REAL-TIME IMPLEMENTATION OF REFRACTIVITY RETRIEVAL: PARTNERSHIP BETWEEN THE UNIVERSITY OF OKLAHOMA, NATIONAL SEVERE STORMS LABORATORY, AND THE RADAR OPERATIONS CENTER

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ABSTRACT

High-resolution, near-surface refractivity measurements have the potential of becoming an important tool for operational forecasting and general scientific studies. Access to measured refractivity fields with high spatial and temporal resolution near the surface opens a new paradigm for understanding the convective processes within the boundary layer. It has been shown via advanced physical models that surface refractivity plays an important role in convective processes and, therefore, is expected to be valuable for forecasting the initiation and intensity of convective precipitation. For this project, the refractivity field is retrieved remotely using S-band radars by measuring the returned phase from ground clutter. Pioneering work of Fabry et al. [1997] has demonstrated the usefulness of this technique. By adopting this refractivity retrieval concept, an independent real-time software platform has been developed. The software was written with a modular design for portability and will be tested during the spring 2007 storm season on two radars in Oklahoma. Both the National Weather Radar Testbed – Phased Array Radar (NWRT PAR), supported by the National Severe Storm Laboratory (NSSL), and the WSR-88D weather radar near Oklahoma City (KTLX), supported by the Radar Operations Center (ROC), will be used for this study. Using the raw Level-I time series data from the radars, the modular software platform will be used to process the data in real-time for refractivity fields, which will be sent to the Norman Weather Forecast Office (WFO). The refractivity fields will be displayed through the Warning Decision Support System - Integrated Information (WDSS-II) for evaluation. Working closely with the WFO forecasters, qualitative assessment procedures will be followed to evaluate the usefulness of the refractivity fields for operational forecasting.

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1. INTRODUCTION

Until recently, moisture measurements were normally only possible by *in situ* instruments. For example, the radiosonde network across the nation with approximately 50-100 km spacing performs hourly measurements. To pursue further understanding and better prediction of convective processes, e.g., convective precipitation and its intensification, the existing surface instruments simply do not provide sufficient spatial and temporal resolution [Weckwerth and Parsons, 2003]. Fortunately, surface moisture is now possible to be retrieved *remotely* using radar echoes from ground targets [Fabry et al., 1997]. The relatively higher spatial and temporal resolution, in comparison with the existing surface instruments, opens up a new paradigm for surface moisture observations.

Based on the work of Fabry et al. [1997], a separate platform to retrieve surface refractivity from the radar echoes from ground targets has been developed here at the University of Oklahoma. Real-time software has been built with a modular design for portability. This real-time software is being tested during the spring 2007 storm season on two independent radars in Oklahoma. Both the NWRT PAR, operated by the NSSL, and the WSR-88D weather radar near Oklahoma City (KTLX), operated by the Norman WFO and supported by the Radar Operations Center ROC, are being used for this study.

2. OVERVIEW OF RADAR REFRACTIVITY RETRIEVAL (SAME AS P8B.9)

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 hPa. 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.,

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

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

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

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.

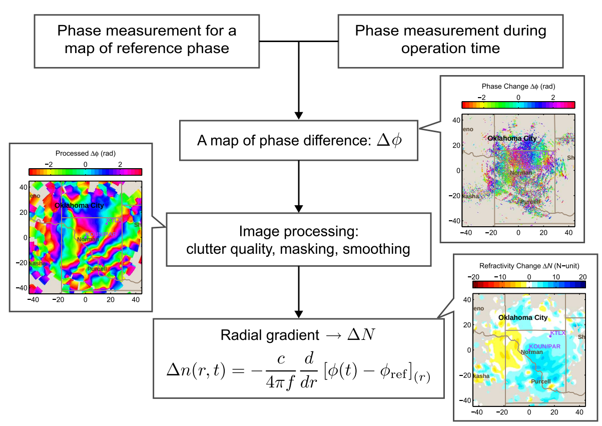

Figure 1: Procedure of refractivity retrieval

3. REAL-TIME DATA PROCESSING, COMMUNICATION, AND DISPLAY

Real-time data processing software for refractivity retrieval has been developed here at the University of Oklahoma. It is designed in a modular architecture in order to provide flexible portability. Such an architecture allows for the application of the processing software from one radar to another with minimal changes. In addition, it also unifies the software changes or upgrades for different radars.

The data flow from the raw I/Q time series to the fully processed radar products, which will be presented to the user (weather forecasters) for product evaluation is shown in Figure 2. The raw time series data are ingested into the processing software through the raw data interface, which can be one that has been standardized, e.g, SIGMET's RVP-8, or one that is completely designed in-house. The raw data are immediately pre-processed, which includes converting the digital samples into appropriate values, re-arranging the radials into a map that is consistent with the reference and any calibration that may be specific to the radar. Subsequently, the standard moment and refractivity products are generated from the pre-processed data. We use a Local Data Manager (LDM) developed by Unidata as the communication software between the workstation at the radar and the Warning Decision Support System - Integrated Information [WDSS-II, Lakshmanan et al., 2006] data server at the National Weather Center (NWC), which stores and serves the radar products. Finally, the radar products are presented to the weather forecasters via WDSS-II software. The WDSS-II display software can be installed on many machines that are connected to the server to retrieve the radar products.

3.1. *Phased Array Radar*

The NWRT PAR is one of the test radar platforms for the real-time refractivity software. This radar system uses electronic beam for rapid steering and, thus, allows for a coverage of 90° within a short amount of time. The coverage time can be as short as 180 ms using a 1-ms PRT and 2-pulse dwell per radial [Cheong et al., 2007]. If desired, a full 360° coverage can be obtained by rotating the pedestal in 90° increments. Since the beam of the PAR is not moving while scanning, smearing effects are eliminated and we anticipate higher quality phase measurements from ground targets for refractivity retrieval.

The raw I/Q data from the PAR are delivered via an optical fiber channel into a distribution switch, which receives the digitized time series and repeats it to several channels for different processing nodes. At the present time, the University of Oklahoma is developing a processing node for real-time refractivity retrieval and is anticipated to be operational in the near future and will be available for the conference. As depicted in conceptual diagram in Figure 2, OU's processing node receives raw

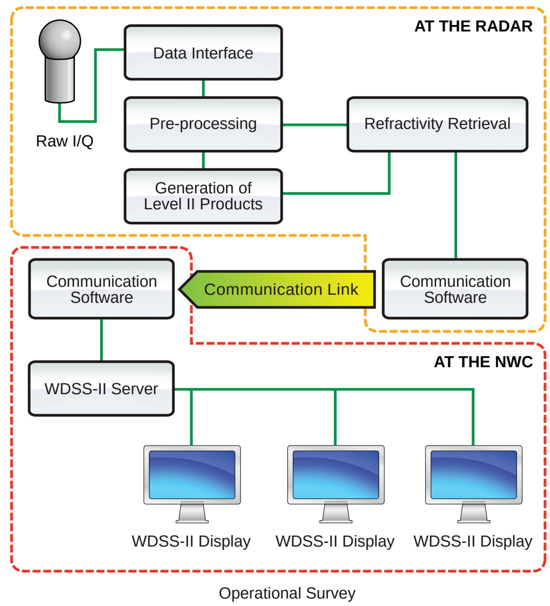

Figure 2: Overview of data flow. Raw data are processed in real-time for refractivity products at the radar site. These products are sent to a WDSS-II data server at NWC and distributed to multiple displays for the users.

time series from the PAR and processes it for refractivity. The radar products are sent to the WDSS-II server via LDM.

To demonstrate the rapid scanning capability of the PAR system, a comparison of refractivity retrieval using different number of pulse samples per radial is shown in Figure 3. In this comparison, the raw data were col-

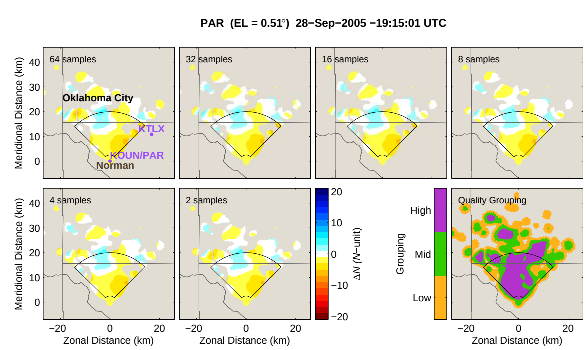

Figure 3: Using different number of pulse samples to calculate the phase map needed for refractivity retrieval, we are able to simulate refractivity retrieved using shorter dwells. From this comparison, it can be seen that a 2-sample average for phase calculation results in refractivity field that is similar to the rest, which are derived from a higher number of samples.

lected using 64 samples per radial but subsets of the samples are extracted to simulate refractivity change retrieved using lesser number of samples. A quality grouping index, shown in the lower right panel, indicates the confidence level of the refractivity field and is derived from the number of usable phase samples within the smoothing window during the interpolation process (refer to Section 2). One can see that even at a 2-sample dwell, the refractivity change map compares well with the other maps that are derived from phase calculated from 4, 8, 16, 32 and 64 samples. For the 2-sample dwell, we can cover a 90° sector within 180 ms as mentioned previously.

3.2. Operational WSR-88D KTLX

The operational WSR-88D weather radar near Oklahoma City (KTLX) is the other platform used to test and evaluate the real-time refractivity software. In order to avoid interruption to any existing operations, the ROC's WSR-88D testbed at Norman (KCRI) was used to test the system stability of the refractivity retrieval processing unit before installation at KTLX.

A 1U rack-mounted workstation is used as the real-time refractivity processing unit, which runs the software and receives the raw time-series from the radar though the Open Radar Data Acquisition (ORDA) RVP-8 system via Gigabit ethernet [Rhoton et al., 2005]. For KTLX, the time series data are ingested into the refractivity retrieval algorithm through the Time Series Application Programming Interface (TSAPI) developed by SIGMET. For security and system stability concerns, a private and dedicated T1 line is used for data communication between the radar and WDSS-II server at the NWC. An example view of absolute refractivity and scan-to-scan refractivity found on WDSS-II displays from KTLX is shown in Figure 4.

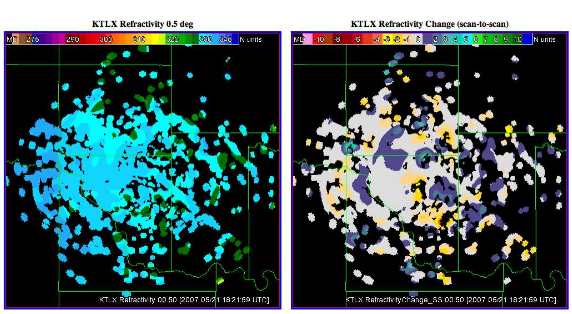

Figure 4: An example view of Refractivity and Scan-to-scan refractivity on WDSS-II

4. DESCRIPTION OF FORECASTER TRAINING AND ASSESSMENT

The purpose of the Spring 2007 KTLX Refractivity Experiment is to evaluate the usefulness of refractivity fields to operational forecasting at the Norman WFO and, ultimately, to decide if these products add enough value to the forecast process to warrant integrating them into the operational WSR-88D and display them on Advanced Weather Interactive Processing System (AWIPS). Since this experiment is in progress (i.e., runs 13 April to 22 June 2007), this section focuses on the design of the evaluation instrument and materials used to educate forecasters prior to their participation in the experiment.

4.1. Design of evaluation instrument

The design of the evaluation instrument or "survey" considered two primary factors: the audience (i.e., forecasters) and the purpose of the experiment. Owing to the longevity of the experiment (approximately two months) and the fatigue of forecasters at the end of each shift (e.g., midnight shifts), the survey length was limited to one page. The time required to complete the survey was also minimized by producing a mix of multiple choice, Likert-scale, and open-ended questions that would best measure the benefits and limitations of refractivity fields to operational forecasting. To attain a complete depiction of forecast utility, survey questions were designed to assess six operationally relevant measures of refractivity fields: 1) scope of relevant forecast concerns, 2) depiction of near-surface moisture fields, 3) benefiting forecast products, 4) forecast benefits, 5) impact relative to other observations, and 6) importance of incorporation into AWIPS. Following this initial survey design, a subset of forecasters were asked to assess the face validity of each of the items, that is, whether the survey items looked like good items for the purpose at hand. Forecaster comments were incorporated into the wording and format of the survey questions and the result is a nine-question, one-page survey with good face validity (Appendix A).

Since the implementation of the survey is a form of "human subject research", the experiment required approval from the University of Oklahoma Institutional Review Board (OU IRB) prior to the starting date (13 April 2007). The OU IRB approved the experiments application package on 10 April 2007.

4.2. Design and implementation of education materials

Like the survey, the design of the education materials considered the forecaster audience and the purpose of the experiment. An interactive lecture instructional strategy was chosen to maintain interest and motivation, and to assess whether the forecasters were meeting learning outcomes. To prepare forecasters to interpret and assess the utility of refractivity fields (both absolute refractivity and scan-to-scan changes in refractivity), education materials were developed to help students achieve the following four learning outcomes:

- define and describe meteorological uses of refractivity measurements,
- explain why and how refractivity can be derived from ground clutter targets,
- demonstrate the ability to interpret refractivity fields, and
- envision how refractivity fields may be used in operations.

Another important component of the education materials was a demonstration of the Warning Decision Support System Integrated Information (WDSS-II) display that forecasters would use to interpret refractivity fields. Aspects of the WDSS-II most important to successful interpretation of refractivity fields were incorporated, including auto-update and looping of data fields, data readout, and overlay of Oklahoma Mesonet observations, to name a few. The ability to overlay Oklahoma Mesonet observations, in particular dewpoint temperature, would provide forecasters with a familiar comparison dataset.

These education materials were implemented during three two-hour training sessions at the Norman WFO. Overall, training sessions were attended by 13 meteorologists, including forecasters, interns, and managers. During each session, meteorologists were also officially invited to participate in the experiment and given a copy of an “Information Consent Form”, as require by the OU IRB. At the writing of this paper, 16 survey responses are completed. The analysis of these and additional survey responses will be presented at the conference.

5. CONCLUSIONS

In this project, an overview of a real-time refractivity processing environment has been provided. The software was tested operationally during the Spring 2007 storm season on two radars in Oklahoma: the NWRT PAR and the WSR-88D weather radar KTLX. In order to prepare forecasters to interpret and access the utility of refractivity products, several training sessions were provided at the Norman WFO. A survey-based evaluation is currently underway in order to determine the usefulness of refractivity for operational AWIPS under various weather scenarios. By the time of the conference, we anticipate a more in-depth assessment of the survey results.

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APPENDIX

An example of the 2-page survey is shown in this section.

KTLX Refractivity Retrieval Questionnaire

Name ______________________ Date ________________

Answer the questions below based on your shift forecasts. Mark responses to multiple choice questions with an "x".

1. Which shift did you work today?

☐ Day ☐ Evening ☐ Night

2. During your shift, which of the following were forecast concerns within ~32 nm (60 km) of KTLX? *Please keep these concerns in mind as you complete the survey.*

☐ Boundaries/wind shifts
☐ Fire Weather
☐ Fog
☐ Potential for severe storms
☐ QPF
☐ Timing of convective initiation
☐ Winds
☐ Other ________________

3. Were you concerned about short-term or long-term forecasts?

4. During your shift, did you consult the refractivity retrievals?
If yes, proceed to question 5. If no, please explain.

___Yes ___ No

Explanation:

5. Rate your confidence in the refractivity retrievals' depiction of the near-surface moisture field. *Explain your confidence ratings.*

Refractivity
Low ① ② ③ ④ ⑤ High

Refractivity_Change_SS (scan-to-scan)
Low ① ② ③ ④ ⑤ High

Refractivity	Refractivity_Change_SS

Page 1

6. List below the forecast product(s) or decisions that benefited from the refractivity retrievals and explain the benefit. *(Some example benefits: higher confidence, greater lead time, more accuracy w/in region where retrievals were available, etc.)*

Product: ______________________________
Benefit:

Product: ______________________________
Benefit:

7. Please rate the impact of the products listed on your forecasts.

Products	Impact of product on your forecast
Oklahoma Mesonet	Low ① ② ③ ④ ⑤ High
Metars	Low ① ② ③ ④ ⑤ High
Refractivity	Low ① ② ③ ④ ⑤ High
Refractivity_Change_SS	Low ① ② ③ ④ ⑤ High
Rawinsonde	Low ① ② ③ ④ ⑤ High
Objective analyses (RUC, LAPS, etc.)	Low ① ② ③ ④ ⑤ High
WSR-88D Radar	Low ① ② ③ ④ ⑤ High
Visible satellite channel	Low ① ② ③ ④ ⑤ High
Infrared satellite channel	Low ① ② ③ ④ ⑤ High
Water vapor channel	Low ① ② ③ ④ ⑤ High

8. Rate the importance of incorporating refractivity retrievals into AWIPS at all WFOs.

Refractivity
Low ① ② ③ ④ ⑤ High

Refractivity_Change_SS (scan-to-scan)
Low ① ② ③ ④ ⑤ High

9. Respond with any other comments.

Page 2