outperform the Unified Model throughout this period, as shown in fig. 7. The correlation of hourly changes between the UM and synoptic stations is weaker for humidity (0.13) than for temperature (0.55) and pressure (0.61) suggesting that humidity is relatively poorly represented in the UM.

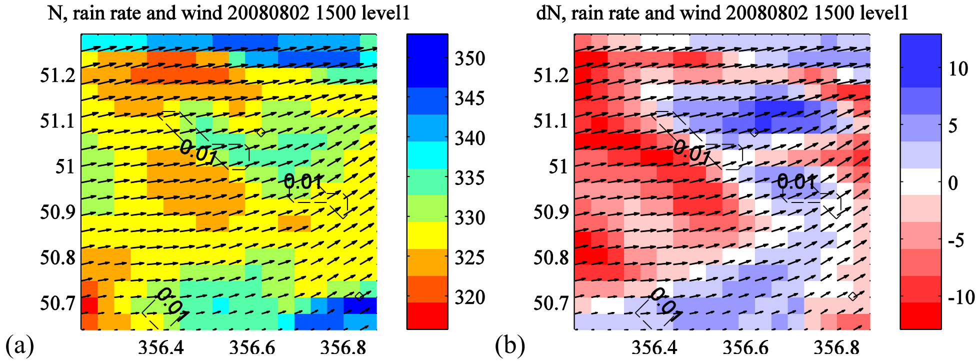


Fig. 6 **(a)** Examples of a UM refractivity field at 1500 UTC 02/08/2008, **(b)** the refractivity change over the previous hour. Contours depict modelled rain rate.

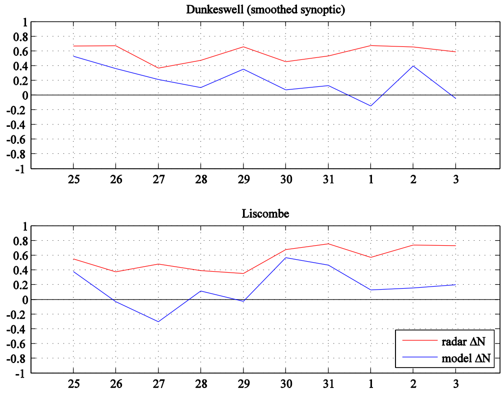


Fig. 7 Correlation of the daily time series, each based on 24 successive hourly changes, of UM (red) and radar-derived (blue) refractivity changes with respect to surface observations during the 10-day UM study period (25/07/2008-03/08/2008) at Dunkeswell (top) and Liscombe (bottom)

CONCLUSIONS

Radar refractivity retrievals have been developed for radars of the UK operational weather radar network. Various considerations which have been discussed require that the time between PPIs used for retrievals is limited to less than a few hours for the current configuration of these radars.

Radar retrievals of hourly refractivity changes show consistently better agreement than the Unified Model, in comparison with synoptic station measurements. Radar refractivity retrievals should benefit data assimilation as the representation of near-surface humidity in the Unified Model is relatively poor. A quasi-operational refractivity retrieval processing system is currently under testing and development within the Met Office as refractivity data are being collected by an increasing number of radars in the operational network throughout 2011.

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