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The Colorado REFRACTT Demonstrations

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Introduction

The lack of detailed, high resolution water vapor measurements in the atmospheric boundary layer is one of the primary limiting factors in being able to predict convection initiation and produce accurate quantitative precipitation forecasts (QPF) from Numerical Weather Prediction (NWP) models (Emmanuel et al, 1995; Dabberdt and Schlatter, 1996; National Research Council, 1998). One of the most promising outcomes of the International $H_2$0 Project (IHOP; Weckwerth et al., 2004) conducted in 2002 was the near surface water vapor measurements extracted from radar using the index of refraction (refractivity) technique developed by Fabry et al (1997). This technique uses radar phase measurements of ground targets to extract index of refraction measurements. A recent study by Weckwerth et al. (2005) comparing the Fabry et al. radar refractivity technique with a variety of surface based and airborne moisture measurements has verified that this retrieval technique can be used to accurately estimate the near surface field of water vapor.

As part of the Colorado **R**efractivity **E**xperiment **F**or $H_2$0 **R**esearch **A**nd **C**ollaborative operational **T**echnology **T**ransfer (REFRACTT), the opportunity now exists to demonstrate the potential value and impact of this high resolution, 2-D moisture field to the operational community through the collection of refractivity data over a multi-radar domain that includes an operational NEXRAD and three 10 cm-wavelength research radars. There are two overarching goals of REFRACTT: 1) build operational advocacy for the refractivity moisture retrieval technique for ultimate installation on the U.S. national network of NEXRADs and 2) improve our understanding of near-surface water vapor variability and the role it plays in the initiation of convection and thunderstorms. This paper presents progress, highlights, and lessons learned from the two REFRACTT demonstrations conducted in NE Colorado during the summers of 2005 and 2006.

2 Data collection and processing

2.1 Refractivity (moisture) retrieval

The refractivity technique is based on the concept that variability in radar wave propagation between the radar and ground targets is due to changes in the properties of the air (i.e., changes in index of refraction) between the radar and targets. Variability of index of refraction (*n*) or refractivity *N* can be measured by the radar as a change in phase of the electromagnetic waves as they travel between the radar and the target. The change in phase (ϕ) is related to the index of refraction by the following relationship,

$$\frac{d(\phi-\phi_{ref})}{dr} = (\frac{4\pi f}{c})(n(r) - n_{ref}(r)), \qquad (1)$$

where *f* is the radar frequency and *c* is the speed of the waves. To obtain accurate average phase information requires the radar to transmit at a constant frequency (*f*). The klystron transmitters used in NEXRAD radars, and also by the research radars used during REFRACTT are believed to have a minimal frequency fluctuation as required for

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refractivity processing. The average phase information is calculated from the I and Q time series data being recorded by each radar; that is, the amplitude of the (I,Q) vector, NIQ and the phase (or angle) of the (I,Q) vector, AIQ. The NIQ and AIQ data from each radar were then reformatted first into netCDF and then into DORADE sweep files for ingest into the downstream refractivity algorithms.

The Fabry et al.(1997) refractivity algorithms made use of the Bean and Dutton (1968) relationship for refractivity *N*,

$$N = 10^6 (n-1) = 77.6 \frac{P}{T} + 3.73 \text{x} 10^5 \frac{e}{T^2}, \qquad (2)$$

which depends on pressure (P, in hPa), temperature (T, in K) and water vapor pressure (e, in hPa) to retrieve the near-surface water vapor measurements. While the first term on the right (proportional to air density) is typically larger than the second (humidity) term, Fabry (2005) has found using IHOP surface data that most of the spatial variability in N is due to variability in water vapor (75% of the total contribution) and less (24%) due to temperature variability. Hence, refractivity measurements collected when the contributions of temperature variability to N are small represent approximations for (N) fields of near-surface moisture.

2.2 Refractivity reference and target ID scans

There are two important steps to successful implementation and production of refractivity fields. The first step is to obtain the *reference* refractivity field $n_{ref}(r)$ used in Eq. 1. This field must be collected during a period of near homogeneous conditions in the atmospheric boundary layer prior to any real-time collections of refractivity $n(r)$. This proved to be a challenging exercise to find one or more days or period of hours when fairly homogeneous conditions were observed in the NE Colorado. Possible atmospheric scenarios for collection of radar phase data during homogeneous conditions included: 1) stratiform (overcast) cloudiness resulting from upslope flow along the foothills of the Rocky Mountains, 2) continuous downslope flow along the foothills onto the eastern High Plains resulting in well-mixed, steady boundary layer temperature and humidity values, or 3) late afternoon, ~3 hr after maximum diurnal heating, when the surface temperatures and dewpoint temperatures remain fairly constant with changes no greater than 1 deg C over the period of an hour. An ideal reference data set is one in which the phase difference over a certain period of time (~ 30-60 min) of "homogeneous" collection is small and the phase angle does not fold more than once within 50 km range from the radar. An example of a reasonable phase difference plots from three of the REFRACTT radars is shown in Fig. 1.

The second important step (target ID step) is to collect data that will help in identifying reliable, strong, and non-moving ground targets. A target quality index field is produced from this data and used in conjunction with the phase information in the refractivity algorithm to assess the quality and

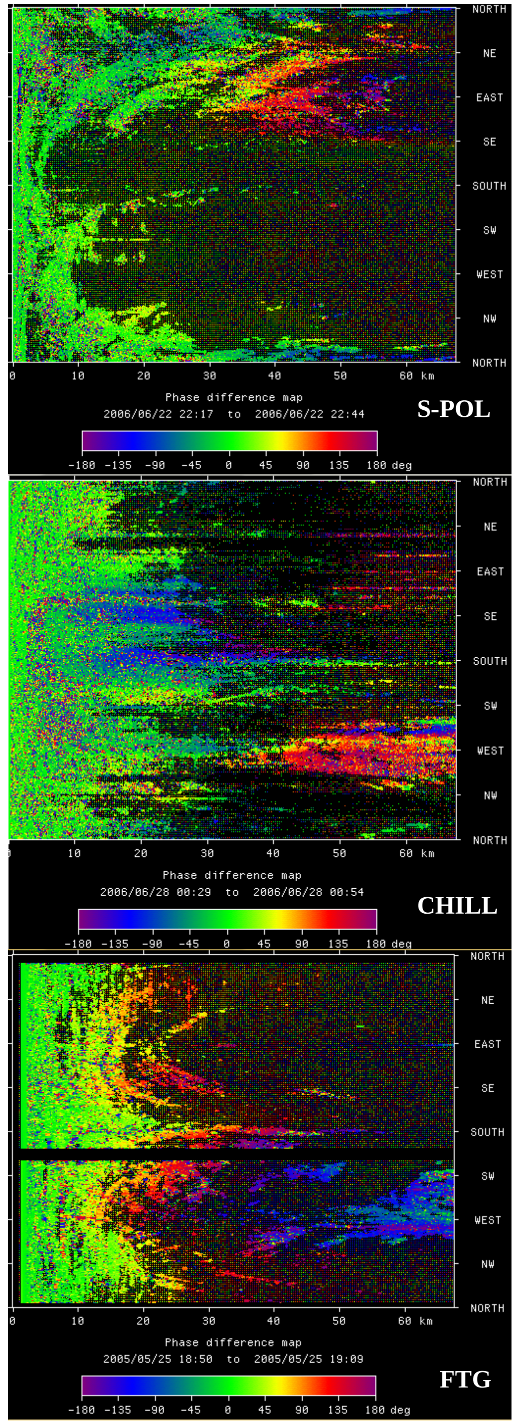

Fig. 1. Examples of B-scan phase difference plots used to identify good reference refractivity datasets. Range from radar is along the horizontal axis; azimuthal direction is along the vertical axis. S-POL and CHILL plots are from 22 June 2006. The FTG plot is from 25 May 2005.

confidence in the real-time refractivity measurements. For the target ID data, radars must be operated on a clear day and with a steady wind to help factor out moving targets that include trees and wind turbines, among others. The three research radars were able to collect target ID information by running the radar transmitter continuously at the 0.0 deg elevation scan over a period of several hours.

Due to national operational regulations, the NEXRAD radars do not collect data at 0.0 deg elevations. Thus, collection of phase and target ID information from the Denver NEXRAD had to be done using the 0.5 deg elevation angle transmitted every 6-10 min.

3. Highlights from REFRACTT

The first REFRACTT demonstration was conducted in NE Colorado from May-August 2005 using the Denver operational NEXRAD (FTG) radar. Following unanimous support of the refractivity technique from the NEXRAD Technical Advisory Committee in 2003, special permission was received from the NEXRAD Radar Operations Center (ROC), the NWS Central Region Headquarters, and the Denver NWS Weather Forecast Office (WFO) to hook an A1DA time series recording unit onto the FTG radar. This A1DA recorder was built in 1995 by NCAR and the ROC specifically for the purpose of archiving NEXRAD I and Q time series data to disk without interference to normal operational data collection.

In addition to the FTG radar, two other radars were used in 2005 to collect the I and Q information required as input to the refractivity technique: the Colorado State University (CSU) CHILL and the NCAR S-Pol 10 cm wavelength radars. Because the refractivity technique is primarily a software processing technique, refractivity measurements can be implemented on research and operational radars with a minimum of expense and impact during operational data collection. In addition to the three radars above, a fourth radar from CSU, the 10 cm Pawnee radar, collected refractivity data during REFRACTT-2006 which ran from 5 June – 11 August 2006 in NE Colorado.

Figure 2 shows the REFRACTT domain and the radar locations in 2006. The 50 km range rings represent the average likely extent of ground target returns detected by each radar. A reduction in coverage was observed for the NEXRAD FTG because of the limitation in having to use the 0.5 deg scan for phase and target information The locations of the four radars were fortuitous as the overlapping radar coverage has allowed us to mosaic the refractivity fields together to provide a continuous picture of moisture transport over an approximately 120 km x 225 km domain. Overlapping coverage also provided a means for comparing moisture estimates from two or more radars. Simultaneous collection of moisture information over a much broader domain will allow the data to be assimilated into mesoscale numerical models and automated nowcasting systems with the goal of improving quantitative precipitation forecasts.

3.1 REFRACTT-2005 demonstration

REFRACTT operations were conducted two days per week from 19 May – 29 August on a total of 26 weather events that included: boundary layer evolution, boundary collisions, convection initiation and thunderstorm evolution. Due to radar maintenance and improvement activities, coordinated collections of SPOL, CHILL and FTG data were possible

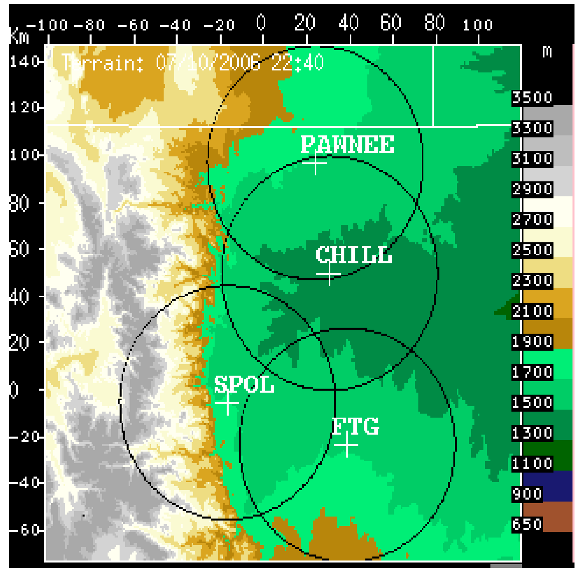

Fig. 2. Topographic map of NE Colorado. The rings represent the 50 km range from each radar and approximate coverage of refractivity data during REFRACTT.

only on a few days in July and August. Thus the desired simultaneous collection of triple-radar refractivity fields occurred on only a few selected days. An example of one of these events on 28 August 2005 is shown in Fig. 3 at 1800 UTC (12:00 noon Local Time). Higher moisture values are observed near the CHILL radar which is located at a lower altitude in the Platt River Valley (see Fig. 2). Data collection by two of the three radars occurred much more frequently.

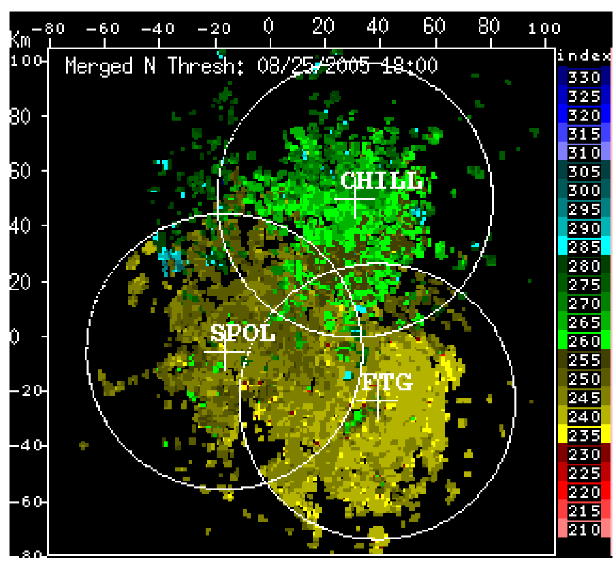

Fig. 3. Mosaic of refractivity (N) data from CHILL, S-POL and the NEXRAD FTG radars on 25 August 2005 at 18:00 UTC. Rings represent 50 km range from the radars. High N values represent regions of higher moisture.

A gust front passing through the FTG radar domain on 25 July is evident in the reflectivity, refractivity N and the delta-N fields in Fig. 4. The delta-N field is the change in refractivity values over two time periods (12 min in this

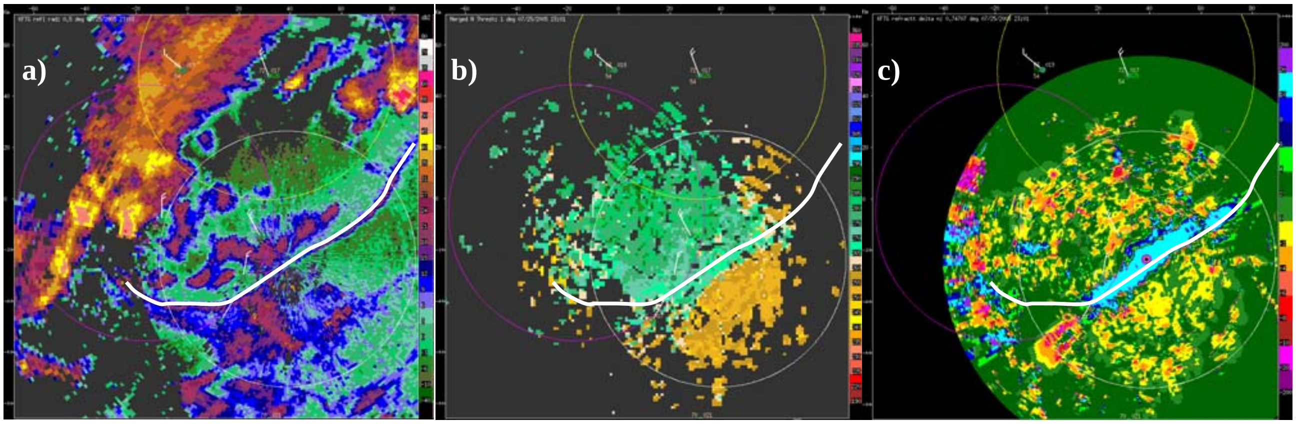

Fig. 4. Gust front passage to the south of the Denver NEXRAD FTG radar (white contour) on 25 July 2005. a) reflectivity, b) refractivity, c) delta-N.

case). Figure 4b is a clear illustration of the moist air advection behind the gust front and the relatively drier air out ahead. Of particular note is the strong increase in moisture (see Fig. 4c) concentrated along the leading edge of the gust front. This 10 unit change in N corresponds to a change in moisture of ~2 g kg^{-1}. Monitoring these fields in conjunction with environmental stability fields may prove very useful for short term nowcasting applications.

Although data was collected from the three radars in real-time, production of the refractivity fields occurred in post-analysis. The Open Radar Data Acquisition (ORDA) system to be implemented on all NEXRADs during 2005 and 2006 has been designed with a second port or interface into the radar processor for access to the I and Q data stream. Because this was not yet installed on the FTG radar in 2005 the NCAR A1DA time series recording unit was used to record the data to a special disk at the radar shelter and brought back to NCAR at the end of each day. CHILL and SPOL data were archived to tape and run later through the refractivity algorithm. There was no real-time aspect to the 2005 demonstration. The objective of getting the real-time mosaics of the refractivity fields in front of the National Weather Service (NWS) forecasters for their feedback and advocacy did not happen until 2006.

3.2 REFRACTT-2006 demonstration

The installation of the ORDA on the Denver FTG radar occurred in March 2006. In April, forecasters at the Denver NWS Forecast Office were trained on the interpretation and potential uses of the refractivity fields in their daily operations. By 3 July, good quality refractivity fields were being derived in real-time from the S-POL and CHILL NIQ and AIQ data and displayed for the NWS forecasters and REFRACTT scientists on a dedicated web page. On 11 July, after receiving final tri-agency (NWS, FAA, and DOD) approval and security clearance for access to the Denver NEXRAD ORDA, collection and processing of I and Q time series data was begun. Additional instrumentation fielded during REFRACTT-2006 include 1) 2 mini-radiometers developed by CSU for water vapor retrieval, 2) 15 GPS receivers for collection of precipitable and slant water vapor measurements, 3) a CASA X-band radar for collection of refractivity measurements and testing ideas to reduce the impact of multiple phase folding at 3 cm wavelength, 4) a mobile GAUS sounding system, 5) application of the differential interferogram technique using the ENVISAT Advanced Synthetic Aperture Radar for comparison with the ground-based refractivity fields, 6) GOES satellite data and 7) surface mesonets. Highlights from the 2006 REFRACTT demonstration and feedback from NWS forecasters will be presented at the conference.

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