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The Capabilities and Limitations of using the ASR–9 as a Terminal Area Precipitation Sensor *†

Bradley A. Crowe, Mark A. Isaminger, Mark E. Weber, and Joseph A. Cullen
Lincoln Laboratory
Massachusetts Institute of Technology

1. INTRODUCTION

The Airport Surveillance Radar (ASR–9) weather channel is an invaluable tool to air–traffic and flight management specialists. The precipitation data from this sensor is currently displayed on air–traffic specialists' radar scopes and is incorporated into the Integrated Terminal Weather System (ITWS). The data are used to determine optimum routes for aircraft operating in and near the terminal airspace. Data from other terminal area precipitation sensors such as the Terminal Doppler Weather Radar (TDWR) and the Next Generation Weather Radar (NEXRAD) are also used for this same purpose.

The primary advantage of using the ASR–9 as a precipitation sensor is its high update rate, e.g. thirty seconds versus about five minutes for TDWR and NEXRAD. The ASR–9 is also quite reliable, with limited down time. Finally, range folding is not a significant problem with this radar. However, during ITWS prototype testing over the past three years, we have identified several limitations of using this radar as a precipitation sensor. For one, the maximum reflectivity of cells can be significantly underestimated by the ASR–9 due to partial filling of its fan–shaped elevation beam and cell–to–cell spatial averaging. Also, the occurrence of underestimation seems to increase when the radar operates in circular polarization mode. In addition, we have analyzed cases where significant precipitation–induced attenuation has occurred. Finally, because most ASR–9s are located on the airport, rain cores developing aloft, above the airport, may be underestimated or missed entirely. This paper focuses on the problems identified through the ITWS prototype testing.

2. ANALYSIS METHODOLOGY

The three radars used for this research were the ASR–9, the NEXRAD, and the TDWR. The ASR–9 is an S–band, fan beam radar with a beam width of 1.4 by 4.8 degrees (Taylor and Bronins, 1985). It can operate in either linear or circular polarization. The NEXRAD is an S–band, pencil beam radar with a 1 degree beam width (Rinehart, 1991). It operates only in horizontal (linear) polarization. The TDWR is a C–band, pencil beam radar with a 0.5 degree beam width, and is also only linearly polarized. The ASR–9 weather channel data is filtered and smoothed before it is displayed (Weber, 1986 and Puzzo et al., 1989). Conversely, the composite data from each pixel from the two pencil beam radars corresponds to the maximum reflectivity over the entire storm vertical extent.

The ten cases presented here were selected at random from weather events in 1996–1997. We attempted to balance the cases between both air–mass or frontal convection, and linear or circular polarization (Table 1). This study focused on the Memphis ASR–9 precipitation data. The three Dallas cases and a comparison with data from the prototype ASR–9 Weather System Processor (WSP) in Orlando (Weber and Stone, 1995) were incorporated to ensure that the underestimations which we observed were not confined exclusively to the Memphis ASR–9.

Table 1.
Summary of analyzed cases

Date/location	Polarization	Weather Type
960618–MEM	Circular	Both
960817–MEM	Linear	Air–mass
960825–MEM	Linear	Air–mass
970303–MEM	Linear	Both
970313–MEM	Linear	Both
970325–MEM	Both	Both
970405–MEM	Circular	Frontal
960412–DFW	–	Both
960607–DFW	–	Air–mass
970404–DFW	–	Both

Visual comparisons of ASR–9 weather data against composite NEXRAD, composite TDWR and ASR–9 WSP data, were performed on the Memphis, Dallas, and Orlando data sets. All of the performance statistics reported herein were based on a Video Integrated Processor (VIP) level discrepancy of more than one between the ASR–9 and at least one of the pencil beam radars. If the maximum reflectivity area of the cell was less than 5 sq km, an average of the two highest VIP levels in the pencil–beam data was used to more accurately capture the assumed operational impact of the high–intensity storm cores. The parameters examined for each underestimated cell were: the range from the radar, the size of the cell (both horizontally and vertically), the area underestimated, the polarization of the ASR–9 (Memphis only), and the degree of underestimation. The main causes for cell underestimation which surfaced during our research were due to beam filling (fraction of the radar sample volume filled by hydrometers), attenuation (process in which the power of the radar beam is dissipated by hydrometers), and the cone of silence (area directly above the radar where echoes cannot be detected).

3. RESULTS

An analysis of Orlando ASR–9 and WSP data revealed that the former generally depicted reflectivity intensities one to two VIP levels lower than those indicated by the WSP data. Only occasionally did the ASR–9 VIP levels exceed those recorded by the WSP testbed. Furthermore, the spatial extent of precipitation regions was often larger in the WSP data. Some small, isolated cells were detected by the WSP, while they were only partially sensed or missed entirely by the operational ASR–9. We believe that these differences are primarily due to an overall calibration deficiency for the Orlando ASR–9 and, to a lesser extent, to the more capable clutter suppression algorithms used by the WSP.

Next, we compared ASR–9 data with that of the pencil beam radars. The Memphis database consisted of 6294 individual cells of which 2265 (36%) were found to be underestimated by more than

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one VIP level (Table 2). The Dallas database consisted of 1147 individual cells of which 409 (35.67%) were underestimated. Thus, the degree of underestimation in the Memphis and Dallas data was virtually identical. This suggests that the underestimation problem is not isolated to the Memphis ASR–9.

During real–time ITWS operations, Memphis site monitors have observed changes in reflectivity levels when the radar switches polarizations. The ASR–9 automatically switches from linear to circular polarization whenever 25% of the ASR–9 range is covered with level two or greater weather echoes in order for aircraft beacons to be more readily identified within regions of high reflectivity. Table 2 shows the degree of underestimation was significantly greater in linear mode with this data set, e.g., 42.17% versus 27.96%. In contrast, during the 1994–1996 real–time operations in Memphis, observations by the Memphis site personnel indicate that the ASR–9 did a better job of detecting the echo intensity while operating in linear mode. The most plausible explanation for these conflicting observations is that the receive paths for both linear and circular mode weather processing are not being held in accurate calibration.

Table 2. Percentage of Underestimated Cells as a Function of ASR–9 Polarization.

ASR–9 Polarization	Memphis	Dallas
Linear	42.17%	–
Circular	27.96%	–
Both	36.00%	35.67%

Of the 2265 problem cells determined for Memphis, 83% were underestimated by 1.5 to 2 VIP levels, while only 17% had a discrepancy of greater than two VIP levels (Figure 1). In contrast ,the Dallas data was more heavily weighted in the two to three VIP level categories. The discrepancy in reflectivity underestimation between Dallas and Memphis most likely reflects the small sample set analyzed for Dallas.

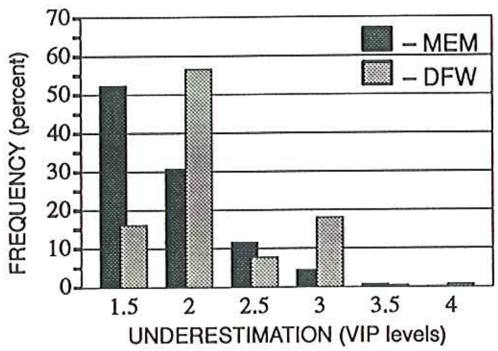

FIGURE 1. Difference in VIP level between the ASR–9 and that of the NEXRAD and/or TDWR for underestimated cells.

The maximum height of each underestimated cell for both data sets was determined by examining the NEXRAD echo tops product (Figure 2). The graph indicates that 85.6% of cells in Memphis which were underestimated had echo tops at or below 28 kft. The much larger mean cell height for underestimated cells in Dallas occurred because a large portion of these data came from squall–line events where echo tops were typically high.

The distance from the ASR–9 sites to each underestimated cell (range) was found as well (Figure 3). Due to its fan beam, the ASR–9 is more seriously impacted by beam filling at greater distances than at close ranges (Engholm and Troxel 1990). As the beam moves away from the radar its volume increases. Thus, the greater the distance to a cell, the larger the cell would need to be to fill the beam uniformly. Over 65% of all underestimated cells in both Memphis and Dallas were found at ranges between 45 and 105 km. However, cells were underestimated at all ranges, with 26% of underestimated cells in Memphis occurring between 0 and 45 km.

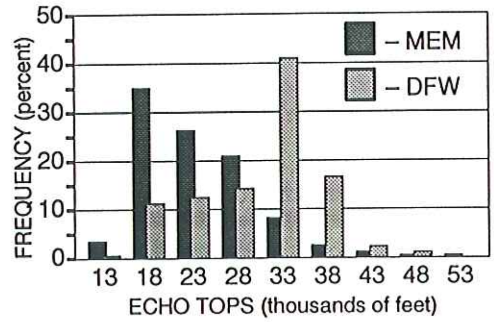

FIGURE 2. Echo tops of the underestimated cells based on ITWS storm cell information data.

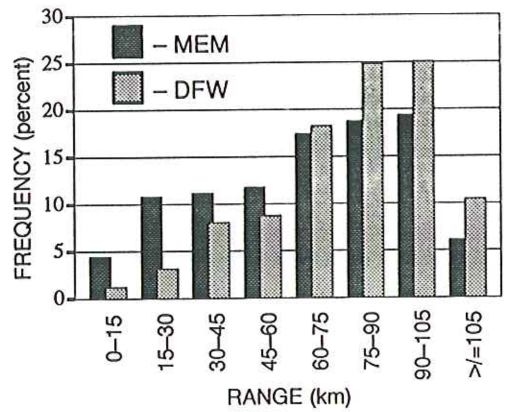

FIGURE 3. Distance of each underestimated cell from the ASR–9 site. The ASR–9s maximum range is 111 km.

Both the total cell area, and the area underestimated by one or more VIP levels were compiled for each underestimated cell (Figures 4 and 5). The data for Memphis shows that 68% of all underestimated cells were 150 sq km or smaller. The area underestimated by at least one level (Figure 5) was small as well. Ninety percent of all underestimated regions were less than or equal to 75 sq km. Data from Figures 2 and 4 suggests that most underestimated cells were small in both vertical and horizontal extent. The one anomaly in Figure 4, a spike in the Dallas data at 525 sq km and greater, reflects the fact that the Dallas data set contained a preponderance of large cells.

4. CASE STUDIES

In this section, we present two case studies to illustrate three of the most significant problems with using the ASR–9 weather channel as a terminal area precipitation sensor. The Memphis case on 960825 at 190043 UT (Figure 6) shows both an underestimation of the maximum cell intensity and the non–detection of a weather echo directly over the sensor. The most significant problem is the complete miss of a level 3/4 echo located along the southern periphery of the north–south runways. The cell size was quite small in both the horizontal and vertical dimensions, e.g., 22 sq km and 18 kft which contributed to the miss. This is an excellent example of our frequent observation that the ASR–9 weather channel may underestimate, or miss entirely, small cells near the radar. The echo located 16 km to the north–northwest is also underestimated by two levels. This cell was shallow in the vertical extent which allowed significant beam filling losses by the ASR–9.

The second case study is presented to illustrate the problems which occur when a line of heavy precipitation tracks over the radar platform. Figure 7 is another Memphis event at 144225 UT on 970405. In this case, a squall–line tracks over the ASR–9 sensor and impacts the airport with level 6 precipitation. The heavy precipitation within the line extends well to the north and south of the runways according to the NEXRAD data. An examination of the ASR–9 data shows gaps in the reflectivity line between 25–40 km north and 20–30 km south. In fact, a level three echo in the ASR–9 reflectivity field between 40–60 km to the north–northwest is actually a level 5/6 cell in the NEXRAD data. To date, "attenuation" of the ASR–9 precipitation data has not been well–documented by any previous research.

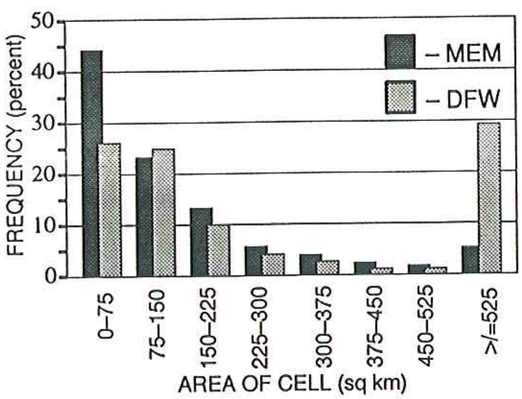

FIGURE 4. Total area of underestimated cells based on NEXRAD composite reflectivity data.

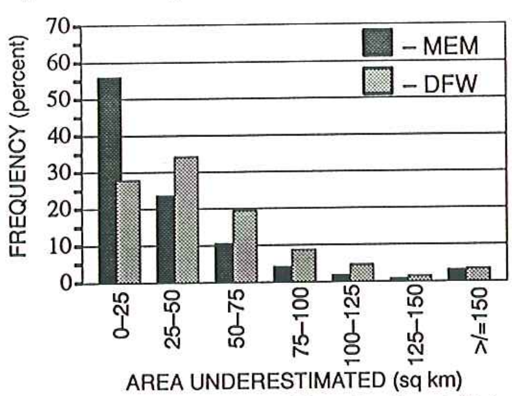

FIGURE 5. Area underestimated by at least one VIP level. Data compiled from NEXRAD composite reflectivity data.

5. SUMMARY AND CONCLUSIONS

This study examined ten cases from Memphis and Dallas where cell underestimation or cell elimination occurred. We also compared four Orlando ASR–9 cases with WSP data. Our research showed that in about one–third of the cases, the ASR–9 significantly underestimated the maximum echo intensity, and can entirely miss cells close to the radar. We also found that the cross–calibration of the two polarization's receive paths is apparently not well maintained.

Beam filling losses are believed to account for most underestimated cells in this study. The ASR employs a model profile of relative reflectivity to attempt to compensate for partial elevation beam filling (Puzzo et al., 1989 and Engholm and Troxel, 1990). The model assumes a constant layer of maximum reflectivity extending from the surface to 4km with a 3dBz per km decrease above. A problem with the current model is that many real reflectivity profiles have shallow maximum reflectivity features whose altitude placement and extent changes with time. Therefore, the current profile model may have contributed to the underestimations we have observed during this study. Engholm and Troxel (1990) have suggested a more aggressive U.S. threshold adjustment which, statistically, would increase the accuracy of the ASR–9. In their study approximately 98% of the cells profiled were assigned a VIP level within one of the maximum reflectivity found by a pencil beam radar. We recommend that the Engholm and Troxel model be installed on operational ASR–9s to help mitigate the underestimation problem.

"Attenuation" of the ASR–9 data was also observed in this study when; a) a very high reflectivity cell was close to or over the radar, or b) when a line of high reflectivity cells impacted the radar. In the later case, cells on the far end of the line were underestimated due to attenuation. Classical microwave path–length attenuation does not readily account for the observed underestimates (>10 dB) in the ASR–9 data. Wexler and Atlas (1963), for example, indicate attenuation rates less than 0.02 dB/km, even at extreme precipitation rates of 100 mm/hr. A more plausible explanation is the depolarization of circularly polarized energy in propagation through and scattering off large, oblate raindrops and irregularly shaped graupel and hail. In circularly polarized mode, the ASR–9 weather channel processes only signals received with polarization orthogonal to that transmitted (i.e., the polarization appropriate for scattering from spherical hydrometeors).

The loss of weather echoes near the radar (i.e., at the airport) could be a very serious operational concern. This occurs because cells near the radar (1) may have a reflectivity core above the top of the beam angle (Engholm and Troxel, 1990) or (2) may be underestimated owing to the aggressive clutter suppression algorithms that are used by the weather channel at short range. The use of an off–airport radar, like the TDWR, for echo information over the airport would be one possible solution for this problem.

We note finally that, where implemented, the WSP modification to the ASR–9 will subsume the functionality of the existing weather reflectivity channel and will address the deficiencies identified above. Specifically, the WSP will incorporate the statistically optimized beam filling corrections recommended by Engholm and Troxel, it will sum energy from both signal polarizations in circular transmit mode to minimize "attenuation" and its more capable clutter suppression processing will minimize biases so introduced in the reflectivity estimate.

6. REFERENCES

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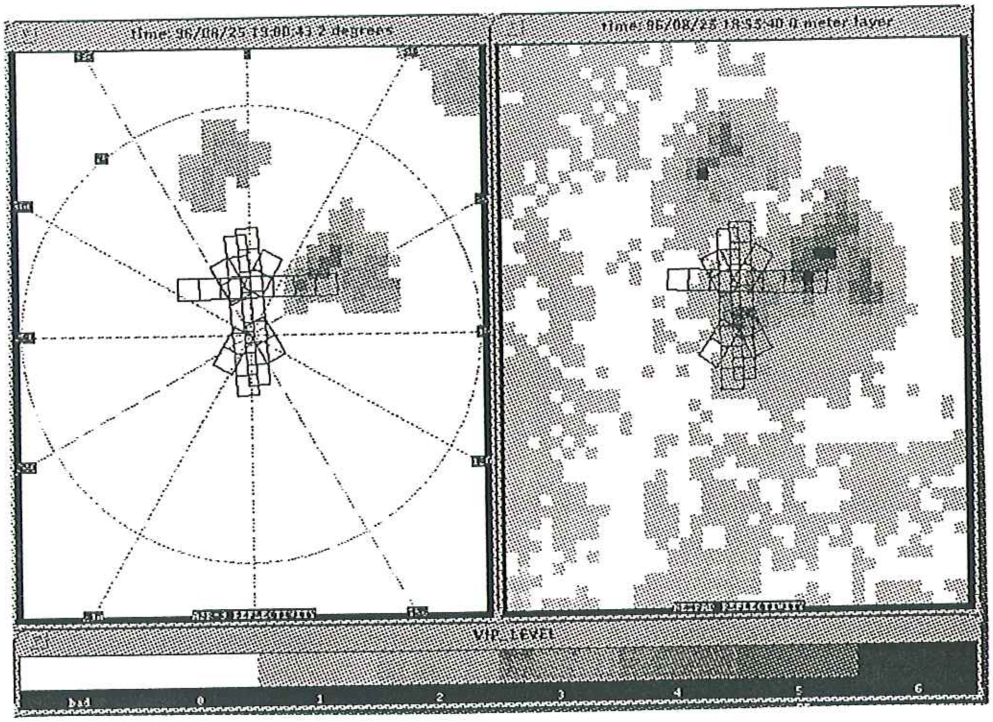

FIGURE 6. The image on the left shows the ASR–9 weather data at 190043 UT on August 26th, 1996. The corresponding NEXRAD composite reflectivity image is on the right. The time difference is related to the different update rate between the two radars. Below the images is a gray–scale bar which indicates the VIP levels used in the 6 level NWS scale. The range rings on the ASR–9 image are in 20 km intervals. The block like image in the center is the Memphis airport ARENAS. Both images are centered on the airport. The ASR data is orientated to magnetic north, while the NEXRAD data is in true coordinates.

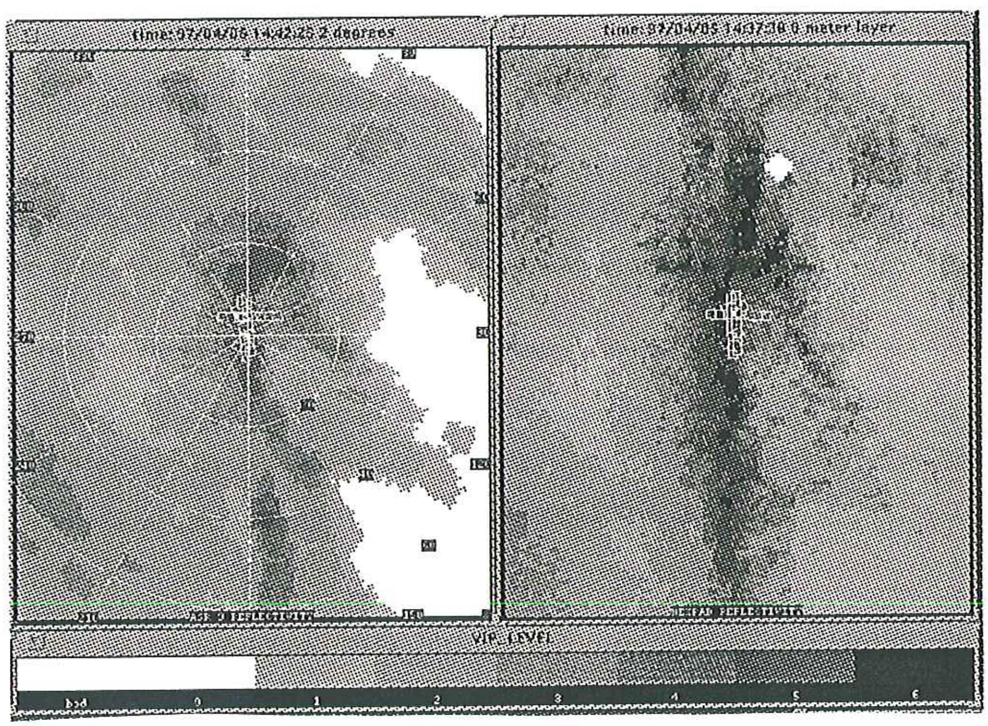

FIGURE 7. The image on the left shows the ASR–9 weather data at 144225 on April 5th, 1997. The corresponding NEXRAD composite reflectivity image is on the right.