Project Report
ATC-270

An Evaluation of the ASR-9 Weather Channel Based on Observations from the ITWS Prototypes

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23 September 1999

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16. Abstract

The Federal Aviation Administration's (FAA) Airport Surveillance Radar (ASR-9) is a high-scan-rate system which provides a "critical" function in terms of air traffic control (ATC). In addition to its primary role of air traffic surveillance, the system also generates precipitation data for display on air traffic specialists' radar scopes and for use by automated systems such as the Integrated Terminal Weather System (ITWS) and Weather Systems Processor (WSP). Air traffic managers use these data to provide optimum routes for aircraft operating in and near the Terminal Radar Approach Control (TRACON) airspace. The primary advantage of the ASR-9 — as an aviation weather radar — over either the Terminal Doppler Weather Radar (TDWR) or the Next Generation Weather Radar (NEXRAD) is the rapid update rate, i.e., 30 seconds, which provides air traffic managers with a more accurate representation of weather echo location within the sensor's domain. This is far superior to either the TDWR or NEXRAD, which takes from 2.5 to 6 minutes to create a volume scan, depending on the scan strategy. The sensor is also quite reliable, with limited down time.

An analysis of ASR-9 data from the ITWS prototypes has uncovered a number of problems, which impact the quality of the precipitation data. The data quality issues discussed are overly aggressive ground clutter suppression, polarization mode issues, hardware failures associated with high beam/low beam switching, attenuation/signal depolarization, beam-filling losses, bright-band contamination, distant weather contamination, calibration issues, and radar/antenna failures.

The recommendations to address the ASR-9 data quality issues can be grouped into three categories: "Variable Site Parameter (VSP)" adjustments, hardware component maintenance checks, and automated flagging of data quality problems. The report includes discussion of the frequency and characteristics of each degradation, presenting both hardware and non-hardware related problems, and concludes with proposed solutions to the problems and recommendations designed to improve the overall utility of the ASR-9 precipitation data.

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ASR-9 Weather Channel
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ABSTRACT

The Federal Aviation Administrations (FAA) Airport Surveillance Radar (ASR-9) is a high-scan-rate system which provides a "critical" function in terms of air traffic control (ATC). In addition to its primary role of air traffic surveillance, the system also generates precipitation data for display on air traffic specialists' radar scopes and for use by automated systems such as the Integrated Terminal Weather System (ITWS) and Weather Systems Processor (WSP). Air traffic managers use these data to provide optimum routes for aircraft operating in and near the Terminal Radar Approach Control (TRACON) airspace. The primary advantage of the ASR-9—as an aviation weather radar—over either the Terminal Doppler Weather Radar (TDWR) or the Next Generation Weather Radar (NEXRAD) is the rapid update rate, i.e., 30 seconds, which provides air traffic managers with a more accurate representation of weather echo location within the sensor's domain. This is far superior to either the TDWR or NEXRAD, which take from 2.5 to 6 minutes to create a volume scan, depending on the scan strategy. The sensor is also quite reliable, with limited down time.

An analysis of ASR-9 data from the ITWS prototypes has uncovered a number of problems, which impact the quality of the precipitation data. The data quality issues that will be discussed herein are overly aggressive ground clutter suppression, polarization mode issues, hardware failures associated with high beam/low beam switching, attenuation/signal depolarization, beam-filling losses, bright-band contamination, distant weather contamination, calibration issues, and radar/antenna failures. The most significant issues, in terms of precipitation underestimation, are overly aggressive ground clutter filtering/mapping, stuck polarizer vane, failure of high-to-low beam microwave switch, attenuation/signal depolarization, and radar/antenna alarms. Often these errors can result in level 3 weather echoes being falsely reported as level 2 or less. An underestimation of this magnitude is operationally significant in terms of providing air crews with accurate weather intensity information. Typically, beam-filling losses are not as severe, but this problem is quite common especially if the cell is small in the vertical/horizontal extent or is located near to or far from the radar. Calibration errors generally account for smaller differences in terms of precipitation underestimation. Problems such as bright-band and distant weather contamination were infrequent and thus do not pose significant operational problems. Anomalous propagation is also a problem with this sensor, but this topic will not be evaluated herein.

The recommendations to address the ASR-9 data quality issues can be grouped into three categories: "Variable Site Parameter (VSP)" adjustments, hardware component maintenance checks, and automated flagging of data quality problems. The "VSP" adjustments which would improve the precipitation measurements are to update the beam-filling loss equation, reduce the range of the high-low beam switching, and verify the calibration parameters between Linear Polarization (LP) and Circular Polarization (CP). The primary calibration parameter of concern is the co-axial waveguide loss, which differs based on the polarization due to varying cable lengths. A maintenance schedule should be incorporated into the commissioned system to check the polarizer vane, beam switch, and microwave runs on a periodic basis. Finally, most remaining data quality issues could be identified and flagged via a monitor program. This might include techniques to inhibit the use of the suspect data in the ITWS precipitation mosaic and to turn-off the TRACON precipitation product at single ASR-9 locales. The monitor program should also notify AT and AF personnel of the problem.

ACKNOWLEDGMENTS

This work could not have been completed without the dedicated work of personnel at all of the ITWS prototype sites. Dr. James Evans, Dr. Mark Weber, and Melvin Stone provided thorough reviews which made the document more cohesive. They also provided helpful insight into possible solutions to some of the ASR-9 precipitation degradations. The authors would also like to acknowledge Wes Johnston, who works at the Albuquerque WSP site, for his help with ASR-9 hardware and calibration issues. Finally, Leslie Mahn provided an editorial review and incorporated the figures into the final document.

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1. INTRODUCTION

The Airport Surveillance Radar (ASR-9) weather channel is a valuable tool to Air Traffic Control (ATC) and flight management specialists. The precipitation data derived from this sensor are currently displayed on ATC specialists' radar scopes and are incorporated into the Integrated Terminal Weather System (ITWS) and Weather Systems Processor (WSP). The weather data are used by the specialists to determine optimum routes for aircraft operating in and near the terminal airspace. The data also are used by ATC managers to determine if and when storms will impact airports within the Terminal Radar Approach Control (TRACON). Thus, it is important that the weather channel provides accurate information about the intensity and coverage of weather echoes within the sensor's domain.

The primary advantage of the ASR-9 as a precipitation sensor is its rapid update rate, i.e., 30 seconds versus up to five or six minutes for either the Terminal Doppler Weather Radar (TDWR) or Next Generation Weather Radar (NEXRAD). The ASR-9 is also quite reliable, with very limited down time (greater than 99 percent on-line availability). However, during ITWS prototype testing over the past five years, several degradations of the weather channel data have been identified which must be addressed. Foremost of these is that the maximum reflectivity of weather echoes can be significantly underestimated due to partial filling of the fan-shaped elevation beam and cell-to-cell spatial averaging. In addition, since most ASR-9s are located on-airport, rain cores developing above or tracking over the runways may be underestimated or missed entirely. It was also discovered that the occurrence of precipitation underestimation varies depending on the polarization mode. The two causes identified for degradation during polarization changes are calibration differences and stuck polarizer vanes. The latter scenario occurs when the mechanical device that converts the transmitted/received signal from Linear to Circular Polarization (CP) does not engage properly. Another hardware problem that can degrade the precipitation product is a failure of the high-to-low beam microwave switch. Furthermore, cases have been analyzed in which significant precipitation-induced echo loss has occurred. Another problem that has been identified is bright-band contamination, or areas of overestimated reflectivity due to the melting of frozen precipitation falling into warmer air. Distant weather contamination also has been documented with this system.

The report is divided into the following sections. A brief overview of the ASR-9 weather channel operational characteristics is reported in Section 2. The analysis methodology is presented in Section 3. Section 4 focuses on the frequency and characteristics of each degradation, presenting both hardware and non-hardware related problems for the discussion. In Section 5, solutions to the data quality problems are discussed. Among these are the employment of the WSP weather channel refinements, which include adjustments to the beam-filling-loss equation, increasing the range resolution of the Clear Day Maps (CDMs), the use of narrower clutter filters, and decreasing the range when switching between the high and low beams in CP. Other solutions include ensuring that the weather channel and radar channels are calibrated and operating the ASR-9s in manual mode whenever possible. Even with these modifications, there will still be unresolved data quality issues which will need to be addressed. Therefore, an algorithm is needed which would monitor the ASR-9 weather channel output. This monitor program should identify situations where the precipitation intensity and areal coverage are significantly reduced as well as provide the users with an alert when the aforementioned problems occur. A summary and key recommendations designed to improve the overall utility of the ASR-9 precipitation data are provided in Section 6.

2. ASR-9 WEATHER CHANNEL DESCRIPTION

The ASR-9, which has been deployed at over 100 airports within the U.S., has the ability to detect and track rapidly-moving targets such as airplanes, as well as weather data. The received signal can be processed by either a low or a high antenna beam, the latter reducing the amount of ground clutter contamination at close ranges. In Linear Polarization (LP) mode, the default high-to-low beam switch occurs at 15 nm, while in CP the low beam data beyond 32 nm are used. The vertical beamwidth (at the -3 dB point) is 4.8 degrees, with the high beam offset by 4.5 degrees (Weber, 1986). The typical elevation of the low beam tilt is set at 2 degrees, while the azimuthal beamwidth is 1.4 degrees.

The radar has both a weather channel and an aircraft detection channel. The separate weather-processing channel allows the system to generate six-level precipitation maps when operating in either LP or CP mode. The radar typically operates in LP until the level 2+ echo coverage within the TRACON exceeds a pre-defined threshold, i.e., 25 percent. The automatic mode switching is crucial in order for the ASR-9 to achieve a significant target-to-precipitation clutter ratio (Taylor and Bronins, 1985). In CP, the processors input is from the orthogonal sense antenna port and will, therefore, minimize attenuation of echoes from spherical hydrometeors. When LP is used, the six-level weather channels input is from the target channel analog/digital (A/D) converters. The six weather levels correspond to the standard National Weather Service (NWS) levels. Levels 2 through 6 are detected on even antenna scans, while on the odd scans the Sensitivity Time Control (STC) function is disabled (when in CP) to permit the detection of level 1 weather (Weber, 1986).

Prior to weather level processing, the ASR-9 data are passed through a bank of four finite impulse response (FIR) clutter filters. One of the filters is an all-pass and the other three are high-pass with increasing rejection of the scan-modulated ground clutter spectrum. The baseline filters provide ground clutter suppression of 12, 29, and 49 dB (Weber, 1986). These filters attenuate ground clutter based on a site-specific CDM of the ground clutter distribution. The appropriate filter output is selected for each range-azimuth cell and for each of the six weather levels. The CDM determines the least attenuation filter that will suppress the ground clutter. This minimizes attenuation of weather echoes. The clutter maps resolution is 1/2 nm in range by 1.4 degrees in azimuth.

Weather thresholds are stored in the ASR-9 processors memory as a function of range-gate, receive beam, and signal polarization. These are compared to the magnitudes of the selected filter outputs. The thresholds can be adjusted to reduce weather measurement ambiguities associated with the fan-shaped elevation beam. Weather data are then smoothed and contoured over 1 nm intervals by requiring that at least 8 of the 16 range-gates in each interval exceed the threshold. The smoothing and contouring processor operates in three stages (Weber, 1986). For each weather cell, the median weather level detected on three successive antenna scan-pairs is computed. This is followed by a spatial filter whose output for each cell is the highest weather level exceeded via an adjustable parameter. If clutter is present, the parameter is reduced proportionately. A second spatial filter outputs the highest weather detection level.

A new precipitation map is generated by the ASR-9 every six antenna scans or about every 30 seconds. The data are transmitted from the radar to the Surveillance and Communication Interface Processor (SCIP) in the six weather levels. Two of the six levels are selected and displayed on the ATC specialists' displays. The data also are output in a digital format from the SCIP as six-level precipitation maps. These data serve as the input to both the ITWS and WSP systems. A more detailed discussion of ASR-9 weather channel characteristics can be found in Taylor and Bronins (1985) and Weber (1986).

3. ANALYSIS METHODOLOGY

The TDWR and NEXRAD composite precipitation maps served as the truth data in this analysis. Due to antenna beam constraints, the ASR-9 would typically depict the average reflectivity, while the TDWR and NEXRAD maps contain the maximum reflectivity within the column. An underestimated cell was defined by a difference of greater than one weather level from both truth radars. A difference of only one weather level would be considered normal based on ASR-9 fan-beam averaging. The pencil-beam data were ignored in cases where the data quality was suspect, i.e., anomalous propagation (AP), attenuation, or bright-band contamination. Finally, several consecutive volume scans of truth data were evaluated to account for possible storm decay. A subjective evaluation of the data from all three sensors was used to classify the type of problem. The ability to distinguish beam-filling losses from attenuation was clouded by the fact that virtually every ASR-9 cell would suffer some degree of beam filling loss or "partial beam filling." Generally, attenuation was inferred in cases where the precipitation suddenly decreased as a squall line impacted the radar or cases where there was "shadowing" behind a level 6 echo. Beam-filling losses were generally attributed to underestimated cells with small vertical/horizontal size and also to larger cells located at far distances from the radar. Problems classified as echo loss near the radar (the "cone of silence") were attributed only to cells that were underestimated near the runways.

4. SYNOPSIS OF WEATHER CHANNEL PERFORMANCE DEGRADATION

Every terminal area precipitation sensor has inherent data quality problems. The primary issues impacting the quality of the TDWR data are attenuation, range ambiguities, and velocity ambiguities (Isaminger, et al., 1996). The NEXRAD data are degraded primarily by AP (Isaminger, et al., 1997) and bright-band contamination. The focus of this section is a discussion of the frequency and characteristics of ASR-9 precipitation underestimation, which have been observed at the ITWS prototypes. These include beam-filling losses, echo loss near the radar, attenuation/signal depolarization, calibration issues, bright-band contamination, distant weather, a stuck polarizer vane, a failure of the high-to-low beam microwave switch, and radar/antenna alarms.

4.1 Frequency of Weather Channel Performance Degradation

A review of the daily operational reports for weather events over a two-year period from the Dallas Ft. Worth (DFW) and Memphis (MEM) ITWS prototypes was used to determine the performance degradation frequency. Figure 1 shows the fraction (in percent) of the reports that listed one of the four degradations shown. The most frequently occurring problem on a daily basis is echo loss near the radar, which was reported on average in one of every nine operational reports. The other three problems (attenuation, distant weather, and bright band) were not recorded as often. Beam-filling losses and polarization issues are unique and thus cannot be evaluated adequately using this approach.

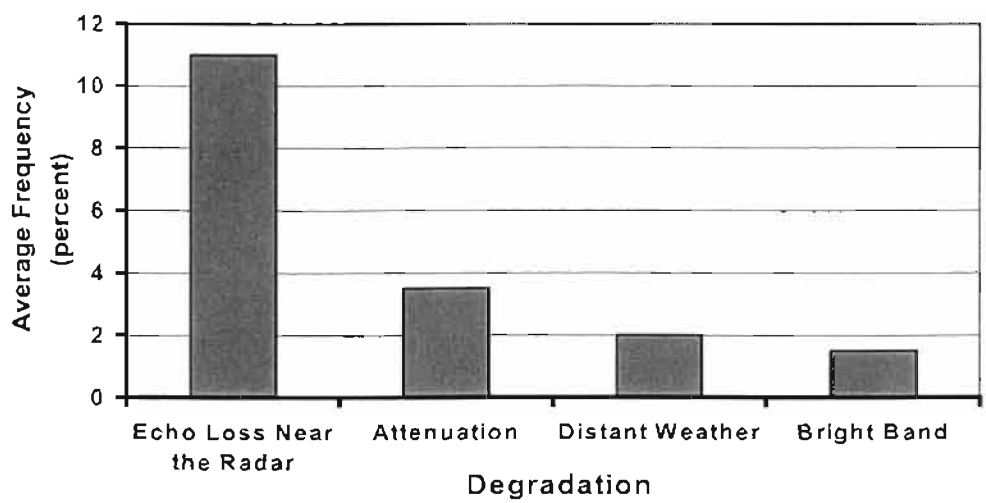

Figure 1. The fraction of ITWS site operational reports listing degradations based on over 400 weather days over a two-year period from both MEM and DFW.

The daily operational reports do not adequately reflect the frequency of beam-filling losses since this problem is an inherent characteristic of the sensor. Also, if a problem were reported only once in a daily report, it would be weighted the same as if it were observed multiple times. Therefore, it makes better statistical sense to evaluate this issue on a cell-by-cell basis. Crowe, et al. (1997) studied seven random cases from MEM where weather impacted the TRACON and found that 36 percent of the 6294 cells examined had greater than one weather level difference when the ASR-9 weather channel data were compared to the NEXRAD maximum composite reflectivity product. If the difference between the two products was greater than one weather level, the most-likely cause for the discrepancy was determined. The vast majority of the underestimated cells (91.3 percent) were attributed to beam-filling losses (Figure 2). The study attributed 2.6 percent of the underestimated cells to echo loss near the radar, while attenuation/signal depolarization accounted for the other 6.1 percent. Notice that on a cell-by-cell basis (Figure 2), echo loss near the radar is a much less frequent problem than on a case-by-case basis (Figure 1). This discrepancy is due to the fact that only one cell has to impact the radar to be included in the daily operations statistics. However, when examining the degradation on a cell-by-cell basis, only a finite number of individual cells will impact the small region near the radar. Regardless of the lower frequency for this problem, just one undetected storm directly over the airport could cause ATC specialists' problems and erode the users' confidence in the ASR-9 precipitation product. Of the seven MEM cases examined herein, each had at least one cell underestimated or missed due to this problem.

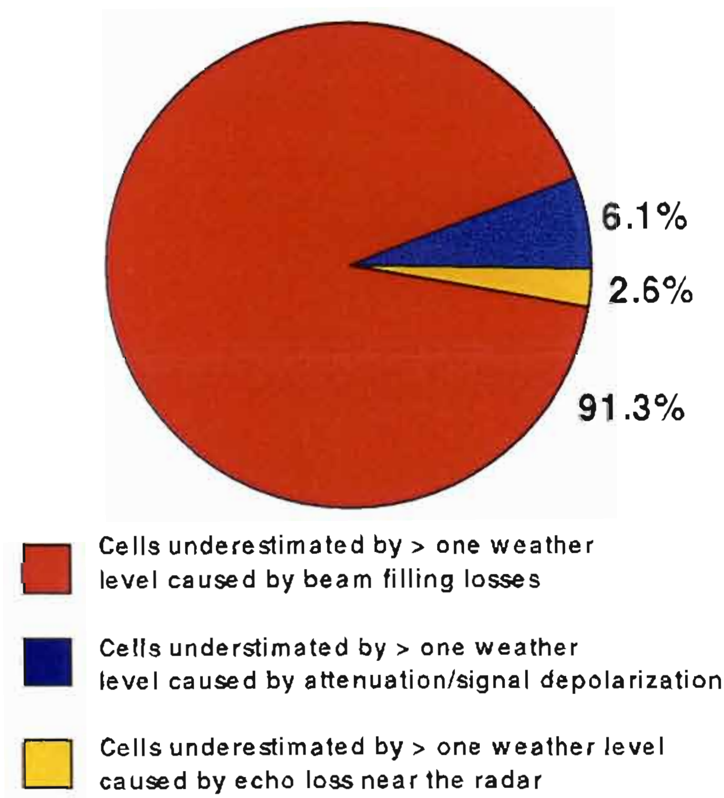

Figure 2. These data show the distribution of degradation causes on a cell-by-cell basis based on seven MEM cases examined in the Crowe, et al. (1997) study.

The frequency of precipitation underestimation when an ASR-9 switches polarity in automatic mode is much harder to quantify. One of the controlling factors is the amount of time the radar spends in automatic mode. Those sites, which exhibit a higher frequency of time in this mode, will also be suspect to a higher frequency of precipitation underestimation. At sites such as MEM, virtually every time the radar changes into CP mode, there is some performance degradation. This high frequency of precipitation underestimation during polarization changes has also been observed in the Stewart (SWF) and Philadelphia (PHL) data. An example of significant fluctuations in weather level intensity during polarization changes is shown in Figure 3. However, at DFW this problem is far less frequent. In summary, beam-filling losses and polarization issues are the most common problems. While degradation from attenuation/signal depolarization and echo loss near the radar is less frequent, the severity of these two problems is worthy of special consideration.

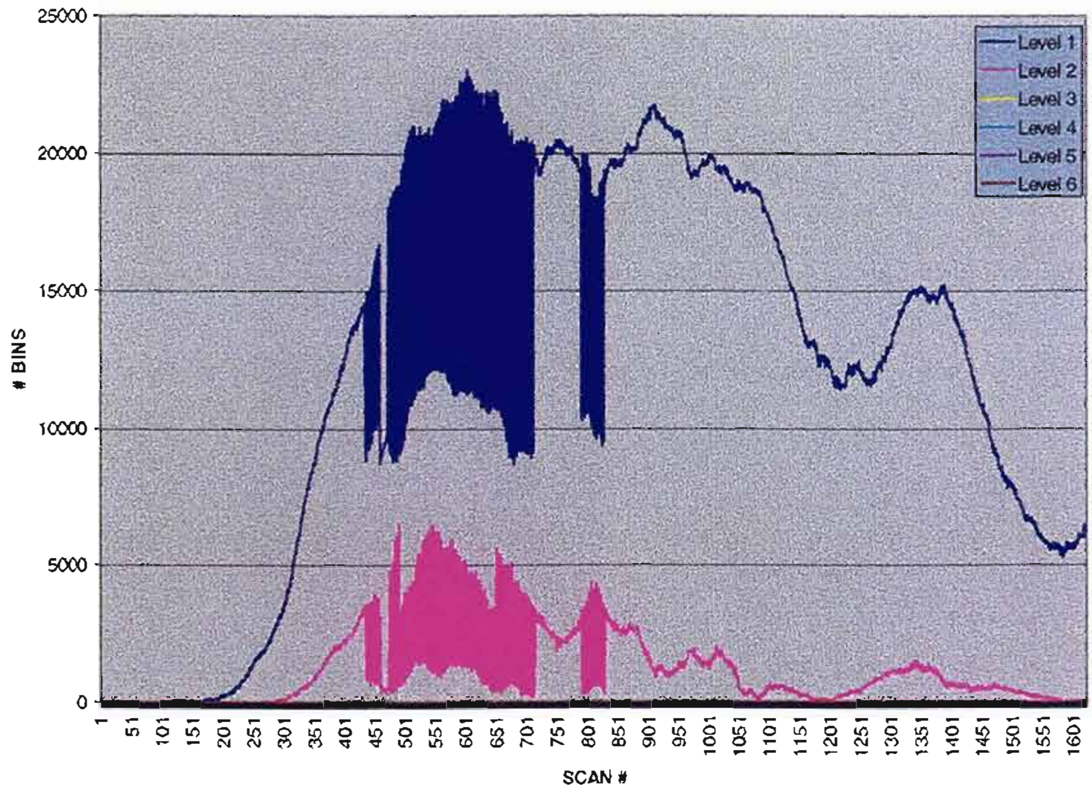

Figure 3. Number of radar resolution cells showing various weather levels versus time. From the SWF ASR-9 on 990228. Notice how the distribution varies widely between scan numbers 440 and 830 due to the radar changing polarization repeatedly over this time frame.

Additional characteristics such as the vertical extent, horizontal extent, and range of each underestimated cell also were noted in the Crowe, et al., 1997 study. These data were used to assess which type of cell was most likely to be underestimated. In terms of the vertical extent, the majority were between 18,000 and 28,000 feet. The radar also was more likely to underestimate the precipitation of cells with smaller horizontal extent (Crowe, et al., 1997). Thus, mature cells were less likely to be underestimated than those in the developmental stage. Finally, the majority of degraded cells in the study were located beyond 45 km from the radar. Even so, the MEM data set showed that one-quarter of the underestimated cells were located within 45 km of the radar. These findings were expected based on the high frequency of beam filling losses documented with this sensor.

4.2 Characteristics of Data Quality Problems Arising from a Nominally Operating System

In this section, the characteristics of data quality problem arising from a nominally operating system, i.e., no hardware failures, are considered. These types of data quality issues are beam-filling losses, echo loss near the radar, attenuation/signal depolarization, calibration differences, bright-band contamination, and distant weather.

4.2.1 Beam-Filling Losses

Beam-filling losses account for the majority of the ASR-9 cell underestimation. As discussed, for example, in Engholm and Troxel (1990), if a cell does not completely fill the ASR-9s fan beam, it may be underestimated. This occurs because the entire volume of the beam is averaged. Therefore, a small cell in the vertical extent, or even a larger cell at a greater distance, may not entirely fill the fan beam of the ASR-9. The lack of data within a portion of the beam coverage pattern can reduce the cell's reflectivity due to spatial averaging. Cells close to the radar site can also be underestimated if the beam is either under-shooting the highest reflectivity or if the beam is intersecting only a small portion of the entire cell. This is consistent with the results from Section 4.1, which showed the radar was more likely to underestimate small cells and those located farther from the radar. Refer to figure 3 in Engholm and Troxel (1990) for an example of beam-filling losses.

Beam-filling losses can be especially significant if weather echoes are underestimated by more than one weather level or if a level 3+ cell is reported only as level 2 or less. The later scenario is significant because ATC specialists tend to advise pilots to avoid cells that reach level 3+ intensity. Figures 4 (ASR-9) and 5 (NEXRAD) are from a MEM event on 960618. The echoes in question are located at 60 km and 015 degrees in the ASR-9 data. The NEXRAD composite map show these cells as level 6, while the ASR-9 indicates the cells are level 4. The same is true for the echo located at 60 km and 295 degrees. These two examples show a difference of 2 weather levels between the sensors.

Since the NEXRAD is a pencil beam radar, it does not average the reflectivity as the ASR-9 does. Also, the composite product displays the highest reflectivity found within a cell, regardless of the thickness of the core. A study conducted by Crowe and Miller (1999) compared the ASR-9 weather channel data to a derived NEXRAD Vertically Integrated Liquid Water (VIL) product. The VIL was first converted into reflectivity and then to weather levels based on a comparison reported in Weber, et al., 1998 (Table 1). Three cases from the Crowe, et al. (1997) study were re-examined comparing the NEXRAD-based VIL to the weather channel data. Based on this technique, only 4.8 percent of the ASR-9s cells were underestimated by greater than one weather level. These results suggest that a NEXRAD-derived VIL product more closely approximates the fan beam ASR-9 data. Figure 6 is a NEXRAD-derived VIL product for the same date and time as the previous images. A comparison between Figures 4 and 6 shows that the NEXRAD VIL-to-weather level data are generally within 1 level of the ASR-9 data. While the use of a derived NEXRAD VIL product would more closely approximate the ASR-9 data, it would not resolve the other problems reported herein.

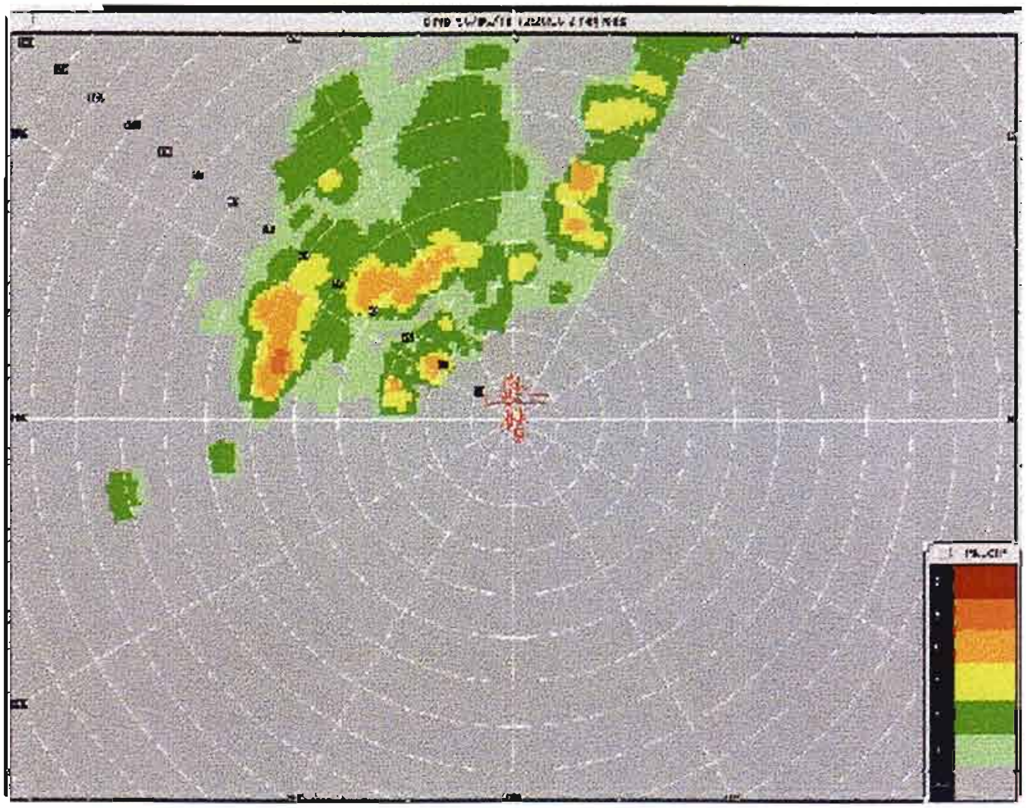

Figure 4. ASR-9 weather channel data for the Memphis case on 960618. The weather echoes are represented in the standard NWS six weather levels. The red polygons in the center of the image are the MEM Areas Noted for Attention (ARENAs). Note the echoes between 50 and 60 km northwest of the airport to compare with the NEXRAD composite and VIL products shown in the next two figures.

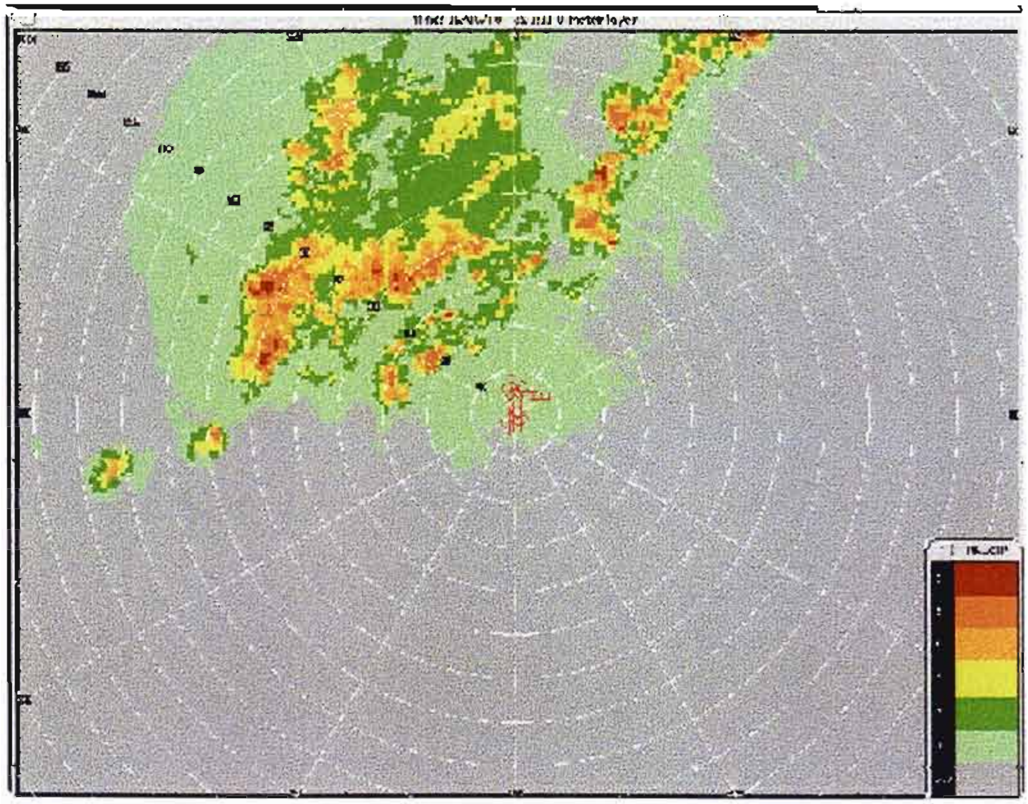

Figure 5. NEXRAD composite reflectivity product data for the Memphis case in Figure 4. The time difference in the two images is due to the time required to complete a NEXRAD volume scan. Therefore, the time stamp on the ASR-9 product is about five minutes earlier than the NEXRAD. The echoes are represented in the standard NWS six weather levels. Note again the area 50 to 60 km northwest of MEM airport.

Table 1.
VIL to Weather Level Conversion

VIL (Kg/m2)	Reflectivity (dBZ)	Weather Level
< 0.14	< 18	0
0.14	18	1
0.76	30	2
3.50	41	3
6.90	46	4
12.0	50	5
≥32.0	≥57	6

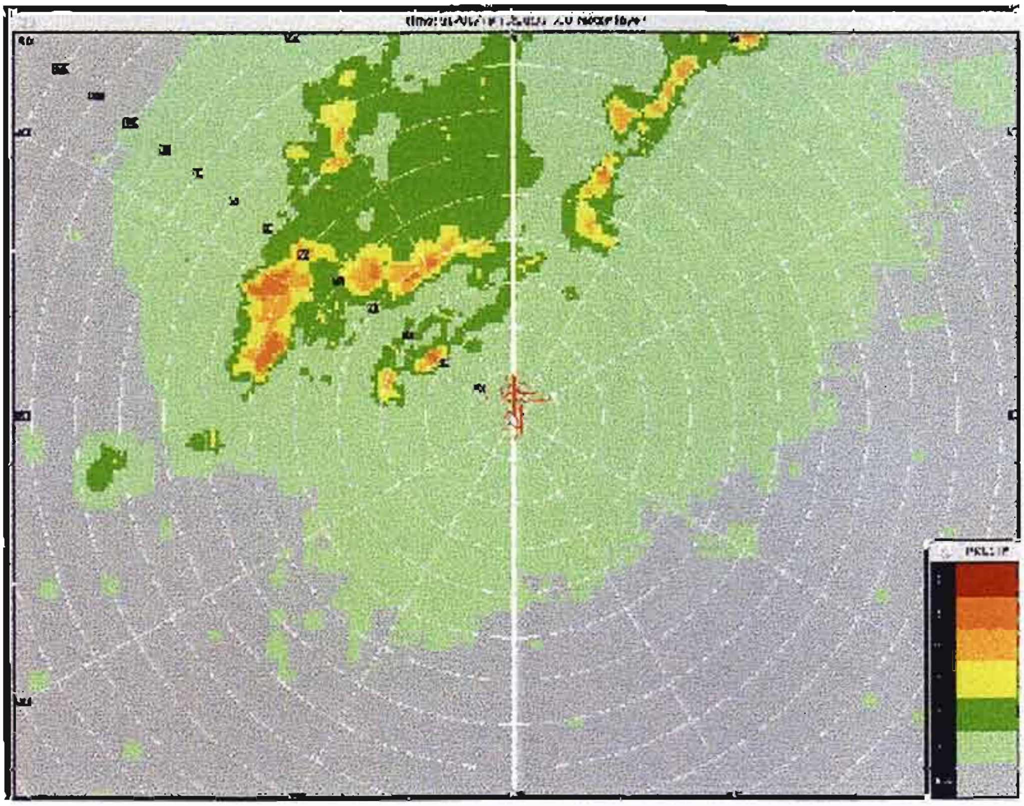

Figure 6. The NEXRAD derived VIL for the MEM case on 960618. The data are presented in the standard NWS six weather levels as in Figures 4 and 5. This was accomplished by applying the conversions from Table 1. Notice that there is at least a one weather level difference between many of the echoes presented here and the composite reflectivity echoes in Figure 5.

4.2.2 Echo Loss Near the Radar

A potential explanation for the loss of an echo near the radar is due to inadequate volume coverage within the "cone of silence." The "cone of silence" is defined as the conical area directly above a radar in which data can be lost because the scan pattern does not adequately cover the region (Rinehart, 1991). Therefore, echoes may not be detected very well near the radar. Additionally, overly aggressive clutter filtering/mapping employed by the ASR-9 can also contribute to the removal of weather echoes in this locale. This data loss can impact safety near the airport where aircraft are in the most vulnerable stages of flight. Since most ASR-9s are located on-airport, a cell that develops directly over the runways may be underestimated or possibly missed altogether by this sensor. Also, cells that track over the radar can be underestimated or dropped as they pass through this region.

A case study is presented to illustrate a significant problem with using a single ASR-9 as a terminal area precipitation sensor. A MEM event from 960825 (Figure 7) shows the non-detection of a weather echo located directly over the sensor. The ASR-9 data are in the upper left, the TDWR surface data are in the upper right, the TDWR composite in the lower left, and the NEXRAD composite is in the lower right. The cell in question is located over the runways, i.e., in the center of the images. When the ASR data are compared to the composite maps, it is apparent that the echo over the southern end of the airport is missing in the weather channel output. The TDWR surface data showed that the reflectivity echo extended all the way down to the surface. Thus, it should have intersected the ASR-9 fan beam. The miss of this level 5 echo located along the southern periphery of the north-south runways is a significant degradation of the data. The non-detection was caused in part by the small cell size in both the horizontal and vertical dimensions, i.e., 22 sq km and 18,000 feet. We suspect that a contributing factor was the overly aggressive clutter filtering/mapping in close proximity to the radar. This is an excellent example of how the weather channel may underestimate, or miss entirely, small cells near the radar site.

The loss of a cell over the runways is not commonly observed at the DFW ITWS field site because all of the ASR-9s are incorporated into a precipitation mosaic. Thus, the "cone of silence" above each sensor is covered by another radar. Additionally, the overly aggressive clutter filtering would not be as significant with multiple radar coverage. Therefore, the mosaic data shown on the DFW Situation Display (SD) do not suffer from this type of degradation. This also indicates a potential solution to the problem. By using a mosaic or a second radar such as the TDWR, there would be additional data to help mitigate the severity of this problem. In the production ITWS, the 5 nm precipitation product will be based on TDWR data to compensate for echo loss by the ASR-9 over the airport. At many non-ITWS airports, the more capable WSP clutter suppression algorithm (high-resolution maps and narrower notch filters) would also mitigate this problem.

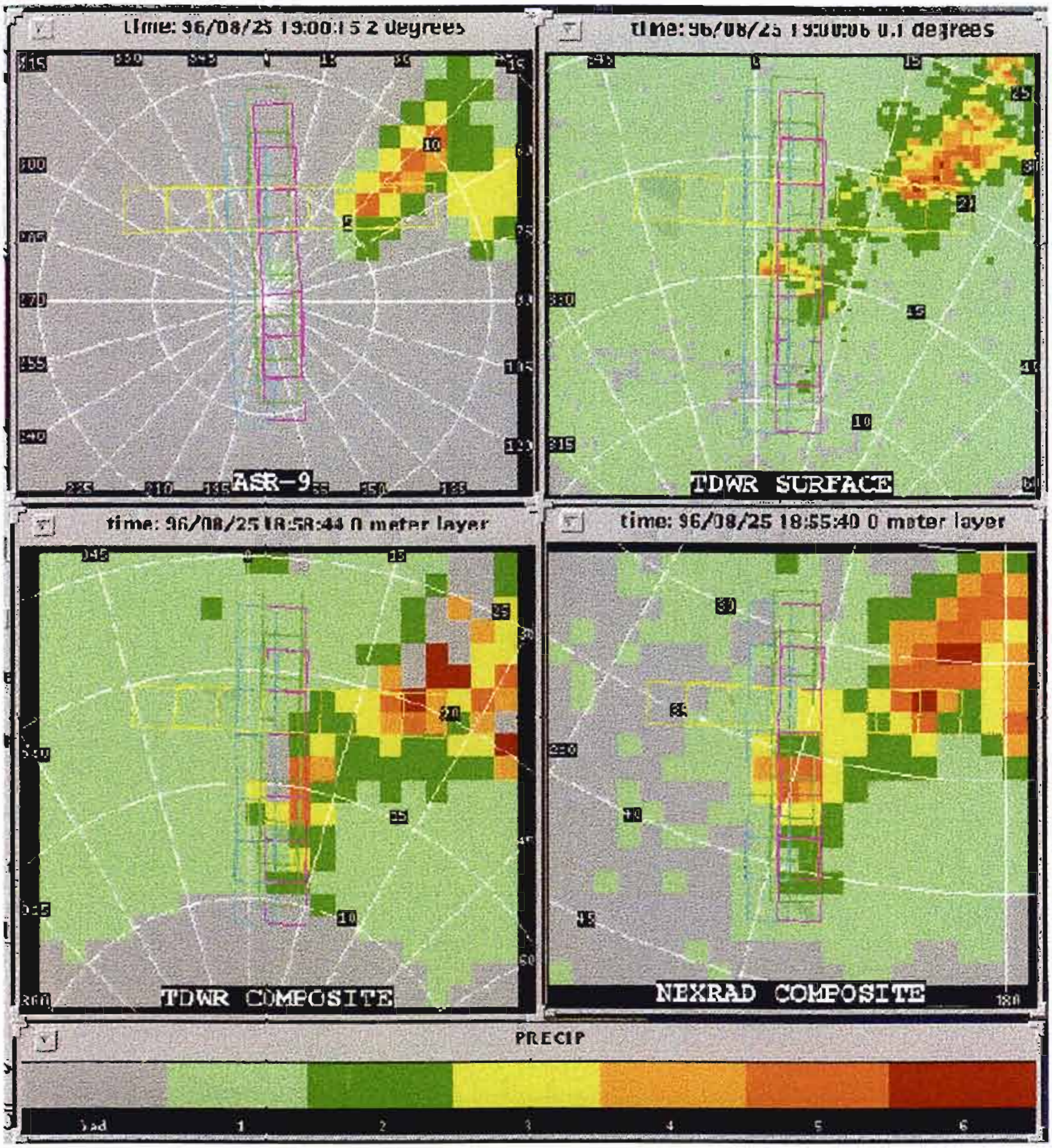

Figure 7. The ASR-9, TDWR and NEXRAD data for a MEM event on 960825. The colored polygons represent the MEM ARENAs. The range rings are spaced at 5 km intervals. The ASR-9 data are oriented to magnetic north, while the TDWR and NEXRAD data are in true coordinates. The time in each panel is for the beginning of the scan. Notice the echo located near the center of the ARENAs is completely missed by the ASR-9. The gray pixels in the TDWR composite represent attenuation flagging.

4.2.3 Attenuation/Signal Depolarization

Attenuation, or loss of reflectivity returns in the weather channel data, although uncommon, has been observed when a line of high-reflectivity cells impacts the site. This type of degradation could be detrimental to ATC specialists charged with assessing optimum routes for aircraft operating within the TRACON. In this section, the results from analyzing numerous squall line cases from MEM and DFW are discussed. The impact of the radar polarization on reflectivity losses also is explored. Finally, the beneficial use of a mosaicked precipitation product is highlighted.

The first case study illustrates that significant reflectivity losses can occur when a line of heavy precipitation tracks over the radar platform. Figures 8, 9, and 10 are from a MEM event on 970405. The radar was operating in CP during the time period, which was analyzed. In this case, the sensor was impacted by level 6 precipitation. Figure 8 shows both the ASR-9 and the NEXRAD composite products prior to the impact. The heavy precipitation within the line extends well to the north and south of the airport. Figure 9 shows the line crossing the ASR-9 site (left panel). The corresponding NEXRAD data are shown in the right panel. An examination of the ASR-9 data reveal gaps and lower intensities in the squall line between 25-40 km north and 20-30 km south. In fact, a level 3 echo in the ASR-9 reflectivity field between 40-60 km to the north-northwest is actually a level 5 to 6 cell in the NEXRAD composite reflectivity data. Figure 10 shows the same line after it cleared the ASR-9 site and both sensors were once again detecting the full length of the squall line. Therefore, the line did not decay as it passed over the radar site, but rather the weather channel suffered significant reflectivity losses.

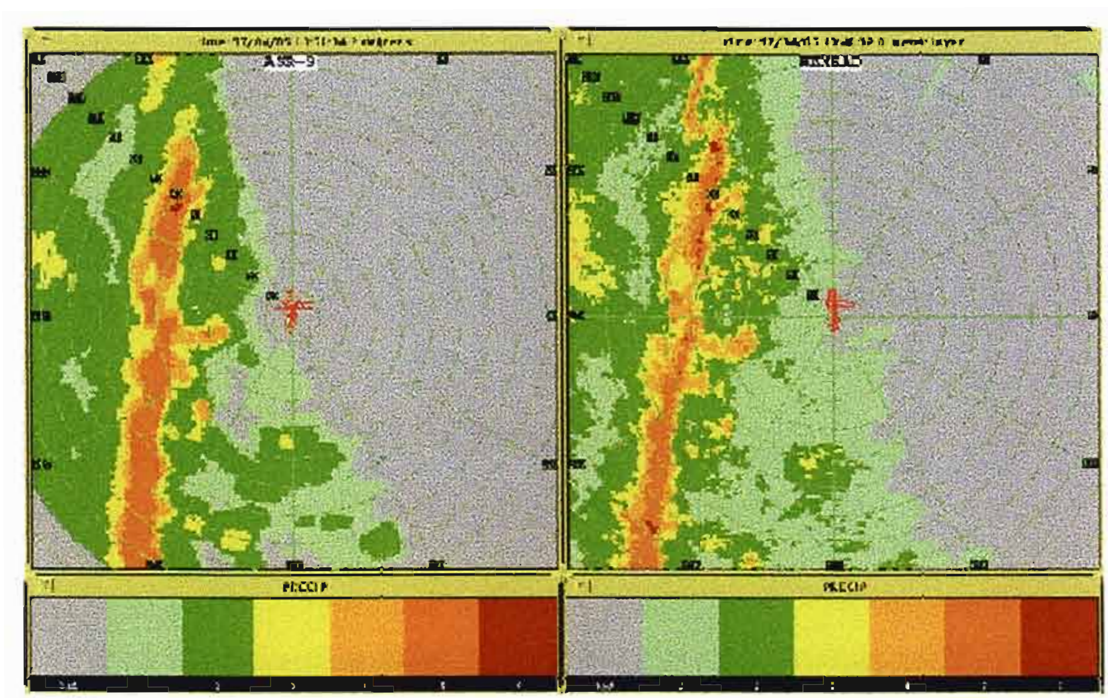

Figure 8. A squall line bearing down on the MEM airport on 970405 at 1351 UT. The red polygons in the center of the images are the MEM ARENAs and the range rings are in 10 km increments. The panel on the left is the ASR-9 data, while the panel on the right is the composite reflectivity product from the NEXRAD.

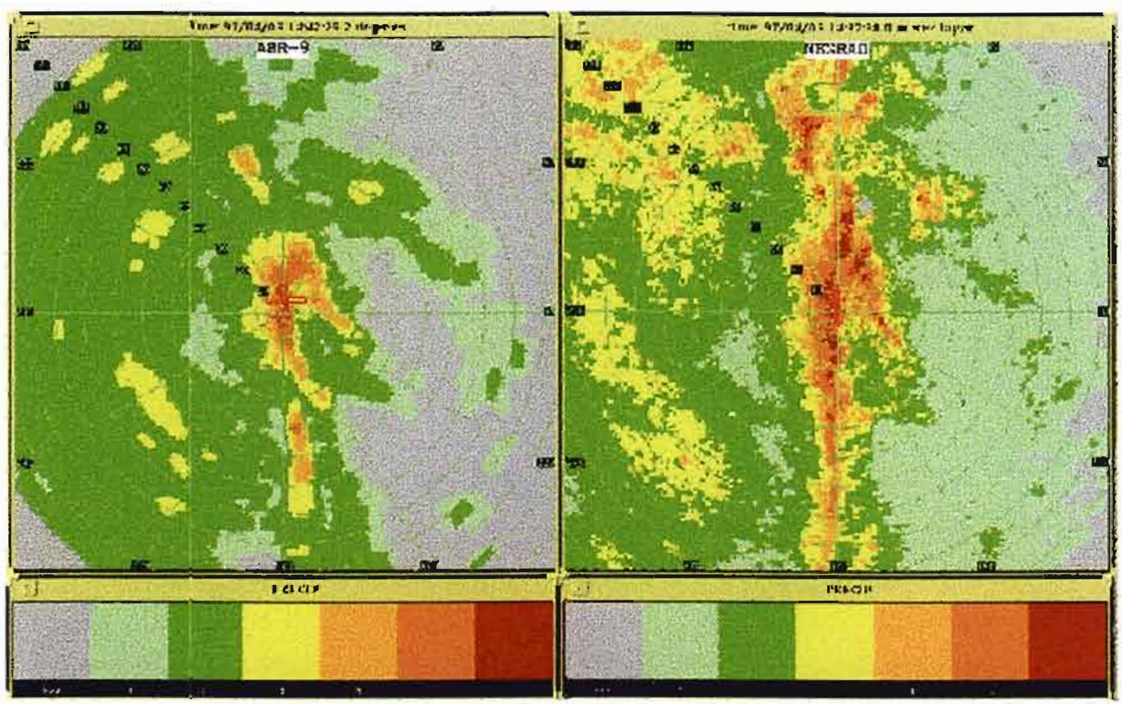

Figure 9. The same as Figure 8, only 40 minutes later as the squall line is impacting the MEM radar site. Notice that the NEXRAD composite product (right) still shows a continuous line of heavy precipitation, while the ASR-9 shows only the level 5 out to 20 km.

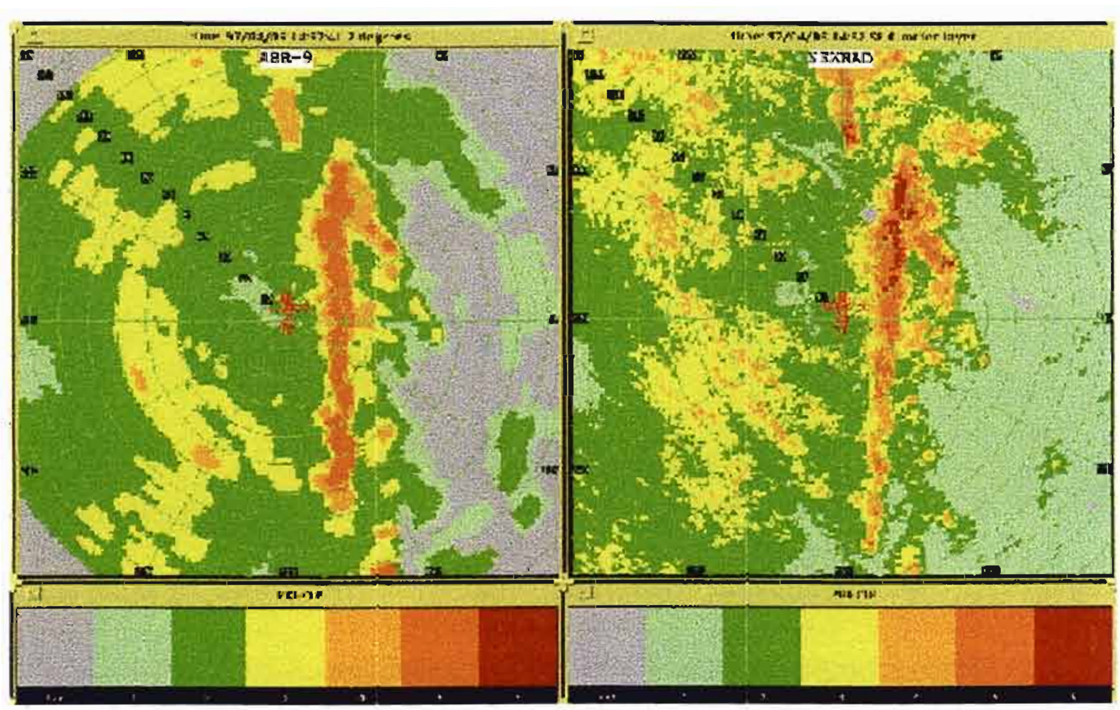

Figure 10. The squall line 15 minutes after Figure 9. The strongest precipitation is now east of the site and the ASR-9 (left) is again detecting the full length of the squall line.

A quantitative analysis of reflectivity losses based on the polarization mode was undertaken to better understand this phenomena. The results from analyzing 18 cases are shown in Table 2. Two time periods were chosen for analysis, i.e., just before and during the squall lines impact. The analysis time before the storm impact was typically 3-6 minutes in order to minimize the effects of storm growth and decay. Even so, the statistics presented here could still be contaminated by storm dynamics. The values in the table represent the reduction in the number of pixels within each weather level. These results showed that all of the cases exhibited reflectivity losses, regardless of the polarization. In general, the degree of reduction was greater at the higher reflectivity levels. In terms of individual cases, the 961107 and 960511 LP events showed almost as much reflectivity loss as the 960601 CP event.

Table 2.
The Reduction in Weather Pixels as a Squall line Impacts the Radar Site

Date	Radar	Polarization	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
961018	MEM	Circular	-	-1.8%	-2.8%	-	-8.3%	-8.0%
970405	MEM	Circular	-	-10.2%	-	-12.3%	-23.8%	-
960601	MI2	Circular	-	-	-	-10.5%	-40.0%	-
990404	MEM	Circular	-6.9%	-	-0.6%	-	-33.0%	-
960601	PA2	Circular	-	-	-25.7%	-5.1%	-60.3%	-
990308	PA2	Circular	-	-	-	-3.8%	-32.9%	-44.9%
990308	DFWE	Circular	-	-2.1%	-4.3%	-	-22.3%	-
990308	DFWW	Circular	-25.0%	-	-	-	-23.7%	-
961107	MEM	Linear	-	-	-	-	-44.3%	-
970715	MEM	Linear	-	-	-	-27.5%	-21.4%	-
960511	MEM	Linear	-1.7%	-	-	-1.2%	-54.1%	-
970302	MEM	Linear	-	-	-	-7.8%	-18.1%	-
981110	MEM	Linear	-3.9%	-	-	-	-25.5%	-
980507	MEM	Linear	-13.8%	-14.8%	-	-	-23.3%	-
990211	MEM	Linear	-4.2%	-	-	-12.9%	-12.1%	-
980319	MEM	Linear	-1.9%	-5.2%	-	-3.0%	-40.4%	-
990103	JFK	Linear	-14.7%	-5.6%	-	-	-31.5%	-

To better classify these results, two metrics were chosen to compare the reflectivity losses between LP and CP. First, the average loss for all weather levels was calculated based on the polarization. This showed the overall reduction in each mode was similar, i.e., ~10 percent. Next, the results of summing the losses within only the level 5 category were compared. In LP mode the average reduction of level 5 pixels was eight percent higher than in CP, i.e., 32 versus 24 percent. Thus, the radar is just as likely to suffer reflectivity losses in LP mode from a squall line.

Classical microwave path-length attenuation at S-band does not readily account for the observed underestimation, which was documented herein. A DFW event was analyzed and the predicted average path-length attenuation in both modes was only 3.2 dB, which is much less than documented here. Referring back to Table 1, a change of only 3.2 dB would typically be less than one weather level. Wexler and Atlas (1963) also indicate attenuation rates of less than 0.02 dB/km for an S-band radar, even at extreme precipitation rates of 100 mm/hr. A more plausible explanation for the majority of the reflectivity losses in CP mode is the depolarization of circularly polarized energy in propagation through and scattering off large, oblate raindrops and possibly irregularly shaped graupel and hail. In CP mode, the weather channel processes only signals received with polarization orthogonal to those transmitted (i.e., the polarization appropriate for scattering from spherical hydrometeors). Therefore, any depolarized data would be lost and thus would mimic attenuation. This explanation does not account for the reflectivity losses encountered in LP mode. They were most likely due to a combination of water intrusion into the waveguide via the rotary joint assembly and some path-length attenuation.

The loss of weather echo intensity as a storm tracks over the radar site has been observed at all of the ITWS prototypes. However, because the radars are mosaicked in DFW and NYC, the attenuation of one radar does not degrade the data as significantly as it would at a single ASR-9 site. An excellent example of this situation from a DFW case on 990308 is shown in Figure 11. When a line of severe thunderstorms impacted the Azle (PA2) site (upper left image), most of the level 3 or greater precipitation beyond 40 km was lost (when compared to the lower left image of the NEXRAD composite product). However, the mosaicked data (lower right) still depict the line much the same as the NEXRAD composite. All of the DFW radars experienced a loss of reflectivity data as the line tracked over the sensor. Since the line impacted the radars at different times, the mosaicked product was not significantly degraded.

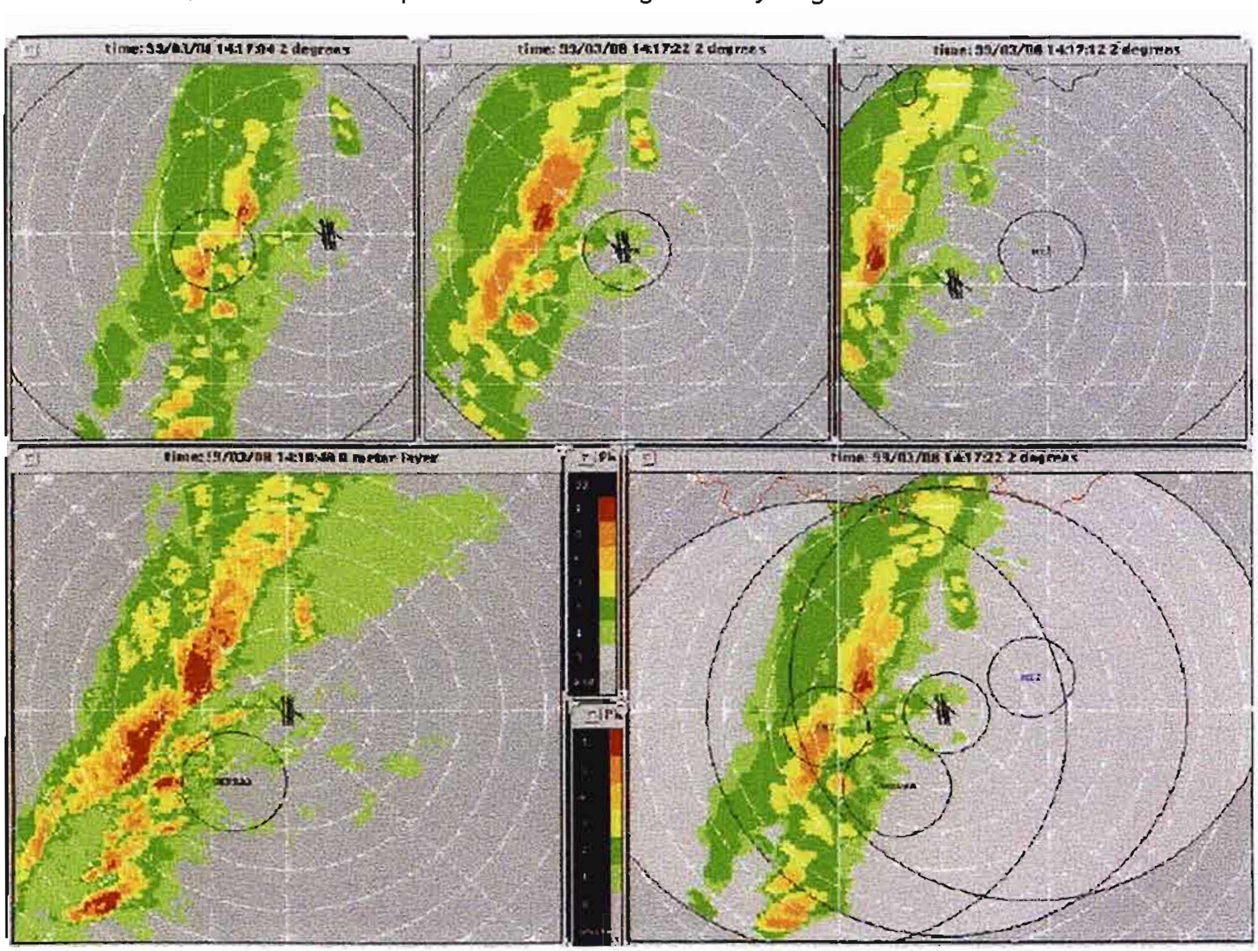

Figure 11. This is a multi-window display showing the impact of a squall line on the PA2 ASR-9 in DFW on 990308. The three upper panels, from left to right, are PA2, DFWE, and Sachse (MI2). Below are the NEXRAD composite product (left) and the ASR-9 mosaicked product (right). The small circles indicate the radar location and the larger circles show each radar's coverage. The black shape in each panel is the DFW airport and all range rings are 10 km apart.

4.2.4 Calibration Differences Between LP and CP

Calibration is a factor in understanding precipitation underestimation since the measurements are based on different hardware components between LP and CP. To better understand the calibration issue, a test was conducted at the MEM and Orlando (MCO) ITWS prototypes. The test involved manually switching the radar from CP to LP when there was sufficient weather in the TRACON to assess any possible differences in precipitation intensity/areal coverage after the switch. The results of this test were quite different between the two sites. In the MCO case, there was little difference in precipitation intensity/areal coverage when switching polarization. The switch to LP showed a small increase in areal coverage, i.e., 15-20 percent, with little affect on precipitation intensity.

By comparison, there was a significant difference in precipitation intensity when switching between LP and CP in MEM. An example of the data before and after the change is shown in Figure 12. There was an increase of approximately one weather level in each cell's intensity after the switch. In fact, one cell located 90 km east increased from level 3 to 5. Another level 5 cell located 40 km east changed very little. So, in the MEM case, the indicated intensity of strong precipitation remained the same or increased when switching polarization. There was also a tendency for the weaker weather echoes to disappear in CP. According to Weber (1986), the detection of level 1 weather is both range and polarization dependent because different STC curves and level 1 data collection schemes are used between LP and CP. We believe calibration differences between the radar and weather channel could very easily account for the precipitation discrepancies shown in Figure 12.

There have been a number of other cases documented where the precipitation returns varied between LP and CP due to possible calibration differences. An example of this scenario is presented in Figure 13. The panel on the left shows the echo coverage from the SWF radar in LP, while the panel on the right shows the weather returns after the radar has automatically switched to CP. An inspection of these images shows a reduction of approximately one weather level after the switch. One area where this reduction is most evident is located between a range of 30-40 km and an azimuth of approximately 210 degrees. A level 4 echo in this locale has decreased to level 3. As with the MEM case discussed previously, the underreporting of level 1 returns in CP is also evident with this event. Based on the data analyzed so far, precipitation underestimation during polarization changes is most likely on the MEM, SWF, and PHL radars. The other radar platforms only show smaller differences in the precipitation intensity when changing polarization.

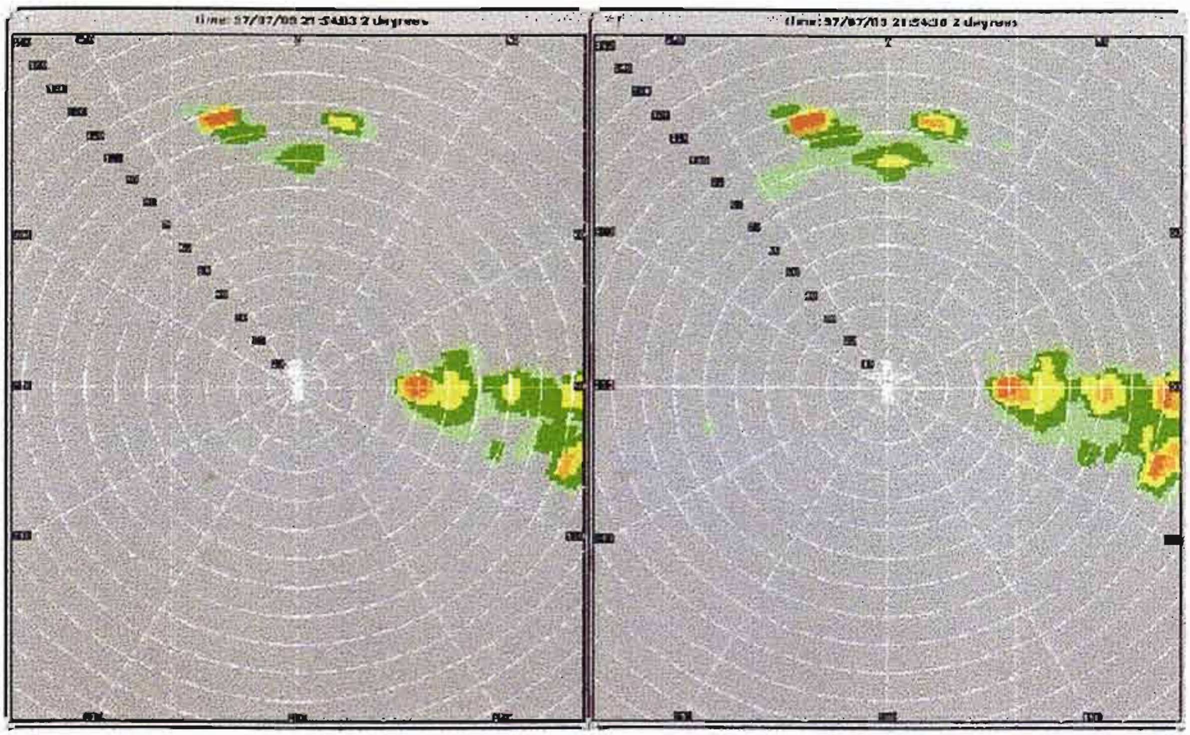

Figure 12. This is an image from MEM on 970709 showing slight calibration differences between LP and CP. The white set of polygons in the center of the image is the MEM ARENAS and the image is centered on the ASR-9. The range rings are at 10 km intervals. The image on the left shows the weather echoes in CP, while the image on the right is 30 seconds later, after the radar was switched into LP.

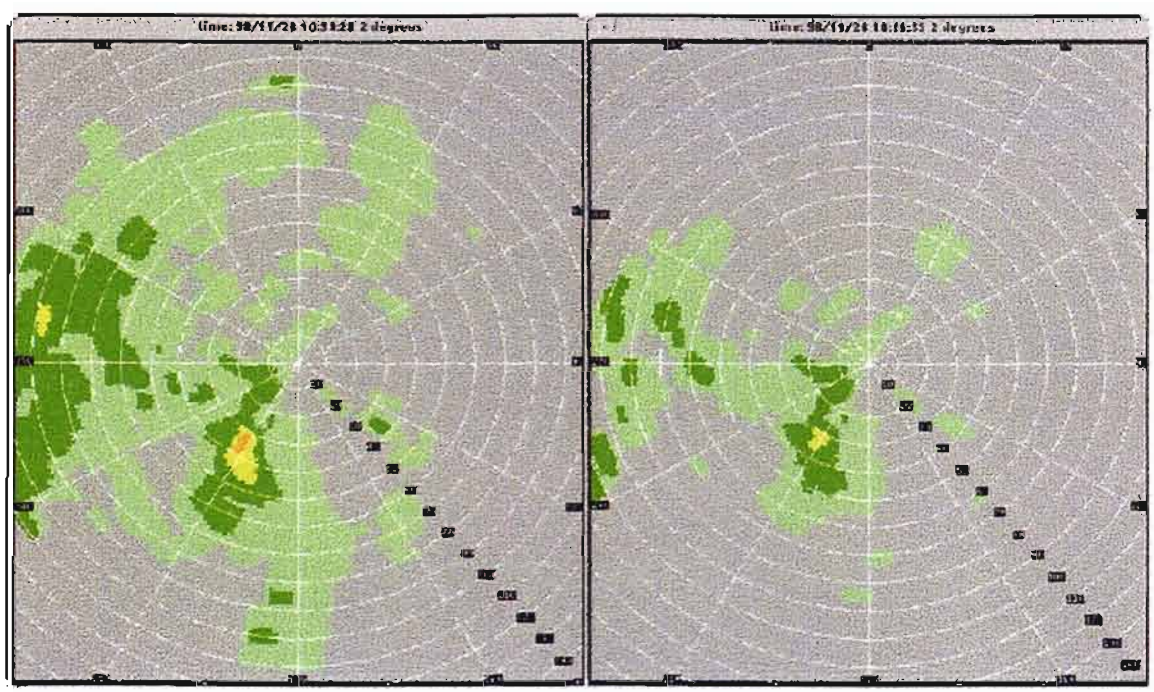

Figure 13. Data from the SWF radar, showing the effect of polarization switching on weather echoes. The image on the left is in LP, while the one on the right (30 seconds later) is in CP.

4.2.5 Bright-Band Contamination

Bright-band contamination occurs from differences in the amount of energy returned to the radar antenna from ice and water scatterers within the atmosphere. In a pencil-beam composite map, a bright-band echo generally appears as concentric bands of high reflectivity centered on the site. During the winter months, this problem has occasionally been observed in the ASR-9 data from all of the ITWS prototypes. However, bright-band contamination is more common in a pencil-beam radar like the TDWR or NEXRAD. Bright-band contamination of the weather channel data can pose a problem for ATC specialists and managers, who might interpret these echoes to be convective. Therefore, the specialists may re-route aircraft around the weather when, in fact, the precipitation is generally stratiform in nature. This increases the workload and can cause longer en route time for the aircraft.

An example of ASR-9 bright-band contamination can be seen in Figure 14. This image shows a band of precipitation tracking over the DFW airport on 971207. The upper left-hand image is from DFW West ASR-9 (DFWW). Notice the band of level 3 around the site. The top center image is the DFW TDWR data, and although the system is in hazardous mode, a portion of the rings can be seen around the radar site. Partial rings also can be seen in the NEXRAD composite reflectivity data (bottom left). The mosaic image (bottom right) does not have the bright-band contamination seen in the single ASR-9 radar image (upper left). This is because the mosaic algorithm typically outputs the median value for each data bin. Since this problem is range dependent, using the median would generally eliminate the data contamination from the mosaic. While this approach would work effectively at ITWS sites with at least three ASR-9s, this type of data contamination would still be a minor problem at those sites with only two radars.

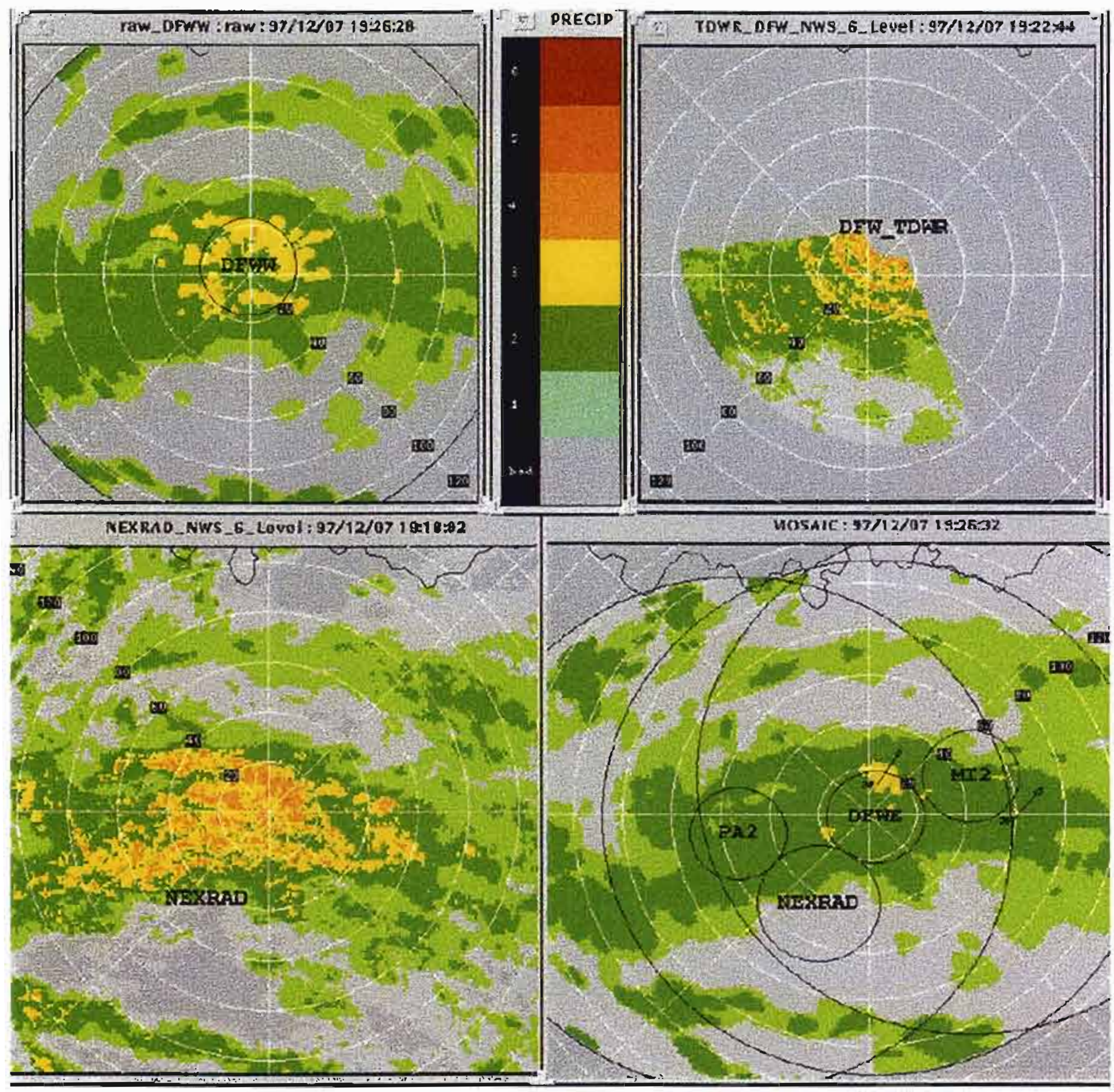

Figure 14. This is an example of bright band contamination from DFW. The DFWE ASR-9 is in the upper left panel, the DFW TDWR is in the upper center panel, the NEXRAD composite product is in the lower left panel, and the ASR-9 mosaicked product is in the lower right panel. The circles in each image are the same as in Figure 11.

4.2.6 Distant Weather Contamination

Echoes outside of the ASR-9s first-trip region (111 km) can, under certain conditions, be displayed within the first-trip region. For the most part, the ASR-9 does a very good job of removing the range ambiguities. However, if a strong weather echo extends over a range interval greater than the difference in unambiguous range between the ASR-9s two PRIs (about 34 km), distant weather echoes can contaminate the data. This causes false weather echoes to appear in the radar data, much like AP. Figures 15 and 16 show a DFW case from 950508 where a strong line of thunderstorms tracked into the coverage region. As shown in the NEXRAD composite data (lower left panel), the line extends well beyond the DFW East ASR-9 (DFWE) detection range (upper center image) and well past the 34 km unambiguous range. In Figure 15, the upper center image is from the DFWE ASR-9. Notice the thin band of level 1 and

2 echo north of the airport. This echo does not exist in the NEXRAD composite reflectivity data. At this time there is no data from either PA2 (upper left) or MI2 (upper right), which is contributing to the mosaic (lower right). Figure 16 shows the same event three minutes later, after MI2 became operational. The level 1 and 2 echoes to the north of the airport are no longer prevalent (lower right panel) because the mosaic process edited the distant weather. We should mention that the MI2 radar was in two-level mode and thus the data would not be used under this condition in the production ITWS. In this case, the two-level data has been incorporated into the mosaic on the northern end of the line, resulting in the removal of the distant weather. [The software to ignore two-level data was not operational in DFW during this event.] This is yet another example of the advantage of using a mosaicked precipitation product. Therefore, distant weather contamination may be more significant at airports with only a single ASR-9.

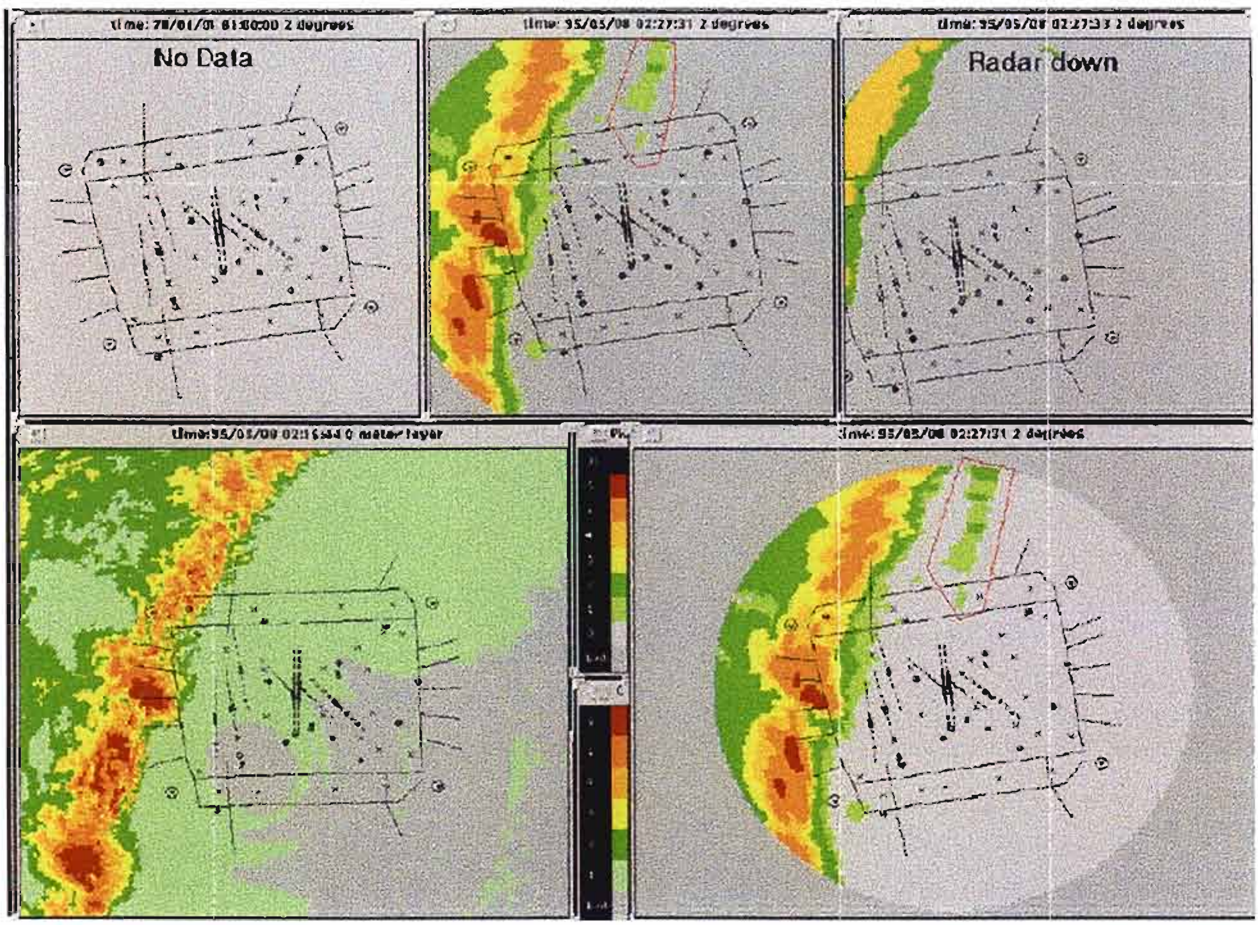

Figure 15. A five-panel display showing an area of distant weather contamination in DFW at 0227 UT on 950508. The large black rectangle in each panel is the "old" DFW TRACON, with the black lines in the center representing the DFW airport. The three upper panels show the ASR-9s (left to right: PA2, DFWE, and MI2), while the lower panels are the NEXRAD composite product (left) and the ASR-9 mosaicked product (right). The level 1 and 2 echoes within the red polygons are the distant weather contamination.

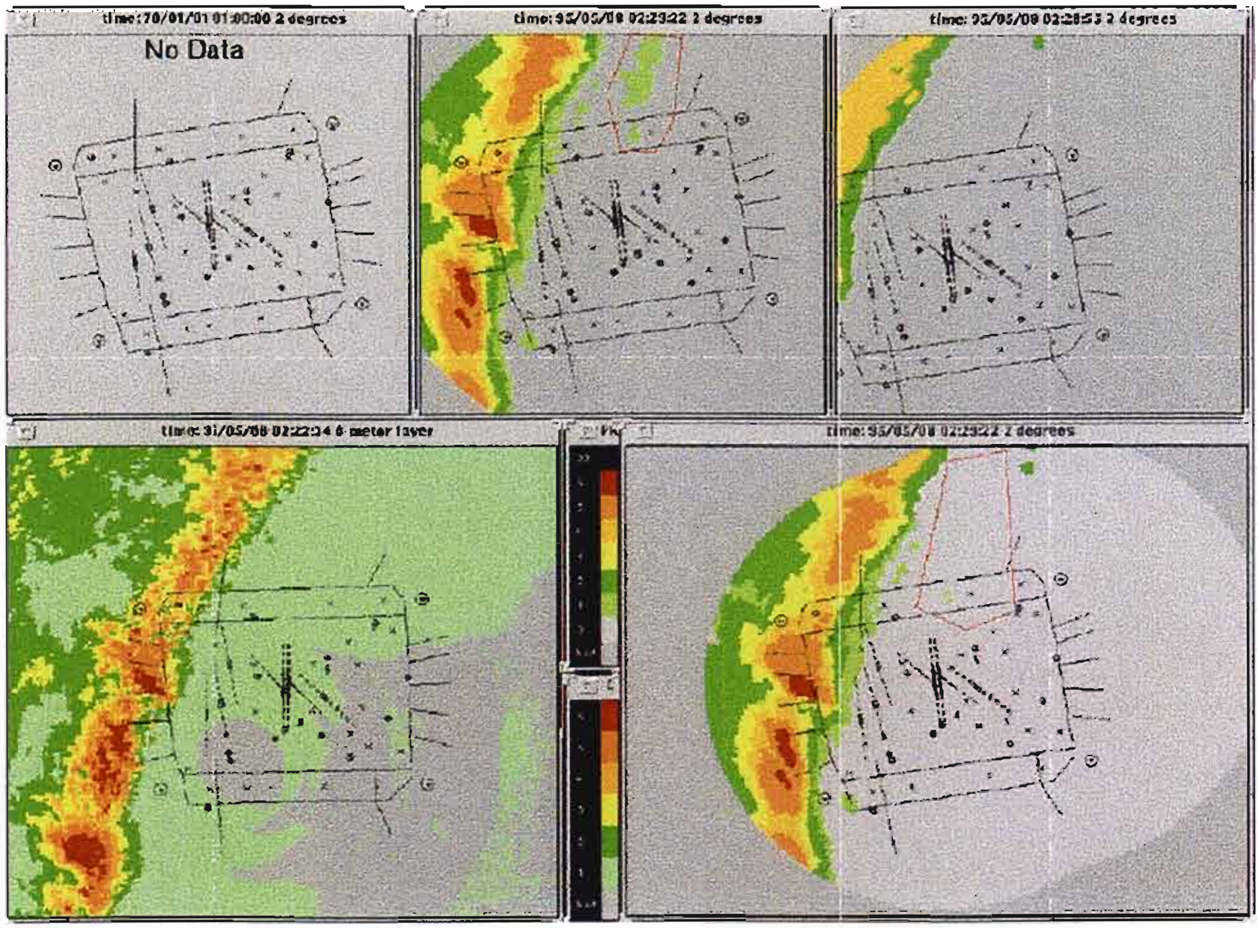

Figure 16. The same as Figure 15, but a few minutes later when the MI2 (upper right) radar came back on line. Notice that the area of distant weather contamination (area within the red polygons) has been edited from the mosaicked (lower right) product.

4.3 Characteristics of Data Quality Problems Arising from Hardware Malfunctions

In this section, the characteristics of data quality problems arising from hardware malfunctions are discussed. These are classified as a stuck polarizer vane, reduced range coverage, and radar/antenna alarms.

4.3.1 Stuck Polarizer Vane

The polarizer in the ASR-9 consists of a "vane" which physically rotates between two positions to receive LP or CP radar returns. Due to excessive wear, the vane polarizer can occasionally stick mid-way during polarization changes. When this happens, the result is a significant decrease in the precipitation intensity. An example of this problem from 960723 in DFW is shown in Figure 17. In this case, the MI2 precipitation intensity and areal coverage decreased dramatically for a one-hour period shortly after the radar attempted a transition from LP to CP. The panel on the left shows there were a number of high reflectivity cells located in all quadrants prior to the vane sticking. After the attempted polarization change (right panel), the maximum echo intensity within the coverage region dropped to level 2. There were also several level 2 and 3 echoes, which disappeared entirely. A sudden decrease in precipitation intensity and areal coverage can be a strong indication that the polarizer vane is stuck, especially if it is correlated with an antenna alarm or failed polarization status message. Performance degradation of this magnitude represents a significant data quality issue with this sensor. The FAA is currently developing a new polarizing scheme that includes an output signal designed to notify the Remote Monitoring System (RMS) of vane polarizer problems.

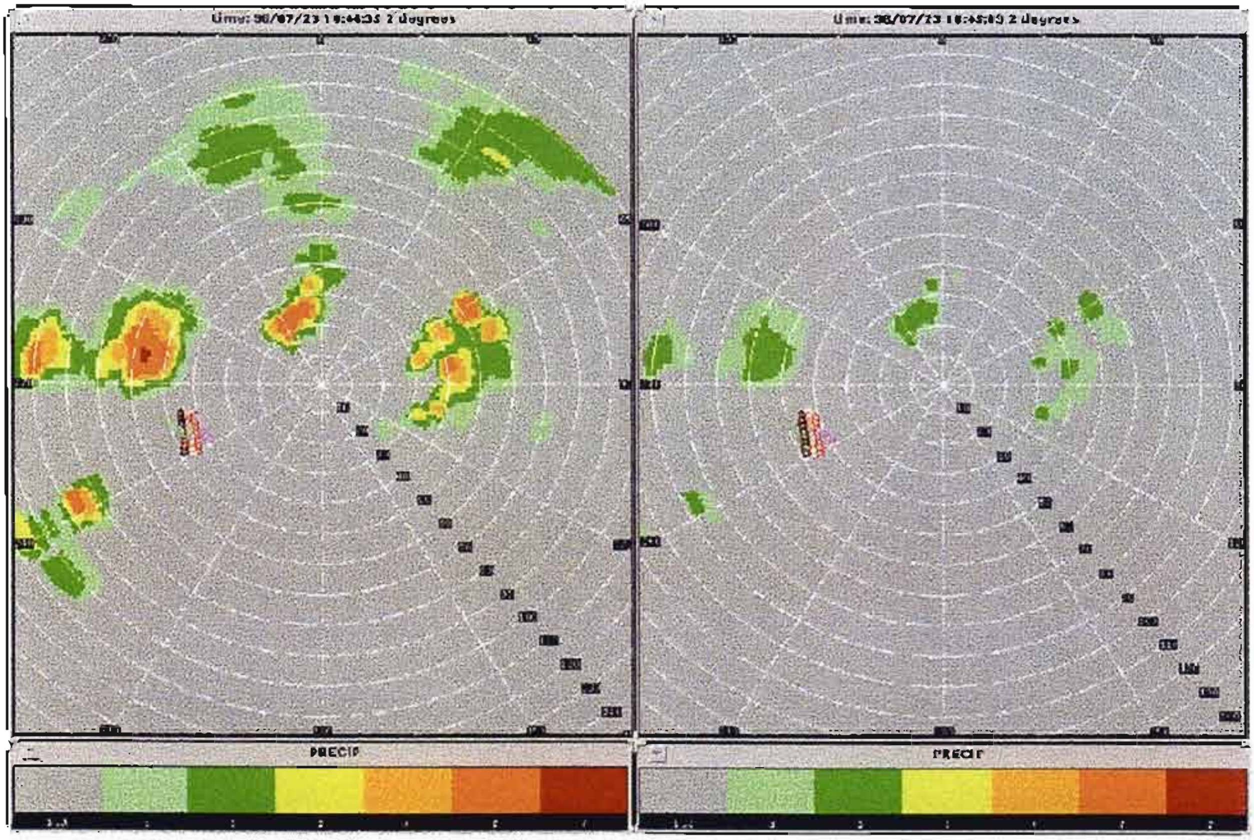

Figure 17. The MI2 ASR-9 when the radar switched between LP and CP (LP on the left and CP on the right). The multi-colored polygons are the DFW ARENAS, and range rings are at 10 km intervals. This figure illustrates the loss of reflectivity due to a stuck polarizer vane.

4.3.2 Reduced Range Coverage

The issue of reduced range coverage was identified shortly after the New York City (NYC) ITWS prototype became operational in the summer of 1998. An example of this problem from the PHL radar is presented in Figure 18. The panel on the left shows that there were extensive level 1-3 returns in all quadrants prior to a polarization change to CP. After the switch (right panel), the weather returns have been clipped at a distance of 60 km. A detailed examination of this case revealed no problem in the total number of range gates after the switch. A potential explanation for this scenario could be a hardware-related failure when switching between the high and low beams. In CP mode, a microwave switch on the antenna pedestal assembly selects the high- or low-beam input for processing by the weather channel. By default, this switch toggles from the high to low beam at 32 nm (~60 km). If the switch failed to properly engage the low beam beyond 60 km, this would result in a reduced range coverage pattern and/or a decrease in weather level intensity due to beam overshooting. This problem exhibits several key characteristics, such as:

- It has been documented only when switching from LP to CP. The problem is probably masked in LP since the beam switch occurs closer to the radar.

- It is characterized by missing data beyond 60 km from the radar. If the echoes beyond 60 km are strong enough, they will be displayed, but at a lower reflectivity level.
- The precipitation intensity inside 60 km generally remains the same. This is in contrast to the cases where the polarizer vane sticks, since this impacts all echoes, regardless of their range.

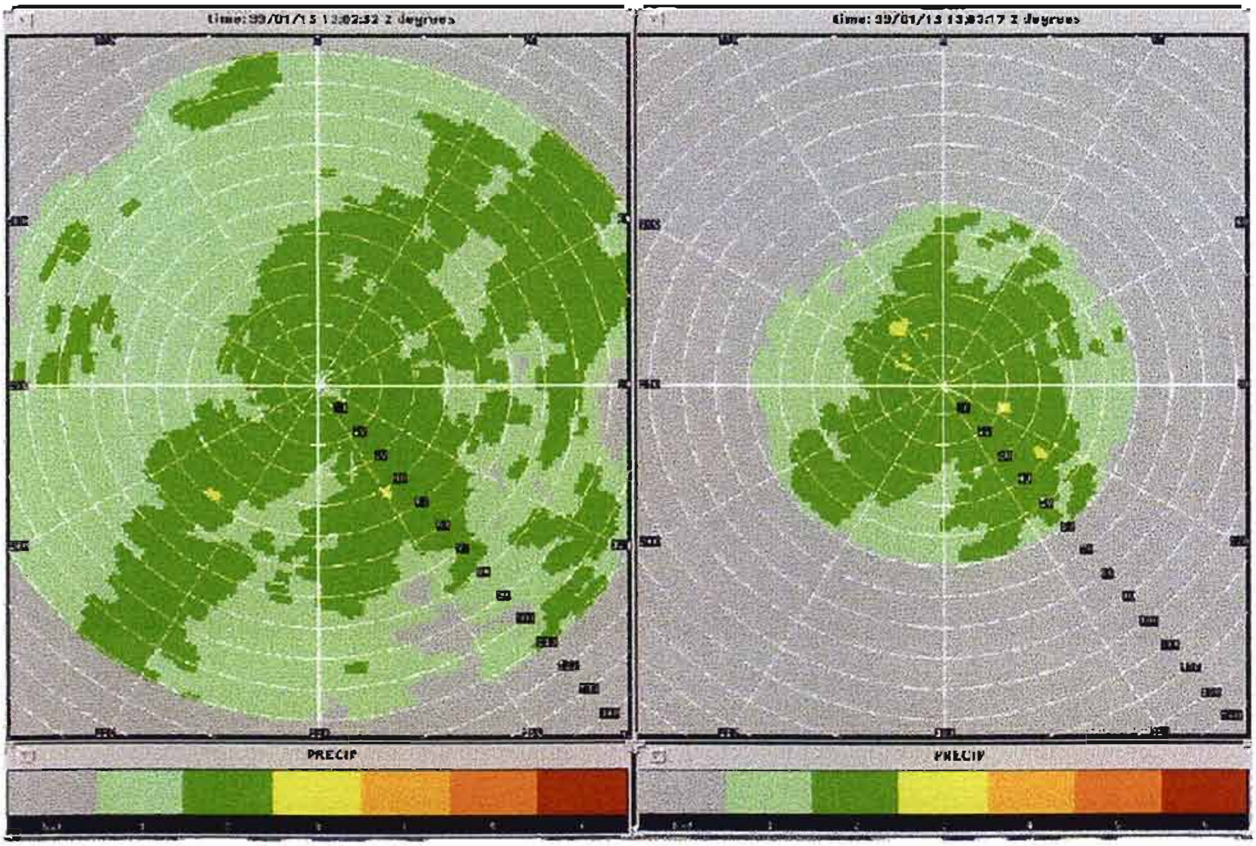

Figure 18. Data from the PHL ASR-9 on 990115 before and after it switched into CP. The panel on the left shows the reflectivity data in LP and the right panel is in CP. Notice that the reflectivity levels stay nearly the same, but all data beyond 60 km are lost.

Another, more complex hardware-related failure from the SWF radar on 990103 is presented in Figure 19. In this case, there was an area of weaker precipitation located ahead of a squall line, which tracked through the NYC domain. The data from SWF are shown in the left panel, while the John F. Kennedy (JFK) data are on the right. There are several discrepancies in the SWF echo intensity and areal coverage, which are of concern. First, there are no level 2 returns beyond 60 km range (similar to the PHL case). The JFK data show that the SWF system is not detecting the level 1-3 stratiform precipitation very effectively. Even more significant, though, is the comparison of the squall line precipitation between the two sensors. The JFK data show a well-pronounced squall line (Level 3-5) aligned north-northeast to south-southwest across the Newark (EWR) ARENAs (red polygons). The SWF radar is reporting a maximum intensity of level 3 for this weather episode and is not detecting the storms over the EWR airport at all. So, this case shows evidence of reduced range coverage and an underestimation of the precipitation intensity within the squall line. Thus, it is likely the radar suffered from both a stuck polarizer vane and a failure of the high-to-low beam microwave switch. This combination of hardware-related failures produced a significant degradation of the data for this event.

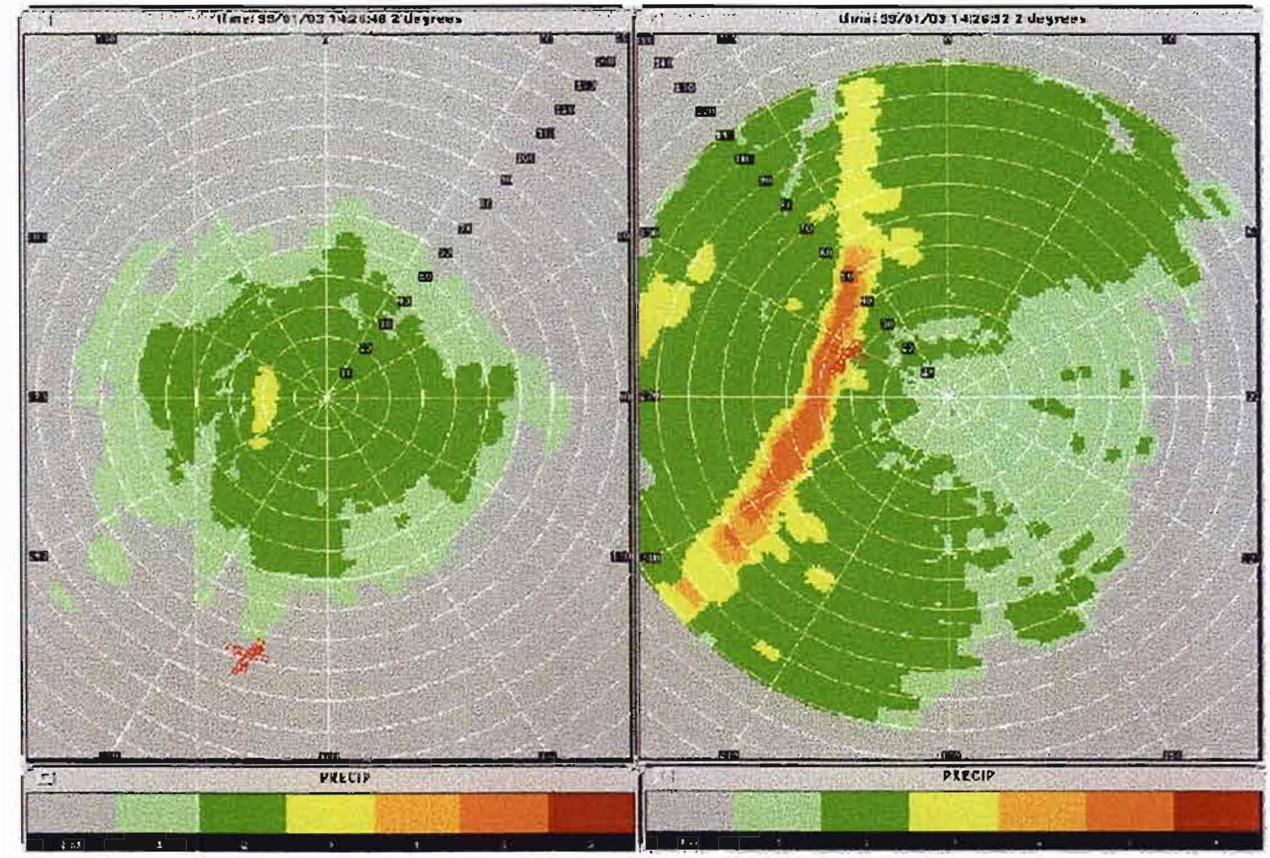

Figure 19. This is an example of a more complex ASR-9 hardware-related failure from the SWF ASR-9 on 990103. The image on the left is from the SWF radar, while weather data from the JFK radar are on the right. The red polygons on both images are the ARENAs for Newark and are added for reference.

4.3.3 Radar/Antenna Alarms

Yet another hardware issue observed in the weather channel data is contamination associated with radar failures or antenna alarms. This scenario can lead to either corrupt data or an underestimation of the precipitation intensity and areal extent. Figure 20 shows an example of this problem from the EWR radar on 990405. In this case, there is a ring of bad data located at a range of ~100 km from the site. There were no valid weather echoes in the area at the time according to any of the other terminal area precipitation sensors. The intensity of the returns fluctuated considerably over the time period the data were corrupted. An examination of the radar status messages revealed the operational channel suffered intermittent failures, which resulted in the data quality problem. A second case from MCO (Figure 21) shows an example of precipitation product degradation after a radar failure. In this case, the weather returns were reduced from levels 3 and 4 to level 1. So, this type of problem can also significantly impact the quality of the ASR-9 data.

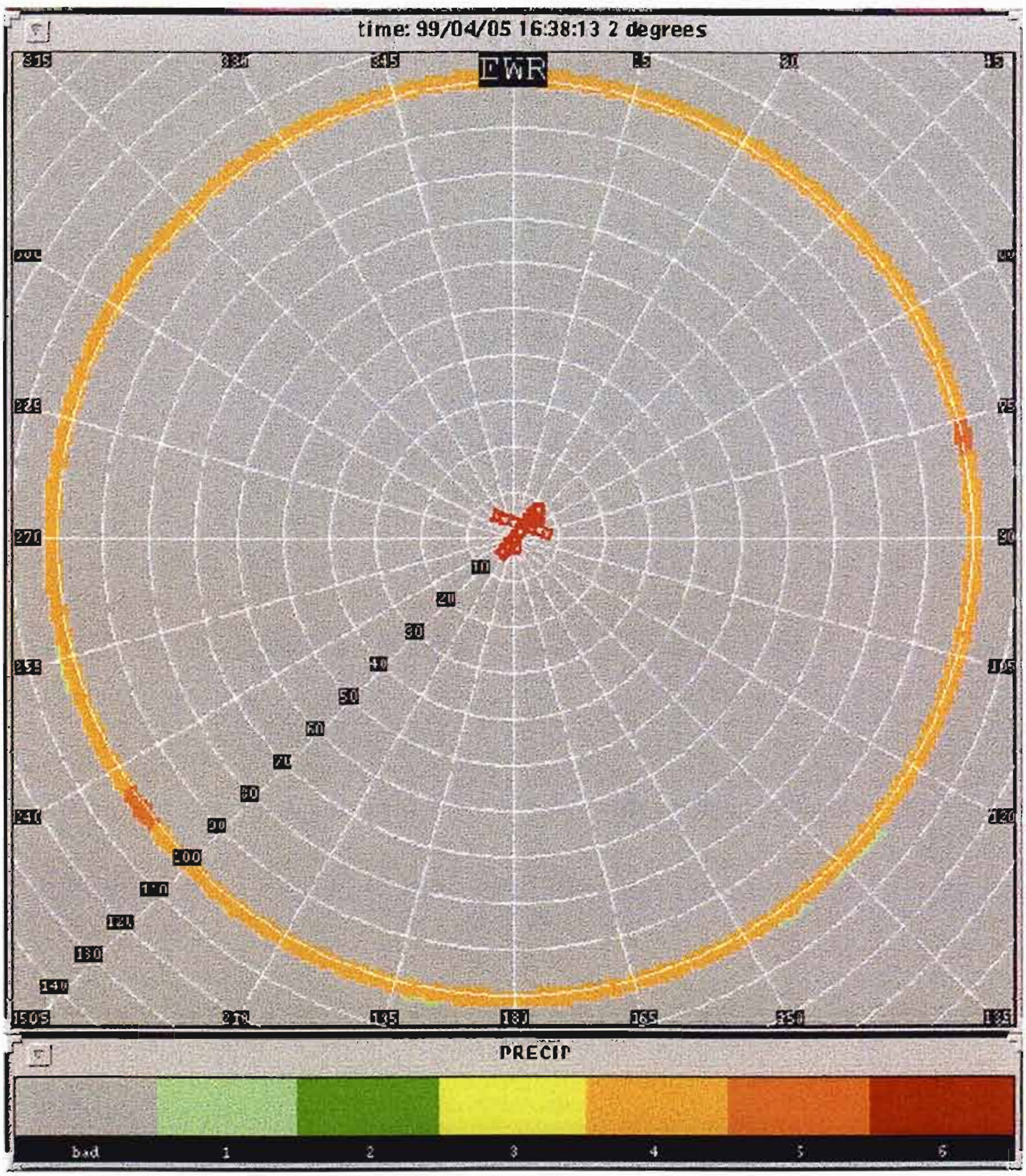

Figure 20. A ring of bad data at ~100 km from the EWR ASR-9 on 990405. Both the radar and antenna system experienced alarms during this time period.

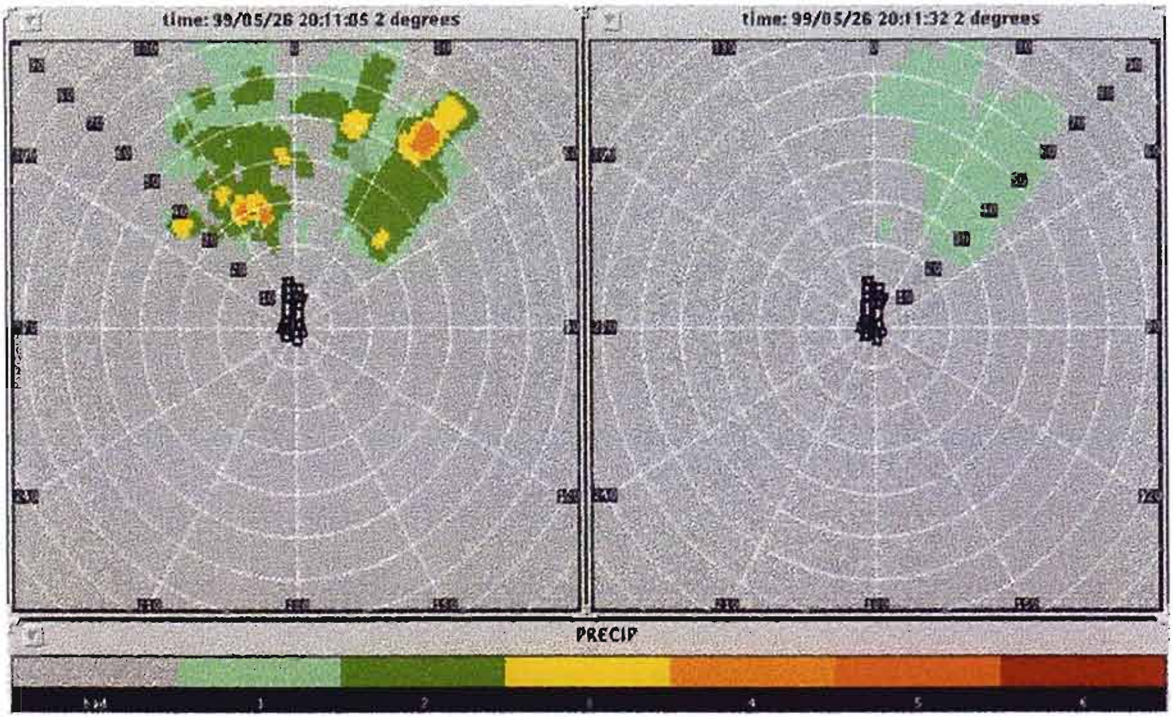

Figure 21. This is an image from MCO on 990526 showing the impact a radar channel failure can have on the data quality. The data on the left is before the radar alarm, while the data on the right shows the product degradation after the alarm.

4.4 Synopsis of Data Quality Issues

This section provides a synopsis of the ASR-9 data quality issues. The failure modes have been divided into two categories: hardware- and non-hardware related. Hardware problems with the polarizer vane assembly and the high-to-low beam microwave switch are responsible for the majority of the most significant performance degradation. Experience garnished from the WSP prototype testing suggests that the failure rate with the vane assembly increases dramatically once the polarizer is worn down. Issues such as echo loss near the radar and attenuation/signal depolarization also can degrade the precipitation product. Finally, beam-filling losses should be mitigated due to the frequency with which this problem is encountered. A more detailed discussion of the calibration issue, which accounts for smaller differences in the precipitation measurements between LP and CP, is presented in Section 5.

5. SOLUTIONS TO WEATHER CHANNEL PERFORMANCE DEGRADATION

5.1 Employ WSP Weather Channel Refinements

Since the mid-1980s, a prototype ASR-9 WSP has collected data at key sites in the Midwest, Southeast, and Western U.S. While this systems primary improvement over the commissioned ASR-9 is the capability to detect wind shear and microbursts via Doppler processing, there also have been a number of improvements in the precipitation processing by the weather channel (Weber, 1998). The main focus of these improvements revolved around the reduction of AP, though there also have been improvements in the accuracy of the precipitation measurements. Four of these improvements are discussed herein; i.e., adjustment to the beam-filling loss equation, increased range resolution of the CDMs, the employment of narrower clutter filters, and reducing the range used when switching between the high and low beams in CP.

5.1.1 Adjustment to Beam-Filling Loss Equation

As shown in this study, beam-filling losses are responsible for a high frequency of precipitation degradation with this sensor. The ASR-9 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 4 km with a 3 dBz 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 observed underestimation. Engholm and Troxel (1990) have suggested a more aggressive threshold adjustment which, statistically, would increase the accuracy of the data. In their study, approximately 98 percent of the cells profiled were assigned a weather level within one of the maximum reflectivity found by a pencil-beam radar. The Engholm and Troxel model should be installed on the operational ASR-9s to help mitigate the underestimation problem. This equation has been used at the WSP prototype sites and provides a more favorable comparison with other terminal area precipitation sensors (Crowe, et al., 1997).

5.1.2 Increased Range Resolution of the Clear Day Maps

To suppress clutter under normal propagation conditions, the ASR-9 employs clutter filters and a CDM. The width and depth of the filter notch are selected on a gate-by-gate basis depending on the intensity of the clutter returns. This ensures that clutter suppression is invoked only to the extent that is necessary to achieve an acceptable signal-to-clutter level (Weber, 1998). Since most ASR-9s are located on-airport, there is a tendency for strong ground clutter illumination at close ranges. As currently specified, the range resolution of the CDM is 1/2 nm in range by 1.4 degrees in azimuth. Thus, the relatively coarse resolution of the maps dictates that strong clutter targets will invoke the more highly attenuating filters over regions larger than the extent of the ground clutter returns (Weber, 1998). The effect of this would be to significantly attenuate the weather signals, especially those in close proximity to the radar. Increasing the range resolution of the CDM to 1/16 nm would reduce the amount of suppression in weather cells located near clutter targets and consequently help to mitigate the removal of weather echoes near the radar.

5.1.3 Employ Narrower Filters and Eliminate Spatial/Temporal Smoothing

Another factor in the removal of weather echoes near the site is the width and depth of the filters. The signal processing techniques used by the WSP, such as "extended coherent processing intervals" (ECPI), could provide improved weather reflectivity measurements at all ASR-9 sites (Weber, 1998). Basically, this approach processes 27 successively transmitted pulses which allow the stop and transition bands of the filters to be narrower than in the current ASR-9 weather channel, reducing the likelihood of significant weather echo attenuation as an unwanted by-product of clutter filtering (Weber, 1998). The WSP filters are applied in each range-azimuth cell so as to minimize the potential attenuation of weather returns. The relatively large number of pulses averaged for the WSP reflectivity estimates also reduces the need for spatial and temporal smoothing relative to the "single pulse" technique of the baseline ASR-9 weather processor (Weber, 1998).

5.1.4 Reduce the Range Used When Switching Between the High and Low Beams in CP

In the commissioned system, the range for switching between the high and low beams varies based on the polarization. In CP mode, the switch occurs at 32 nm, while in LP the transition point is 15 nm. The default value used by the WSP system was changed to 15 nm in CP mode. This change was made since testing showed the low-beam data were not corrupted by clutter returns beyond this distance. Using the low-beam data at a distance of 15 nm in both modes would provide more reliable precipitation measurements, since the beam would be less likely to overshoot the strongest precipitation returns. It would also mitigate precipitation underestimation when switching between the high and low beams. This variable site parameter (VSP) should be changed in the commissioned system to allow for more accurate precipitation measurements.

5.2 Ensure the Radar Channels and the Weather Channel are Calibrated

One of the most obvious recommendations to help alleviate ASR-9 product degradation is to ensure that the radar channels and the weather channel are calibrated. In LP mode, the operational radar channel generates the weather returns. Since there are two radar channels, there is a possibility of the precipitation returns varying due to calibration differences. In CP mode, the weather channel provides the precipitation estimates, which is independent of the radar channel. Calibration differences between these sources could account for some of the observed precipitation underestimation.

A case from DFW (Figure 22) is used to illustrate calibration differences between sensors operating in the same environment. The panel on the left shows the precipitation field from DFWE, while the data on the right are from DFWW. These two radars are located within 1 nm of each other, which should eliminate any possible discrepancies arising from beam-filling losses. Both of the radars were operating in LP, thus polarization issues should not be a factor, either. An inspection of the data revealed that DFWE was underestimating the precipitation by 1 level when compared to DFWW. Most of the DFWE echoes that are displayed as level 2 actually should be level 3. The data from the DFW TDWR, Dallas Love (DAL) TDWR, and Ft. Worth (FWS) NEXRAD radars (not shown) also support the notion that DFWE was underestimating the precipitation. These small differences in reflectivity measurements between the two radars most likely represent calibration errors. Recently, the DFW mosaicked precipitation product was modified to include the data from both DFWE and DFWW, which should alleviate this problem somewhat for users of the ITWS composite. However, air traffic controllers using a poorly calibrated ASR-9 would have misleading data.

The WSP system employs several procedures to ensure an accurate calibration of the weather channel. The primary calibration technique is to inject a known signal level in a coupler ahead of the active components and measure the input and output power. Additionally, during radar operations, test targets are injected in the front end before the amplifiers to measure the STC levels. An STC reference or Minimum Detectable Signal (MDS) alarm would result if the calibration were off by more than a few dB. This in turn would cause the system to automatically switch to the redundant channel. These two techniques should serve to maintain a fairly accurate calibration of the weather channel. By comparison, the commissioned ASR-9s use factory defaults, which could account for slight calibration differences in the weather channel due to variability from one system to the next. The main area of concern though between LP and CP in terms of calibration issues is that in CP a co-axial cable is used to transmit and receive the weather channel's signal. A loss factor is hardwired in the system for the loss expected from a fixed tower height of ~45 feet. The loss can vary by ± 3 dB due to differences in tower height/cable length between systems. We believe the software should account for the calibrated co-axial loss via a VSP.

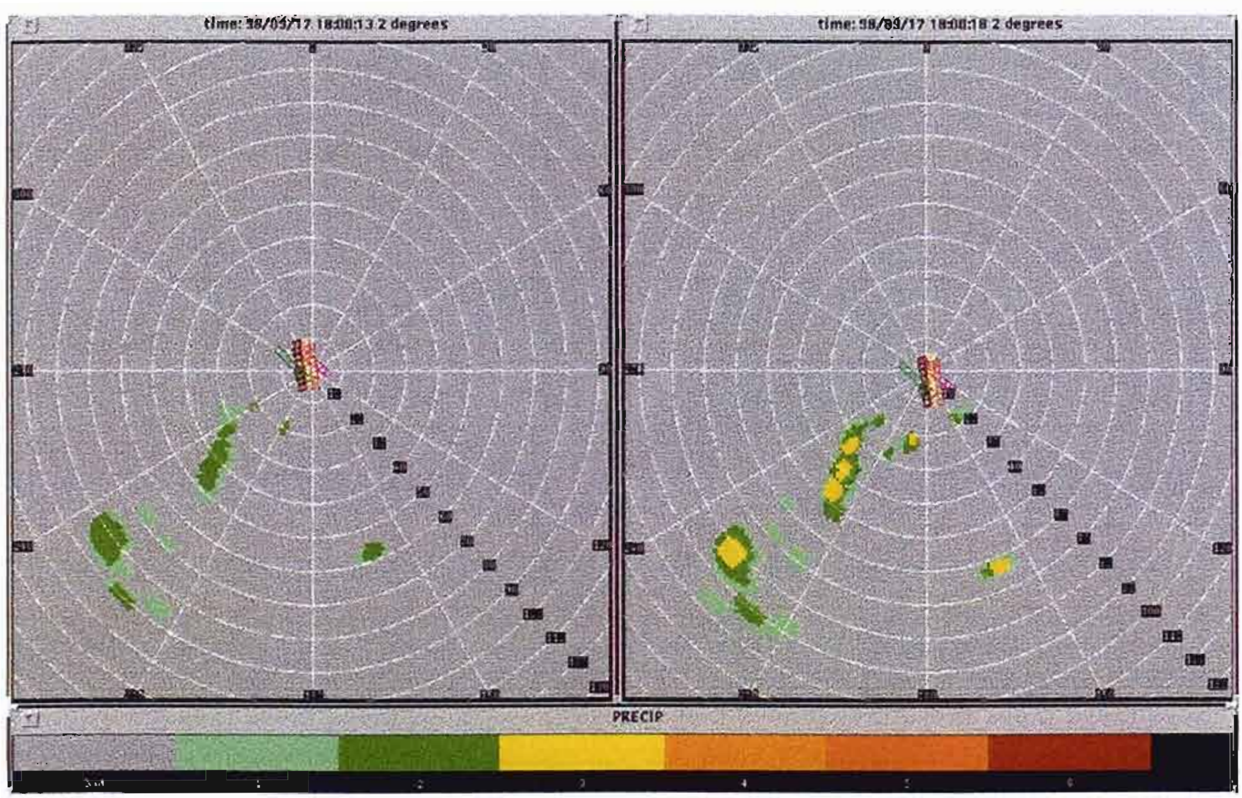

Figure 22. Comparison of co-located ASR-9s at DFW to illustrate calibration issues. The data on the left is from DFWE, while the data on the right is from DFWW.

5.3 Modify the Areal Coverage Threshold/Operate the Radar in LP Mode

Another technique to help mitigate precipitation underestimation during polarization changes would be to change the default areal coverage threshold for mode switching. As mentioned previously, the radar switches to CP when at least 25 percent of the coverage region contains level 2+ echoes. If this threshold were increased to 50 percent, the radar would spend more time in LP, which also would reduce the frequency of product degradation. This option is highly attractive since the automatic mode switching still would be viable to achieve a sufficient target-to-precipitation clutter ratio and thus not degrade from the "critical" function of ATC surveillance. An alternate recommendation would be to operate the radar in LP mode at all times. Operating the radar in LP would eliminate problems incurred during polarization changes. The option to switch the radar to automatic mode would still exist if the weather echoes suppressed the primary radar aircraft targets.

5.4 Discussion of Monitor Program Algorithm Design Options

In this report, several types of ASR-9 performance degradation were documented. The main problems were caused by beam-filling losses, hardware failures during polarization changes, aggressive clutter filtering/mapping near the radar, and attenuation/signal depolarization. The primary recommendations to deal with these issues involve modifying the beam-filling loss correction factor, increasing the CDM range resolution, less aggressive clutter filtering, refining the calibration techniques, and modifying the areal coverage threshold for changing polarization. Even if these upgrades were incorporated, the data still would contain a variety of other errors that have been observed during the operation of the ITWS prototypes.

A monitor program could be used to identify and flag a wide range of operationally significant inaccuracies in the precipitation data. Problems such as a stuck polarizer vane, missing radials, a hardware problem that leads to reduced range coverage, and radar channel failures could be identified by this program. Variables such as the precipitation intensity distribution, echo coverage, type of polarization, and the number of radials would form the key components of the program. Currently, the Lincoln ITWS prototype software identifies only cases where the ASR-9 is operating in two-level mode. The proposed ASR-9 data quality-monitoring program can classify a much wider variety of error states and should be sensitive to sudden changes in echo coverage caused by echoes entering/exiting the field of view. Since the thrust of the program is to identify data quality problems by sudden changes in the precipitation intensity and coverage, situations where the echo coverage changes at the edge of the detection range should be ignored. The output of this program would be beneficial to both ATC specialists and maintenance personnel.

In the initial deployment, this program should identify problems caused by stuck polarizer vanes, high-to-low beam microwave switch failures, radar channel alarms, switches to two-level mode, LP/CP calibration discrepancies, and missing radials. The two main components of the proposed program are a histogram of the output weather levels and radar status messages. The first step is to identify large scan-to-scan changes in the weather level histogram. Table 3 shows a histogram of changes in the number of ASR range/azimuth cells per weather level caused by various data quality problems. The data were compiled by examining the variability in the number of cells within each weather level category on a scan-by-scan basis. The variability is represented by the percentages, which show the net increase or decrease.

There were a number of similarities in the histogram frequency, regardless of the problem. First, the number of gates without valid data (Level 0) generally increased (i.e., precipitation coverage decreased). However, in the case of missing radials and some radar channel failures (990405 EWR), this category actually decreased or stayed the same. Also, the frequency of valid data at each weather level generally decreased or increased quite dramatically. There is one exception to this rule, which must be accounted for. In the case of the radar switching to two-level mode, there will always be an increase in the frequency of the level 2 and 4 returns. Third, in most of the cases the amount of change in at least one of the categories exceeds 75 percent. Based on analyzing ~80 failure cases, the following site-adaptable thresholds should be used in the histogram technique.

(1) A minimum of 100 pixels at each weather level should be used for identifying hardware-related failures. This threshold will be used to mitigate inconsistencies in the histogram resulting from too few data samples.

(2) At least two of the valid data levels (Levels 1-6) should show a change (decrease, increase, or both) of at least 25 percent. This requirement ensures that the weather intensity must reach level 2 to be identified by the program and that the change in weather levels is sufficient to pose a concern.

(3) The product degradations should be associated with a status message indicating a polarization change, a change to two-level mode, a radial count other than 256, or a radar/antenna alarm. The associated status message information will eliminate any program failures in cases where storms enter/exit the field of view.

(4) For most problems, the impaired condition flag should remain active as long as conditions (2) and/or (3) are still valid. In the event of a polarization problem, a switch back to LP mode is required to clear the impaired condition flag. The minimum number of pixels rule should also be invoked when clearing the flag.

Table 3.
Histogram of Weather Level Changes
Caused by Various ASR-9 Hardware Problems

Date	Radar	Problem	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
960723	MI2	Vane	+16 %	-52 %	-62 %	-100 %	-100 %	-100 %	-100 %
980907	SWF	Vane	+29 %	-42 %	-62 %	-80 %	-100 %	-100 %	ND
990124	PHL	Two-Level	+74 %	-91 %	+27 %	-76 %	+300 %	ND	ND
981208	PHL	Radar	+63 %	-92 %	-100 %	-100 %	ND	ND	ND
981208	PHL	Radar	+66 %	-100 %	-100 %	-100 %	ND	ND	ND
971128	MI2	Radar	+21 %	-88 %	-100 %	-100 %	ND	ND	ND
990405	EWR	Radar	0 %	+31 %	-38 %	+368 %	ND	ND	ND
981126	SWF	Polarization	+22 %	-18 %	-58 %	-77 %	ND	ND	ND
980907	SWF	Polarization	+30 %	-46 %	-55 %	-100 %	ND	ND	ND
980927	SWF	Polarization	+16 %	-63 %	-75 %	-100 %	-100 %	-100 %	ND
981208	PHL	Range	+36 %	-46 %	-59 %	ND	ND	ND	ND
990115	SWF	Range	+35 %	-58 %	-84 %	-100 %	ND	ND	ND
960412	MI2	Radials	-53 %	-50 %	-52 %	-54 %	-30 %	+150 %	ND
980106	DFWE	Radials	-51 %	-7 %	-3 %	-13 %	0 %	0 %	ND

The histogram technique should be able to identify the vast majority of the ASR-9 hardware problems documented at the ITWS prototypes. According to the results in Table 3, the only problem that might not be detected adequately is the case of missing radials. This is due to the fact that the magnitude of change in the histogram could vary quite significantly based on the deviation in the number of radials from the norm and whether the missing radials contain valid data. For instance, if only a few radials are missing, the histogram would change very little. According to these results, the magnitude of change was greater for the 960412 MI2 case than the 980106 DFWE case. Thus, the amount of change in the DFWE case would not be captured by this technique. Since this problem typically persists for only one scan, the monitor program should flag scan-to-scan radial discrepancies, but no further maintenance action would be warranted.

An alternative approach to the histogram technique would be to perform a pixel-to-pixel comparison of the weather data from successive scans. The images would be correlated after adjustments were made to account for storm motion. This technique would focus on large changes in the weather channel output based on the standard deviation calculated from one image to the next. The main advantage of this approach would be capturing all of the ASR-9 failure modes with the same basic software design. Each of these techniques will be further evaluated before reaching a final decision on the monitor program design.

There are several types of ASR-9 product degradation that might not be addressed by either technique, i.e., echo loss near the radar and signal depolarization. With respect to the former, the histogram technique could be modified to monitor the frequency distribution on a range-selected basis. Since this problem will only be encountered in close proximity to the radar, the histogram should be based on the number of pixels within a site-adaptable distance, such as 5 km. If there is a significant decrease in the histogram frequency within this domain, the monitor program should flag the product as degraded. This approach should work adequately if the weather echo tracks over the ASR-9 locale, but would not work effectively if the cell develops directly over the sensor. In this case, the radar data from the TDWR could serve as a surrogate to provide ATC with a more accurate representation of the precipitation intensity over the airport. Once again, the monitor program should flag this type of problem, but no further action is warranted. As for the attenuation/signal depolarization problem, there is generally a gradual decrease in the histogram frequency as the squall line impacts the sensor. The problem is also short-lived, which makes it less important in the overall scope of ASR-9 product degradation. Based on these considerations, this problem would not be flagged by the initial monitor program design.

Once the failure modes have been identified, they should be reported on the ITWS SD via either a user-selected or pop-up window. A message would be sent to the window reporting the exact nature of the problem, along with any recommended maintenance action. In the initial state, the message for most failure modes would be "ASR-9 PRECIPITATION PRODUCT DEGRADED." Additionally, the message for echo loss near the radar might be "ASR-9 PRECIPITATION PRODUCT DEGRADED OVER AIRPORT." In the case of missing radials and echo loss near the radar, the message could be appended with the text "NO MAINTENANCE ACTION REQUIRED." For all of the other problems discussed herein, the exact type of problem should be reported so the appropriate maintenance action could be initiated. For instance, a switch to LP mode could remedy a polarizer vane failure. These status messages will also serve as guidance for the users to rely on data from the other terminal area precipitation sensors until the ASR-9 problem has been resolved. The exact details of the reporting mechanism would have to be determined by the ITWS Users Group.

6. SUMMARY AND RECOMMENDATIONS

6.1 Summary of ASR-9 Performance Degradation

Beam-filling losses, which are due to the inherent fan-beam averaging of the ASR-9, were determined to be the most commonly observed degradation. The other types of ASR-9 degradation include echo loss near the radar, polarization issues, attenuation/signal depolarization, antenna/radar alarms, bright-band contamination, and distant weather contamination. Of these, the loss of echoes over the radar is problematic. This loss has been attributed to "cone of silence" problems in past reports, but may in fact have more to do with the overly aggressive clutter filtering/mapping near the radar. The polarization issues include possible differences in calibration between the radar and weather channel, a stuck polarizer vane, or a failure of the high-to-low beam microwave switch. Often these errors can result in level 3 weather echoes being falsely reported as level 2 or less. An underestimation of this magnitude is operationally significant in terms of providing air crews with accurate weather intensity information. Reflectivity losses due to "attenuation" of radar energy have been observed at all of the ITWS prototypes. An examination of LP and CP attenuation cases showed that strong line storms, which impact the ASR-9 site, could cause a loss of data regardless of the polarization. Radar channel failures can also corrupt the product and cause the precipitation intensity to be underestimated. Bright-band contamination is mainly a winter time phenomenon which does not impact the ASR-9 sensor as severely as pencil-beam radars. Lastly, distant weather contamination occurs with this radar, but is very rare.

6.2 Summary of Solutions to the Observed Performance Degradations

This report examines several solutions to the observed ASR-9 weather channel degradations. Among these are the employment of the WSP weather channel refinements, including adjustments to the beam-filling loss equation, increased range resolution of the CDMs, and employing narrower filters. Other solutions include ensuring that the weather and radar channels are correctly calibrated, operating the ASR-9s only in LP mode, changing the default threshold for mode switching, and inspecting the polarizer vane assembly and high-to-low beam switch.

A monitor program should be designed to flag and report scenarios where the ASR-9 precipitation product is degraded. The monitor program would achieve this by evaluating variables such as precipitation intensity distribution, echo coverage, and radar channel failures. There are two approaches to such a program. One is to use a histogram technique designed to identify large scan-to-scan changes in the number of pixels within each weather level. The second approach would be to perform a pixel-to-pixel comparison of the weather channel data, after adjusting for storm motion. Further study is needed to determine which design would be best suited for the product. This program would report failure modes to the ITWS and/or WSP SD users in a textual fashion and alert system users if the precipitation product had been degraded. The output also would serve as guidance for users to rely on other precipitation data until the problem was resolved.

6.3 Recommendations

This report illustrates several distinct types of ASR-9 performance degradation. To assist FAA personnel, the recommendations to resolve these problems are grouped into three categories: "VSP" adjustments, hardware component maintenance checks, and automated flagging of data quality problems.

The "VSP" adjustments which would improve the precipitation measurements from this sensor include updating the beam-filling loss model equation based on the study by Engholm and Troxel (1990); reducing the range of the high-low beam switching; and add a VSP to account for calibration differences in CP. The primary calibration parameter of concern is the co-axial cable loss, which differs based on the tower height/cable length. A maintenance schedule should be incorporated into the commissioned system to check the polarizer vane assembly, beam switch, rotary joints, and microwave runs on a periodic basis.

Any residual data quality issues should be identified and flagged via a monitor program. This algorithm also might include techniques to inhibit the use of the suspect data in the ITWS precipitation mosaic and to turn off the TRACON precipitation product at single ASR-9 locales. The output of this program also should notify ATC and AF personnel of the problem.

We also recommend that routine procedures be developed for AF and AOS personnel to review the ASR-9 weather channel data in relationship to the TDWR and NEXRAD data. Currently, there is no operational capability for recording ASR-9 weather channel data. This lack of recording makes it very difficult for AF or AOS personnel to analyze anomalies reported by ATC. Moreover, neither terminal facility AF personnel have convenient access to NEXRAD data, nor do they have software to accomplish such a comparison.

The ITWS SD recording would provide a convenient mechanism for an initial data inspection and comparison. Full sensor data recordings can be accomplished with ITWS, but may not be made in all cases. We recommend that techniques be developed now so that procedures to accomplish such a data review can be prototyped when the initial ITWS articles are deployed in 2001.

GLOSSARY

A/D	Analog/Digital
AOS	Airways Operational Support
AP	Anomalous Propagation
ARENA	Area Noted For Attention
ASR-9	Airport Surveillance Radar version 9
ATC	Air Traffic Control
CDM	Clear Day Map
CP	Circular Polarization
dB	Units of power, i.e., decibels
dBz	Radar Reflectivity Factor
DAL	Dallas Love
DFW	Dallas/Fort Worth
DFWW	DFW West ASR-9
DFWE	DFW East ASR-9
ECPI	Extended Coherent Processing Interval
EWR	Newark
FIR	Finite Impulse Response
FWS	Fort Worth
ITWS	Integrated Terminal Weather System
JFK	John F. Kennedy ASR-9
LP	Linear Polarization
MCO	Orlando
MDS	Minimum Detectable Signal
MEM	Memphis
MI2	Sachse ASR-9 (Dallas)
NEXRAD	NEXt generation weather RADar
ND	No Data
NM	Nautical Miles
NWS	National Weather Service
NYC	New York City
OT&E	Operational Test and Evaluation
PA2	Azle ASR-9 (Dallas)
PHL	Philadelphia ASR-9
RMS	Remote Monitoring System
SCIP	Surveillance and Communications Interface Processor
SD	Situation Display
STC	Sensitivity Time Control
SWF	Stewart ASR-9 (New York)
TRACON	Terminal Radar Approach Control
TDWR	Terminal Doppler Weather Radar
UT	Universal Time
VIL	Vertically Integrated Liquid Water
VSP	Variable Site Parameter
WSP	Weather Systems Processor

REFERENCES

Crowe, B.A., M.A. Isaminger, M.E. Weber, and J.A. Cullen, 1997: The Capabilities and Limitations of Using the ASR-9 as a Terminal Area Precipitation Sensor, 28th Conference on Radar Meteorology, Amer. Meteor. Soc., Austin, TX, 168-171.

Crowe, B.A., and D. W. Miller, 1999: The Benefits of Using NEXRAD Vertically Integrated Liquid Water as an Aviation Weather Product, 8th Conference on Aviation, Range, and Aerospace Meteorology, Amer. Meteor. Soc., Dallas, TX, 244-248.

Engholm, C.D. and S.W. Troxel, 1990: Beam Filling Loss Adjustments for ASR-9 Weather Channel Reflectivity Estimates, MIT Lincoln Laboratory, Lexington, Mass., Project Report ATC-177, FAA-NR-90-6.

Isaminger, M.A., B.G. Boorman, and B.A. Crowe, 1996: Discussion of the Impact of Data Contamination on TDWR Algorithm Performance, Workshop on Windshear and Windshear Alert Systems, Amer. Meteor. Soc., Oklahoma City, OK, 80-89.

Isaminger, M.A., B.A. Crowe, B.G. Boorman, J.E. Evans, and R.A. Boldi, 1997: Performance Characteristics of an Algorithm Used to Remove Anomalous Propagation from the NEXRAD Data, 28th Conference on Radar Meteorology, Amer. Meteor. Soc., Austin, TX, 317-319.

Isaminger, M.A., B.A. Crowe, and E.A. Proseus, 1999: Designing a Monitoring Program to Identify and Flag Hardware-Related Degradation of the ASR-9 Precipitation Data, 29th International Conference on Radar Meteorology, Amer. Meteor. Soc., Montreal, Canada.

Puzzo, D.C., S.W. Troxel, M.A. Meister, M.E. Weber, and J.V. Pieronek, 1989: ASR-9 Weather Channel Test Report, MIT Lincoln Laboratory, Lexington, Mass., Project Report ATC-165, FAA-PS-89-3.

Rinehart, R.E., 1991: *Radar For Meteorologists* Second Edition, University of North Dakota, Grand Forks, ND.

Taylor, J.W. and G. Bronins, 1985: Design of a New Airport Surveillance Radar (ASR-9). IEEE Proc., 73, 284-289.

Weber, M.E., 1986: Assessment of ASR-9 Weather Channel Performance: Analysis and Simulation, MIT Lincoln Laboratory, Lexington, MA, Project Report ATC-138, FAA-PM-86-16.

Weber, M.W., E.R. Williams, M.M. Wolfson, and S.J. Goodman, 1998: An Assessment of the Operational Utility of a GOES Lightning Mapping Sensor, MIT Lincoln Laboratory, Lexington, MA, PROJECT REPORT NOAA-18.

Weber, M.E., 1998: Lincoln Laboratory internal memorandum.

Wexler, R. and D. Atlas, 1963: Radar Reflectivity and Attenuation of Rain, *J. Appl. Meteorology,* 2, 176-280.