Retrieval of surface-layer moisture fields using CSU radars

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Abstract

The surface-layer refractivity, i.e., the refractive index of air near the earth's surface, can be retrieved from radar by examining the phase of stationary ground targets. Stationary ground targets are those that return strong radar echoes and do not produce rapid phase changes under slowly varying humidity levels, unlike vegetation, for example, that adds a significant random component to the measured phase as it moves in the wind. The index of refraction is a function of pressure, temperature, and humidity, and variations are dominated by humidity in warmer weather. Since the refractivity has a significant impact on the phase of propagating radar waves, it can be measured by observing the range integrated phase change between two stationary ground targets. This index, in turn, can be used to estimate the water vapor near the surface to explore convective storm initiation and storm evolution, and to enhance quantitative precipitation forecasts. This procedure was recently performed using the CSU-CHILL and Pawnee S-band radars, in addition to several other radars in Colorado such as the NCAR S-Pol and National Weather Service WSR-88D (KFTG), during the Refractivity Experiment For H_2O Research And Collaborative operational Technology Transfer (REFRACTT 06) project. Estimated refractivity fields and the result of automatic stationary target identification are presented as well as an algorithm to merge refractivity fields from overlapping radar coverage area.

Automatic Stationary Target Identification

It is impractical to manually select the stationary ground targets to use for refractivity measurements; therefore, the phase coherence of targets over time are analyzed to identify good targets. Each target (range cell) is assigned an index to indicate its reliability for use in refractivity retrieval, where an index of 1 indicates strong phase coherence as seen in Figure 2. Since a goal of REFRACTT was to demonstrate that the refractivity algorithm can run on the NWS radars, the prescribed scanning strategy was a 4 minute volume scan from 0° to 10° elevation rotating at 12°/second to match a typical KFTG scan. The target ID map from the CSU-CHILL radar which was found to provide the best results, however, was generated on its first operational day (2006/6/22) after hardware upgrades, using consecutive 3°/sec scans as seen in Figure 2d.

To investigate the effects of a slower scan rate and consecutive scans, an experiment was conducted on 2006/10/27. Raw time series data were recorded from CHILL at 0° elevation alternating between a 3°/sec scan and 3 to 4 12°/sec scans. Despite the fact that the phase from the slower scan involves averaging 4 times the number of samples from the faster scan, the resulting target ID maps between the slow scans and the faster scans separated by a similar time interval (3 ½ - 4 minutes) are almost identical as seen in Figures 2a-b. This is likely due to the fact that the phase has a roughly uniform probability distribution so increasing the number of samples does not decrease variance. However, Figure 2c shows a noticeable improvement occurred when all of the faster scans were used, even with the periodic 2 minute gaps from the slow scans.

While the target ID map depicted in Figure 2c appears to indicate more reliable targets than the original map generated from 6/22 data (Figure 2d), the overall impact on a resulting refractivity field does not indicate a similar scale of improvement as seen in Figures 3a and b. The N fields only contain values where the phase error measures, depicted in Figures 3c-d, are defined. Because the 6/22 target ID map indicated a higher reliability in the 60 – 70 km, 250 - 300° azimuth region, more error measures are defined from 6/22 (Figure 3d). The overall error measure indicates how an error in the smoothed phase observation relates to errors in dϕ/dr, which relates to errors in N. This measure is lower, in general, for the 10/27 target ID, providing a slightly higher confidence in refractivity estimates, but the coverage area is slightly reduced.

Merging Refractivity from Multiple Radars

The CSU operated Pawnee radar, located about 50 km north of CHILL, became operational in mid-August. The considerable overlap in coverage between the 2 radars provided an opportunity to explore refractivity estimation using multiple radars. Figure 4 displays the N field difference of the 2 radars, and indicates that the difference can be quit large (~40 – 50 N units) in some places. For reference, a change in air temperature of 1 °C or 0.2 °C change in dewpoint temperature, will produce a 1 N change at T = 18 °C. For the real-time display of merged refractivity fields during REFRACTT 06, the merging algorithm used was to select the maximum N value where multiple values are available. Figure 5a shows the result of this algorithm for the time shown in Figure 4. Since the Pawnee N tends to be higher in this case, it overrides values from CHILL and produces a visible discontinuity in the merged result. However, we can take advantage of the error fields (see Figures 3c-d) to provide a smooth transition by calculating a weighted average. The composite value, N_{comp}, is given by

$$N_{comp} = \mathbf{a}^{\mathrm{T}}\mathbf{w}$$

where $\mathbf{a}$ is the vector of refractivity values from p radars at a given point, and $\mathbf{w}$ is the vector of weights. The weights, w, are a function of the errors measures, e, given by

$$w_k = \frac{\frac{1}{p-1}\sum_{q=1,q\neq k}^{p} e_q}{\sum_{q=1}^{p} e_q} \quad \text{with} \quad \sum_{k=1}^{p} w_k = 1 \quad \text{and} \quad e_q > 0, \forall q$$

The results of this merger algorithm are shown in Figure 5b.

Background

The relationship between refractivity, temperature, pressure and humidity is given by

$$N = 77.6P/T + 3.73E5e/T^2$$

where P is pressure (mb), T is temperature (K), and e is the vapor pressure (mb). The refractivity, N, is essentially the change of the index of refraction, *n*, from free space in parts per million, N = (n – 1)10^6.

As the air moisture content changes, the refractivity changes which alters the path of the radar wave. This is observed as a change in phase, integrated over range, r, given a travel time, τ_r and transmit frequency f (or wavelength, λ):

$$\phi(r) = 2\pi f \tau_r = \frac{4\pi}{\lambda}\int_0^r n[x(r'), y(r'), z(r'), t]\,dr'$$

In order to address the phase wrapping problem, which occurs at the radar wavelength, the change between 2 colinear targets, T_1 and T_2 is used to retrieve N[1]:

$$\Delta\phi(T_2) - \Delta\phi(T_2) = \left(\phi(T_2,\tau_1) - \phi(T_2,\tau_0)\right) - \left(\phi(T_1,\tau_1) - \phi(T_1,\tau_0)\right) \approx \frac{4\pi}{\lambda}\left[\int_{r(T_1)}^{r(T_2)} \left[n(r',\tau_1) - n(r',\tau_0)\right]dr'\right]$$

This algorithm was independently verified by Weckwerth, et al.[2] in the International H_2O Project.

The calculation of N from phase relies on having a reference phase map and an associated refractivity value based on surface measurements. This reference phase is typically generated from 10 – 20 minutes of 360° (PPI) scans when the phase change is minimal, indicating a relatively uniform moisture field. Figure 1a depicts the phase difference map over the 12 minute reference period used in REFRACTT 06, in contrast to Figure 1b which indicates a non-uniform change in refractivity over a similar time period on a different day.

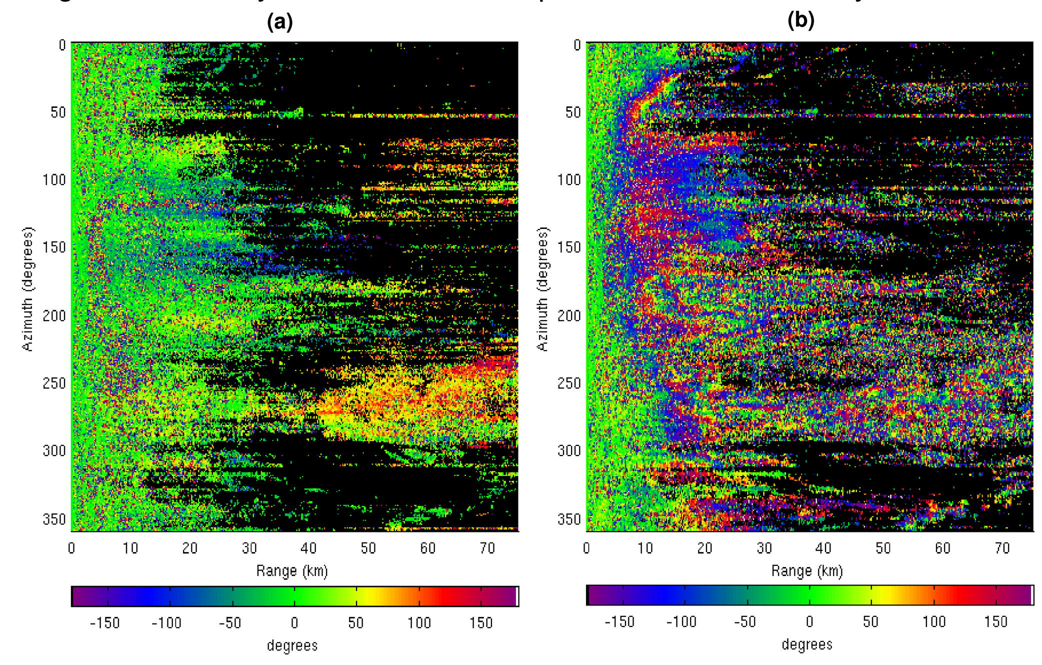

Figure 1. Phase difference a) suitable for reference phase (6/22/06), b) changes non-uniformly, i.e., not suitable for reference phase. Black means no data (SNR <= 1).

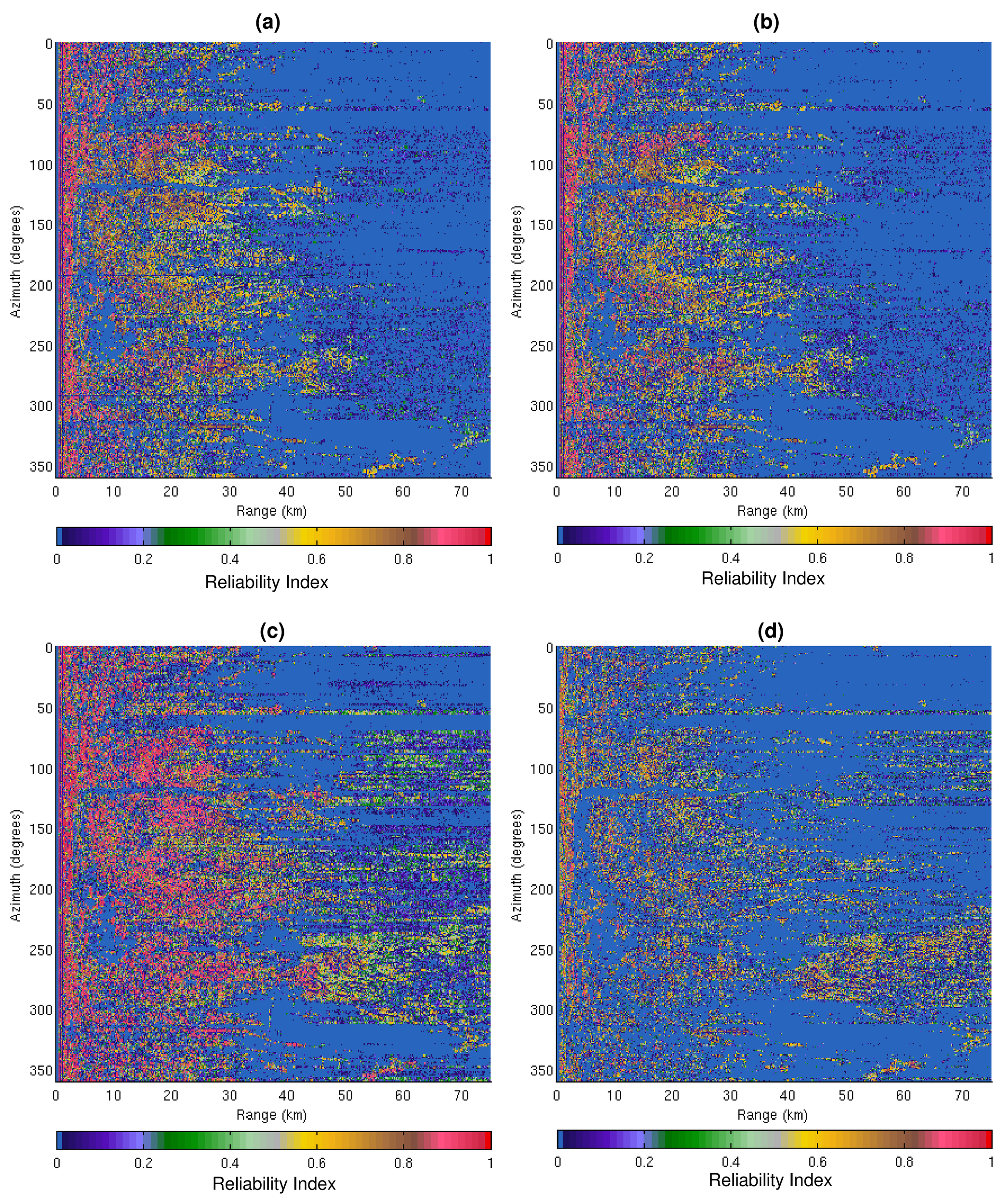

Figure 2. Target Reliability Index (ID). a) from 10/27 3°/sec scan, b) from 10/27 2nd 12°/sec scan, c) from all 10/27 12°/sec scans, d) from 6/22 scans

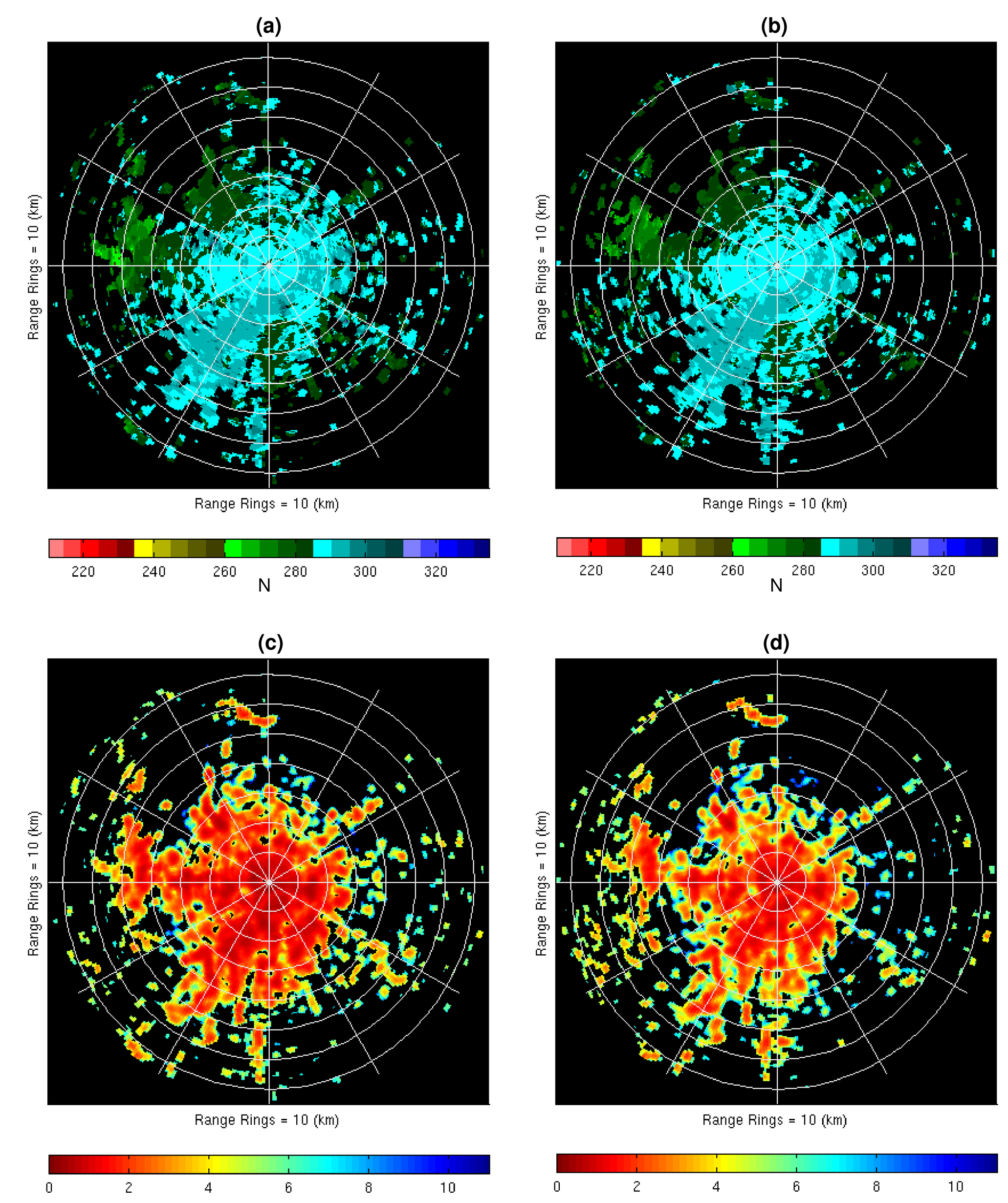

Figure 3. Refractivity results from 2006/08/01 using the 6/22 reference phase. a) refractivity field using 10/27 target ID, b) refractivity field using 6/22 target ID, c) error measure using 10/27 target ID, d) error measure using 6/22 target ID

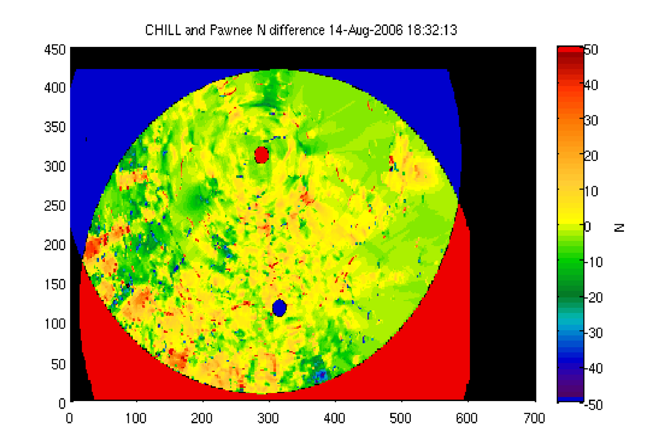

Figure 4. Refractivity difference ($N_{CHILL} - N_{Pawnee}$)

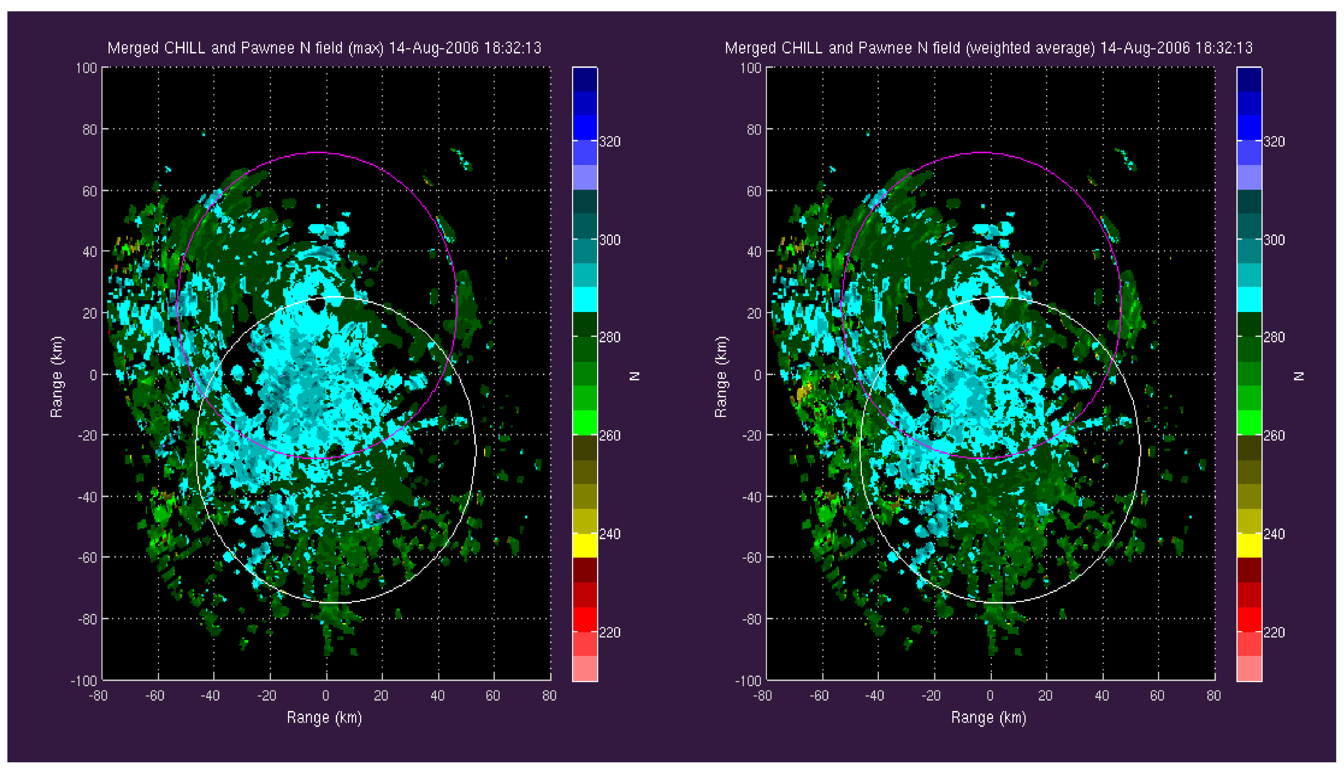

Figure 5. Merged CHILL and Pawnee Refractivity a) using the maximum value, b) using the error weighted average

Conclusions

There are several conclusions to reach as a result of this preliminary research.

- Increasing the number of samples in a fixed beam does not increase the reliability index of targets
- Using consecutive scans for target ID does increase the overall reliability index of targets
- For increased coverage of the N field, it is more important to have stationary targets covering a larger area than targets with a higher reliability index
- The weighted average merging algorithm accounts for lower confidence values (higher error) in overlap regions
- The weighted average algorithm provides a smoother transition of refractivity values across multiple radars

References

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