Toward a National High Resolution Field of Water Vapor
REFRACTT_2006

1. Introduction

It is proposed to conduct a field program from June 5 to July 28, 2006 in Northeast Colorado that would collect radar refractivity data from the S-Pol, CHILL, Pawnee and Denver NEXRAD radars, as well as dual-wavelength radar measurements from S-Polka. The field program is called REFRACTT (**R**efractivity **E**xperiment **F**or H_2O **R**esearch **A**nd **C**ollaborative operational **T**echnology **T**ransfer).

1.1 Goals

The goals of this proposal have both a scientific research and an operational application component. However both have the goal of greatly enhancing the observed field of water vapor over the nation thus leading to improved precipitation forecasts. The scientific goal is to utilize multiple radars and GPS receivers to simultaneously obtain very high resolution measurements of water vapor variability and transport in the convective boundary layer and to assess potential improvements these enhanced water vapor measurements may have in numerical model forecasts of quantitative precipitation. The applications goal is to demonstrate the ability to collect radar refractivity data on the NEXRAD (WSR-88D) radars and to demonstrate the forecast value of this field to NWS forecasters. *The ultimate goal is to implement radar refractivity measurements on the national network of operational radars*. Before achieving this goal it is necessary to demonstrate that high resolution observations of near surface water vapor will actually lead to improved forecasts. While implementing radar refractivity measurements on operational radars will not be expensive because it requires only the addition of new software the utility of the measurements must be demonstrated before such implementation would be allowed.

1.2 Motivation

Several national study committees have reported that the lack of detailed, high resolution water vapor measurements in the atmospheric boundary layer is a primary limiting factor in being able to predict the initiation of convective storms 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). The International H_20 Project (IHOP) conducted in 2002 (Weckwerth et al, 2004) took a first step in rectifying this problem by assembling and deploying a large and diverse set of instrumentation over the Great Plains of the U.S. for the purpose of collecting detailed spatial and temporal measurements of water vapor.

1.3 IHOP field program

One of the more promising outcomes of IHOP was the near surface water vapor measurements extracted from the NCAR S-Pol radar using a new index of refraction (refractivity) technique developed by Fabry et al (1997). A recent study by Weckwerth et al. (2005) comparing Fabry's 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 (see Fig 1). Using the refractivity data collected by the NCAR S-Pol radar during IHOP, Fabry (2005) has documented the spatial variability of moisture in the boundary layer and its impact on a limited number of convection initiation cases that occurred within the S-Pol domain. Because of the dependence of the refractivity technique on ground targets (see more detailed discussion below), the maximum effective range of the refractivity data was 40-60 km from the radar. *The tremendous impact that this refractivity field can have, particularly when collected over a multi-radar domain, on short term nowcasting of convection by forecasters and for assimilation into mesoscale numerical models has yet to be realized.* This proposal takes the first step in addressing this issue.

Another promising result from IHOP was the capability of ground based GPS stations to precisely monitor both three-dimensional and column integrated water vapor fields associated with squall line evolution and boundary layer convergence (Braun and Xie; 2003). A case study of GPS derived three-dimensional moisture fields indicated a vertical transport of $2gm^{-3}$ from the surface to 3 km altitude during the passage of a squall line. This elevated moisture most likely influenced and strengthened a second storm that passed through the region less than 12 hours later. Comparisons of GPS derived integrals of slant water vapor (SW) to refractivity fields from the S-Pol radar showed complementary views of the boundary layer. The radar refractivity resolved the surface moisture field while GPS SW captured its spatial and temporal fluctuation through the depth of the boundary layer. From these comparisons, *it is expected that a combination of these two techniques creates an opportunity to make significant improvement in moisture fields through the depth of the boundary layer. The assimilation of these fields into mesoscale numerical weather models may lead to measurable improvements in the prediction of summertime convection events.*

Following IHOP, Roberts gave a presentation to the NEXRAD Technical Advisory Committee (TAC) in 2003 recommending that the refractivity technique be installed on NEXRAD radars. The TAC gave unanimous support of this effort, recognizing the great potential benefit of this moisture field to NWS forecasters. Roberts has been working closely with the NWS and following their NWS-OSI five step process for getting formal approval to have this technique installed on NEXRADs. As a first step, we received official approval from the NEXRAD Radar Operations Center and the NWS Central Region Headquarters to install a radar time series recording unit on the Denver NEXRAD (KFTG) radar starting in the summer of 2005. *It is anticipated that results from a 2006 experiment to collect refractivity data from the Denver KFTG radar, the NCAR S-Pol radar, and the two Colorado State University radars (CHILL and Pawnee) will provide the justification and validation information required (steps 1-3 of the NWS-OSI five step process) for final approval and implementation of refractivity collection on NEXRADs.*

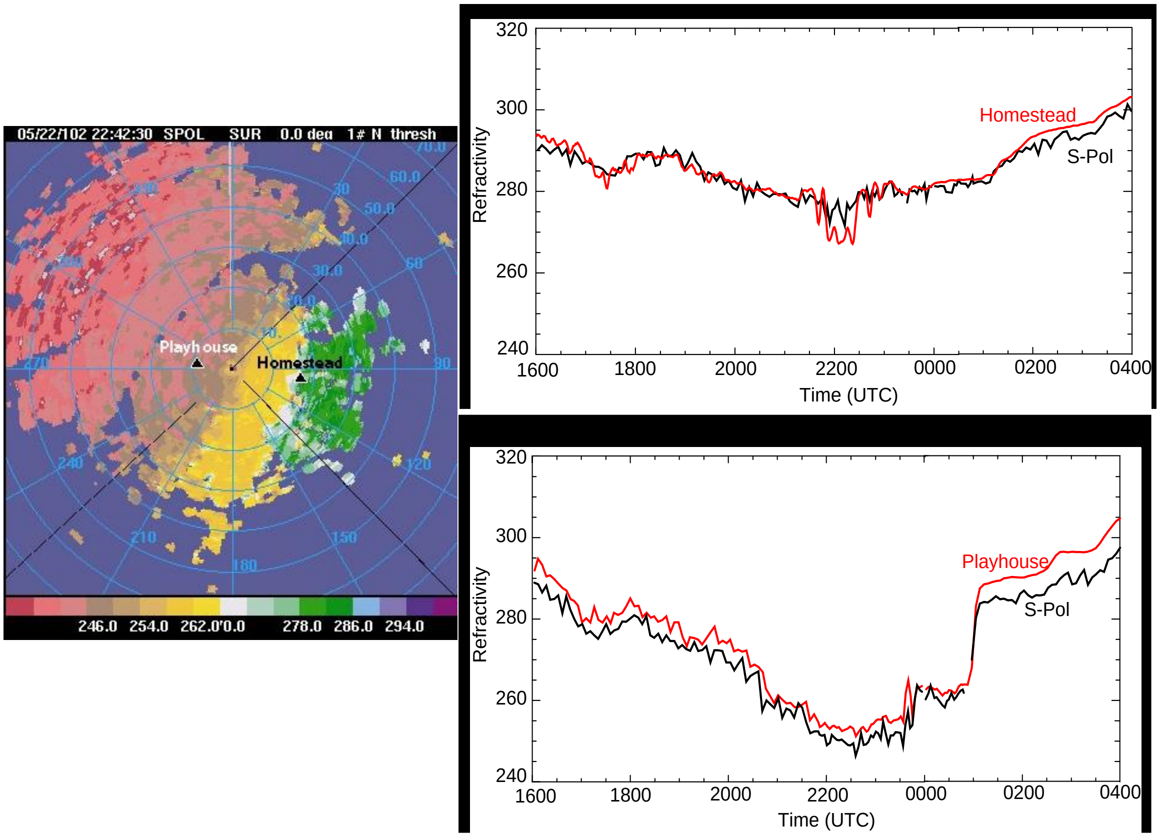

Fig 1. Example of a field of radar refractivity measurements during IHOP (left panel) and comparison of refractivity time series plots between S-pol and two surface stations (Homestead and Playhouse) (right two panels). The colors in the left panel represent variations in water vapor of about 6 g/kg from northwest to southeast. Range marks are at 10 km intervals. The refractivity extends to about 60 km in the northwest. From Weckwerth et al (2005).

2. Hypotheses

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a) High temporal and spatial resolution of near surface observations of water vapor will improve short term convective storm forecasting and quantitative precipitation forecasting. This hypothesis will be tested by 1) assimilating the high resolution observations into the cloud resolving forecast model of Sun and Crook(1998) called Forecast VDRAS (Variational Doppler Radar Analysis System), 2) providing the data in real time to forecasters at the Denver National Weather Service and 3) introducing the water vapor data into the NCAR Auto-nowcaster (Mueller et al. 2004).

b) 3-dimensinonal water vapor measurements obtained from combining radar refractivity and GPS slant range measurements will improve convective storm and quantitative precipitation forecasts. This hypothesis will be tested by assimilating the high resolution 3-dimensional water vapor fields into forecast models like the WRF and MM5.

c) Near-surface water vapor measurements will enhance our understanding of the exchange of moisture among soil/vegetation, land-surface, and boundary layer and determine the degree to which the boundary-layer moisture heterogeneity is related to land-surface heterogeneity. This hypothesis will be tested through comparison of this observational data set with land-surface model output.

d) The implementation of radar refractivity measurements on the national network of WSR-88D's with the new open radar data processor will be inexpensive and non-intrusive to other radar activities. This hypothesis will be tested by implementing on the Denver WSR-88D.

e) Accurate, path integrated, moisture estimates in the boundary layer can be obtained from dual-wavelength radar reflectivity measurements of clouds, resulting in horizontal and vertical moisture distributions. These derived moisture distributions are dependent on the arrangement of the clouds and clouds must be present for this technique to be applicable. This hypothesis will be tested by retrieving moisture from the dual-wavelength S-Polka measurements and comparing the results to the refractivity, GPS, MGAUS and surface station data.

3. Moisture Retrieval

3.1 Radar Refractivity

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 the targets. Variability of index of refraction 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. Fabry et al.(1997) then made use of the Bean and Dutton (1968) relationship for refractivity *N*,

$$N = 77.6\frac{P}{T} + 3.73\text{x}10^5\frac{e}{T^2}, \qquad (0.1)$$

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 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, the S-Pol refractivity measurements collected during IHOP when the contribution of temperature variability to N was small represent approximations for fields of near-surface moisture. Comparison of the S-Pol refractivity fields to moisture measurements from IHOP surface mesonet, low-flying aircraft and other vertical profiling sensors show high correlations, validating the refractivity retrieval technique as a good approximation for humidity measurements in the lowest ~250 m of the boundary layer (Weckwerth et al., 2005).

3.2 Global Positioning System (GPS)

Fundamentally, GPS receivers measure the time it takes for a signal to propagate from a transmitting satellite to a receiving antenna. The signal is delayed as it passes through the atmosphere. This delay is then used to infer the atmospheric state, including the integrated amount of water vapor along the path of the signal (Rocken et al; 1995, Businger et al; 1996, Braun et al; 2003). In the same manner as the radar phase observation, the delay of the signal is a function of refractivity. GPS can be used over a range of conditions, including heavy clouds and precipitation, without measurable degradation of its observational capabilities (Solheim et al; 1999). Data from GPS stations can be analyzed to retrieve vertically integrated precipitable water (PW), integrated slant water (SW), and three dimensional water vapor fields (using data collected from a network of stations). Observational comparisons to a microwave water vapor radiometer show root mean square agreement of 1.5 mm.

3.3 Dual-wavelength Radar

The S-Pol radar has recently added the capability to collect simultaneous dual-wavelength radar measurements by mounting a Ka-band (0.8 cm wavelength) cloud radar on the S-band (10 cm wavelength) antenna. The S- and Ka-band radar beams are matched temporally and spatially in order to sample similar volumes simultaneously. This allows for accurate estimates of Ka-band gaseous attenuation (dB/km) along radials from the radar to weather echoes, provided the Rayleigh scattering approximation is satisfied for both radars at the nearest edge of the cloud. It should be noted that the absorption due to O_2 and H_2O is small at S-band. Gaseous attenuation at radio frequencies is primarily due to absorption by O_2 and H_2O molecules and depends on the concentration of both. In the troposphere, O_2 is evenly distributed and the concentrations are well known for given pressures. Therefore, the primary contribution to variations in atmospheric attenuation at Ka-band, within a given layer, is water vapor concentration, although a weak dependence on temperature exists. The radiative transfer model of Liebe (1985), which computes atmospheric attenuation for given atmospheric conditions, is used to compute a path integrated water vapor content. Depending on cloud echo locations, numerous paths at differing elevation angles can be used to produce horizontal maps and vertical profiles of water vapor content.

4. Scientific and Engineering Challenges

As stated in hypothesis a) the primary scientific challenge is to demonstrate that high resolution water vapor estimates will improve forecasts of convective storms and quantitative precipitation. This hypothesis will be tested by collecting radar refractivity data from each of the radars shown in Fig. 2. This data will then be ingested into the algorithms that comprise the refractivity technique to produce the water vapor fields. A mosaic of the individual water vapor fields will be prepared in real-time and made available to REFRACTT scientists and Denver NWS forecasters. Three methods are proposed for testing the utility of the high resolution water vapor fields. The first is to assimilate the water vapor fields into the cloud resolving model called Forecast VDRAS to test if there are improvements in forecasting convective storm evolution. The necessary model modifications to ingest this data have already been accomplished and tested using a small sample of refractivity data from IHOP.

The second method is to provide the mosaic near surface water vapor fields in real time to forecasters at the Denver NWS for use in their very short period thunderstorm forecast and warning activities. The NWS forecasters have expressed great interest in participating in the experiment and evaluating the operational utility of the water vapor measurements. An important step in the path to implementing radar refractivity on the national network of NEXRADs is obtaining the support of the operational forecasters.

The third method is to input the high resolution mosaic water vapor fields into the NCAR Auto-nowcaster to determine if there is improvement in the 0-2 h thunderstorm forecasts. At present monetary support is not available for this third effort but it is anticipated that the availability of a high resolution water vapor field will heighten the likelihood of obtaining such support.

Hypothesis b) states that water vapor fields obtained from the combination of radar refractivity and GPS slant range measurements will improve convective storm and quantitative precipitation forecasts. The first step will be developing optimum procedures to combine these data sets. The second step will test their impact in numerical forecast models like WRF or MM5. A significant problem in forecasting convective initiation is determining the depth of water vapor convergence within the boundary layer. GPS provides an integrated observation of boundary layer moisture, simultaneous slant measurements in the direction of between 6 and 12 satellites identifies the spatial variability of the boundary layer. The inclusion of soundings collected with the mobile sounding system (MGAUS) will provide additional constraints on the moisture field. Funds have yet to be obtained for studies associated with hypothesis b), but it is anticipated that the availability of a data set such as the one proposed will increase the likelihood of obtaining this support.

Hypothesis c) states that near-surface water vapor measurements will enhance our understanding of land-surface exchange of low-level moisture through comparison of this observational data set with land-surface model output. A preliminary comparison of the S-Pol refractivity data to surface evaporation fields produced from a **H**igh-**R**esolution **L**and **D**ata **A**ssimilation **S**ystem (HRLDAS) model during an IHOP event of strong soil moisture heterogeneity due to a recent rainfall event, showed good correspondence between the two fields (Chen et al., 2005). Collection of refractivity data over a domain much larger than IHOP and in an area of NE Colorado that experiences large temporal (diurnal and seasonal) and spatial variability in moisture, caused by diverse landuse and small-scale convective precipitation, will provide a novel opportunity to verify the HRLDAS spatial distribution of latent heat flux (evaporation) fields with high resolution water vapor fields, and therefore to improve HRLDAS. Combining GPS boundary layer moisture, refractivity derived near-surface moisture, and HRLDAS soil moisture and surface evaporation fields will allow us, probably for the first time, to investigate 1) the degree to which local soil and vegetation processes affect local and regional distribution of water vapor in the boundary layer, and 2) how the above affect convection initiation. The ability of the HRLDAS model output to represent the evolution of the surface evaporation and latent heat transport will then be compared to the near-surface high resolution, mosaic water vapor field over a variety of weather regimes and boundary layer scenarios.

Hypothesis d) states that radar refractivity measurements can be implemented on research and operational radars with a minimum of expense and impact on present operational capabilities. At the time this proposal is being prepared an informal, preliminary field program called REFRACTT_2005 is being conducted in NE Colorado to address this issue. This effort involves the Denver NEXRAD, CHILL and S-Pol radars. The primary effort is to develop and test software for collecting and displaying radar refractivity data in real-time. Frederic Fabry of McGill University, the original developer of the refractivity technique, is working directly with scientists and engineers from both Colorado State and NCAR to install the necessary software for each radar to extract the refractivity measurements from the radar time series data.

Another important engineering effort is to establish procedures for obtaining a reference radar refractivity field which is then used to determine the refractivity field at all other times. Because of maintenance and development time constraints with both S-Pol and CHILL coordinated collections will only be briefly possible during 2005 and thus desired simultaneous multi-radar refractivity fields will only occasionally be obtained. In addition no real time mosaic of the refractivity fields will be possible. Thus we look at REFRACTT_2005 as mostly an engineering effort to develop and test procedures and REFRACTT_2006 as the scientific experiment to test the utility of refractivity measurements to improve convective storm and quantitative precipitation forecasting.

Hypothesis e) states that 3-D boundary layer moisture can be retrieved from simultaneous dual-wavelength (S and Ka) radar measurements and displayed in horizontal maps and vertical profiles. A prototype of this algorithm has been tested on a limited number of cases from the Rain In Clouds over the Ocean (RICO) experiment and compared to drop-sonde data. The initial comparisons are very promising and show agreement within 10% of the drop-sonde humidity profile. The important challenges for this method are further verification using established humidity estimates and design of an automated algorithm. The proposed project would provide a unique opportunity to investigate both of these challenges.

5. Experiment Design

We propose to conduct the REFRACTT_2006 experiment from 5 June – 28 July 2006 in Northeast Colorado. Time series phase information will be collected from four radars, CSU's CHILL and Pawnee radars, the NCAR S-Pol radar and the Denver NEXRAD

(KFTG) radar to produce refractivity fields. It is proposed that CHILL and S-Pol remain in their home locations thus dramatically reducing costs. Figure 2 shows the domain for the 2006 experiment and radar locations. The 50 km range rings represent the average likely extent of ground target returns from each radar. It can be seen that the location of these radars is fortuitous as the overlapping coverage from the radars will enable us to mosaic the water vapor fields together to provide a continuous picture of moisture transport over an approximately 200 km by 140 km domain. This will provide a much broader domain of observations that can be assimilated into the Variational Doppler Radar Assimilation System (VDRAS; Sun and Crook; 2001) and compared with the HRLDAS land-surface numerical model (Chen et al., 2005). The locations of the existing GPS receivers are also shown in Fig. 2. Not shown are the approximately 170 mesonet stations (e.g. AWOS, ASOS, APRS, CDOT, UDFCD, MesoWest, and RAL) in NE Colorado that are already available in real-time for display and archival.

In Colorado, there are approximately 12 GPS receivers located along the Front Range and over the High Plains of NE Colorado. The location of most of these stations can be seen in Fig. 2. GPS SW is derived in the direction of all satellites visible to the ground station. A satellite will move 30° across the sky in elevation and/or azimuth over an hour, and there are typically between 6-12 satellites in view at any instant. These GPS receivers operate continuously and will collect data throughout the summer of 2006. Pending the approval of this proposal, attempts will be made to deploy additional GPS receivers in NE Colorado to supplement the existing network of stations shown in Fig. 2. The additional stations will augment the existing network, allowing for an estimation of the three-dimensional water vapor field.

As stated above research will be undertaken to determine optimum methods for combining vertically integrated slant path GPS water vapor measurements with high resolution radar near surface water vapor measurements

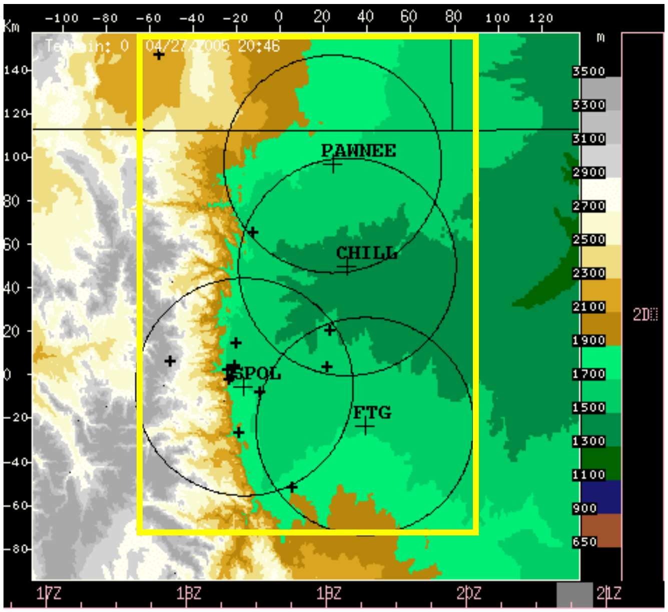

Figure 2. Topographic map of NE Colorado. The thick, rectangular yellow box marks the instrumented domain for the proposed 2006 experiment. Large black crosses mark the radar sites. Black rings represent the 50 km range from each radar. The small, thick black crosses indicate the locations of the GPS stations.

MGAUS will be deployed to specific locations to obtain soundings on either side of tight horizontal water vapor gradients and to a variety of other locations to help obtain representative measures of vertical water vapor profiles to correlate with the near surface refractivity measurements. In addition we request the MGAUS be periodically driven to all the ASOS and AWS surface station sites in NE Colorado to compare these observational sensor measurements against the calibrated MGAUS surface sensors (temperature, dewpoint temperature, pressure). ASOS and AWS measurements are used in the process for deriving the refractivity reference field and it is important to document offsets in the operational surface measurements relative to a reference dataset; the MGAUS surface sensor measurements would provide the benchmark reference dataset.

Data collections will routinely be made 5 days a week from about 1000 to 1800 local time to correspond to the typically convective storm initiation cycle in the Colorado Front Range. Radar scanning will emphasize full 360 deg scans at low elevation angles (0-1.5 deg). Higher elevation scans will be included to observe convection initiation and storm precipitation. Scan cycle times will be on the order of 5-10 min. While observations will be made routinely emphasis will be on days with expected large near surface horizontal variations in water vapor such as would be typical with outflow boundaries and the Denver convergence zone.

6. University Collaborators

Professors and students from both McGill University and Colorado State University, and a student from Norfolk State University will play active rolls in this field project and subsequent analysis. Dr. Frederic Fabry from McGill is the key member of the team in that it is his expertise that is guiding the development of the refractivity retrieval software and implementation on the radars. Dr. Fabry will have at least one graduate student (ShinJu Park) participating in the experiment and analysis.

Dr. Steven Rutledge, Dr. V. Chandrasekar, Pat Kennedy, Dave Brunkow and Jason Fritz (graduate student) from Colorado State University are very interested in having the refractivity technique running in real time on both their CHILL and Pawnee radars and studying the performance of the refractivity in the vicinity of complex terrain. An expression of interest was demonstrated by Dr. Rutledge in providing CHILL availability for REFRACTT_2005. CSU researchers will collaborate with NCAR staff on the retrieval of water vapor fields and real time interpretation of the data fields. CSU is particularly interested in studying possible correlations and relationships between the retrieved water vapor field and the locations of heavy rain and hail events as diagnosed by their real time rain and hail mapping software, which in itself, has been the focal point of ongoing collaborations with the national weather service in Denver.

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