P5B.12 THE U.S. NATIONAL WEATHER RADAR TESTBED (PHASED ARRAY):

POTENTIAL IMPACT ON AVIATION

Leslie R. Lemon, Basic commerce & Industries, Inc, Independence, Missouri
and
Elizabeth M. Quoetone, National Weather Service, Warning Decision Training Branch, Norman, Oklahoma

1. INTRODUCTION

A unique Doppler Weather Radar, a "Phased Array" radar (PAR) forms the heart of the U. S. National Weather Radar Testbed (NWRT). This facility is being built in Norman, Oklahoma to study and develop a variety of PAR applications for several agencies including the Federal Aviation Administration (FAA). It is anticipated that the PAR will provide faster and more accurate warnings, analysis, and forecast techniques for severe and hazardous weather while tracking aircraft. More generally, the FAA has a stated overall objective to provide more accurate and timely weather information to the Air Traffic community. Forsyth (2002) reported on the development of the NWRT by a U. S. government/university/industry team consisting of the FAA's William J. Hughes Technical Center, Basic Commerce and Industries Inc, the National Oceanic and Atmospheric Administration's National Severe Storms Laboratory (NSSL), the National Weather Service (NWS) Radar Operations Center, the United States Navy's Office of Naval Research, Lockheed Martin Corporation, the University of Oklahoma's Electrical Engineering Department and School of Meteorology, and the Oklahoma State Regents for Higher Education. The total cost is approximately $25 million US. The radar is a converted US Navel fire control AEGIS phased array system (also known as the SPY-1) that will be used as a meteorological research radar testbed serving the needs of the atmospheric research community.

In this paper, we will discuss the system design and differences with other current weather radars as well as changes to weather information display for aviation. We also offer some suggestions for PAR meteorological research for aviation concerns. Further, we examine the impact of human factors and how those factors should be considered in the potential implementation of operational PAR technology.

2. PHASED ARRAY DOPPLER RADAR

Surveillance weather radars use a pencil beam with the position mechanically controlled and scanned. But in order to obtain a number of independent echo samples for these radars, relatively long dwell times (~ 50 ms) are required. These dwell times are necessary for the accurate estimates of Doppler spectral moments. Of course, those spectral moments include power returned (reflectivity); mean radial velocity, and velocity spectrum width. Thus, the volume update times are limited by the mechanically steered antenna, and weather signal correlation time.

However, phased array Doppler radars, equipped with the proper waveforms and signal processing, offer routine atmospheric sampling with volume scan rates on the order of 1 minute. Doviak, et. al. (2000) discusses these aspects and much more of the phased array Doppler radar including design, functionality, and benefits. For detail, the reader is referred to that paper. Currently the fastest operational scan mode, Volume Coverage Pattern (VCP) 11 with the WSR-88D Doppler weather radar provides 5- minute samples.

Phased array Doppler radars, however, provide multiple beams. These beam agile phased arrays have been used as fire-control radars by the military to detect and track point targets. As further explained by Doviak et. al. (2000) a multiple beam radar transmits simultaneously several pencil beams along contiguous elevation directions, each at a different frequency so that upon reception and filtering, receivers process, in parallel, echoes from a swath in elevations (typically 5 to 10 deg). Because the reduction of volume update time is inversely proportional to the number of simultaneous beams, the antenna for some radars, e.g., the AEGIS radar, is in the form of a cube requiring no scanning. However, these radars are extremely expensive. Thus, in order to substantially reduce the radar cost for the NWRT, one face of the cube is mechanically scanned while electronically shaping and placing the multiple beams. (Figures 1, 2)

Although substantially faster then the conventional radar, the multiple beam radar requires large spectral bandwidth where the frequency regions are often very crowded. But the agile beam phased

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*Corresponding author address: Leslie R. Lemon, Basic Commerce and Industries, 16416 Cogan Drive, Independence Mo, 64055 e-mail: lrlemon@compuserve.com.

array system can alleviate the wasteful use of radar resources. Below, we will briefly discuss many other aspects of the NWRT phased array Doppler weather radar.

3. COMPONENTS

Here the components of the National Weather Radar Testbed (NWRT) are shown in block diagram form (Figure 1). (The reader is directed to Forsyth et al., (2002) for further details of the following). They include one face of the AEGIS antenna and beam programmer, enclosure, pedestal and radome, a WSR-88D transmitter modified to transmit at 3.2 GHz, an environmental processor (EP) (digital receiver/signal processor), and real-time controller (RTC) (Figure 2).

The environmental processor will be located in the User Facility or the Testbed Control Center (TCC). The Radar Facility will house all of the above remaining components. Lockheed Martin has finished the Integration and Testing of the above components. Additionally the EP has been built and software and documentation received. The EP, however, experienced some timing problems that have subsequently been solved. Thus, it has undergone integration and testing as well. The sparing estimates have been identified and maintenance training concepts and plans have been developed.

The first data sets will be collected using a sector scan mode rather than full antenna rotation. The capability for full and continuous antenna rotation is scheduled for implementation in late 2003. By 2004, the initial data sets, which will be used for the ambitious multiagency research, will be collected.

4. SUGGESTED RESEARCH APPLICATIONS FOR AVIATION INTERESTS

As mentioned previously, the FAA anticipates that the PAR will provide faster and more accurate forecasts and warning techniques for severe and hazardous weather while tracking aircraft. Overall the FAA has a stated objective to provide more accurate and timely weather information for Air Traffic and the aviation community in general. To further that goal we have some suggestions for PAR research.

The information currently being displayed on Air Traffic radar screens includes a precipitation intensity estimate by use of the six-level (or sometimes a three-level) depiction of the reflectivity scale. It will be instructive if we briefly consider the origin of this six-level depiction. The first network weather radar system was developed for use of the U.S. Weather Bureau and fielded in 1957. That radar was the Weather Surveillance Radar 1957 or the WSR-57. It employed vacuum tube technology and used a ~ 2.2° beam with pulse volumes having a depth of ~ 1 nautical mile. A linear analog signal was transmitted. The first sidelobes were down ~ 22 db from the main half-power beam. During the 1960's, work at NSSL developed a logarithmic reflectivity display replacing the original linear reflectivity. Additionally the Digital Video Integrator and Processor or "DVIP" was developed converting the log reflectivity estimate to a digital estimate, which was contoured in the displays allowing the rapid recognition of intensity levels. In order to assist radar use by the old Weather Bureau and what then became the U.S. National Weather Service, the 6-level display was developed by NSSL. These levels were roughly correlated with precipitation intensity and based on limited observations of storm severity. Then with additional processing, these levels were reproduced via ATC radars. However since that time, radar technology has progressed considerably. One of those advances includes the development of weather radars that deliver far higher resolution estimates (beam width ~ 0.95°, pulse depth ~ 250 meters) employing new signal processing techniques and thus, far more accurate estimates. Estimates of 46 dBZ (4th level) made by a 1957-vintage radar (and now by ARTC radars) as compared to the same value arrived at by a modern weather radar are as "apples and oranges". They don't compare! For this reason alone the old ATC 6-level displays are considerably outdated and don't relate to reflectivity estimates made with weather radars today, some 40 years later.

Additionally, we now know that estimates of storm strength and severity should not be confined to reflectivity alone. Obviously with current Doppler weather radar we can also estimate two other spectral moments (mean radial velocity and velocity spectrum widths) in addition to the equivalent radar reflectivity factor, Z_e. We now know that wind shear and other kinematic flows such as mesocyclones, tornadoes, and vertical drafts and turbulence are also measures, of a storm's severity. Again, this argues against the continued use of the quite outdated 6-level ATC "weather" display.

However, the above addresses the current weather radar capability and does not even consider the leap forward that the NWRT PAR will provide. With the NWRT, research will consider the above along with the added capability of the PAR as it relates to the advanced displays for Air Traffic Management.

Additionally, Wilson and Ruem (1986) and Zrnic (1987) discuss the relatively rare phenomena of "three-body scattering" and its association with Mie scattering. Lemon (1998) examined further the physics of the signature and derived operational criteria for applying the S-band radar "Three-Body Scatter Spike" to warnings for large, damaging hailfalls. In fact, Lemon concluded that when detected, this was without doubt a signature of a very dangerous aviation threat aloft. However, very little of this has impacted aviation interests such as Air Traffic Management. It is suggested that this signature and its detection by the PAR and its potential rendition on ATC displays for the aviation community be examined.

Another aviation threat found within some severe thunderstorms that has not yet been introduced to the aviation community is what Lemon and Burgess (1993) and Lemon and Parker (1996) called the Deep Convergence Zone or the DCZ. When detected with the WSR-88D, this narrow (~250 m to ~ 2 km wide) zone extends form the surface gust front position (it is the surface gust front) upward to heights of 10 km to 13 km and separates the intense updraft from the intense downdraft. Measured wind shears within the boundary, both horizontal ($2.16 \times 10^{-1} S^{-1}$) and vertical ($2.25 \times 10^{-2} S^{-1}$) are extreme and the velocity spectrum width are that of "white noise". Additionally, very large hail is typically falling within this zone. With these extremes, any aircraft penetrating such a boundary would almost certainly be destroyed. This feature should be further investigated with the PAR.

Another characteristic of these DCZ boundaries is that at times, extreme reflectivity gradients also accompany the boundary. This feature has ramifications when considering PAR transmitter design such as the use of pulse compression. With pulse compression the associated antenna side-lobes are actually "forward lobes". In other words, this hardware limitation will tend to obscure these strong reflectivity gradients in the radial direction. Thus, the delectability of such boundaries by the PAR (possibly using pulse compression) should be examined as well as methods of displaying or including the location of such threats to ATC and ATM communities.

5. HUMAN FACTORS CONSIDERATIONS

With the introduction of any new technology, including weather and ATM radars, comes the challenge of considering its incorporation and application by the human end-user. This should involve all phases of the technology implementation, from design to training to operational use. If these factors aren't considered and accounted for, the result may be a mistrust or misuse of the technology, or a conscious decision to simply ignore it. Even with the best design and training, there is an attendant operationally-based learning curve which must be dealt with by each user on an individual basis. This can only be met by gaining experience, simulated or operational, with the technology itself.

In the case of the PAR, meteorologists and other users will have to make a learning leap similar to what was made when going from WSR-57 radar technology to the WSR-88D (NEXRAD) Doppler radar technology. As important as learning the technology will be, learning the operational methodologies and strategies which must now be adapted to accommodate the new technology will be equally as important. For example, what has been refined in the use of NEXRAD technology over the last 14 years of operational use, may not translate to the new PAR radar system. An example of this has already been cited with the use of the six-level reflectivity displays. The six VIP Levels were "transferred" to the NEXRAD system via image products, which appeared to duplicate the same familiar intensity (dBZ) levels. These have then in turn been "transferred" to ATC and ATM radars. However, the three systems did not arrive at intensity levels the same way so trying to apply rules which went with WSR-57 reflectivity values into the WSR-88D environment was flawed. In addition, using the old "rules of thumb" did not take full advantages of additional information available in the WSR-88D. For example, the WSR-88D could refine data levels such that one wasn't limited to six data levels but could have a wider range of values (-8 dBZ to 75 dBZ) with 16 data levels (or even the newly available 256 data level 8-bit reflectivity which has a range of –32 dBZ to 90dBZ). Further, with the WSR-88D and the inclusion of velocity information, one could and should refine their interpretation of the reflectivity values by incorporating the relevant velocity signatures. The end result was that using a methodology developed for the WSR-57 severely limited the amount of insight which could be gleaned by using the higher resolution of the WSR-88D together with additional data sets. One factor that may have contributed to a resistance in using the better data resolution (when transferred to the ATC radar systems) and other data sets was a lack of comfort with and understanding of the images associated with the WSR-88D displays. Even though the data were better, they were not being used by some because either they weren't understood or they could not be incorporated into a new methodology.

Klein (2003) discusses the factors which help or hurt in the implementation of new technology. He notes that technology, properly infused into an operational environment, can facilitate expertise by allowing an expert to apply their critical thinking skills, and providing a means for the novice to gain understanding and thereby develop expertise. On the other hand, technology which is not properly designed or implemented can have harmful impacts on the user and their environment. These impacts include fostering a mistrust of the data by not allowing a means by which the user can validate output or automated guidance. The opposite of this can happen if the user is a novice and thus may end up over-relying on the automated guidance without developing the ability to distinguish good from suspect guidance. Another unwanted by-product is that of data overload. With the arrival of the WSR-88D, the amount of data available to the user increased by orders of magnitude. As Heideman et. al. (1993) point out, there appears to be a point of diminishing return whereby adding more data actually decreases the decision quality. For the new users of the WSR-88D, not only were there more choices for data sets to look at (and some of these were new and previously not understood data sets), but there were also more opportunities for data to conflict. In one instance, three pieces of information might suggest a tornado, 4 might not, with 2 remaining pieces of information inconclusive. As a result, the job became much more complex and the need to know what data could be considered most valuable in particular situations and thereby help resolve data conflicts became critical. To account for data overload, the user had to know what was important and when, the best way to view it, and the proper timing. In other words, they had to modify their methodology. But first they had to experience enough events to understand what those modifications needed to be. Andra et al (2002) found that during the May 3rd Oklahoma tornado outbreak where 66 tornadoes occurred in a span of 10 hours, the excellent service provided by the forecast staff was a result of using a methodology which relied on several factors. Radar data, albeit a large component in the decision making process, was weighed against other inputs. These included the use of conceptual models, ground truth, other data sets such as satellite and surface observations, additional technology, warning strategies and human expertise. The success in that case was due in large part to a deep understanding of the role and use of WSR-88D data in the full context of a warning event and a refined methodology, developed with much experience, which allowed the benefits of all inputs to be maximized.

The arrival of the PAR will likely bring another shift in the way severe storms are analyzed, and perhaps even understood. In addition, there will be much more data arriving at more frequent intervals. Much research will be needed to discover what characteristics are now visible with the new data sets, and the significance of these features. Judgments will have to be made concerning if and how this information is to be displayed on ATM consoles. A recent Cognitive Task Analysis was conducted on the position of severe weather warning forecaster for the NWS (Hahn 2003). This report draws on similarities between the warning forecaster and the air traffic control environment, especially with regard to the use of technology. This analysis focused on the cues that a warning forecaster is looking for in order to make an expert warning decision. Corresponding cues also exist in the realm of the ATM decision maker. Regardless of which domain one comes from, the same cues and information needs will exist in the future. In many ways, these needs will be independent of the technology but should be supported by the technology. The question use to be how does an expert on the WSR-57 transfer that expertise to the WSR-88D radar? The question will now be how will the current expertise in the era of the WSR-88D be transferred to the Phased Array Radar era and, in turn, to the ATM displays?

One of the ways this challenge is currently being met in the NWS is with the introduction of the Weather Event Simulator (Magsig and Page, 2002). This technology duplicates the workstation warning environment which NWS forecasters experience. The ability to replay radar and other data sets in a displaced real-time fashion has created a safe yet realistic environment for forecasters to attain experience, as well as develop methodologies and refine skills. This is especially useful for those who are new to the job or whose climatological location doesn’t offer enough “nature provided” events with which to maintain or gain expertise. It is also a beneficial way to experiment with ways of incorporating new products and new interfaces. (Ferree and Quoetone, 2002) Having a simulator with the capabilities of playing back PAR data and the resulting ATM data would go a long way in developing improved understanding and appropriate methodologies, as well as advancing expertise.

7. CONCLUSIONS

Weather information is critical as are many factors affecting the aviation community. Here we have described the PAR research objectives and the importance of new weather radar information relevant to the aviation concerns. Specifically we have considered many relevant aspects of the Phased Array weather radar forming the focal point of the U.S. National Weather Radar Testbed (NWRT) recently constructed in Norman, Oklahoma. We have described the NWRT structure as well as the advantages of this multibeam system design and explained how it increases the timeliness (1-minute volume scans) and accuracy (narrow beam and small pulse depth) of the system. In light of the outdated character of the six-level weather reflectivity data now displayed with ATC/ATM displays, further potential improvements to the displayed weather information for ATM should be researched. Finally, understanding the applications of the PAR data and effectively translating these applications into the working environment will be critical.

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References available upon request.