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Anomalous Propagation Ground Clutter Suppression with the Airport Surveillance Radar (ASR) Weather Systems Processor (WSP)

J. A. Cullen

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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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16. Abstract

Ground-clutter breakthrough caused by anomalous propagation (AP)—ducting of the radar beam when passing through significant atmospheric temperature and/or moisture gradients—is a significant issue for air traffic controllers who use Airport Surveillance Radar (ASR) weather channel data to guide aircraft through the airport terminal area. At present, these data are often contaminated with AP, leaving the controller unsure about the validity of information on storm location and intensity.

The Weather System Processor (WSP), which is scheduled for deployment at 33 airports in the U.S., includes an AP-Editing algorithm designed to remove AP based on its Doppler-spectrum characteristics in ASR-9 data. This report provides a description of the algorithm currently used in the FAA/Lincoln Laboratory WSP prototype and a measurement of the performance of the algorithm during nine episodes of AP and/or true weather in Orlando, Florida in 1991 and 1992.

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ABSTRACT

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The Weather System Processor (WSP), which is scheduled for deployment at 33 airports in the U.S., includes an AP–Editing algorithm designed to remove AP based on its Doppler–spectrum characteristics in ASR–9 data. This report provides a description of the algorithm currently used in the FAA/Lincoln Laboratory WSP prototype and a measurement of the performance of the algorithm during nine episodes of AP and/or true weather in Orlando, Florida in 1991 and 1992.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

Current Airport Surveillance Radars (ASR–9s) [Taylor and Bronins, 1985] feature a dedicated digital processor that detects and displays six calibrated levels of precipitation reflectivity on terminal Air Traffic Control (ATC) radar scopes. The following parameters of the ASR–9 and its "weather channel" make this system well suited to provide storm location and intensity information for terminal ATC operations:

1. Operation at a non–attenuating 10 cm wavelength,
2. A vertically integrating, cosecant–squared antenna elevation pattern that detects precipitation echoes over the entire altitude interval of concern for terminal operations,
3. An update rate (30 seconds) consistent with the tight temporal and spatial tolerances of terminal ATC, and
4. Real–time display of precipitation reflectivity on the same Data Entry and Display System (DEDS) and Bright Radar Indicator Tower Equipment (BRITE) scopes that radar and tower controllers employ for monitoring aircraft position.

In view of these attributes, the Federal Aviation Administration's (FAA) National Airspace System (NAS) development plan has always considered ASR–9 weather channel as the primary source of storm reflectivity information in terminal airspace, even at airports that are equipped with the Terminal Doppler Weather Radar (TDWR) [Evans and Turnbull, 1989] for low–altitude wind shear detection. ASR–9 weather channel data will likewise be a key input to the Integrated Terminal Weather System (ITWS) [Klingle–Wilson, 1995] which will be deployed at major U.S. airports to provide comprehensive, user–oriented information about weather conditions affecting terminal airspace.

Widespread operational use of the ASR–9 weather channel has revealed one significant issue: ground clutter breakthrough caused by anomalous propagation of radar signals (AP) – superrefractive propagation in an environment characterized by strong, low–altitude moisture and/or temperature gradients. After processing by the weather channel's aggressive spatial and temporal smoothing [Weber, 1986], this clutter breakthrough is largely indistinguishable from actual meteorological echoes. As described in Battan, 1973, such breakthrough can occur both during widespread temperature inversions and as a result of thunderstorm outflows of moist, rain–cooled air. The latter is particularly stressing operationally since the AP–induced "false weather" coexists with actual thunderstorms that are affecting terminal area operations. Numerous "unsatisfactory condition reports" (UCRs) have been filed by air traffic controllers in response to this problem.

The Weather System Processor (WSP) [Weber and Stone, 1995] is a developmental add–on to the ASR–9 that provides detailed automated information on precipitation reflectivity, storm motion, and associated low–altitude wind shear by processing received echoes for meteorological Doppler content. Where implemented, the WSP will assume the functionality of the current ASR–9 six–level weather channel, providing six–level weather reflectivity images to both existing controller scopes (DEDS and BRITE) and a color Geographic Situation Display (GSD) intended for use by supervisory personnel and traffic management specialists. Analysis of the Doppler spectrum and "high" versus "low" receiving beam relative amplitudes of received echoes provides a mechanism for the WSP to discriminate between true meteorological echoes and AP–induced ground clutter breakthrough. This capability has been demonstrated operationally on the Lincoln Laboratory / FAA WSP prototype in Orlando, FL and Albuquerque, NM with good success.

The current FAA NAS architecture calls for deployment of the WSP only at smaller airports not equipped with a TDWR. At the larger TDWR–supported airports, AP–editing will be accomplished by ITWS, which compares ASR six–level reflectivity data with reflectivity data from other weather radars to identify and edit regions of AP contamination [Klingle–Wilson, et al., 1995]. Deficiencies in this technique can occur when the radar used for comparison also experiences AP or when AP conditions are changing rapidly, as relevant data from other radars may be several minutes old. Furthermore, a "cone–of–silence" exists around the corroborating radars due to scanning strategies that do not allow full sampling of nearby storms. Therefore, because of the possibility of editing true–weather echoes, AP editing cannot be performed within this region. Finally, ITWS does not provide AP–edited precipitation on controller's DEDS and BRITE displays. As a result, supervisory personnel at the 45 TDWR–equipped airports where ITWS is planned for deployment will have to verbally relay AP information from their GSD to controllers. This arrangement will increase controller workload.

This report describes the WSP AP–Editing Algorithm and evaluates its performance using data collected during prototype WSP operations in Orlando, FL – an environment subject to frequent and intense episodes of anomalous propagation. Section 2 describes the current FAA / Lincoln Laboratory WSP prototype and its AP–editing approach. Section 3 summarizes the data set used to score the algorithm and describes the scoring exercise. Section 4 lists performance results and Section 5 compares these with off–line ITWS (Integrated Terminal Weather System) AP–Editing results for some of the same test cases. In Section 6, we conclude the report by describing a modular WSP architecture that would allow for relatively low–cost implementation across the NAS of the subset of WSP hardware and software required to generate AP–free precipitation reflectivity information.

2. FAA / LINCOLN LABORATORY WSP PROTOTYPE DESCRIPTION AND AP–EDITING APPROACH

The Weather System Processor is an outboard radar receiving channel and data processing computer, sharing the transmitter, timing signal generation and antenna subsystems of the ASR–9. A high speed vector–oriented processor performs signal input, interference suppression and base–data generation. The base data generated by these operations—precipitation reflectivity (DZ), radial velocity (V), spectrum width (SW) and signal–to–noise ratio (SNR)—are then reformatted by an output processor and distributed to meteorological detection algorithms. These algorithms are implemented by single–board computers or UNIX workstations, and the resulting graphical and/or alphanumeric output is sent to remote workstations and monitors in the air traffic control tower for use by controllers and their supervisors [Weber, 1992].

The signal processing algorithms suppress ground clutter using techniques that are analogous to those employed by the ASR–9's six–level weather processor [Weber, 1987]. "Clear Day Maps" (CDM) are constructed that encode—for each range–azimuth resolution cell—the mean residual clutter power output from each of three separate 17–point finite impulse response (FIR) high–pass filters as well as the mean unattenuated clutter level. The three filters achieve suppression of nominally 16, 31 and 45 dB with associated stop–band widths (at the 3–dB down points) of 2.8, 4.7 and 6.1 m/s, respectively. For each range gate, the least attenuating clutter filter (or an all–pass function) is chosen that permits output signal power to exceed the corresponding mean clutter residue level in the CDM by a threshold (nominally 10 dB). This method minimizes the possibility of reflectivity estimate bias due to filtering of low–Doppler precipitation echoes. Unfortunately, as with the existing six–level weather processor algorithm, AP–induced ground clutter will often be passed through the WSP's clutter suppression module unattenuated since it is not accurately represented by the CDM.

Following clutter suppression, the signal processing algorithms generate DZ, V, SW and SNR products as follows. Autocorrelation function estimates for lags varying from zero to four times the mean pulse repetition interval are computed for both beams and used to generate weather echo spectrum moments. Precipitation reflectivity factor and signal–to–noise power ratio are computed using the low–beam data and a pre–determined estimate of system noise level in each beam. The phase angle of the low–beam estimate provides the Doppler–velocity estimate for the gust front algorithm. Low– and high–beam Doppler–velocity estimates are combined to create a surface velocity field for the microburst detection algorithm [Weber, 1989]. Finally, spectrum width in the low beam is generated by applying a weighted, quadratic regression to the logarithms of the magnitudes of the autocorrelation function estimates.

Puzzo, et al. [1989] suggest various techniques for identifying and censoring AP in ASR–9 data. The method employed in the current WSP prototype involves 1) flagging all range bins with spectrum–width value less than 0.7 m/s as AP, as well as neighboring range bins within a "window" of five range bins, centered on the selected bin, and 2) reducing the possibility of editing true weather by removing the flag for range bins containing Doppler–velocity values greater than 1.0 m/s, even if they lie within the five–bin window mentioned above. These spectrum–width and Doppler–velocity thresholds were chosen based on expected spectral characteristics of clutter breakthrough (e.g., antenna–scan modulation width) and testing with actual data. The current technique and individual parameters employed by the algorithm remain under scrutiny and may be modified. For example, visual comparisons between simultaneous low and high–beam ASR–9 data indicate signal return from the former exceeds that from the latter by 10 dB or more during AP episodes, with larger differences prominent during severe AP cases. This information could also be incorporated into the WSP AP–Editing Algorithm as an additional discriminant. Thus, the results reported here should be viewed as the lower limit of the AP–editing success that is achievable in the WSP.

3. TEST CASES AND SCORING METHODOLOGY

The database used to evaluate performance of the WSP AP–Editing algorithm was limited to time periods when both unedited and AP–edited files were archived. This restricted possible test cases to the late summer of 1991 and early summer of 1992 when the ASR–9 testbed was located in Orlando, FL. Furthermore, data were not routinely collected during late evenings or early mornings when nocturnal inversions often induce AP. The main source of AP episodes, therefore, was cool moist thunderstorm outflows (gust fronts) that passed over the radar site. These episodes typically lasted more than 30 minutes and sometimes a few hours. Table 1 shows the time periods that were identified after an extensive search through the candidate data and subsequently used to evaluate WSP AP–Editing algorithm performance. Three time periods featuring no AP (true weather echoes only) and two periods containing no true weather echoes (AP only) were included in the test set. (The two time periods from 8/9/91 provided one example of each.)

Table 1.
Time Periods Used For WSP AP–Editing Algorithm Evaluation

DAY OF DATA	TIME PERIOD (UT)
8/2/91	2055–2225
8/9/91	2055–2145, 2210–2300
8/10/91	2035–2200
7/10/92	1930–2045
7/13/92	1910–2010
7/15/92	0110–0130
7/17/92	1930–2100
7/18/92	2145–2210
7/20/92	1850–1950

ASR–testbed reflectivity data in 5–dBZ increments and at one or two–minute intervals from these time periods were examined to generate AP truth. The presence of AP was clearly discernable when viewed in this manner because of its highly mottled appearance in contrast to true weather echoes which exhibited smooth transition between dBZ levels (Figure 1). ASR low–beam velocity fields and Terminal Doppler Weather Radar (TDWR) testbed data served as additional guides in the truthing process, as AP returns are usually associated with zero–Doppler velocity and the TDWR was not as susceptible to AP as the ASR. Locations of AP with respect to the radar location were written to data files by using interactive display software that allowed the "truther" to enclose within polygons any AP regions on a particular scan. Then an automated scoring program which compared unedited and AP–edited display files on a pixel–by–pixel basis ascertained whether AP and/or true–weather pixels were correctly/incorrectly edited by referring to the corresponding AP truth file. The scoring software generated cumulative counts for the total number of AP and true–weather pixels within the range considered (28.8 km from ASR), and of the number correctly/incorrectly edited, to yield Probability of Editing AP (PEAP) and Probability of Editing Weather (PEW) statistics. The scoring program also provided an option to ignore regions of contiguous pixels having total area less than a specified value. For this evaluation, pixels comprising contiguous–pixel regions of area less than 1.0 square kilometer were not considered since these small AP patches likely would not be perceived as significant weather by an operational user of the data.

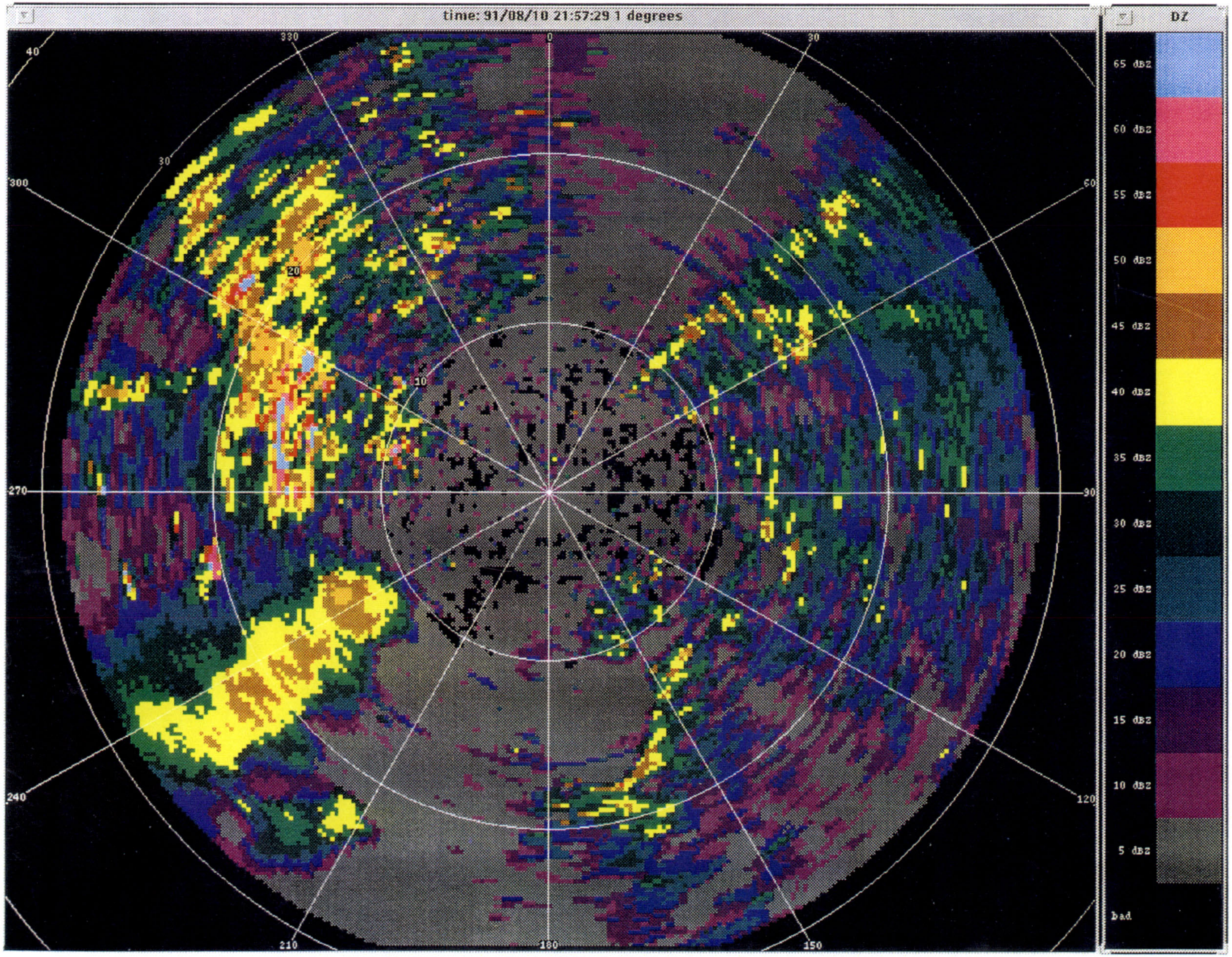

Figure 1. *ASR–9 data showing visual difference between anomalous propagation and true–weather echoes. Ragged echoes to the west through northwest and northeast through south of the radar are caused by AP, while smooth echoes southwest of the radar represent actual precipitation. These visual differences are not apparent to users of ASR–9 data because it is presented in VIP six–level format and smoothed extensively.*

4. PERFORMANCE STATISTICS

Two of the nine data cases (8/10/91 and 7/17/92) had unedited and AP–edited scans that differed by approximately thirty seconds. Initial scoring of these cases revealed that scan–to–scan variation in reflectivity values associated with true weather was too significant to obtain reliable PEW values because **any** change in video integrator processor (VIP) level for a particular pixel location was scored as an "edit." For example, if displacement of a Level–2 weather pixel by a Level–1 pixel was caused by movement of weather during the 30–second interval or by statistical fluctuations in echo strength between the unedited and AP–edited scans, the pixel was deemed edited. This problem was not as pronounced in corresponding PEAP statistics, however, because AP echoes exhibit greater temporal stability. Table 2 summarizes PEAP and PEW statistics obtained from scoring the test data set. For each case, PEAP is expressed as the ratio of AP pixels that were (correctly) edited to the *total* number of AP pixels, while PEW is expressed as the ratio of true–weather pixels that were (incorrectly) edited to the total number of true–weather pixels.

Table 2.
AP–Editing Statistics: WSP AP–Editing Algorithm

DATE	PIXELS ≥ VIP Level 3				PIXELS ≥ VIP Level 2			
	PEAP	%	PEW	%	PEAP	%	PEW	%
8/2/91	1755 / 1889	93	24 / 3431	0.7	16,445 / 17,414	94	579 / 15,883	3.6
8/9/91 *	17,014 / 17,640	96	0 / 2622	0	59,688 / 64,799	92	22 / 11,336	0.2
8/10/91	4047 / 4290	94	NA	–	22,550 / 24,525	92	NA	–
7/10/92	215 / 225	96	10 / 434	2.3	6012 / 6784	89	306 / 3473	8.8
7/13/92	no AP	–	94 / 15,859	0.6	no AP	–	437 / 46,066	0.9
7/15/92	no AP	–	140 / 30,918	0.5	no AP	–	709 / 72,944	1.0
7/17/92	5914 / 6024	98	NA	–	30,091 / 30,721	98	NA	–
7/18/92	913 / 950	96	0 / 358	0	5573 / 5896	95	51 / 2240	2.3
7/20/92	1160 / 1261	92	–	–	7168 / 7713	93	0 / 108	0
TOTALS	31,018 / 32,279 (96.1%)		268 / 53,622 (0.5%)		147,527 / 157,852 (93.5%)		2104 / 152,050 (1.4%)	

* PEAP statistics are from 2055–2145 time period; PEW statistics are from 2210–2300

PEAP for the individual cases varied from 92–98 percent for VIP level 3 or greater, and 89–98 percent for VIP level 2 or greater. PEW varied from 0–2 percent and 0–9 percent for these categories, respectively. As expected, the performance statistics improve with stronger intensity echoes which occur less frequently but are more easily distinguishable as true weather or AP. Close examination of data from instances of mis–editing indicated most failures to edit actual AP (i.e., PEAP less than 100 percent) involved very small areas of residual breakthrough, while editing of actual weather (i.e., non–zero PEW) involved mainly VIP level 2 returns that were typically on the edge of a precipitation region. Figure 2 is a side–by–side comparison of unedited and AP–edited images that provides an example of the latter occurrence. An overall qualifier of the WSP AP–Editing Algorithm's performance observed with this data set is that all significant AP regions were edited sufficiently to prevent misinterpretation of residual breakthrough as a plausible storm cell, and that no precipitation cells with cores greater than or equal to VIP level 3 were reduced entirely to VIP level 2 or below.

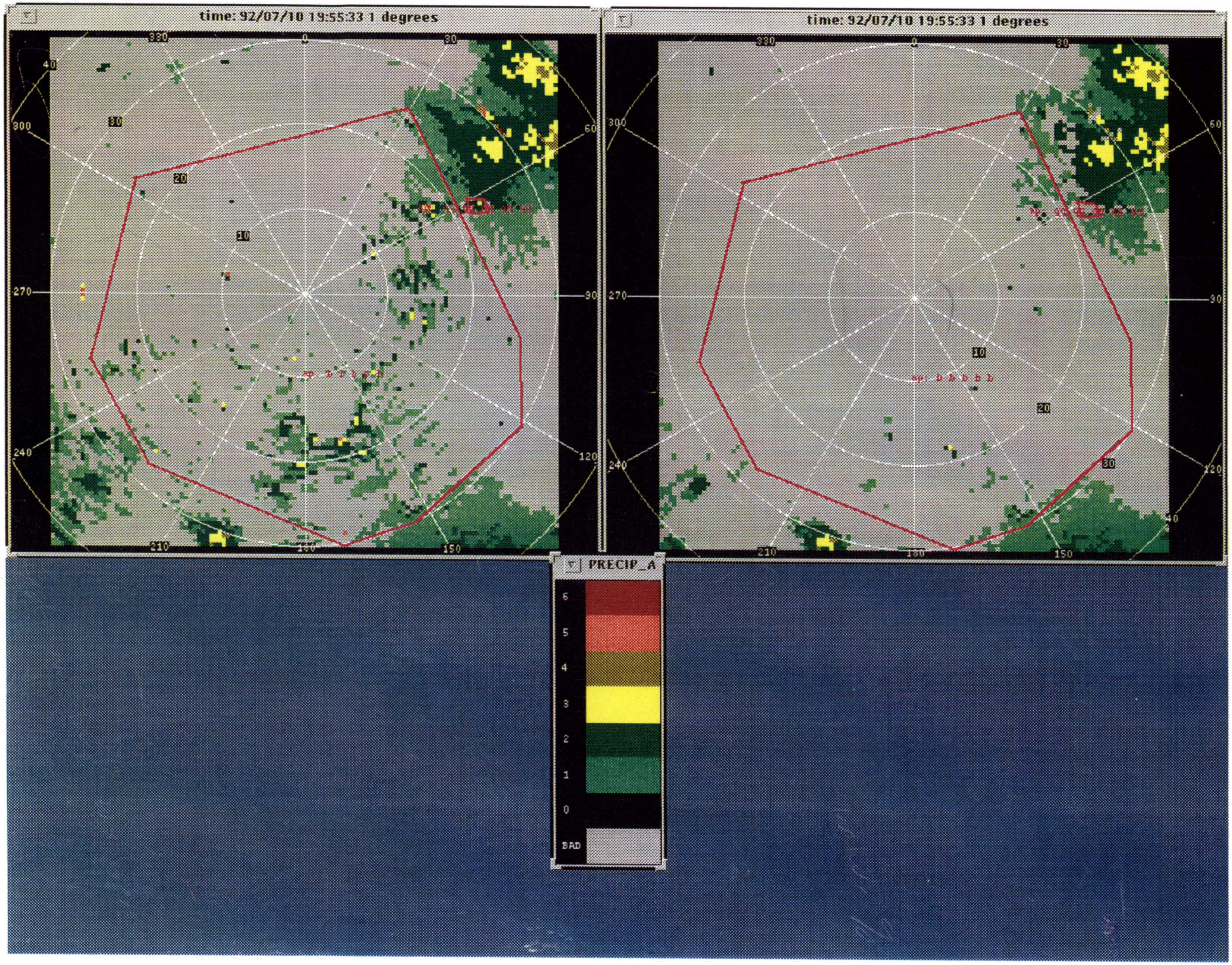

Figure 2. Unedited (left) and corresponding AP–Edited data (right) from 7/10/92. Note removal of most AP–induced echoes within AP–truth region denoted by pink polygon. VIP Level 2 weather echoes approximately 25 km northeast of radar were also edited, resulting in relatively high PEW for this scan.

5. COMPARATIVE RESULTS

As indicated previously, ITWS will censor AP breakthrough on ASR–9 weather channel data displayed on dedicated Situation Displays at supervisors' positions. To obtain a sense of comparative performance, an off–line version of the ITWS AP–Editing Algorithm was run on three of the test cases used to evaluate WSP AP–Editing results. The three cases chosen were among the most active AP periods. To simulate the performance of the ITWS AP–editor, TDWR volume scans were "layered" to serve as the Composite Maximum Reflectivity (comprefl) product needed by the algorithm to perform editing (Klingle–Wilson, et al., 1995). In the layering process, the maximum reflectivity value found within the vertical column above each 0.5 square–kilometer resolution bin was used for the composite. Because the testbed TDWR was often in *hazardous* scanning mode during these time periods, the scoring had to be restricted to the sector scanned by the radar. This usually corresponded to a region spanning 100–150 degrees in azimuth. Furthermore, although the height of the highest TDWR elevation scan (40–60 degrees) was significantly higher than in the current NEXRAD (NEXt Generation Weather RADar) scanning strategy (approximately 20 degrees), a TDWR cone–of–silence did exist and required that no editing (or scoring) be done within five kilometers of the TDWR. The results of the ITWS AP–Editing simulation appear in Table 3, and a comparison of these with corresponding WSP AP–Editing results are shown in Table 4.

Table 3.
Simulated ITWS AP–Editing Results

DATE	PIXELS $\geq$ VIP Level 3		PIXELS $\geq$ VIP Level 2	
	PEAP	PEW	PEAP	PEW
8/2/91	712 / 719	0 / 2349	4062 / 4990	40 / 10,976
8/9/91	8271 / 10,276	0 / 2009	26,116 / 40,720	0 / 7424
7/17/92	619 / 619	0 / 289	2841 / 3304	0 / 3052

Table 4.
Comparison of ITWS and WSP AP–Editing Results

DATE	PEAP ($\geq$ VIP 3)		PEW ($\geq$ VIP 3)		PEAP ($\geq$ VIP 2)		PEW ($\geq$ VIP 2)	
	ITWS	WSP	ITWS	WSP	ITWS	WSP	ITWS	WSP
8/2/91	99%	93%	0%	0.7%	81%	94%	0.4%	3.6%
8/9/91	80%	96%	0%	0%	64%	92%	0%	0.2%
7/17/92	100%	98%	0%	N/A	86%	98%	0%	N/A

These limited results indicate the performance of the WSP AP–Editing algorithm is comparable to that of the ITWS AP–Editor. The ITWS version is clearly more conservative in its editing, as evidenced by frequent PEWs near zero percent. This conservatism is also the cause of lower PEAPs at the VIP 2 intensity level relative to the WSP version. A recent performance evaluation of the ITWS AP–Editing algorithm (Klingle–Wilson, et al., 1995) yielded overall PEAPs of 91 percent for pixels greater than or equal to VIP level 3 and 80 percent for pixels greater than or equal to VIP level 2. The corresponding WSP AP–Editing numbers reported here (Table 2) are 96.1 percent and 93.5 percent, respectively. In the Klingle–Wilson evaluation, PEWs were 0 and 1 percent for the above VIP–level categories, while corresponding WSP AP–Editing PEWs reported here are 0.5 and 1.4 percent.

6. CONCLUSION AND RECOMMENDATION

The results presented in this report indicate the WSP AP–Editing algorithm can provide a reliable capability for editing anomalous propagation contamination from ASR–9 weather–channel reflectivity data. The algorithm takes full advantage of the rapid update rate of the ASR radar in determining what data pixels should be edited, and covers all of the terminal airspace. Scoring comparisons with the ITWS AP–Editing algorithm indicate the WSP AP–Editing algorithm provides comparable performance in editing strong AP (VIP level 3 or greater) and appears superior in editing lower intensity AP. The WSP AP–edited data will also be directly available to air traffic controllers on their DEDS and BRITE displays.

Figure 3, a high–level architecture for the WSP, indicates that the Radar Data Acquisition (RDA) unit—the subsystem responsible for extraction of necessary signals from the ASR–9 and generation of base data fields—can be cleanly separated from subsequent wind shear and storm motion product generation and display. We have recommended that the production WSP be designed so that the RDA can be deployed, standalone, as a six–level weather channel replacement at non–WSP sites. This approach would allow the FAA to resolve the AP problem, as well as other identified deficiencies of the weather channel, at larger airports that do not require the full WSP owing to the deployments of TDWR. As noted previously, although ITWS will display AP–edited weather channel data to ATC supervisors at these airports, radar and tower controllers will not have direct access to this information. A decision to deploy this configuration could be made on an airport–by–airport basis, but would probably be very beneficial, in terms of cost, at many large airports.

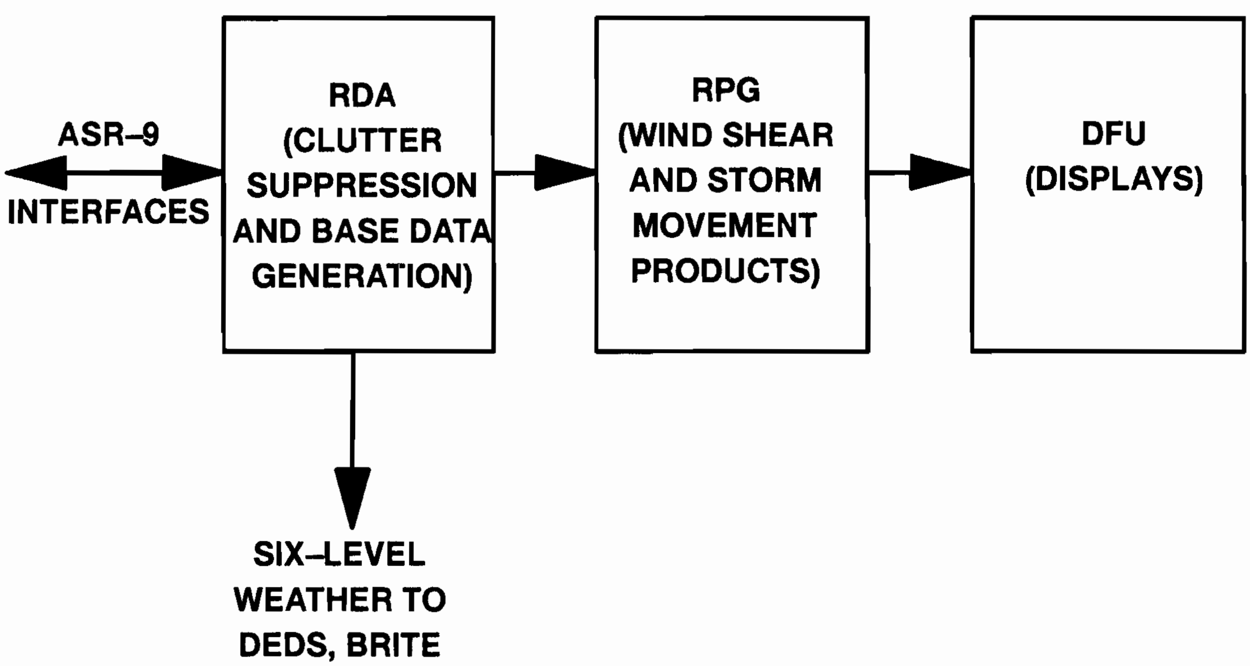

Figure 3. WSP high–level architecture.

GLOSSARY

AP	Anomalous Propagation
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
BRITE	Bright Radar Indicator Tower Equipment
CDM	Clear Day Map
DEDS	Data Entry and Display System
DZ	Precipitation Reflectivity
FAA	Federal Aviation Administration
FIR	Finite Impulse Response
GSD	Geographic Situation Display
ITWS	Integrated Terminal Weather System
NAS	National Airspace System
NEXRAD	NEXt Generation Weather RADar
PEAP	Probability of Editing AP
PEW	Probability of Editing Weather
RDA	Radar Data Acquisition
SNR	Signal–to–Noise Ratio
SW	Spectrum Width
TDWR	Terminal Doppler Weather Radar
UCR	Unsatisfactory Condition Report
V	Radial Velocity
VIP	Video Integrator Processor
WSP	Weather System Processor

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