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NEW SCIENCE FOR THE WSR-88D: STATUS OF THE DUAL POLARIZATION UPGRADE

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1. INTRODUCTION

The NEXRAD tri-agencies (DOC, DOD, DOT) determined that adding dual polarization to the WSR-88D will provide increased information that will enhance the decision making of the users who rely on the national network of weather radars. The mission of the Radar Operations Center (ROC) is to manage the life-cycle support of this network and ensure that any upgrades are validated and ready for deployment.

In 1997, the National Severe Storms Laboratory (NSSL) installed a prototype polarimetric capability on the WSR-88D research radar, KOUN, in Norman, OK. In 2003, NSSL conducted a year-long data collection and operational demonstration project using the KOUN radar (Schuur, 2003). This was a major component of the NEXRAD agency's decision to proceed with the dual polarization program. The NWS Office of Science and Technology (OST) has led this project and in 2007, a competitively bid contract was awarded to L-3 STRATIS for the design, implementation and deployment of the modifications. L-3 STRATIS and Baron Services, Inc. teamed for the development with L-3 ESSCO selected to handle the deployment. This is the most significant and complex upgrade of the WSR-88D since the initial WSR-88D deployment. Before committing to deployment of the upgrade, the ROC verified that the WSR-88D base moments continued to meet requirements and that the dual polarization upgrade added value to the network. The dual polarization upgrade deployment is underway and 25 operational systems have been modified with the dual polarization technology.

This paper summarizes the many collaborative efforts employed in the project's validation process and acknowledges the many organizations who contributed and made the dual polarization upgrade a success. Additionally, this paper provides background information, such as an overview of the upgrade.

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2. DUAL POLARIZATION UPGRADE OVERVIEW

As a result of the 1997 WSR-88D dual polarization research, the NSSL team recommended several key design features for a production polarimetric WSR-88D. These related to the fundamental polarimetric approach, the antenna modification, and calibration.

The NSSL engineers chose the Simultaneous Transmit and Receive (STAR) method for generating the additional (vertical) polarization channel. This, as opposed to the alternating approach, allowed the system to retain the baseline volume acquisition times without reducing the number of samples for each parameter. This also avoided potential hardware cost and recurring logistics and maintenance issues related to the fast alternating switch.

The NSSL team also chose to retain the baseline three strut feed support and waveguide assembly in order to keep antenna side lobe levels low. For the prototype, the team replaced the baseline horizontally polarized feed assembly with a new ortho-mode transducer and feed supplied by the original manufacturer. The trade off in terms of bias in differential reflectivity due to the asymmetric strut configuration was deemed acceptable.

The final primary design decision related to differential reflectivity calibration. The traditional method in the research community and early operational systems is to vertically point and rotate the antenna in light precipitation. The WSR-88D antenna pedestal baseline design does not support this approach without costly modifications. Also, taking an operational radar off-line to conduct calibration during precipitation events negatively impacts forecast and warning operations. The NSSL team recommended a so called "Engineering Calibration" based on careful power measuring and signal path loss measurements using instruments traceable to standards. The contractor team implemented a version of this approach.

The production upgrade kit was designed by a commercial team, working in close cooperation with US government experts at NSSL, National Weather Service, and the Radar Operations Center. It is of the simultaneous transmit and receive type (STAR). The existing 28 foot (8.53 m) parabolic reflector is modified by replacing the single horizontally polarized transducer/feed assembly with a new Ortho-mode transducer and feed. The antenna design retains the existing three strut approach but utilizes all new waveguides, support strut, and feed assembly mounts.

Design particulars include two antenna elevation arm mounted units, the Radio Frequency (RF) Pallet (Figure 1), and Antenna Mounted Electronics (AME, Figure 2). The RF Pallet functions include power division via a variable phase power divider, appropriate directional couplers for calibration and monitoring, transmit – receive isolation via circulators and TR limiters, electromagnetic interference rejection filters, and low noise amplification. The interference rejection filters are fixed tuned, custom selected for each site frequency. The variable phase power divider allows for computer controlled selection of any combination of H and V transmit power at the output, but is normally set for 50% power in each channel. It is capable of supplying near 100% in either the horizontal or vertical transmit channel, a feature useful for supporting an external calibration method such as cross polarization power. The AME enclosure is climate controlled via a Peltier cooler and includes the RF to IF down conversion function and all necessary built-in-test equipment for establishing and maintaining calibration and monitoring system health.

Pedestal modifications feature a new four channel rotary joint for supplying RF and IF signals. The existing slip ring assembly was retained and used for supplying AC power for the new antenna mounted equipment. The four rotary joint channels are used for: (1) transmit pulse, (2) STALO from the existing RF generator located in the ground equipment shelter, (3) Horizontal IF, and (4) Vertical IF.

The baseline digital receiver and signal processor (Vaisala/Sigmet RVP8) and system control computers were retained. The RVP8 digital receiver was reconfigured to employ dual channel inputs for the H and V IF signals.

An extensive software development was necessary in order to integrate the baseline, custom, user software into the available RVP8 dual polarization processing features. This was accomplished by the contractor team and extensively tested by a joint contractor – government team in Norman OK over approximately a two year period which will be discussed in the next section. The software includes a straightforward clutter filtering approach for the polarimetric variables which is a modification of the Sigmet Gaussian Model Adaptive Processing (GMAP) clutter filter. While the baseline, non-polarimetric WSR-88D signal processing features an automatic clutter identification function, this feature was not incorporated into the polarimetric software and will be added in the first post development software release from the Radar Operations Center in the 2012 calendar year.

3. DATA QUALITY DUAL POLARIZATION SUBCOMMITTEE

In 2005-2006, the ROC upgraded the Radar Data Acquisition (RDA) subsystem of the WSR-88D with the Open RDA (ORDA). Since the ORDA upgrade impacted the radar's foundational data, a.k.a., reflectivity (Z), velocity (V), and spectrum width (W) collectively known as the base moments or base data for single polarization radars, it was imperative to ensure its quality. Thus, the Data Quality Team was established to evaluate the base data from the ORDA upgrade and to determine if any of the signal processing changes impacting base data affected the Radar Product Generator (RPG) products. This included evaluating the base data from the new Sigmet signal processor, the RVP8, and the new Sigmet Gaussian Model Adaptive Processing clutter filter (GMAP). (Ice 2004, 2005, Chrisman, 2005). In 2006, the ROC led Data Quality Team had 17 members from the ROC, NSSL, Warning Decision Training Branch (WDTB), and the contractor team performing the upgrade, with member expertise spanning hardware, software, and systems engineering, meteorology, electronic maintenance, and training. (Lee, 2005).

During the last five years, the Data Quality Team has grown to nearly 80 members and has continued to meet weekly to evaluate RDA base data and RPG products. Some of the major projects supported by the Data Quality Team after the ORDA upgrade are range ambiguity mitigation using phase encoding, automatic clutter identification, increased resolution of the base data, velocity mitigation using multiple scans with different Pulse Repetition Frequencies (PRF), Automatic Volume Scan Early Termination (AVSET), improvements to Vertical Wind Profile (VWP), tiger team for Mesocyclone and Tornado Detection Algorithms (MDA/TDA) false alarms, and evaluations/explanations of observed anomalies from operational sites. The agencies with members in the Data Quality Team include the ROC, NSSL, OHD, OST, FAA/MITLL, WDTB, and, during the dual polarization upgrade, the contractors performing the upgrade.

The dual polarization upgrade is the largest and most complex since the establishment of the Data Quality Team. The significant hardware and signal-processing software changes to the RDA were mentioned in the previous section. To accommodate the extra effort needed for this evaluation, the Data Quality Team established a subcommittee called the Data Quality Dual Polarization (DQDP) Subcommittee. The focus of the DQDP Subcommittee was to evaluate the RDA performance of the upgrade only, i.e., the base data which are the combined the base moments (reflectivity, velocity, and spectrum width) and newly added dual polarization base variables (differential reflectivity (Zdr), differential phase (PhiDP), and correlation coefficient (CC, a.k.a., RhoHV). The subcommittee was co-chaired by a member from WDTB, who provided dual polarization meteorology expertise, and by a member from ROC Engineering, who provided WSR-88D engineering expertise. The DQDP Subcommittee summarized, and sometimes provided a full review, of data analyzed at the Data Quality Team meetings. While the DQDP Subcommittee was evaluating the RDA upgrade, the Data Quality Team worked to validate the government supplied dual polarization algorithms, such as HCA and QPE. The DQDP Subcommittee met for two years from September 2009 through August 2011. (Saxion, 2011).

The dual polarization contractor used the NSSL research radar, KOUN, as the dual polarization prototype. This greatly facilitated validation of the dual polarization upgrade because approximately 250 meters away to the northeast is the ROC test-bed radar, KCRI. Figure 3 shows an image illustrating the proximity of the two radars. Having the dual polarization prototype collocated with a single polarization WSR-88D allowed for almost direct comparison of the base moments.

Since an upgrade of this magnitude had not been performed on the WSR-88D before, the DQDP Subcommittee refined the validation process as the upgrade progressed. In the beginning, the initial process was to evaluate four qualities for each of the three base moments, reflectivity, velocity, and spectrum width. Specifically, we evaluated (1) texture, or variance in the data, (2) coverage, or sensitivity of the system, (3) structure, or expected appearance of weather events, and (4) magnitude, or expected values of the base moments by comparing to KCRI. The goal was to ensure that, except for power loss due to splitting the beam, there were no changes in the base moments resulting from the dual polarization upgrade. Once the subcommittee was confident that base moments were otherwise unaffected by the upgrade, we applied the same process to the new base variables, differential reflectivity, differential phase, and correlation coefficient. The evaluation of the dual polarization base variables relied on expert's knowledge of meteorology of the event and expected dual polarization values for the conditions. It is important to acknowledge the team effort of the subcommittee while evaluating the base data and exchanging ideas. Through this subjective evaluation, the subcommittee was able to identify a number of hardware and software issues that the dual polarization contractor quickly addressed.

4. THE VALIDATION PROCESS: A collaborative effort

During the subjective evaluation of the base data, a number of other processes developed. These include sensitivity analysis and reflectivity calibration comparisons between KOUN and KCRI, operational assessments, and Z/Zdr scatterplots to determine Zdr calibration accuracy. These additional processes will be addressed in the following subsections.

4.1 The Upgrade

The first collaboration mentioned here was the dual polarization contractor's willingness to work with ROC Engineering and the NSSL during the initial testing phase of the dual polarization prototype. L-3 STRATIS, Baron Services, Inc., and L-3 ESSCO partnered to design, implement, and deploy the dual polarization upgrade. Since L-3 ESSCO's role is to support deployment of the upgrade, the ROC primarily worked with L-3 STATIS and Baron Services, Inc. (L-3/Baron) during the validation effort.

Early in the testing phase when comparing the dual polarization radar, KOUN, base moments to the single polarization radar, KCRI, base moments, both sensitivity (coverage, in the parlance of the subjective evaluation) and calibration (magnitude) had unexpected differences. While working to understand and correct the differences, ROC Engineering and L-3/Baron held weekly Technical Interchange Meetings (TIM). During these meetings, L-3/Baron explained technical details about their design. This helped the ROC Engineers better understand the operating parameters of the system. Also, ROC Engineering provided technical expertise about the WSR-88D. This helped L-3/Baron better understand the nuances of the baseline platform they were changing. The information exchanged during these meetings helped to resolve outstanding issues more quickly thus enhancing the dual polarization upgrade functionality and enabled better explanations by ROC Engineering to the rest of the validation community.

4.2 Engineering

Much of the initial validation of the base moments relied on comparing base moments from KCRI to base moments from KOUN. While a 3 dB difference due to KOUN splitting the power for the H and V channels was expected, the observed difference appeared to be greater. ROC Engineering developed a method for investigating differences in reflectivity and sensitivity by calculating, bin by bin, the reflectivity difference and sensitivity difference between KOUN and KCRI. Sensitivity differences were determined by signal-to-noise ratio (SNR). All of the differences for a radial were averaged, then all of the radial averages were plotted. This resulted in a radial vs. average reflectivity difference and a radial vs. SNR difference. Both of these curves were plotted on the same graph. An example of the graph and its associated PPI reflectivity scan are shown in Figure 4. This gave insight into each weather event and revealed consistent differences for moderate reflectivity values where all assumptions for Rayleigh scattering are met (Saxion, 2011).

With KCRI and KOUN located so closely to each other, the two radars have assigned transmit frequencies at the opposite end of the allocated frequency band for S-band weather radars (KOUN: 2705 MHz, KCRI: 2995 MHz) to avoid interference. It was always known that the frequency difference between the two radars would have some impact, but exactly how much could not be determined until some of the elements of the system had been fully analyzed, such as antenna gain. After evaluating enough data to be certain that the sensitivity difference was consistent and after learning more about the upgrade design, ROC Engineering performed an analysis to determine the sensitivity difference that would be expected due to frequency differences alone. The result was about 1.5 dB. This amount added to the 3 dB difference expected due to the power split and additional, yet minimal, losses due to the new hardware totaled the observed sensitivity difference between KOUN and KCRI (Ice, 2011).

Additionally, there were differences in the magnitude of reflectivity values when comparing KOUN and KCRI, indicating differences in reflectivity calibration. Information exchanged during the TIMs with L-3/Baron revealed that both KOUN and KCRI had minor discrepancies with the reflectivity calibration procedures. After resolving these discrepancies, moderate reflectivity values, i.e., less than 40 dBz, compared very well. However, in regions of extremely high reflectivity values, i.e., greater than 40 dBz, KOUN and KCRI data did not compare. Again, this was due to frequency differences between the two radars (Ice, 2011). (Saxion, 2011)

To evaluate the health of the dual polarization upgrade over time, ROC Engineering monitored the Performance Maintenance Data (PMD) that is stored in Level II data. Occasionally, ROC Engineering was able to quickly identify when the prototype system may have been having issues. The information and knowledge of the system that ROC Engineering learned from L-3/Baron during the monitoring allowed for better system understanding which helped during Beta Test and early deployment. Through this effort, ROC Engineering determined that the dual polarization upgrade exhibited calibration stability (Saxion, 2011).

Another task performed by ROC Engineering was the signal processing validation. The goal of the validation was to show that the dual polarization system did not change the base moments, thus verifying that the base moments continued to meet system requirements. In the test lab on a stand-alone RVP8, ROC Engineers played the same Level I data from the H channel only through the baseline, single polarization version of software and through a dual polarization version of software and compared the results. This lab analysis focused only on the signal processing software, removing any impacts of the system such as losses due to splitting the power. This effort tested and validated that the dual polarization base moments met the same requirements as the legacy WSR-88D for both nonclutter filtered and clutter filtered processing for all operational volume coverage patterns (VCPs). (Saxion, 2011)

4.3 Verifying Impacts on Forecasts and Warnings

In order to preserve WSR-88D atmospheric scan times, the dual polarization design transmits horizontal and vertical channels simultaneously. To minimize cost and complexity, the design used the existing WSR-88D transmitter, splitting the total power between the two channels. It was understood and accepted that a dual polarization radar would have 3 dB less power than a single polarization radar due to power splitting alone. Additionally, one could expect less than 1 dB loss due to the new hardware. Unfortunately, early in the upgrade validation process, the observed loss in sensitivity was much greater. This section outlines the quick and thorough response by ROC Applications Branch in collaboration with the WDTB and the NSSL to quantify and assess the impact of sensitivity loss on forecasters' mission.

In December 2010, only months after the dual polarization validation had begun, ROC Applications Branch and WDTB organized a subject matter expert (SME) panel for the first sensitivity loss assessment. They organized local forecasters and NSSL scientists, each with a strong background in operational forecasting, to review single polarization base data with 3 dB, 4 dB, and 6 dB sensitivity loss applied, thus mimicking possible sensitivity losses observed in the dual polarization upgrade. According to the SME report executive summary,

"*As a result of the simulated reduction in sensitivity the SMEs noted a reduction in areal coverage of weaker reflectivity returns as well as increasing difficulty detecting outflow boundaries,* *dry lines and fronts. … After examining and discussing the data, the SME panel recommended that a 4 dB sensitivity loss, associated with DP [dual polarization] conversion, is operationally acceptable."* The 1st SME Assessment report stated that *"If the sensitivity loss cannot be limited to 4 dB, the panel recommended a formal operational sensitivity assessment be accomplished using a variety of operational forecasters before any decision is made to field DP capability.*" (Applications Branch (1), 2010)

In January 2010, L-3/Baron improved on the design of their receiver, significantly improving sensitivity. In March 2010, the ROC Applications Branch and the WDTB organized a second assessment of sensitivity loss in the dual polarization upgrade to assess the impacts of the improvements. Also at this time, ROC Engineering had confirmed that the dual polarization upgrade would decrease sensitivity by only about 3.5 dB and that additional observed losses when comparing KOUN to KCRI were due to frequency differences. The 2nd SME panel's executive summary stated

"*After viewing base data and products, the 2nd Panel confirmed the results of the 1st SME panel in regards that a 4 dB sensitivity loss is not operationally significant. Therefore, it was the 2nd SME Panel's opinion that the focus of the upcoming Operational Sensitivity Assessment, recommended by the 1st SME Panel, should shift more to a Training, Technology Exposure and Transition Exercise*." (Applications Branch (2), 2010)

In August of 2010 in response to the 2nd SME panel's recommendation, the ROC Applications Branch and the WDTB partnered again to conduct the Operational Assessment of Pre-Deployment WSR-88D Dual Polarization Data. They hosted a group of 20 experienced NWS and Air Force forecasters and presented a number of dual polarization case studies that represented key forecasting and warning challenges faced by forecasters. Through assessment surveys, they were able to determine the improvements the forecasters saw in forecasts with the added dual polarization variables. The largest improvement was in forecasting winter weather. Another area that showed improvement was flash flood forecasting because dual polarization variables provided the ability to identify areas with the heaviest rain rates. The forecasters saw improvement in severe convective weather, not in the forecasting of it, but in detecting the presence of hail in general and very large hail specifically. Forecasters did not see any potential benefits in increasing tornado lead time with the addition of the dual polarization variables. However, forecasters did note *"the potential for DP data confirming the presence of a damaging tornado for storms within 40 – 50 nm of the radar."* (Cocks et al., 2011)

4.4 Meteorology

Throughout the testing phase of the dual polarization upgrade, the WDTB captured and presented single polarization KCRI base data and dual polarization KOUN base data from weather events that passed through Central Oklahoma. They compared the base moments from both radars and explained the new base variables from KOUN. The NSSL scientists who developed dual polarization supported this effort by providing technical expertise. The ROC Applications Branch also supported the effort by evaluating weather events and helping to select the best data for evaluation. The enthusiastic education about the dual polarization variables helped the entire subcommittee see the insights gained by forecasters.

During the two-year evaluation, a number of interesting weather events occurred, including hail, tornados, snow, and rain. Two of the most notable are a blizzard that occurred on 1 February 2011 and a tornado event on 10 May 2010. The following are excerpts from the DQDP Subcommittee minutes summarizing these events.

"Case I: Sleet and Snow.
2/1/11 0748 UTC
KOUN: VCP 21

A blizzard dumped 6-8 inches over Central Oklahoma with a band of 12-20 inches from Ada northeast to Tulsa. There were drifts locally over 3 feet. Start of the +SN band over Pottawatomie and Seminole Counties. There was also heavy sleet.

Given the environment before 0748 Z on 1 February 2011, forecasters knew there was a high potential for sleet and a small chance of freezing drizzle/rain early, changing over to snow as the event progressed. High reflectivity (55+ dBZ) values to the east of the radar would normally indicate regions of bright banding and thus an expectation of sleet at the surface [Figure 5a]*. Very high correlation coefficient (CC) values on the western half of the radar coverage indicate homogenous precipitation, all snow. However, a sharp transition zone of higher to lower (CC) values to the east show the snow to sleet transitions* [Figure 5b]*. Interestingly, there is a band of high CC values (0.99) in the high reflectivity region to the east of the radar indicating very heavy snow. This was confirmed by surface observations of 12 inches of snow in that region. The snow in this region was not dry,* *aggregated, but higher density graupel and perhaps slightly wet graupel. It is certain it was all snow, it is not as certain what kind of snow led to very high Z, ZDR near 0 dB, and CC at 0.99. The subcommittee examined differential reflectivity values (ZDR)* [Figure 5c]*. In regions of all snow to the west of the radar, the expected ZDR values would be 0.2 dB with no negative ZDR values in that region. However, there were regions of 30 dBZ reflectivity values, high CC values where ZDR values were 0.6 to 0.7 dB. The subcommittee believes that this is plausible since this could be a region where ZDR values are biased high due to the presence of non-aggregated ice crystals in the snow."* (DQDP Subcommittee Minutes, 2011)

"*Case II: Tornado outbreak throughout Norman.*
5/10/10 2212 UTC
KOUN – VCP 12

Low CC and ZDR values collocated with a velocity couplet indicate that a tornado is lofting a considerable amount of debris, signifying that the tornado is causing, or has caused, damage on the ground. It is not a precursor signature to a tornado, but can increase the confidence a forecaster has when issuing warnings and updates which can be reflected in the warning text. Sometimes, this is not an easy signature to discern when embedded with ground clutter, but with training, it will provide additional vital information to forecasters.

A good example where this signature would have definitely helped the forecaster was at 2245 UTC in eastern Cleveland and western Pottawatomie counties [Figure 6]*. A circulation was embedded in 45-55 dBZ echoes* [Figure 6b] *with no clear indication of a debris ball as with the other tornadoes in the region. The rotational signature* [Figure 6a] *was embedded in heavy rain and ground truth of a tornado would have been next to impossible. However, the dual-pol variables indicated a localized region of reduced CC* [Figure 6c] *and slightly negative ZDR collocated with the velocity couplet. A damage survey confirmed that a tornado had occurred in this area. A warning forecaster for this storm most likely would have had a warning out based on the velocity signature, but with the dual-pol signatures, they would have been able to confidently say a tornado was on the ground causing damage as soon as that signature was detected.*

Data from the Moore-Choctaw and Norman-Little Axe tornadoes were also examined. It was noted that the Norman-Little Axe tornado debris signature (TDS) was not as clearly defined due to the ground clutter surrounding it. However, it was shown that the TDS did co-exist with a velocity couplet and was associated with higher reflectivity and slightly negative ZDR supporting a TDS. It was also noted that the dual-pol signatures associated with TDS (i.e. low CC and ZDR) must be co-existent with a velocity couplet. This will be covered extensively in the training provided to forecasters." See Figure 6 for the associated images. (Schlatter 2011) (DQDP Subcommittee Minutes, 2010)

4.5 The Zdr Calibration Conundrum

The requirement by the Hydrometeor Classification Algorithm (HCA) and the Qualitative Precipitation Estimate (QPE) algorithms that Zdr values be within 0.1 dB of true Zdr values has been long understood. Many research dual polarization radars use the vertical pointing method to ensure accurate Zdr calibration. Disrupting the operational status of the WSR-88D during a precipitation event to vertically point was not a viable option for the national network. As mentioned previously, the NSSL recommended and L-3/Baron executed an engineering calibration approach. It provides the initial snapshot of the biases existing in the system. L-3/Baron also designed and implemented online tests to track any changes in the system between offline calibrations. PMD and Zdr data monitoring showed that the online calibrations exhibited stability in Zdr values over time. However, finding an independent method for verifying that the offline differential reflectivity calibration was accurate to the required 0.1 dB was an especially difficult task for the DQDP Subcommittee.

The DQDP Subcommittee began by subjectively comparing Zdr weather radar returns with observed ground truth. While this was good for a general estimate of the accuracy, there were too many uncertainties to determine the accuracy of the Zdr calibration to within 0.1 dB. Regardless, it was very useful early in the validation process while the subcommittee determined other processes with higher accuracy.

It was winter when the subcommittee members began attempting quantitative analysis of Zdr values. Since there were few cases with liquid precipitation to analyze, the subcommittee began by interrogating Zdr values in regions just above the melting layer where dry aggregated snow is often observed. Dry aggregated snow has expected Zdr values between 0.2-0.3 dB. Unfortunately, the biases calculated by taking the difference between the observed Zdr values in these regions and the expected 0.2-0.3 dB had wide variations due to the difficulty in accurately identifying regions of dry aggregated snow that was also free of melting layer contamination. The NSSL determined that this could only be accurate to within 0.3 dB and therefore was not viable for determining Zdr calibration accuracy. (Melnikov, 2010)

In the early Spring of 2011, an independent consultant from Colorado State University (CSU) joined the subcommittee at the request of L-3/Baron. Their approach was to capture data below the melting layer, ensuring only liquid precipitation was captured, since expected Zdr values in precipitation is better understood and, for stratiform rain, has less variance. Bins of base data only liquid precipitation were selected then reflectivity versus differential reflectivity (Z/Zdr) was plotted in a scatterplot. The expectation was that the curve of mean of the Zdr values across all reflectivity values would asymptotically approach zero as reflectivity values became small. If the asymptote approaches a Zdr value other than zero, then that represented the Zdr bias not accounted for by the Zdr calibration. At about the same time, the NSSL developed a similar method for evaluating Z/Zdr scatterplots for precipitation. Using the same selection criteria, they expected to see a mean Zdr value of 0.23 dB for reflectivity values between 20-22 dBz. For that reflectivity value range, the difference between the observed mean Zdr value and the expected Zdr value of 0.23 dB revealed the Zdr bias. While the two scatterplot methods were slightly different, the theory was similar and both were based on extensive disdrometer data collection and analysis. For an example of scatter plots from each of the two techniques and the associated reflectivity and Zdr PPI scans from the Morehead City, NC radar, KMHX, see Figure 7. The willingness of the NSSL and the CSU consultant to participate in the evaluation was a significant contributor in helping the subcommittee move forward with the independent validation of Zdr calibration accuracy.

Before the entrance into Beta Test phase in the spring of 2011, the WSR-88D at Vance Air Force Base, KVNX, was upgraded to dual polarization in support of the ROC's efforts to validate the dual polarization upgrade. Since KVNX and KOUN have overlapping coverage, one expectation was to compare Zdr values from two dual polarization radars in close proximity. Unfortunately, the weather did not cooperate. An important criterion for the type of precipitation used for the Z/Zdr scatterplot evaluation is stratiform rain. During the spring and summer of 2011, central Oklahoma endured a drought and only saw occasional convective storms. This resulted in highly varying calculated Zdr biases from the Z/Zdr scatterplot analysis. During the summer of 2011, as Beta Test sites were installed and more stratiform rain cases were collected, Zdr bias began to converge to smaller more acceptable values. Analysis by ROC Applications Branch is ongoing.

In August 2011, L-3/Baron provided an analysis of their engineering calibration approach. In this analysis they showed that their calibration technique was accurate to within 0.1 dB by identifying sources of error in the measurement steps then quantifying the worst case scenario. They also reviewed empirical data that showed the stability and repeatability of the Zdr calibration approach. The government accepted this analysis as showing the accuracy requirement had been met and endorsed moving into deployment. (Baron, 2011)

A final independent method for validating the accuracy of Zdr calibration discussed here is the NCAR Cross-Polarization (CP) Power technique. This method relies on sun scans, all H and all V ground clutter scans, and radar reciprocity to determine the Zdr bias introduced by the system (Hubbert, 2011). ROC System Engineering recognized that Zdr calibration would be difficult to validate and pursued this technique as a solution (Ice, 2011). This technique is well proven on the NCAR S-Pol radar. ROC engineering is working with NCAR to validate the method on the L-3/Baron dual polarization WSR-88D. The effort is ongoing.

The system stability, the L-3/Baron analysis, the convergence of Zdr biases determined by Z/Zdr scatterplots to the requirement, the usefulness of relative Zdr values to forecasters, and the promise of the cross-polarization power technique contributed to the DQDP Subcommittee endorsing entrance into deployment. After the endorsement, the DQDP Subcommittee disbanded and rejoined the Data Quality Team. Through the Data Quality Team, Zdr calibration validation efforts continue. The efforts by L-3/Baron, NSSL, CSU, NCAR, WDTB, ROC, and Air Force KVNX staff contributed to the success of the validation process and confidence to proceed with deployment.

5. DEPLOYMENT STATUS

Following a beta test period with operational radars, full-scale deployment began in the Summer of 2011. By the end of 2011, 20 network radar sites have been modified with dual polarimetric capability. As of this conference, 26 radars have been modified with dual polarimetric capability (Figure 8). See http://www.roc.noaa.gov/WSR88D/DualPol/Default.aspx for the ongoing deployment status.

6. SUMMARY

To validate the dual polarization upgrade, the Radar Operations Center Data Quality Team established the Data Quality Dual Polarization Subcommittee. For two years, the DQDP Subcommittee worked diligently to ensure the data quality of the dual polarization upgrade, which was the most complex upgrade since the WSR-88D itself. Through close collaboration of all of the team members, the validation process engendered confidence that the deployment will be a success. This was achieved through a number of specific efforts, such as supporting the contractor performing the upgrade, validating the base moments and monitoring engineering parameters, evaluating meteorological events, ensuring the operational usefulness of the upgrade, and validating Zdr calibration. All of the efforts by everyone involved helped the NEXRAD program meet its mission of protecting lives and property.

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Appendix – Figures

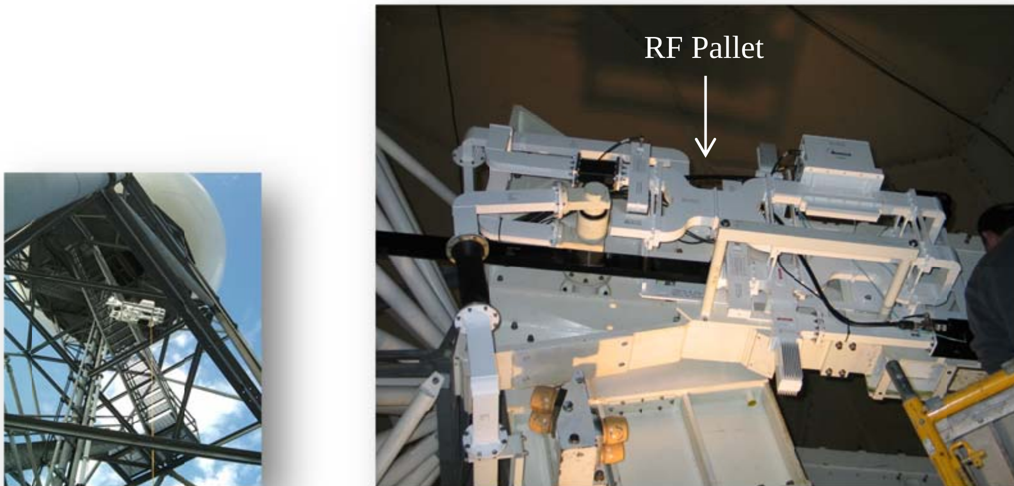


Figure 1 – Baron Services, Inc. RF Pallet

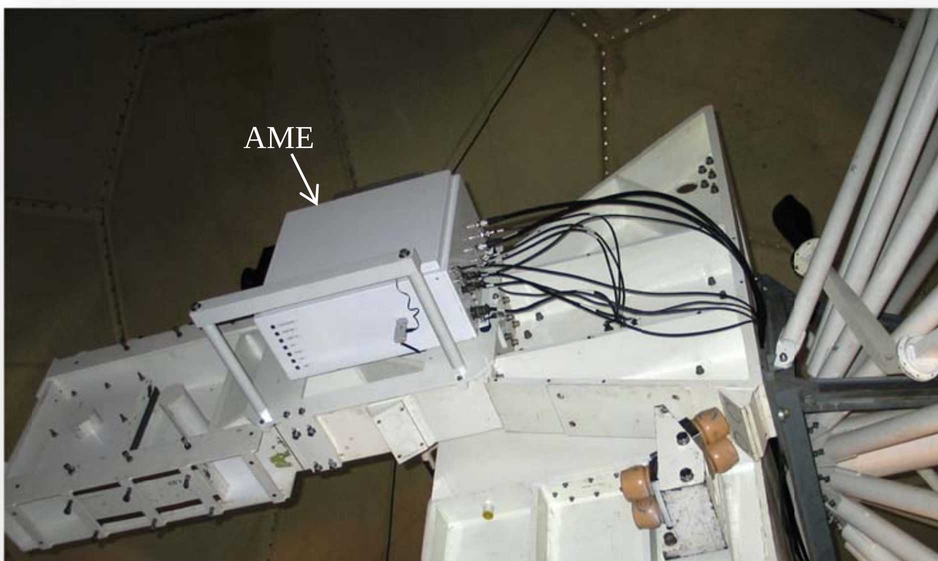


Figure 2 – Baron Services, Inc. Antenna Mounted Equipment (AME)

Figure 3 – Co-location of the WSR-88D Test-bed radars in Norman, Oklahoma: KOUN (left) and KCRI (right)

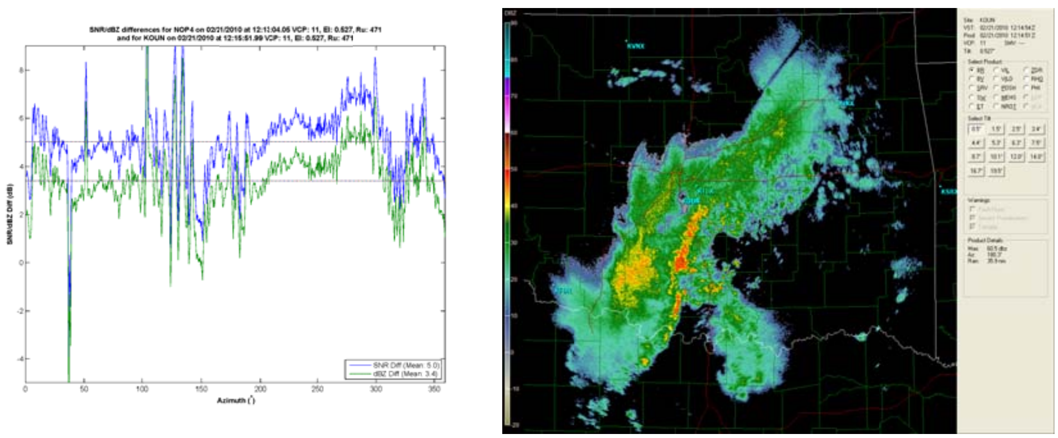
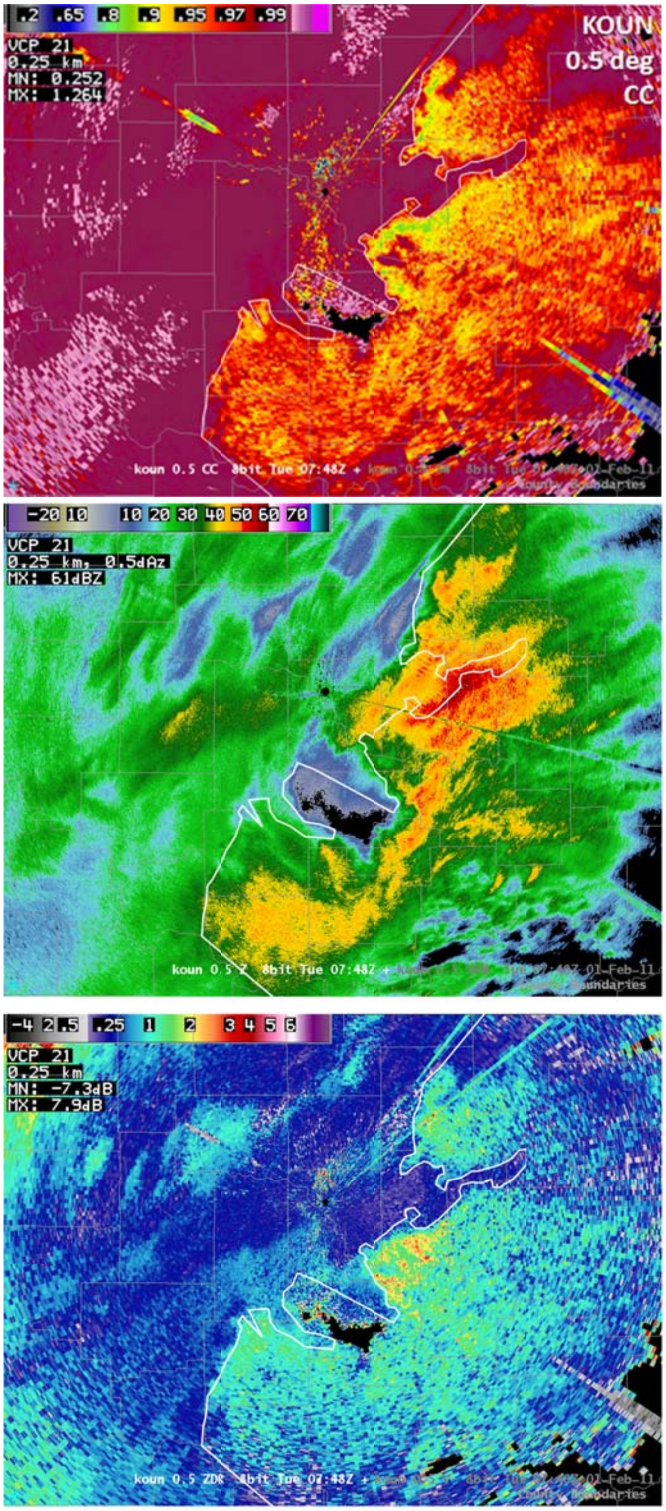


Figure 4 – Sensitivity and Calibration Analysis.
The plot on the left shows azimuth vs. reflectivity (green) and azimuth vs. SNR (blue). The plotted reflectivity and SNR values are the average difference between KOUN and KCRI for the entire radial at the given azimuth. On the right is the associated KOUN reflectivity PPI for the graph (KCRI reflectivity is not shown). Zero degrees in azimuth corresponds with due North. From the plot, SNR difference is 5.5 dB in regions of moderate reflectivity where Rayleigh scattering requirements are met. At the time of this analysis, reflectivity calibration differences had not been fully identified, thus the Reflectivity difference between KOUN and KCRI was approximately 4 dBz.

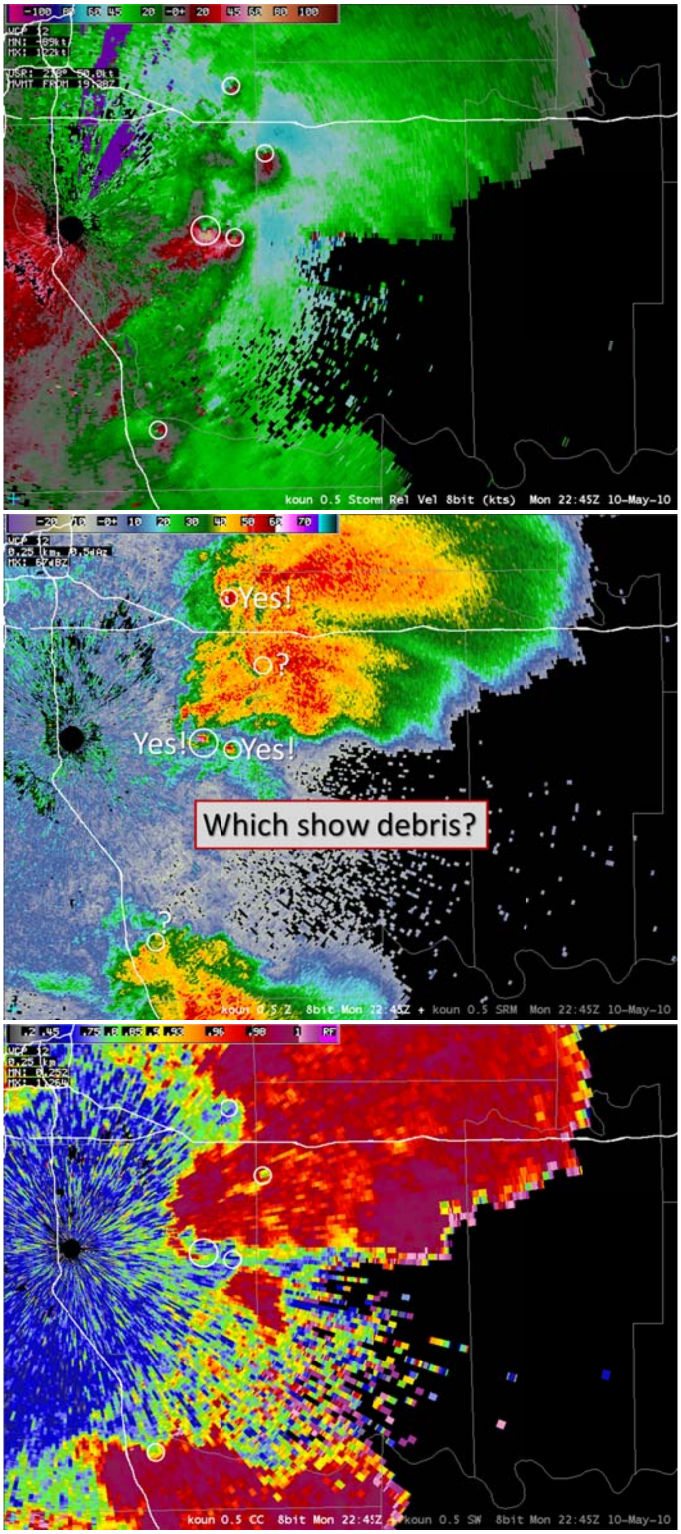


(a) Correlation Coefficient

(b) Reflectivity

(c) Zdr

Figure 5 – Images from KOUN during a blizzard in Norman, Oklahoma on 1 February 2011 illustrating the benefits of dual polarization variables in winter weather events. The Correlation Coefficient PPI (a) shows a clear transition between all snow (maroon colored CC values) and mixed phase (green, yellow, and orange). The outline of the transition is overlaid onto the reflectivity PPI where the band of snow to the northeast is not discernable. The Zdr PPI shows low Zdr values to the northeast supporting the presence of snow with mixed phase surrounding it indicated by high Zdr values.



(a) Velocity

(b) Reflectivity

(c) Correlation Coefficient

Figure 6 – Images from KOUN during the tornado outbreak in Norman, Oklahoma on 10 May 2010. Velocity PPI (a) shows five couplets (circled) indicating rotation. The same five regions are circled in the reflectivity PPI. Only three show increased reflectivity values. Correlation Coefficient (c) shows reduced correlation in all five regions.

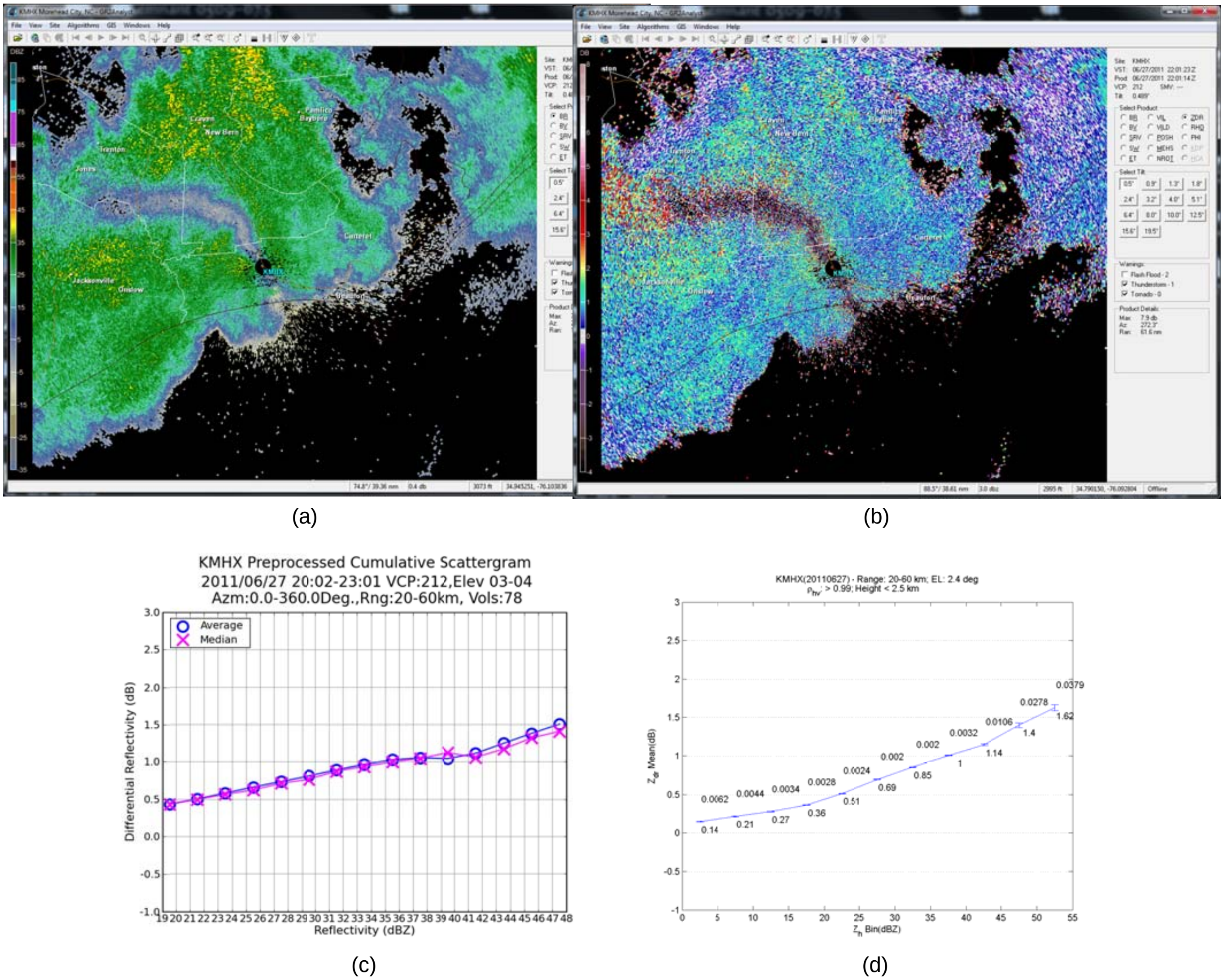


Figure 7 – Example of the Z/Zdr scatterplots from KMHX, Morehead City, NC. Reflectivity (a) and differential reflectivity (b) illustrate a rain event on 27 June 2011. Two analysis methods are shown, Z/Zdr scatterplots comparing Zdr values for Z values between 20-22 dBz to the expected 0.23 dB (c) and observing the Zdr curve where it asymptotically approaches zero. Note the different analysis methods are examining different VCP elevation angles.

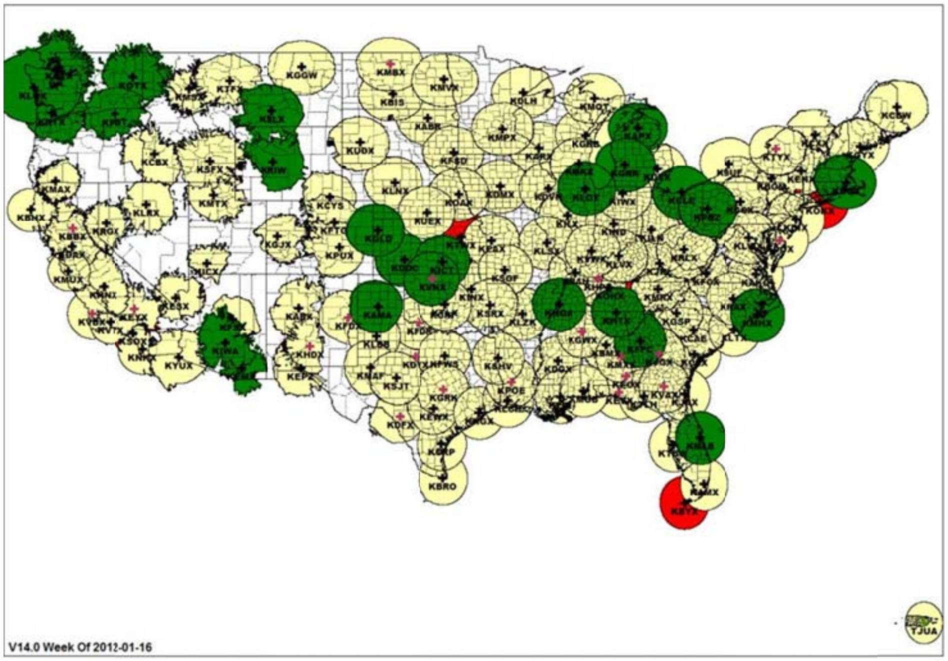


Figure 8 – Expected dual polarization deployment status as of 16 January 2011.
Green indicates completed upgrades.
Red indicates upgrades in progress.
Yellow indicates upgrades not started.