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THE JOINT POLARIZATION EXPERIMENT – A SUMMARY OF DUAL-POLARIZATION WSR-88D RADAR DATA COLLECTION AND ANALYSIS

Terry J. Schuur, Alexander V. Ryzhkov, Pam L. Heinselman,
Donald W. Burgess, and Kevin A. Scharfenberg

Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma
Norman, OK, 73019

1. INTRODUCTION

In the spring of 2003, the National Weather Service (NWS) Office of Science and Technology tasked the National Severe Storms Laboratory (NSSL) with providing data collection and analysis to support a WSR-88D dual-polarization decision briefing to the NEXRAD Program Management Committee (NPMC). This decision briefing came at the end of a year long data collection and operational demonstration project referred to as the Joint Polarization Experiment (JPOLE), which was designed to 1) evaluate the engineering design and data quality of the polarimetric KOUN WSR-88D radar, and 2) demonstrate the utility of polarimetric radar data and products to operational users. JPOLE goals and objectives are described in detail by Schuur et al. (2002) and Schuur et al. (2003a).

In this paper, we describe JPOLE data collection and processing techniques, provide an overview of the KOUN data archive, and present analyses that demonstrate the radar's ability to improve Quantitative Precipitation Estimates, discriminate between hydrometeor types, and improve data quality through the elimination of non-meteorological artifacts. We also describe how KOUN data and products were used by operational forecasters. NSSL reports that thoroughly document JPOLE data collection and operations (Schuur et al. 2003b) and improvements in data quality and hydrometeor discrimination (Schuur et al. 2003c) and rainfall estimation (Ryzhkov et al. 2003) are available on the JPOLE web site, located at http://cimms.ou.edu/~schuur/jpole.

2. DATA COLLECTION

In preparation for the full WSR-88D radar test, the NSSL began to introduce polarimetric radar data and products from the NSSL Cimarron polarimetric radar to operational forecasters at the Norman, Oklahoma NWS Forecast Office in the spring of 2001. Due to mechanical limitations of the Cimarron pedestal, it was only possible to collect data at 0.0°, 0.5°, and 1.0° and a maximum rotation rate of 6°/s. Nevertheless, the occasional delivery provided operational forecasters, with the assistance of an NSSL observer, an opportunity to familiarize themselves with polarimetric data and products, and the use of those data and products in the warning decision process. Data and products delivered included radar reflectivity (Z), differential reflectivity (Z_{DR}), correlation coefficient (ρ_{HV}), differential phase (Φ_{DP}), specific differential phase (K_{DP}), and a hydrometeor classification product.

Note that the Cimarron radar transmits an alternate sequence of horizontally and vertically polarized waves. Consequently its polarimetric variables are not exactly equivalent to the polarimetric variables obtained via the simultaneous scheme on the KOUN. Therefore it was important to determine if there would be detrimental differences between the two schemes.

2.1 Early JPOLE data collection/delivery

The polarimetric upgrade to KOUN WSR-88D radar was completed in the Spring of 2002. At that time, the data feed for the operational delivery was switched from the NSSL Cimarron research polarimetric radar to the KOUN radar. A polarimetric radar training seminar was prepared and delivered to the NWS forecasters (a growing data base of case studies available for forecaster training has also since become available on the WWW at: http://cimms.ou.edu/~kscharf/pol/). Much effort during the first few months of data collection was devoted to addressing calibration issues and improving the delivery system. After approximately 3 months of evaluation and testing, the first high-quality dataset was delivered to the NWS on 16 June 2002. This dataset, of an areally extensive MCS that exhibited high winds, heavy rainfall, and large hail, is discussed by Schuur et al. (2003a). Because Volume Coverage Patterns (VCPs) that included higher elevation angles had not been developed yet, all data during this early JPOLE data collection/delivery period were collected with VCPs that included only 0.0°, 0.5°, 1.0°, 1.5°, and

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Corresponding author address: Terry J. Schuur, National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK, 73069;
email:schuur@nssl.noaa.gov

2.5° base scans (although with a much faster 20°/s scanning rate than was possible with the Cimarron radar).

Through the summer and fall of 2002, work continued to improve data quality, enhance algorithm performance, and streamline the real-time data processing and delivery system. From the early data collection, it had become apparent that it was difficult to maintain an accurate reflectivity calibration. Through comparison with verification datasets, much data analysis time was therefore devoted to developing techniques to assure higher-quality calibration. The real-time hydrometeor classification algorithm was modified to include corrections for differential attenuation and the hydrometeor classification algorithm upgraded to include winter precipitation products. Several real-time polarimetric rainfall accumulation (1-hour, 3-hour, and storm-total $R(Z)$, $R(Z, Z_{DR})$, $R(K_{DP})$, and $R(K_{DP}, Z_{DR})$) estimates were also developed and added to the suite of algorithms.

Fairly regular real-time data delivery to the NWS began in the fall of 2002. Polarimetric KOUN data collected during several widespread precipitation events in the early fall proved to be useful in the estimation of rainfall accumulation at far ranges. In one event that occurred from 18-20 October, 2002, the forecaster noted that $R(K_{DP})$ estimates in far southeastern Oklahoma matched the Mesonet rainfall accumulations so well that he had greater confidence that flooding was not a serious problem and that it was safe to spend more time monitoring and updating other aviation and public forecast products. Polarimetric KOUN data collected during several winter precipitation events also proved useful in the warning decision process. In depth analyses of winter precipitation events are presented by Scharfenberg and Maxwell (2003), and Miller and Scharfenberg (2003).

2.2 The JPOLE Intense Observation Period

In the spring of 2003, plans were made to conduct a more extensive JPOLE Intense Observation Period (IOP). During the IOP, emphasis was placed on providing uninterrupted data delivery to operational forecasters, obtaining more extensive forecaster feedback on the use of the polarimetric data in the warning decision process, and collecting high-quality verification datasets that could be used to assess the KOUN radar data and product quality. This JPOLE IOP was conducted from March 15, 2003 through June 15, 2003. During the IOP, KOUN data collection was designed to more closely resemble that of a standard WSR-88D radar. That is, whereas most data prior to the IOP had been collected with VCPs that only included low-elevation surveillance scans, VCPs used during the IOP were designed to, as much as possible, emulate the elevation angles, scanning rates, and volume coverage times of the standard WSR-88D VCP 11 (the VCPs used during the IOP are described in detail in Schuur et al. 2003b). A greater emphasis was also placed on the collection of verification datasets. Hail data were collected by two hail intercept vehicles that were deployed to locations where the polarimetric hydrometeor classification algorithm was indicating hail. In-situ cloud microphysics data were collected by the South Dakota School of Mines and Technology T-28 aircraft, which was participating in an electrical study that coincided with the final month of the IOP.

2.3 The JPOLE data archive

The KOUN data archive from the year-long JPOLE experiment contains an unprecedented collection of meteorological and non-meteorological events. In total, 98 events were catalogued both chronologically and by event-type, and subsequently described within an online database at

http://cimms.ou.edu/~heinsel/jpole/database.html
http://cimms.ou.edu/~heinsel/jpole/stormtype.html

This archive includes several significant hazardous weather events, including two consecutive tornado outbreaks in the Oklahoma City area, several non-tornadic supercells, a severe storm that produced up to 5” diameter hail, a 20” snowfall over Ponca City, and a flash flood event. The KOUN database also contains many seasonal rainfall events, such as convective cells, warm- and cold-season stratiform precipitation, MCSs, rainbands, mixed precipitation, and snow. This archive supplies the data needed to demonstrate the advantages of using polarimetric hydrometeor classification and rainfall estimation algorithms in NWS and other weather-sensitive operations.

In addition to precipitation events, a wide variety of non-meteorological phenomena were observed also by the KOUN radar. These include anomalous propagation, birds, insects, and chaff. Many of these non-meteorological phenomena were measured by KOUN in clear air conditions (15 events), whereas others were associated with precipitation (31 events). Non-meteorological phenomena associated with precipitation may be embedded within precipitation, may correspond with density currents, or occur behind a squall line.

3. KOUN DATA ANALYSES

Data collection during JPOLE provided a large data set that was used to demonstrate the ability of a polarimetric WSR-88D radar to improve: (1) rainfall estimation, and (2) data quality and hydrometeor discrimination. Those analyses are described in detail in Ryzhkov et al (2003) and Schuur et al. (2003c), respectively. Here we present a summarization of those results.

3.1 Rainfall estimation

Using a data set that includes 24 (22) events with a total of 50 (84) hours of observations, Ryzhkov et al. (2003) present analyses that compare polarimetric rainfall estimation, using a variety of different combinations of polarimetric rainfall relations and assumed drop aspect ratios, with rain gage data obtained from the ARS micronet (Oklahoma mesonet). Figs. 1 shows one-hour individual rain gage and mean areal rain rate estimates from the R(Z) and $R(Z,K_{DP},Z_{DR})$ algorithm (Ryzhkov et al. 2003). It indicates that the "synthetic" polarimetric algorithm, $R(Z,K_{DP},Z_{DR})$, is the most robust with respect to radar calibration errors, DSD variations, uncertainty of the raindrop shapes, and possible presence of hail, shows the best overall performance. The most significant improvement is achieved in areal rainfall estimation and in measurements of heavy precipitation, which is often mixed with hail. These advantages have important practical implications for 1) river flash flooding forecast and management that require reliable measurement of areal rain accumulations regardless of rain intensity and 2) urban flash flooding forecast that requires accurate estimation of heavy rain with high spatial resolution.

The mesonet data were useful for investigating rainfall estimation at distant ranges. At the distances less than 125 km from the radar, most polarimetric algorithms clearly outperform conventional algorithms (although the degree of improvement might be noticeably "weighted" by few spring heavy rain events). In terms of RMSE, polarimetric algorithms outperform the conventional relation R(Z) up to distances of 200 km from the radar. However, beyond 200 km, all algorithms perform poorly due to beam overshooting precipitation, beam broadening, and loss of sensitivity.

Seasonal variability was also observed. For "cold" season cases dominated by stratiform rain with low bright band, the $R(K_{DP})$ algorithm is the best at ranges where bright band is intercepted by the beam at lowest elevation. Delineation between rain and snow (bright band detection) is necessary to select an optimal algorithm. For "warm" season cases dominated by convective rain, the $R(Z,K_{DP},Z_{DR})$ algorithm is the best at all ranges (in terms of RMSE). However, all K_{DP}-based rain estimates tend to underestimate rain at long distances. This might be attributed to possible Φ_{DP} aliasing and negative K_{DP} caused by non-uniform beam filling.

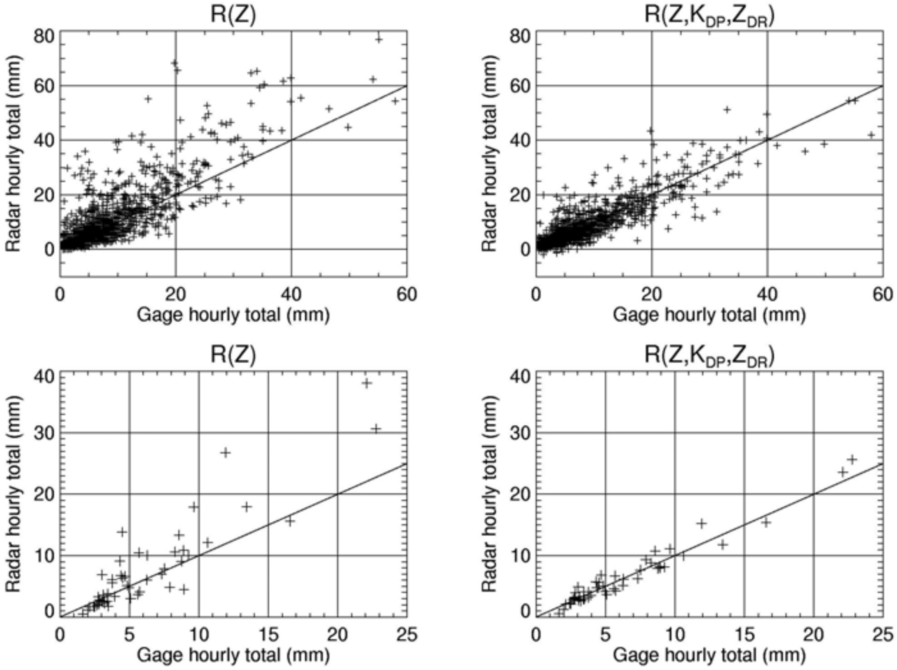

Fig. 1: One-hour individual gage accumulations and mean areal rain rates from gages versus their estimates from the R(Z) and $R(Z,K_{DP},Z_{DR})$ algorithms (24 rain events, 50 hours of observations).

3.2 Data quality and hydrometeor discrimination

Three separate fuzzy-logic-based classification algorithms were used to conduct the echo classification analyses. The first algorithm was designed to discriminate between meteorological and non-meteorological scatterers. The second, referred to as the "summer" classification algorithm, identified hydrometeor types in warm-season precipitation systems while, the third, referred to as the "winter" classification algorithm, included ice categories.

Three different methods of using polarimetric radar to improve data quality are presented. These include: 1) polarimetric discrimination techniques to filter out non-meteorological echoes, 2) application of Φ_{DP} to increase the accuracy of radar reflectivity measurements or self consistency checks among Z, Z_{DR}, and K_{DP}, and 3) information extraction about biological scatterers to better retrieve Doppler winds in clear air. Conclusions drawn from the application of these methods are summarized below:

Filtering out non-meteorological echoes: Using version 1 of the algorithm, non-meteorological scatterers can be correctly identified and removed from meteorological echoes. The analysis indicates that, if the SNR is > 10 dB, the number of pixels classified as non-meteorological (meteorological) in pure rain (AP/ground clutter) areas is generally < 1%. Misclassification rates deteriorate to approximately 5% if a SNR threshold of > 5 dB is used.

Improving the accuracy of reflectivity measurements: Polarimetric data can be used to improve radar reflectivity measurements. With the first technique, differential phase is used to directly correct Z for a case of extreme attenuation along a squall line. With the second technique, a self consistency check that utilizes Z, Z_{DR}, and K_{DP} is used to demonstrate that it is possible to correct Z to within 1.0 to 1.5 dB for cases of poor calibration and/or partial beam blockage (Ryzhkov et al. 2003).

Improving Doppler wind measurements in clear air: Most clear echoes are caused by biological scatterers such as birds and insects. Polarimetric radar can discriminate between the two and thus identify contaminated Doppler wind estimates.

Data were also used to detect tornadic debris, identify the location of hail, and discriminate hydrometeor type in a variety of precipitation systems. Examples of these data are shown below. Fig. 2 shows polarimetric KOUN data for a supercell storm that produced an F4 tornado on May 8, 2003 and Fig. 3 data for a sever hailstorm (hail > 13 cm) that occurred on May 14, 2003. Fig. 4 depicts the hydrometeor classification results for the hail storm shown in Fig. 3.

These analyses demonstrate the ability of polarimetric classification techniques to improve hydrometeor discrimination (as well as identify the location of non-meteorological scatterers that are embedded within meteorological echoes). Examples are provided for 4 different types of precipitation systems. These include the ability to: 1) detect tornadic debris, 2) identify the location of hail, 3) identify hydrometeor types (and the location of the radar bright band) in an MCS, and 4) identify hydrometeor types (and the location of the rain/snow line) for a winter storm. These applications are summarized below:

Detect tornado debris: An investigation of two significant tornado events that occurred close to the KOUN radar during JPOLE provide confirmation of repeatable polarimetric signatures associate with tornadic debris. Several conclusions can be drawn from this work. For example, polarimetric data can confirm tornado warnings, confirm tornado damage, and pinpoint current tornado location. Additional data collection and research is required to determine whether polarimetric radar data can be used to detect tornadic debris at distant ranges or to identify polarimetric signatures that might be associated with possible microphysical precursors to tornadogenesis.

Identify the location of hail: The data demonstrate the ability of polarimetric radar to improve hail detection. Previous radar-based hail algorithms only provide estimates of hail (or severe hail) probability for any given storm. On the other hand, the polarimetric classification algorithm pinpoints hail location within the storm. A statistical analysis presented in this report demonstrates the advantages provided by the polarimetric classification algorithm. The analysis results indicate that the polarimetric Hydrometeor Classification Algorithm (HCA) outperforms the operational Hail Detection Algorithm (HDA) in terms of both overall accuracy and skill. Whereas the statistics show that the HCA attains superior overall performance compared to the HDA, the algorithm performance varies on individual days. Additional research is required to enhance algorithm performance, identify microphysical signatures that might be associated with hail embryo regions, and to determine hail size.

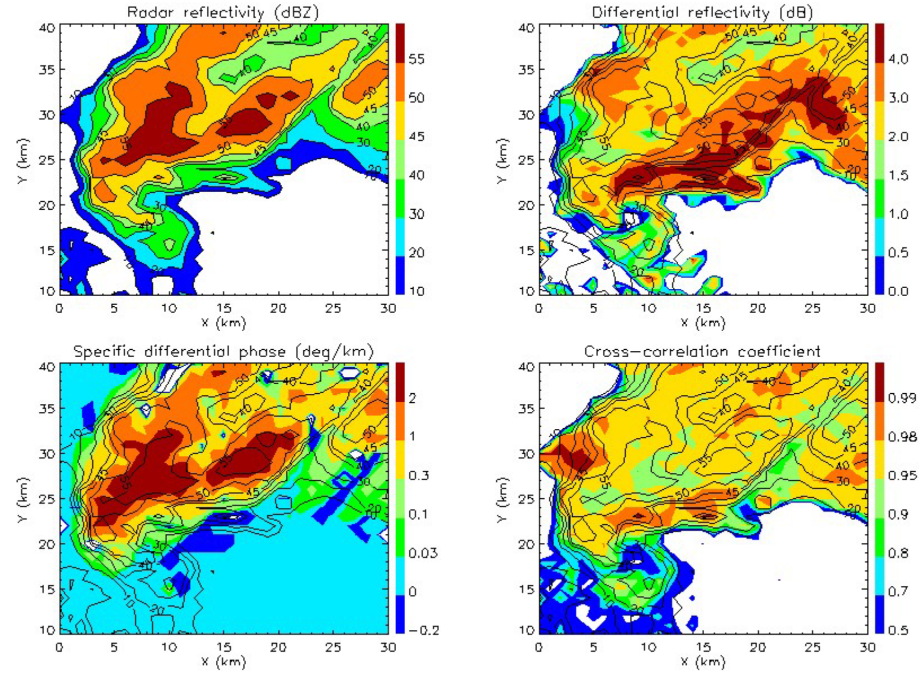

Fig. 2: Four panel image for the Moore/Southeast Oklahoma City tornado of May 8, 2003: (upper left) reflectivity, (upper right) differential reflectivity (Z_{DR}), (lower left) specific differential phase, and (lower right) cross-correlation coefficient (ρ_{hv}). Time is 2228 UTC on May 8, 2003. The tornado signature in Z_{DR} and ρ_{hv} is at the tip of the hook echo (X=9 km, Y=18 km).

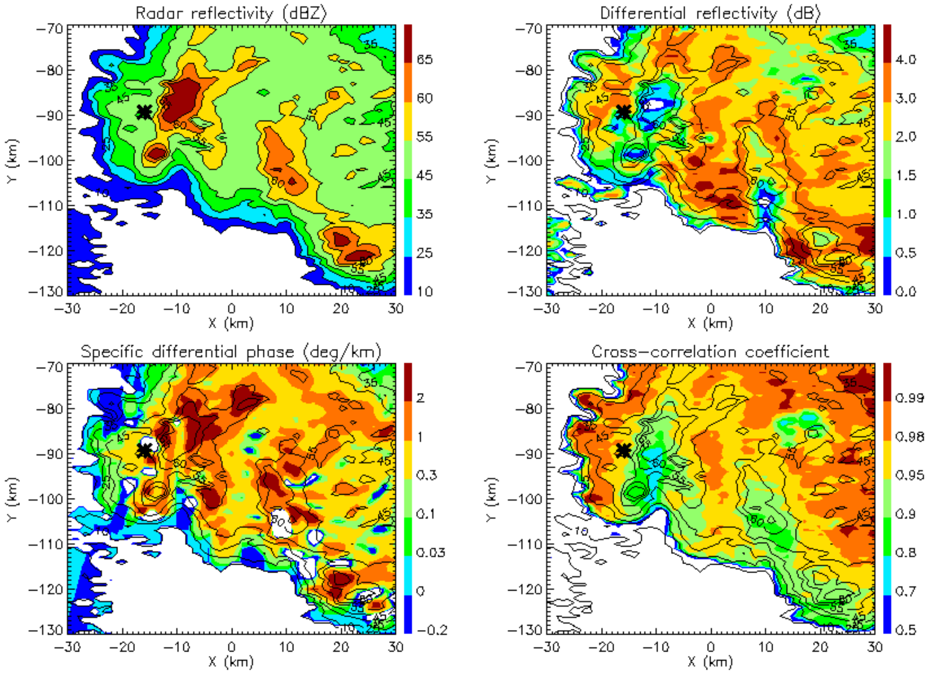

Fig. 3: Fields of polarimetric variables (PPI presentation) of the May 14, 2003 hail event at 0834 UTC. PPI is at 0.5° elevation. The panels display radar reflectivity (dBZ), differential reflectivity (dB), specific differential phase (°/km) and cross-correlation coefficient, respectively. The location of the 13 cm diameter hail report is indicated by the star.

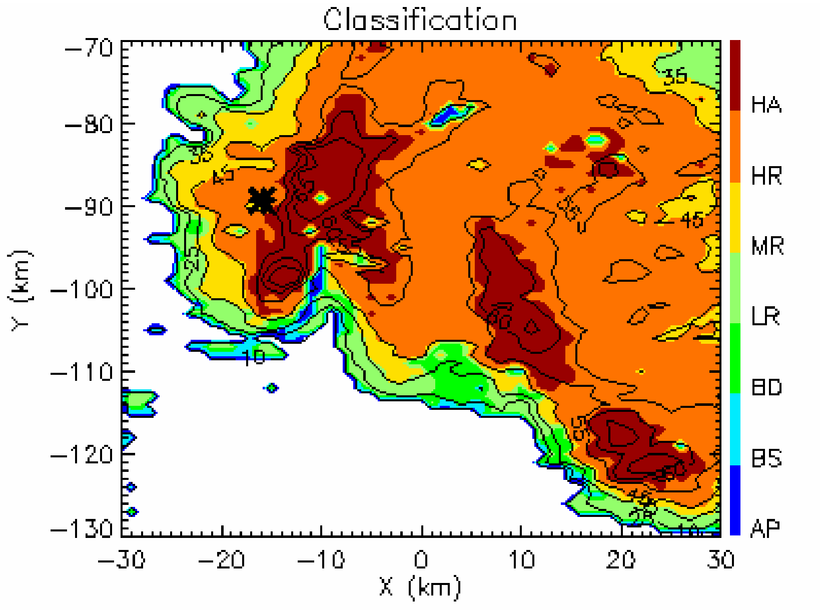

Fig. 4: Hydrometeor classification results of the May 14, 2003 hail event at 0834 UTC. Results are for an elevation of 0.5° (corresponding to the four data panels in Fig. 11). The location of the 13 cm diameter hail report is indicated by the star. In the color bar, AP = anomalous propagation, BS = biological scatterers, BD = big drops, LR = light rain, MR = moderate rain, HR = heavy rain, and HA = hail.

Identify hydrometeor type in an MCS: Application of the hydrometeor classification algorithm to a MCS demonstrates the ability of the polarimetric hydrometeor classification algorithm to identify hydrometeor types in a large, warm-season precipitation system. The algorithm also shows great utility for locating the bright band, which is a region where rainfall is often greatly overestimated by conventional R(Z) relations. Additional research is required to gather information that might boost algorithm performance, as well as provide data that could justify inclusion of additional ice categories in the classification scheme.

Identify hydrometeor type in a winter storm: Application of the hydrometeor classification algorithm to a winter storm demonstrates the ability of the polarimetric hydrometeor classification algorithm to identify hydrometeor types in a large, cold-season precipitation system. The algorithm also shows great utility at determining the location of the rain/snow transition line.

During JPOLE, several polarimetric KOUN WSR-88D radar measurements and hydrometeor classification products were delivered to operational forecasters at the Norman, OK NWS forecast office. Application of these data and products in the warning decision process is discussed by Schuur et al. (2003a).

4. OPERATIONAL DELIVERY

The insight of operational forecasters was vital to the evaluation of WSR-88D radar products. During the IOP, a greater emphasis was therefore placed on forecaster interactions. To obtain more feedback, NSSL observers were scheduled to assist NWS forecasters in the analysis and interpretation of the polarimetric radar data and products for each event that occurred during the 3 month JPOLE IOP (NSSL observers assisted NWS forecasters on a much more irregular basis during the early data collection/delivery phase of JPOLE data collection). After each event, feedback and forecaster comments were then obtained from evaluation forms, which were designed to determine the usefulness and performance of each polarimetric measurement and product. Scharfenberg et al. (2004) provide a more comprehensive overview of the JPOLE operational demonstration.

A total of seven post-shift evaluation forms were received after warning operations. All respondents either agreed or strongly agreed the following were a positive contribution to the warning process during their shift:

- The Hydrometeor Classification algorithm
- The QPE rate and accumulation algorithms
- Polarimetric base products such as Z_{DR} and K_{DP}
- KOUN polarimetric WSR-88D radar as a whole

A total of six end-of-season evaluation forms were also received. Respondents rated KOUN and various products on a zero to five scale, with a score of five representing best performance. These average scores refer to the overall usefulness of the tool in warning and "nowcasting":

- Hydrometeor Classification Algorithm - 3.875.
- Polarimetric QPE accumulation algorithms - 4.8.
- Polarimetric QPE rate algorithms - 3.5.
- Z_{DR} - 4.5.
- K_{DP} - 4.5.
- ρ_{HV} - 4.0.
- KOUN overall - 4.33.

Respondents were also asked to rate on the same scale the help received from available training materials, case studies, and from NSSL staff on duty:

- Online training - 4.0.
- Online case studies - 4.25.
- NSSL staff - 4.67.

The responses received strongly suggest the KOUN polarimetric WSR-88D and its products, including base products, the hydrometeor classification algorithm, and the QPE algorithms, were quite useful to forecasters in making short term forecasts and warning decisions. "The program was a wonderful success", wrote one forecaster, who used KOUN data extensively.

In some cases, respondents said the QPE products were used in the decision NOT to issue Flash Flood Warnings, in the cases where the traditional R(Z) radar rainfall estimators were too high. This is "one of the best aspects of dual-pol[arization radar]", said one forecaster. In addition, several forecasters stated KOUN products help them better define the exact locations and areal extent of the hail threat. This "increased confidence in warnings", according to one forecaster.

The base data also helped forecasters identify thunderstorm updrafts, increasing their understanding of storm morphology in real time. One forecaster said, "...the ability to identify these updrafts AND their location relative to the echo core explicitly, was very important in short term forecasting of storm evolution." Additional examples of how KOUN data were used in the warning decision process is provided by Scharfenberg et al. (2003), Scharfenberg and Maxwell (2003), and Miller and Scharfenberg (2003).

5. SUMMARY

The Joint Polarization Experiment (JPOLE) was designed to test the engineering design and determine the data quality of the polarimetric KOUN WSR-88D radar, demonstrate the utility and feasibility of the radar to operational users, and to collect data and information that could be used to perform a cost/benefit analysis. JPOLE data collection was conducted in three phases. During the first phase, from March 15, 2002 through June 15, 2002, efforts primarily focused on addressing calibration issues, improving the delivery system, and resolving an interference problem with a nearby radar. During the second phase, from June 15, 2002 through March 15, 2003, KOUN data were intermittently collected and delivered to operational forecasters at the Norman, OK NWS office on a case by case basis. Work also continued to improve data quality, enhance algorithm performance, and streamline the real-time data processing and delivery system. Finally, during the third phase, from March 15, 2003 through June 15, 2003, a concerted effort was made to collect a comprehensive dataset (including ground-based verification data) for all weather events. A KOUN scanning strategy was designed to, as much as possible, emulate the elevation angles, scanning rates, and volume coverage times of the standard WSR-88D VCP 11. Furthermore, to obtain more feedback from forecasters, NSSL observers were scheduled to assist NWS forecasters in the analysis and interpretation of the polarimetric radar data and products for each event that occurred during this “intense” 3 month data collection period. In several instances, KOUN data and products proved to provide value-added information to the warning decision process. Results of the operational use of the polarimetric data and products, as well as a summary of the forecaster evaluations and comments, are presented within this report.

In total, KOUN data were collected for 98 events during the entirety of the JPOLE data collection period. A summary of these data is described online at http://cimms.ou.edu/~heinsel/jpole/database.html (events listed chronologically) and http://cimms.ou.edu/~heinsel/jpole/stormtype.html (events listed by storm type). Overall, the KOUN radar was found to routinely produce polarimetric measurements of exceptional quality. An engineering evaluation of the calibration and performance of the KOUN radar, which further discusses data quality during the early stages of JPOLE data collection, is presented by Melnikov et al. 2003.

Analysis of the JPOLE data has also been a crucial element of the JPOLE effort. Analyses demonstrate the polarimetric KOUN radar’s ability to improve rainfall estimation and hydrometeor classification capabilities, respectively (details of these analyses are provided above and in the NSSL reports by Ryzhkov et al. 2003 and Schuur et al. 2003c). Since KOUN is a proof-of-concept polarimetric WSR-88D radar, and the first in a possible future national network of polarimetric WSR-88D radars, improvements in data quality, rainfall estimation, and hydrometeor identification have far reaching implications. These economic benefits from such improvements are summarized in a decision briefing to the NEXRAD Program Management Committee on polarimetric WSR-88D radar.

NSSL reports that thoroughly document JPOLE data collection and operations (Schuur et al. 2003b) and improvements in data quality and hydrometeor discrimination (Schuur et al. 2003c) and rainfall estimation (Ryzhkov et al. 2003) are available on the JPOLE web site, located at http://cimms.ou.edu/~schuur/jpole.

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