REFRACTIVITY RETRIEVAL USING THE CASA X-BAND RADARS

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Abstract

For most weather radars, such as the WSR-88D, reflectivity, radial velocity and spectrum width are the only parameters estimated. Recently, a technique to retrieve near-surface refractivity has been developed by Fabry et al. [1997]. The technique relies on the returned phase from ground clutter which changes according to the refractivity of the atmosphere. Until recently, most refractivity measurements have been focused on S-band radars. These radars are usually designed, however, to observe long ranges and are therefore limited in range by the earth curvature effect. As part of the CASA NSF Engineering Research Center, higher-frequency X-band radars have been designed for observations of the lower atmosphere. The initial network (IP-1) consists of four radars and is located in south-west Oklahoma. Because of the closer spacing of these radars (approximately 30 km), in comparison to the WSR-88D network, the IP-1 network is less susceptible to the earth curvature effect and can provide more complete coverage of estimated refractivity. A significant challenge arises, however, with shorter wavelength radars in the implementation of refractivity retrieval. The refractivity retrieval technique relies on the phase change between two radar scans. One is referred to as the reference scan and the other as the measurement scan. A typical field of phase-change between these two scans exhibits a phase wrapping signature that depends on the refractivity change between the two scans and the radar wavelength. For X-band radars, the phase obviously wraps more frequently in comparison to S-band radars, which makes subsequent processing steps problematic. To mitigate this problem, we have proposed an algorithm called *Differential Refractivity Retrieval* (DRR), which accumulates phase differences from scan-to-scan rather than over a longer time period, as is currently the practice. As a result, typical atmospheric changes over such a short time (less than 5 min) do not cause a significant change in signal phase, minimizing phase wrapping. As a possible drawback, error accumulation caused by the DRR algorithm will be investigated as a limitation of the technique. A field experiment was conducted during REFRACTT-2006 using a mobile X-band radar (XPOL) developed by the University of Massachusetts. Results from the XPOL radar and the CASA IP-1 network will be presented to illustrate the feasibility of refractivity retrieval using X-band radars.

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1. INTRODUCTION

Often suggested as a proxy to estimate the surface moisture, the refractivity field retrieved from radars have recently received increasing attention in the meteorological community. The moisture field near the earth's surface is highly related to convective precipitation initiations [e.g., Dabberdt and Schlatter, 1996; Koch et al., 1997]. The accuracy of convective rainfall prediction can be improved by having an accurate forecast of when and where convection will develop. Using the surface refractivity from radars, higher spatial and temporal resolution can be achieved compared to the measurements from existing surface instruments. For example, radiosonde networks provide hourly measurement but this is insufficient for prediction and understanding of fast evolving convective processes [Weckwerth and Parsons, 2003].

Based on the concept by Fabry [2004], a similar but independent refractivity retrieval algorithm has been developed here at the University of Oklahoma [Cheong et al., 2007] and has been tested on X-band radars. For the X-band magnetron-based radars, the algorithms were modified in order to accommodate the complications induced by the shorter wavelengths, i.e., more frequent phase wraps in comparison to S-band radars, and, thus, complicates the subsequent processing. A proposed algorithm referred to as Differential Refractivity Retrieval (DRR) accumulates refractivity change over a short period of time, e.g., a 3-minute scanning cycle that is currently used by the CASA IP-1 network, to mitigate the rapid phase wrapping phenomena. As a result, relatively small atmospheric changes over such a short time do not cause a significant change in the signal phase, which minimizes phase wrapping. A possible and pertinent drawback of the DRR is the accumulation of error over a long period of time.

2. OVERVIEW OF RADAR REFRACTIVITY RETRIEVAL (SAME AS P8B.8)

Refractive index, n, of a medium is defined as the ratio of the speed of light in a vacuum to the speed of light in the medium. For the air near the surface of the earth, this number is typically around 1.003 and changes are on the order of 10^{-5} [Bean and Dutton, 1968]. For convenience, a derived quantity referred to as *refractivity* is used in many scientific studies, and is mathematically formulated as follows

$$N = 10^6(n-1) \quad (1)$$

Refractivity is related to meteorological parameters as shown below [Bean and Dutton, 1968]

$$N = 77.6\frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (2)$$

where p represents the air pressure in hectopascal (hPa), T represents the absolute air temperature in Kelvin (K) and e represents the vapor pressure in mb. The first term in equation (2) is proportional to pressure p and is, therefore, related to the air density. The second term is proportional to vapor pressure e, which is dominated by moisture. Near the surface of the earth with relatively warm temperatures, most of the spatial variability in N results from the change in the second term.

In theory, given that the received phase from stationary targets is a path-integrated function of the refractive index, which is described as follows

$$\phi(r) = -\frac{4\pi f}{c}\int_0^r n(\gamma)d\gamma \quad (3)$$

where f represents the frequency, c represents the speed of light (299,792,458 m s^{-1}) and r is the range. In practice, the radar wavelength that is on the order of cm and $n \approx 1$, so the phase wraps many times within a resolution volume depth which makes deriving refractivity directly from a single scan (Equation (3)) problematic. To mitigate this phase wrapping problem, Fabry et al. [1997] proposed that the change of refractivity between two scans can be obtained instead, i.e.,

$$\begin{aligned} \Delta\phi(r) &= \phi(r,t_1) - \phi(r,t_0) \\ &= -\frac{4\pi f}{c}\int_0^r \left[n(\gamma,t_1) - n(\gamma,t_0)\right] d\gamma. \quad (4) \end{aligned}$$

If the refractivity field of the reference scan (t_0) is known, the measurement of the change of refractivity allows us to obtain the absolute refractivity map simply by adding the difference to the reference map. By performing a range derivative in equation (3), it can be shown that

$$\frac{d}{dr}\left[\phi(r,t_1) - \phi(r,t_0)\right] = -\frac{4\pi f}{c}\left[n(r,t_1) - n(r,t_0)\right]. \quad (5)$$

where measurement at time t_0 is referred to as the reference, i.e., *reference phase* and *reference refractivity*.

Fortunately for our studies, Oklahoma has a reliable, high-quality network of surface stations, known as the OK Mesonet [Brock et al., 1995; McPherson et al., 2007]. We will use this network to provide an estimate of the reference refractivity map. Under conditions where the spatial structure of refractivity is not complex, the OK Mesonet allows us to derive an accurate reference refractivity map.

A flowchart of refractivity retrieval algorithm is provided in Figure 1. First, a map of reference phase measurements from the radar, associated with the time of the reference refractivity from OK Mesonet are collected. In general, we would like the structure of the field to be relatively simple, so that the coarse sampling of the Mesonet can be used to produce an accurate reference refractivity map. During normal scanning time, a map of phase measurement is obtained and subsequently used to derive a map of *phase difference* from the reference. Then, regions without *good* ground targets (based on ground clutter coverage and its quality) are masked out to retain only those phase measurements that are useful for refractivity retrieval. A process of spatial interpolation and smoothing is applied to this masked phase-difference map in order to fill the map. By computing radial derivatives (refer to Equation (5)) of this smoothed phase-difference map, *refractivity change* can be obtained. Another smoothing is applied to this refractivity change map to reduce the inherent uncertainty in the measurement and derivative operation. Finally, absolute refractivity can be obtained by adding the reference refractivity map to the refractivity change map.

3. DIFFERENTIAL REFRACTIVITY RETRIEVAL

Using X-band radars in comparison to S-band, the shorter wavelength introduces a rapid phase wrapping

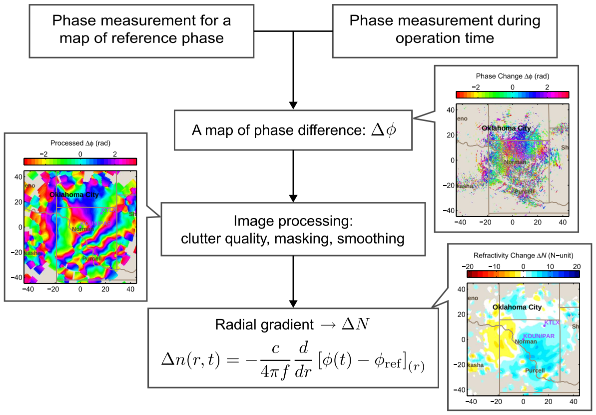

Figure 1: Procedure of refractivity retrieval

in the map of phase difference (refer to Equation (4)). The interpolation and smoothing process (refer to Section 2) often fails when phase wrapping is too rapid. In order to mitigate the rapid phase folding, DRR was proposed given that atmospheric change over a short amount of time is expected to be minimal and, thus, the phase wrapping is minimized [Palmer et al., 2006]. By accumulating the refractivity change over these short time intervals, a total change is obtained. An obvious drawback of this technique is that estimation error/bias can accumulate over time which would diverge the estimate far away from the true values.

Another complication from using the XPOL and the IP-1 radars is the frequency drift of the magnetron oscillator. During the REFRACTT-2006 campaign, the mobile XPOL radar from University of Massachusetts was used for initial test of refractivity retrieval using an X-band radar. At that time, the effects of frequency drifts on the refractivity retrieval algorithm were not well understood. Therefore, raw phase measurements and the frequency of the magnetron were monitored and stored in the hope of re-processing the data later in order to account for the effects induced by the drifting frequency. Later, however, we learned that even without correction of frequency drift, the estimates of refractivity change were well compared with the surface measurements. To resolve this issue, we began by investigating the procedure of retrieving refractivity change, which can be described as

$$\Delta N = -10^6 \frac{c}{4\pi f}\frac{d}{dr}\left[\phi(r,t_1) - \phi(r,t_2)\right]. \tag{6}$$

One can see that Equation (6) is simply a rearrangement and conversion from refractive index to refractivity of Equation (5). In practice, the derivative operator in Equation (6) is applied as a finite-difference operator described by Equation (7).

Due the frequency drift of the magnetron, additional phase offsets are introduced from time t_0 to time t_1 at the phase measurements. Here, we represent the phase offsets as $\phi_{\Delta f}$ and ϕ_ϵ in Equation (8). Note that the amount of phase offset due to frequency drift are close to each other for range bins $(r - \Delta r)$ and r. That is, range bin $(r - \Delta r)$ and r both have the total phase offsets of $\phi_{\Delta f}$ and $\phi_{\Delta f} + \phi_\epsilon$, respectively. As such $\phi_{\Delta f}$ cancels due to the derivative operator in the refractivity algorithm and we are left with the residual term $\phi_{\Delta f}$, which is small and insignificant for the DRR method. This residual phase offset can be described mathematically as

$$\epsilon_\phi = -\frac{4\pi\Delta f}{c}\Delta r. \tag{10}$$

The 3-minute frequency difference of the magnetron of XPOL as an example frequency drift expected from a 3-minute volume scanning configuration is shown in Figure 2. As mentioned earlier, this amount of frequency drift results in negligible effects using DRR. For example, given $\Delta r = 30$ m, $\lambda = 0.03$ m and $\Delta f = 10$ kHz, the resultant phase error is merely 0.72° (0.0126 rad), which is much less than the typical measurement noise. Therefore, the refractivity change from DRR should be in agreement with the surface measurements from radiosonde without any compensation for the frequency drift of the magnetron.

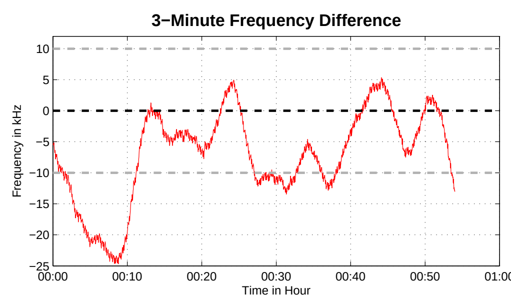

Figure 2: A typical 3-minute frequency difference of the magnetron of XPOL obtained by calculating the total basedband frequency drift within a 3-minute running window. Similar but a less severe frequency-drifting behavior can be expected from IP-1 radars since the magnetron is housed inside a temperature-conditioned environment.

4. EXPERIMENTAL RESULTS AND FINDINGS

As part of the REFRACTT 2006 campaign, an experiment was conducted during July 2006 using the XPOL radar, which is an X-band, magnetron-based mobile radar developed by the University of Massachusetts, Amherst. Real-time raw data were processed for phase

$$\frac{d}{dr}\left[\phi(t_1)-\phi(t_0)\right] \rightarrow \frac{1}{\Delta r}\left\{\left[\phi_{t_1}(r)-\phi_{t_0}(r)\right]-\left[\phi_{t_1}(r-\Delta r)-\phi_{t_0}(r-\Delta r)\right]\right\} \quad (7)$$

$$\frac{d}{dr}\left[\phi(t_1)-\phi(t_0)\right] \rightarrow \frac{1}{\Delta r}\left\{\left[\phi_{t_1}(r)-\phi_{t_0}(r)+\phi_{\Delta f}+\phi_{\epsilon}\right]-\left[\phi_{t_1}(r-\Delta r)-\phi_{t_0}(r-\Delta r)+\phi_{\Delta f}\right]\right\} \quad (8)$$

$$= \frac{1}{\Delta r}\left\{\left[\phi_{t_1}(r)-\phi_{t_0}(r)+\phi_{\epsilon}\right]-\left[\phi_{t_1}(r-\Delta r)-\phi_{t_0}(r-\Delta r)\right]\right\} \quad (9)$$

measurements and the standard moment for refractivity retrieval. Frequency drift of the magnetron was recorded via the transmit pulse in the raw data for later post-processing. As mentioned earlier in Section 3, however, frequency drift correction is negligible for DRR processing and, thus, results from this section are not frequency corrected.

Another investigation was conducted using the dataset collected on September 17, 2006 using two CASA radars of the IP-1 network. At the present time, the CASA IP-1 allows for user input for the operation of the system. Each cycle is at an increment of 30-second interval, or a so-called "heartbeat" [Brotzge et al., 2006]. Depending on the volume coverage pattern, each elevation maybe revisited every 5 heartbeats, i.e., the lowest elevation can be expected to be revisited no longer than 3 minutes and, thus, the frequency drifting behavior should be less severe than the 3-minute difference of the XPOL's magnetron mentioned in Section 3.

4.1. Results from REFRACTT 2006 Using XPOL

Since the core of the refractivity retrieval algorithm derives *refractivity change*, comparisons with other instruments are essential. Using one of the longest contiguous dataset collected during REFRACTT 2006 with XPOL, i.e., a 6-hour contiguous data from July 27, 2006, we compare the refractivity change derived from the XPOL radar and values of refractivity change derived from surface measurements (via Equation (2)) from the nearby radiosonde (RAOB) stations. These RAOB stations are located approximately 2 km and 30 km away from the XPOL radar, respectively. During this time period, a refractivity change of more than 20 N units was recorded and can be seen to be in good agreement in Figure 3.

4.2. Preliminary Results From IP-1 Network

From the dataset recorded on September 17, 2006 with the CASA IP-1 network, a 2-hour contiguous subset with two radars operating simultaneously from 13:55 to 15:55

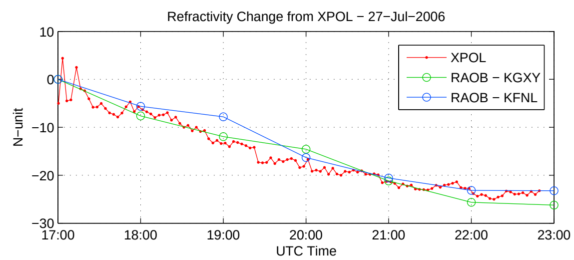

Figure 3: A 6-hour ΔN retrieved using the XPOL and from the surface measurement of nearby radiosonde are in good agreement. The two RAOB stations KGXY and KFNL are approximately 2 km and 30 km, respectively, away from the XPOL radar.

UTC were selected for the investigation with the DRR. During this time period, a weak storm was passing from the west of the domain. Differential refractivity fields are accumulated for the total change of refractivity since 13:55 UTC and is shown in the time history plot in the top half of Figure 4. The same quantity is derived from the surface measurements of the OK Mesonet and is shown in the bottom half of Figure 4. From this comparison, one can easily see a general agreement between the measurements from IP-1 network and OK Mesonet during this 2-hour period. More importantly, an apparent spatial structure annotated in ovals can be seen from both measurements. With this comparison, we can see the promising potential of retrieving refractivity using the CASA IP-1 network.

5. CONCLUSIONS

In this project, the possibility of retrieving refractivity using CASA X-band radars were investigated and found to show significant potential. The field experiment during the REFRACTT-2006 using the XPOL radar provided us an opportunity to learn that DRR produces refractivity change that is consistent with the surface measurement despite the frequency drifting behavior inherent in the magnetron oscillator. The DRR algorithm was developed with the goal to overcome rapid phase wrapping using shorter wavelengths such as the CASA X-

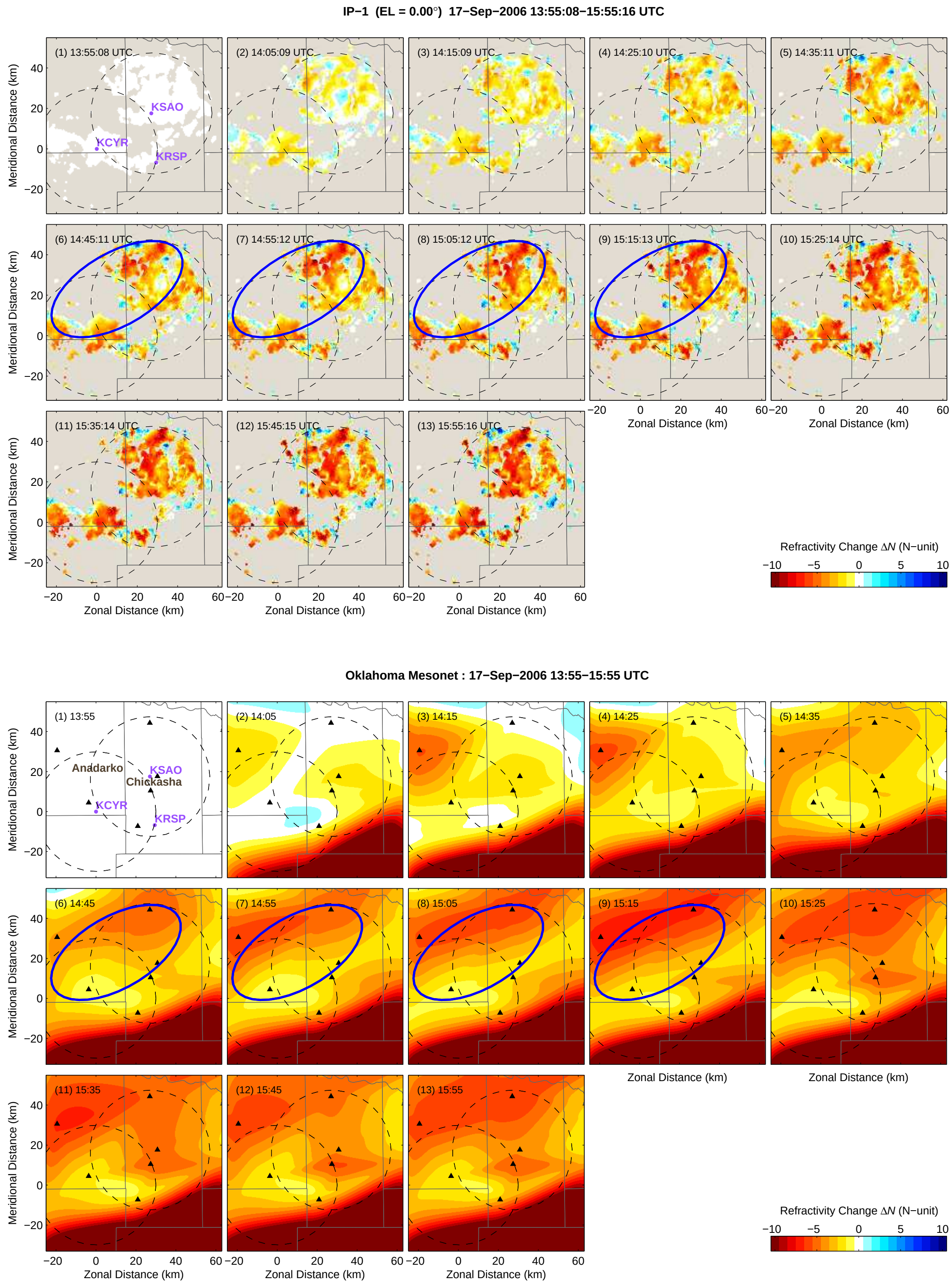

Figure 4: Total refractivity change since 13:55 UTC using the phase measurements from IP-1 network and surface measurements from the OK Mesonet are in agreement. By using the DRR method, frequency drift effects is minimal.

band radars. In addition, in this paper, we revealed that by using the DRR algorithm, moderate frequency drift, e.g., 10 kHz in 3 minutes for the XPOL radar, can be neglected if the DRR algorithm is applied. Future work include the investigation of error propagation using the DRR method.

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