IDENTIFYING CRITICAL STRENGTHS AND LIMITATIONS OF CURRENT RADAR SYSTEMS

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ABSTRACT

The Next-Generation Weather Radar (NEXRAD) network of Weather Surveillance Radar-1988 Doppler (WSR-88D) radars is nearing the end of its expected 20-year engineering design lifetime. One replacement system currently under consideration is multifunction phased array radar (MPAR). The purpose of this study is to illustrate the critical capabilities of current radar systems to decision-makers and to determine the suitability of MPAR to users' needs. Interviews were conducted with National Weather Service (NWS) forecasters and broadcast meteorologists to collect stories which exemplify radar strengths and limitations.

The roles served by participants strongly affected their use of radar. NWS forecasters use radar to provide information to a variety of user groups across their forecasting area. During severe weather events, they use volumetric data to monitor storm evolution and make warning decisions, and also to evaluate rapid low-level scans to warn for small-scale signatures. Broadcast meteorologists use radar to anticipate and interpret warnings issued by NWS, make decisions about cutting into regular programming to provide severe weather coverage, and illustrate the current threat to viewers. Broadcast participant use their own radars to obtain rapidly updating low-level reflectivity data so that they can pinpoint the time and location of NWS warnings.

Limitations identified in the study include radar horizon issues, de-aliasing problems, beam spreading, and detection of precipitation type. PAR capabilities will help to mitigate the effects of many of these limitations.

1. INTRODUCTION

The process of designing and implementing a new radar system involves identifying the critical strengths and limitations of current radar systems and their effects on operations. A new radar system should possess the important capabilities of current systems and address current radar deficiencies. This paper explores current radar strengths and limitations, as identified by two stakeholder groups. The suitability of phased array radar (PAR) technology to users' needs is assessed according to these critical radar capabilities. Specific PAR capabilities discussed are rapid temporal updates and adaptive scanning strategies. Readers interested in the financial, operational, and technological aspects of PAR may wish to reference Weber et al. (2007). Specific advantages of using PAR for weather observations and data quality improvements are discussed in Zrnić et al. (2007) and Heinselman et al. (in press).

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The critical incident technique (CIT) was used to interview radar users. The CIT is a common technique in qualitative analysis, and involves asking for stories which exemplify key capabilities. In this study, participants were asked to recall incidents in which radar did or did not provide critical information. These incidents were used to illustrate radar strengths and limitations.

Our study's relation to previous work is given in section 2, along with an explanation of the development and use of the CIT. Section 3 describes the data collection and analysis methodology. The results of the study are discussed in section 4, including the role perception of each stakeholder group and the radar strengths and limitations identified by each group. Section 5 includes a comparison of the two groups, in terms of radar use and critical radar capabilities. These critical capabilities are then related to PAR technology.

2. BACKGROUND

This study is compared to other qualitative studies in the field of meteorology in terms of goals and data collection methods. Because of the purpose of our study, we determined the critical incident technique was the best data collection method. The development and use of the critical incident technique is discussed, along with the importance of using this technique for the study.

2.1 *Relation to Previous Work*

Qualitative research is becoming more and more common in the field of meteorology. Many people are expressing an interest in the social science aspects of weather and the cognitive processes involved in forecasting (Demuth et al. 2007). For example, a 1997 study by Pliske et al. used the critical decision method to conduct interviews with forecasters and identify distinguishing characteristics of expert and non-expert forecasters in the United States Air Force. The critical decision method is used to determine on what knowledge decisions are based. Participants in the study were asked to give detailed accounts of specific forecasting incidents, including their evaluation of the situation, the basis for their judgments, their expectations of the outcome, and the options they chose to evaluate. By using the critical decision method, the researchers identified the critical cognitive elements involved in producing an expert forecast. Readers interested in a more detailed description of the critical decision method may see Hoffman et al. (1996).

A 2007 study by Morss and Ralph used observations and interviews with National Weather Service (NWS) forecasters and emergency managers to determine how information collected during the CALJET and PACJET-2001 experiments had been used. The researchers also examined how NWS forecasters and emergency managers use information in general. By observing participants, the researchers learned how NWS forecasters use information on a daily basis, rather than during specific, significant events. Interviews were semi-structured and included open-ended questions; several interviews included more general discussions about information use.

Our study also uses interview data to learn more about the roles of forecasters and the information they use to make decisions. However, unlike the studies discussed, our study does not directly involve cognitive processes. We are more interested in the information forecasters and broadcast meteorologists use to make critical decisions and more importantly, how they can obtain this information from radar. Thus, our study focuses less on how information is used to prepare a forecast and more on how radar capabilities specifically affect forecasting operations of two stakeholder groups.

User radar needs have been studied once before by Philips et al. (2007). A study was conducted to determine radar user needs and integrate them into the design of the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) network. Similar to our study, the researchers conducted interviews with radar users from different stakeholder groups, asking them about how they used radar data to make decisions. The researchers also distributed questionnaires to collect their data. However, researchers in the CASA study asked participants how they thought CASA data would be beneficial to them, and how they believed the strengths and limitations the CASA network related to their roles.

In this study, PAR is not pre-supposed as the answer to current radar deficiencies; instead, the suitability of PAR to users' needs is determined. This study moves beyond the assumptions about the ways people use radar by going straight to the radar users themselves to ask them which radar capabilities *they* think are most important. We are using the CIT to gather a collection of stories which show how radar capabilities actually affect operations and to illustrate these capabilities to decision-makers.

2.2 *Critical Incident Technique*

The CIT is an effective way of gathering specific, factual information about human behavior. The CIT has been used to conduct studies in a variety of fields and is a popular, easily adaptable method in qualitative research (e.g., Oliver and Roos 2003; Kraaijenbrink 2007; Schluter et al. 2008). The CIT was used for this study in order to attain specific information about radar capabilities and how these capabilities affect operations.

Flanagan (1954) defines an incident as "any observable human activity that is sufficiently complete in itself to permit inferences and predictions to be made about the person performing the act." A critical incident must have a clear purpose and consequences with definite effects. In this study a "critical incident" is an event that illustrates how the strengths and weaknesses of weather radar affect a meteorologist's ability to perform his/her job.

The practice of asking for critical incidents can be traced to the studies of Sir Frances Galton during the 19th century. However, the CIT as it is known today began to evolve during World War II. The United States Air Force needed a way to select and train pilots as quickly as possible and enlisted the help of John C. Flanagan and the newly formed Aviation Psychology Program (Flanagan 1954). An initial study was conducted to determine why 1,000 pilots had failed training programs and how these programs could be better designed to produce competent pilots. The researchers examined evaluations and found many general, stereotypical statements — "lack of inherent flying ability", "poor judgment", "insufficient progress." Flanagan asserted that it would be much more useful if the evaluations contained incidents in which pilots showed these qualities.

To attain this information, Flanagan developed a questionnaire and distributed it to flight instructors, asking them about pilots' behavior during critical situations, and why this behavior was either effective or ineffective. The information gained from this study helped to develop a new training program for pilots (Flanagan 1954). Under the guidance of Flanagan, the CIT was developed further and given its present name. The CIT is now a common and well-respected method in qualitative research.

3. DATA AND METHODOLOGY

The data for the study were collected through interviews with radar users. An overview of the participants in the study is given, along with a discussion of our sampling strategy and interview format.

3.1. *Participants*

A purposive sampling strategy (Patton 1990; Kuzel 1992) was used to strategically select participants for interviews. Participants were selected based on their roles during weather events and their radar experience. Our goal was to gather information from people who have worked with a variety of radar systems, both before and after the establishment of the current Weather Surveillance Radar-1988 Doppler (WSR-88D) network, and with people who serve in a variety of roles during weather events. Participants were responsible for providing warning information to a variety of users, which strongly affected their use of radar.

Two key stakeholder groups were selected for interviews, National Oceanic and Atmospheric Administration (NOAA) NWS meteorologists and broadcast meteorologists. An interview lasting no longer than an hour was requested. In the end, nine interviews were conducted with participants in the Southern Plains of the United States, including five NWS forecasters and four meteorologists from the broadcast community. Of the five participants working at NWS offices, two were Science and Operations Officers (SOOs), two were Warning Coordination Meteorologists (WCMs), and one was a lead forecaster. Of the four participants working as broadcast meteorologists, three were on-air meteorologists and one was a weather producer.

3.2 *Interviews*

Interviews were conducted at times and locations convenient to the participants. Because of our interaction with human research subjects, we completed an online training course entitled "The Protection of Human Research Subjects." This course reminded us of the importance of protecting confidentiality and anonymity when people are willing to share their thoughts and experiences. We also submitted an application to the Institutional Review Board at the University of Oklahoma, which included a description of the study, an interview format, and a consent form. At the beginning of each interview, the consent form was given to the participant to read and sign. The consent form explained the purpose of the study and the potential benefits of participation. It also assured each participant of the confidentiality of the study and allowed him/her to choose whether to be audio recorded and quoted directly.

Interviews were conducted using the CIT, as described by Dunn and Hamilton (1986). Dunn and Hamilton stress the importance of establishing rapport within the first few minutes of an interview, believing it is counter-productive to ask for critical incidents right away. We established rapport at the beginning of each interview by asking participants to describe their roles and responsibilities during weather events. In the main part of the interview, participants were asked to describe critical incidents in which radar affected their ability to perform their job, and the degree to which this was dependent on the type of weather event or the time of day. Finally, the participants were asked to describe the information they can obtain from current radar systems and how this differs from other radar systems they have used. Participants were also asked to describe their ideal radar system.

3.3 *Coding and Thematic Analysis*

Interviews were examined using a qualitative analysis technique known as coding. Gibbs (2002) describes coding as a way to organize data by applying labels to portions of text from interview transcripts. Phrases or sentences embodying a particular theme were "flagged" in the transcripts, and a code was applied to group this text with text from other parts of the data set. Over eighty categories and sub-categories were created and defined, and several common themes began to emerge.

Themes included radar strengths and limitations, capabilities of an ideal radar system, participant's role and its effects on radar use, methods of mitigating radar deficiencies, radar experience, and issues faced due to participant's role. Boyatzis (1998) describes this perception of common themes as the first step of thematic analysis.

Several approaches can be taken to conduct a thematic analysis. The data-driven approach seemed to most closely match our research goals, due to the inductive nature of the study. Other approaches included a theory-driven approach and a prior-research-driven approach, which we felt relied too strongly on prior theories and studies (Boyatzis 1998). Our goal was to go beyond assumptions and theories and learn about radar capabilities directly from radar users.

A data-driven approach to thematic analysis lets your data guide you in the development of codes and themes. Instead of looking for data to support previously developed theories, the researcher allows themes to emerge naturally from the data. The data-driven procedure described by Boyatzis (1998) strongly emphasizes the development of sub-samples of data and the comparison of themes across these sub-samples. This approach can be useful when the researcher wishes to identify distinguishing characteristics or capabilities between two groups of people. However, our intention was to gain a broader perspective on how people use radar, rather than study how the radar strengths and capabilities needed by each group differed. We separated critical radar strengths and limitations by stakeholder group after the coding had been completed, but we did not allow the different sub-samples to guide our coding process. Therefore, a more hybrid approach to thematic analysis was taken in this study.

The main themes that emerged from the data were radar strengths and limitations, participant's role and its effects on radar use, and methods of mitigating radar deficiencies. Participants' roles were used to place radar capabilities into context. Critical incidents were selected from the interviews to help illustrate these radar capabilities and their effects on operations.

3.4. *Interrater Reliability*

To determine the consistency and reliability of the coding, we completed an interrater reliability process. Two researchers independently coded the interviews, then compared the information they had coded and the categories they had created. If the researchers are not consistently agreeing on codes or themes, Boyatzis (1998) advises dropping the code from the study or redefining the code until some degree of consistency is achieved. The codes which have achieved interrater reliability at the end of the process are considered to be a reliable set of codes (Boyatzis 1998).

We found that our coding was largely consistent. After analyzing one coded interview, we made a few changes and additions and easily came to a consensus on the set of codes being used. The interrater reliability process helped assure us that our coding was repeatable and reliable, and that we were not overlooking any important issues in the interviews.

3.5 *Addressing Biases*

Flanagan (1954) stresses the importance of addressing biases at each step of the critical incident research process — sampling strategy, data collection, and interpretation. Addressing biases or sources of error is important for any kind of study, because it shows that the researcher is aware of his/her prior beliefs or expectations and is trying to assure these biases are handled as effectively as possible.

In this study, we identified three possible biases. The first bias involves the funding source, which could have affected the data we chose to highlight. Since the research was funded by the PAR project, it would seem tempting to emphasize statements from the interviews which support PAR capabilities. However, we did not want to pre-suppose PAR as the answer to the next radar system. We did not ask participants directly about PAR, but instead learned about their thoughts on current radar systems in order to assess the suitability of PAR technology to users' needs. To help address this bias, the PAR project funded a third party to conduct the interviews and to analyze the data.

The second bias involved competition amongst broadcast meteorologists, which may have had an effect on the specificity of the information obtained. Broadcast meteorologists must pay attention to ratings, and therefore are unwilling to share information about their radar systems or forecasting techniques with meteorologists from other television stations. Although we provided a consent form, ensuring the participants confidentiality and anonymity, we still felt that the broadcast participants may have been withholding information or speaking about radar capabilities in a vague manner. Overall, we found that the NWS forecasters provided more critical incidents and specific information than the broadcast participants.

The third and most significant bias involved the time and location of the interviews. All nine interviews were conducted during the late spring and early summer in the Southern Plains region. As a result, severe convective weather was at the forefront of everyone's minds, and severe weather events dominated most of the interviews. To address this bias, we probed for nonsevere weather events during the interviews and encouraged interviewees to discuss their use of radar during these events.

4. RESULTS

This section describes the major strengths and limitations of radar, as identified by the two stakeholder groups. Radar capabilities are related to the roles and audiences of each stakeholder group.

4.1 *NWS Forecasters*

4.1.1 *Role*

People who work in a NWS Weather Forecast Office serve a variety of roles. In addition to issuing forecasts and warnings, they must maintain situational awareness, ensure their message is consistent, conduct briefings with emergency managers, broadcast media, and amateur radio operators, and keep information flowing between their forecasting office and affected areas during a severe weather event. Radar is one of many data sources used to accomplish these job responsibilities.

4.1.2 *Radar Strengths*

Severe convective weather was a common topic in the interviews, and radar capabilities during these events will be covered later in the section. First, radar use during nonsevere weather events will be discussed.

Several NWS forecasters stressed the versatility of radar and how it can be used for a variety of different weather and nonweather events. A few participants mentioned using radar to detect smoke plumes from fires. One participant was able to see debris from a space shuttle re-entry on a radar image. Another major strength of radar is its dependability and availability — unlike many other data sets, such as upper-air data and satellite images, radar is available all the time. Said one forecaster, "...it's there twenty-four hours a day and it's pretty reliable, and we've learned to trust the data."

Another strength of radar is its ability to detect boundaries; convergence zones and fronts, outflow boundaries, and dry lines are some examples. Boundary detection can be used to predict dramatic wind shifts. One forecaster recalled a large wildfire which dozens of firefighters were struggling to extinguish. An incoming boundary caused a dramatic wind shift, and the firefighters had to change their positioning. If radar had not been used to detect this boundary, many firefighters would have been seriously injured or killed.

Radar is often used during flooding events. Although rainfall estimates derived from radar data can be inaccurate, forecasters use radar to see the areas of heaviest rainfall, and infer where the heaviest precipitation is moving. One participant said that he uses radar during severe weather events to identify the transition from a primarily severe hail and wind phase into a flooding phase, looping base reflectivity to determine where heavy rainfall is starting to occur.

Three forecasters discussed the ability of radar to measure wind. Two forecasters mentioned examining radar data for downburst signatures, such as convergence at mid-levels, and monitoring surging rear flank downdrafts. Another forecaster mentioned using radar to detect winds in the remnants of a hurricane as they were strengthening back to tropical storm intensity.

NWS forecasters valued the importance of examining rapid low-level scans to look for small-scale signatures, although obtaining these scans can be difficult. Three forecasters had seen people in their office re-start a volumetric scan in order to get a more rapid update at the lowest elevation angle.

Participants who had access to Terminal Doppler Weather Radar (TDWR) data also discussed the advantage of having rapid, low-level updates. One forecaster mentioned that greater spatial and temporal resolution at low-elevation angles helped him understand the evolution of short-lived features — "tornado cyclones, tornadic vortex signatures, microbursts, circulations that form on gust fronts." He described a late spring event in which a violent tornado touched down in a metropolitan area. TDWR was well-positioned to observe the storm, allowing this forecaster to see a rapidly developing mesocyclone with intense convergence. This information gave the forecaster confidence to intensify his warning message, because he knew tornadic development was imminent.

Nearly every forecaster mentioned the advantages of displaying volumetric radar data. This volumetric data is necessary to monitor storm evolution and to make warning decisions. For example, one forecaster described the four-panel display he used to study three-dimensional storm structure, and how he could easily study storm top divergence and low-level signatures on the same display, providing a more complete picture of the storm. A few forecasters mentioned using Gibson Ridge software to create cross-sections of radar reflectivity.

A few forecasters viewed radar-derived algorithm output as a strength. Two participants discussed the Maximum Expected Size of Hail (MESH) algorithm, which uses a composite of radar data to calculate hail size. These participants found MESH to be much more reliable than traditional hail size algorithms, stating that it is a "quick way to confirm that this [storm] is severe or probably it's not." Two forecasters spoke about algorithms on more general terms, describing them as safety nets to confirm or deny what the radar is showing.

NWS forecasters value the versatility of radar, which allows them to provide information to a variety of user groups. They also emphasized the strengths of volumetric data to study storm evolution and to make warning decisions, and the use of rapid, low-level updates to look for small-scale signatures.

4.1.3 *Radar Limitations*

Radar-derived algorithm data can also be a radar limitation. Radar reflectivity-rain rate (Z-R) calculations can often lead to inaccurate precipitation rates. In addition, most forecasters mentioned the impossibility of detecting precipitation type with a nonpolarimetric WSR-88D radar. This is particularly a limitation during winter events, when forecasters are trying to infer the location of a snow/ice demarcation. Several forecasters discussed hail contamination in reflectivity data, and how they were not sure whether the high reflectivity values were produced by a large amount of small hail or a small amount of large hail. One forecaster spoke about a storm that had a reflectivity signature indicative of large hail — baseball-size or larger — but "quarter hail is all we could dig out of it." NWS forecasters found ground truth information to be extremely important, especially in assessing the reliability of algorithm output. One forecaster recalled placing phone calls to law enforcement officers, emergency managers, business owners, and city residents in order to attain storm reports.

A few forecasters discussed the difficulty of warning for severe straight-line wind events, particularly when a storm is moving across the radials of the radar beam. This limitation was also discussed in one of the broadcast meteorologist interviews. One broadcast participant mentioned the difficulty of detecting microbursts, because velocity data are not measured perpendicular to the radar. In addition, he finds it difficult to monitor a descending reflectivity core when volume scans are only completed every four minutes. He recalled a recent microburst event which occurred without warning, at 8 o'clock in the morning, and produced a considerable amount of straight-line wind damage. One forecaster mentioned that warnings for wind events are normally based more on reflectivity signatures than on velocity data. Three forecasters also brought up issues with de-aliasing and range-folded echoes, and how they often have to change the pulse repetition frequency (PRF) or volume coverage pattern (VCP) to fix these problems.

Two major radar limitations discussed by NWS forecasters were beam spreading and radar horizon. One forecaster stated that small-scale signatures are difficult to detect because of beam spreading, and "you may have a tornado warning at long ranges, simply because of uncertainty." Another forecaster discussed a storm with high convective available potential energy (CAPE) values, and how he was "watching [the] storms fester for quite awhile." Once the CAPE was released, four or five tornadoes touched down within an hour. The first tornado was on the ground for at least six miles before the radar showed classic tornadic reflectivity and velocity signatures. The forecaster attributes this time lapse to beam spreading and radar horizon, because the rotation began at low levels and preceded a mid-level mesocyclone.

Beam spreading and radar horizon are two major radar limitations identified by NWS forecasters. They also spoke about the difficulty of warning for severe straight-line wind events and the necessity of using ground truth information to supplement algorithm output.

4.2 *Broadcast Meteorologists*

4.2.1 *Role*

Broadcast meteorologists stated their main role is to deliver timely, accurate information to the public and inform them of the safety precautions they need to take. All the broadcast meteorologists we spoke with worked at television stations with high- resolution radars, with update times of 30 s to one min., which they found extremely useful to do their jobs. By examining high-resolution spatial and temporal data at the lowest elevation angle, broadcast meteorologists are able to interpret and specify the location of warnings issued by NWS.

As part of their role, broadcast meteorologists often show radar images on the air to illustrate the current weather threat to viewers. However, since the general public is not familiar with radar data, some on-air interpretation is required. Broadcast meteorologists find it very difficult to interpret radar data on the air — while the broadcast meteorologist is mentally doing a sophisticated radar analysis, he needs to be giving simple, understandable information to the public.

Although broadcast meteorologists receive up-to-the-minute information on warnings issued by NWS, they need to know the reasoning behind these warnings and when NWS is considering issuing another warning. All the broadcast meteorologists noted that anticipating warnings issued by NWS would help them make wiser decisions about when to cut in with severe weather coverage and what information to show or discuss on the air. For example, one broadcast meteorologist mentioned that on a few occasions, he has interrupted regular programming to provide severe weather coverage, only to go off the air and discover that NWS had just issued a warning.

4.2.2 *Radar Strengths*

Broadcast meteorologists use the strengths of their own radars to pinpoint the exact time and location of a severe weather event. In general, television station radars allow broadcast meteorologists to see small-scale signatures that occur on time scales of one min. or less. One participant spoke about the detailed storm structures which she had never seen before she had access to high-resolution radar data. She stressed the importance of being able to react to these rapid changes, because the signatures were significant and produced damage.

Broadcast meteorologists can overlay their own radar reflectivity data with major road arteries, specifying exactly where the most dangerous part of the storm is located and relating this threat to where people actually live. This way, people can better understand the true imminence of the threat. This street-based warning system is made possible by the small beam width and rapid updates of television stations radars, along with supplemental information from their storm spotters.

For instance, one participant spoke about a spring 2008 event in which two tornadoes touched down within an hour, producing minor damage in a metropolitan area. Warnings were issued in the middle of the night, and people woke up, confused and scared, to emergency sirens. After examining data from his high-resolution radar, the participant issued statements over the radio and related the tornado locations to familiar streets, assuring people that if they lived west of a particular street, they would be safe. He felt that pinpointing the affected area helped keep people calm during this particular event.

Broadcast meteorologists identified fast, low-level scans as the primary strength of their own radars. The information obtained from these scans helps them pinpoint the “when” and “where of warnings issued by NWS.

4.2.3 *Radar Limitations*

Although television station radars possess many critical strengths, they are not nearly as powerful or as versatile as the WSR-88D radars used by NWS. WSR-88D data includes better-quality velocity and reflectivity data, detects echoes at longer ranges and without the major second trip echo problems of television station radars, and always includes volumetric scans. Broadcast meteorologists use WSR-88D information to supplement their own radar data, but update time is a major concern. One participant explained that because of financial limitations, his station had to wait eight min. to obtain volumetric scans from the nearest WSR-88D radar. The dissemination of WSR-88D information from NWS to the broadcast media was a common limitation discussed in the interviews.

However, broadcast meteorologists did not consider velocity data and volumetric scans to be as vital as reflectivity data and sector scans. Because of their role providing specific warnings, broadcast meteorologists are more concerned with catching low-level signatures than monitoring the overall evolution of a storm to make warning decisions. All the broadcast meteorologists we spoke with used radars with short wavelengths, which meant they obtained high-resolution data with a fair amount of velocity folding. One broadcast participant revealed that aliasing issues made his velocity data impossible to use. However, he felt that this was not a major issue, since the high-resolution reflectivity data obtained from his radar supplied him with enough information to do his job. In addition, the broadcast participants were much less concerned with volumetric scans. One broadcast meteorologist we spoke with explained that the processing time for a volumetric scan with his radar was so long that his station's radar was often left on the lowest elevation angle. Rather than letting the radar follow a prescribed volume coverage pattern, he was more interested in controlling the radar himself, doing sector scans on storms of interest. While other radar users may be more concerned with de-aliasing issues and volumetric data, broadcast meteorologists found that this information was not entirely necessary to perform their roles.

One participant noted that radar network coverage was a limitation at a television station where he had previously worked. That station did not operate its own radar, so meteorologists there relied completely on the WSR-88D network. It was often difficult to detect low-level radar signatures when storms were located at long ranges from the WSR-88D radars, due to radar horizon and beam spreading. After having worked at a television station with its own radar, this participant realized the vital information he had been missing.

All the broadcast meteorologists discussed the issue of inaccurate algorithm output, which is directly related to the quality of radar data. One participant mentioned that algorithms can force the user to examine false tornadic vortex signatures and overestimated hail sizes. Z-R calculations can lead to inaccurate precipitation estimates, particularly during tropical rain events. One participant noted that he is hesitant to show the storm total precipitation image on the air, because he knows it is often an over or underestimate of the actual rainfall. However, all the broadcast meteorologists stressed the importance of gaining ground truth information to assess the reliability of algorithm output. Ground truth information helps them evaluate overall storm trends, narrow down a warning area, or intensify their messages. One participant mentioned that many radar-indicated circulations do not produce tornadoes, and it helps to have someone in the field to confirm or deny what the radar is showing.

Broadcast meteorologists identified velocity de-aliasing and range-folding as two major limitations of current radar systems. However, they did not feel that these issues significantly affected their operations. Broadcast meteorologists use ground truth information to complement radar data and to identify inaccurate algorithm output, making their warnings as specific and accurate as possible.

5. DISCUSSION

To determine similarities and differences among different radar users, the two stakeholder groups are compared in terms of their radar use and the radar capabilities they found to be most critical.

Critical radar capabilities identified by both groups are then related to PAR technology.

5.1 *Comparison of Two Stakeholder Groups*

Broadcast meteorologists and NWS forecasters showed some similarities in terms of what they considered to be critical radar capabilities. Participants from both groups mentioned the difficulty of detecting severe straight-line wind events using radar. Both groups also recognized the limitations of algorithm output, discussing the inaccurate precipitation amounts produced by Z-R relationships. Most importantly, both groups realized the significance of detecting low-level small-scale signatures which were appearing on times scales of one min. or less. All the broadcast meteorologists spoke extensively about using their own radars to collect high-resolution data to help them provide more specific warning messages. NWS forecasters who had used TDWR data in real time echoed the advantages of viewing high-resolution radar data at the lowest elevation angle.

Most of the differences between the two stakeholder groups originated from their differing roles and audiences. Although they counted people from all walks of life as part of their audience, broadcast meteorologists emphasized the general public as their main, on-air audience. As a result, broadcast meteorologists primarily use radar to create specific warning messages during severe weather events. NWS forecasters counted many more user groups as part of their audience, including the general public, broadcast media, emergency managers, business owners, and aviation managers. Because of their widely ranging audience and the information their audience needs, NWS forecasters use radar for a variety of different severe and nonsevere weather events. For instance, NWS forecasters may use radar to detect wildfires, because emergency managers are part of their audience, and this information is important to them. However, this information is not usually significant for the general public, so broadcast meteorologists do not need to use radar in this way. In addition, NWS forecasters counted more knowledgeable radar users among their audience members, while broadcast meteorologists did not. Consequently, the radar information used and disseminated by NWS forecasters was much more complex than that utilized by broadcast meteorologists. On-air meteorologists simply do not have the time to interrogate storms and analyze velocity data. This was likely the reason why they did not see de-aliasing and range-folding as major limitations of radar.

The differing uses of radar were also affected by the specificity of warnings provided by each stakeholder group, and the location of these warnings. In order to provide more specific warning messages, broadcast meteorologists mainly examined rapidly updated data from the lowest elevation angle, looking for storm movement and rapid spin-ups. However, NWS forecasters are often concentrating on several storms at the same time and studying the three-dimensional aspects of storm evolution to obtain a more thorough view of the storm as a whole and to make warning decisions. Thus, NWS forecasters valued volumetric scans and velocity data more than broadcast meteorologists. In addition, NWS forecasters must provide warnings for a large forecasting area, while broadcast meteorologists are only concerned with their viewing area. As a result, NWS forecasters were more concerned with the effects of radar horizon and beam spreading, since they often need to monitor storms located far from their radars.

5.2 *Relation to PAR Technology*

PAR technology will address many of the critical radar limitations identified in this study. While PAR will not directly fix every radar deficiency in the WSR-88D, its capabilities may provide users with additional valuable information so they can still make informed warning decisions.

Participants who'd had access to high-resolution radar data described small-scale signatures which were appearing on short time scales and were producing significant damage. Both stakeholder groups believed it was important to detect and warn for these signatures, because they indicate weather that is affecting people and producing damage. The rapid scanning capability of PAR — producing a full volume scan in less than one min. (Heinselman et al., in press) — will enable radar users to detect these rapid changes in hazardous weather. In addition, higher temporal resolution volumetric data will help users study storm evolution in greater detail. One broadcast meteorologist mentioned that being able to see a rapidly descending reflectivity core would give him a much better handle on microburst events.

Radar horizon and beam spreading are mechanical radar issues which many participants discussed. While PAR will not directly fix these deficiencies, PAR capabilities can help to mitigate the effects of these limitations. Wavelength and network configuration can be considered by PAR researchers to prevent radar horizon and beam spreading from affecting forecasting operations. In addition, rapid temporal sampling at upper levels will help users get a better understanding of how the storm is evolving as a whole. While a radar user may not be able to see a descending reflectivity core because of radar horizon, seeing strong convergence at upper levels with frequent updates will confirm his belief that a microburst event is about to occur.

Many participants considered aspects of current radar control to be inflexible and user-dependent. Changing the PRF or re-starting the VCP of a radar were common techniques of mitigating radar deficiencies, but they required effort from the user. In addition, several NWS forecasters wished they had the ability to do sector scans on storms of interest, a nearly impossible task with a WSR-88D radar. The adaptive scanning capabilities of PAR will allow users to easily alter the VCP and complete sector scans, making radar control more flexible and independent.

Finally, several participants from both stakeholder groups discussed the impossibility of detecting precipitation type using a nonpolarimetric radar. If PAR obtains polarimetric capabilities, it can provide improved estimates of precipitation rates, and improved identification of precipitation types in winter storms (Ryzhkov et al. 2005).

6. SUMMARY

A critical incident technique was used to interview radar users from two key stakeholder groups in the Southern Plains: NWS forecasters and broadcast meteorologists. Critical radar capabilities were identified for each group and related to their roles and audiences.

An important role of NWS forecasters is making warning decisions and providing information to a variety of user groups that range from emergency managers to the general public. Participants from this group used volumetric data in addition to rapid low-level scans to study storm evolution and identify rapid changes in hazardous weather. Since they must monitor weather over a large forecasting area, NWS forecasters felt radar horizon and beam spreading were significant radar limitations.

Broadcast meteorologists also serve an important role, because most members of the general public get their weather information from television. They report and interpret warnings issued by NWS and use radar images to illustrate the current weather threat to viewers. Broadcast meteorologists use their own high-resolution radars to make their warning messages as specific as possible. They asserted that rapid, low-level scans were crucial for providing their audience with the information they needed. The main radar limitation identified by broadcast meteorologists was inaccurate algorithm output, which they correct with information from storm spotters and reports from the public.

Both groups recognized the importance of using rapid, low-level scans to detect small-scale signatures, and the need for flexible scanning strategies to study storm evolution. Rapid updates and adaptive scanning capabilities provided by PAR will help to address these limitations and promote more timely, accurate warnings. Participants voiced common concerns with radar limitations, such as the effects of radar horizon and beam spreading on radar data, and the impossibility of detecting precipitation type using current radar systems. Wavelength and network configuration can be considered by PAR researchers to address the effects of radar horizon and beam spreading. In addition, it is important to implement dual-polarimetric capabilities into PAR in the future so radar users can easily distinguish precipitation types.

7. ACKNOLWEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. ATM-0648566.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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