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# ASR-9 WEATHER SYSTEMS PROCESSOR (WSP): WIND SHEAR ALGORITHMS PERFORMANCE ASSESSMENT\*‡

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## 1. INTRODUCTION

Under Federal Aviation Administration sponsorship, Lincoln Laboratory has developed a prototype Airport Surveillance Radar Weather Systems Processor (ASR-WSP). This prototype has been used for field measurements and operational demonstrations since 1987. Measurements so acquired provide an extensive database for development and validation of the algorithms used by the WSP to generate operational wind shear information for Air Traffic Controllers. In this paper we assess the performance of the current versions of the WSP's microburst and gust front wind shear detection algorithms on data from each of the locations at which our prototype system has operated. Evaluation of the associated environmental characteristics (e.g., storm structure, radar ground clutter environment) allows for generalization of these results to the major U.S. climatic regimes where the production version of WSP will be deployed.

The WSP addresses two forms of thunderstorm-generated low-altitude wind shear. Microbursts occur when intense, small-scale downdrafts from thunderstorms reach the earth's surface and diverge horizontally in a roughly cylindrically symmetric pattern. Aircraft penetrating the resulting surface wind outflow encounter a dangerous headwind to tailwind velocity transition (i.e., loss of airspeed) and may experience additional control problems associated with the core downdraft or other smaller scale circulations in the microburst. Microburst onset times may be extremely short, with the divergent outflow reaching peak intensity within a few minutes of the downdraft first reaching the surface.

Gust fronts are the leading boundary of larger-scale thunderstorm outflows which may propagate tens of kilometers away from the generating precipitation. Convergent wind shear (i.e., an increasing headwind) encountered by an aircraft penetrating a gust front is considered less hazardous than the loss associated with

a microburst. The winds behind the front, however, are turbulent and the long-term change of wind speed/direction following passage of the front affects runway operations. Tracking and predicting gust front arrivals before they reach an airport allows for more efficient use of runways.

Runway-specific microburst alerts (losses equal to or exceeding 30 kts or approximately 15 m/s) or wind shear alerts (losses less than 30 kts and all gains) are displayed on an alphanumeric ribbon display terminal (RDT) to be read verbatim to affected pilots by the Tower local controller. A color Geographic Situation Display (GSD) provides ATC supervisory personnel general information on convective weather in terminal airspace, showing the location and movement of thunderstorm cells and gust fronts and the position of microbursts. This information is generated in a totally automated fashion using computer algorithms that:

1. Process the "raw" echoes received by the radar to generate base data, which is imagery of precipitation reflectivity and Doppler spectrum content; and
2. Recognize operationally relevant features in the spatio-temporal structure of these base data images; for example, the presence, intensity and movement of low-altitude wind shear.

The accuracy of the operational products provided by the WSP is a function of both stages of algorithm processing. The performance assessments provided here are end-to-end in the sense that "truth" for the wind shear products scoring is provided by examination of data from sensors (generally pencil-beam weather radar) that are independent of the ASR-9.

Section 2 of this paper provides background on the WSP prototype system, its data processing algorithms, and the scoring methodology we have used to quantify performance. For each of the testbed deployment sites, Section 3 describes relevant radar configuration details, information on the weather and ground clutter environment, and finally, the results of our microburst and gust front detection performance assessment. In Section 4 we summarize expected wind shear characteristics in the major U.S. climatic regimes in which the WSP will be deployed and use the results of our site-specific analysis to estimate WSP performance in each regime.

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## 2. WSP PROTOTYPE SYSTEM, DATA PROCESSING ALGORITHMS AND PERFORMANCE ASSESSMENT METHODOLOGY

The FAA/Lincoln Laboratory WSP testbed was originally deployed in 1987, hosted on an ASR-8, and instrumented primarily to acquire and record quadrature video samples for both high- and low-beam receive paths out to the range of operational concern for wind shear detection. A real-time signal processor was added in 1988, and full-up WSP prototype operational tests began in 1990 and have continued each summer thereafter. Throughout these later operations, full capability to archive both base data and "raw" radar samples has been maintained. In this section, we describe relevant details of the testbed configuration, the data processing algorithms that have been developed to generate wind shear products, and the methodology we employ to quantify performance.

### 2.1 Prototype System Overview

The prototype Weather Systems Processor as it has operated since our first operational demonstration in 1990 is comprised of:

1. An ASR-8 or ASR-9 host radar;
2. Interfaces to extract necessary radio frequency (RF) and timing signals;
3. Identical receivers and A/D converters for the high- and low-beam receiving channels of the host radar;
4. A digital signal processor that suppresses interference (e.g., ground clutter) and computes base data (i.e., estimates of weather reflectivity, Doppler velocity and spectrum width for each range-azimuth resolution cell)
5. Recorders to archive both unprocessed in-phase and quadrature (I and Q) radar samples, and base data;
6. Single-board computers and workstations that run the microburst and gust front detection algorithms, the storm motion algorithm, generate precipitation reflectivity maps, and transmit the resulting products to the air traffic control tower; and
7. Remote workstations and monitors that provide graphical and alphanumeric displays to air traffic controllers and their supervisors.

It is important to note that this prototype has not fully emulated engineering design details that will be realized with the production WSP. In particular, the prototype's receive chain design has evolved over the testbed's operating history in order to achieve increasing sensitivity for the detection of "dry" wind shear phenomena such as gust fronts. During its early years of operation, net receive chain sensitivity was 5 to 15 dB less than will be achieved with the production WSP.

This fact precludes quantitative assessment of gust front detection capability at the first two prototype sites (Huntsville and Kansas City).

### 2.2 Synopsis of Relevant Algorithms

#### 2.2.1. Base Data Generation Algorithms

The principal elements of the base data generation algorithms are described in Weber [1987, 1989]. For each radar resolution cell, these algorithms suppress ground clutter and estimate the reflectivity, mean low-altitude Doppler velocity and spectrum width of the meteorological echoes. High- and low-beam signals are processed on alternating scans of the antenna. Ground clutter suppression is accomplished using a data adaptive approach that minimizes distortion of the weather echo spectrum in the filtering process. The output of the clutter suppression module is passed to an auto-correlator that generates estimates of the signal auto-correlation function for both high and low beams at delays from zero to four times the average pulse repetition interval. The precipitation reflectivity factor, Doppler velocity and spectrum width are calculated using the output of the auto-correlator. Data quality flags are generated where contamination from ground clutter breakthrough, out-of-trip weather and velocity folding occur and are used by the meteorological product algorithms in assessing the validity of associated base data.

#### 2.2.2. Microburst Detection Algorithm

The WSP microburst detection algorithm is a two-stage process. The first stage, described by Newell and Cullen [1993], searches for candidate divergence signatures in the low-altitude Doppler velocity field. A straightforward radial-by-radial search is performed for the characteristic increasing (with range) velocity signature associated with microburst outflows. The resulting shear segments are then subjected to scan-to-scan continuity tests, grouped azimuthally and passed on to the second stage verification process that ensures that the candidate microburst detections are physically plausible. This verification process utilizes advanced image processing and expert system technology to assess whether the spatial and temporal structure of the liquid water (i.e., reflectivity) field associated with candidate microburst detections is consistent with physical expectations.

#### 2.2.3. Gust Front Detection Algorithm

The WSP's Machine Intelligent Gust Front Detection algorithm [Delanoy and Troxel, 1993] exploits image processing/expert system technology developed at Lincoln Laboratory originally in the context of Automatic Target Recognition. MIGFA employs multiple,

independent functional template correlators that search the WSP's reflectivity and Doppler velocity imagery for features that are selectively indicative of gust fronts. Because the ASR-9's intrinsic sensitivity is often inadequate to directly measure the convergent radial velocity pattern associated with gust fronts, MIGFA's feature detectors are designed to recognize manifestations of the thin line echo along a front's leading edge. This subtle feature can be recognized as a slight enhancement in radar reflectivity relative to background and/or as a line of spatially coherent Doppler velocity estimates embedded in a noise background where gate-to-gate estimate variance is much higher. Movement of thin lines through a background of stationary ground clutter residue and slower moving storm cells aids in their identification.

The outputs of the feature detectors are expressed as interest images, whose values (0 to 1) specify the degree of evidence that a gust front is present. The multiple interest images are fused to form an overall map of evidence indicating the locations of possible gust fronts. From this image, fronts are extracted as chains of points (events) and correlated with prior events to establish speed and direction of motion. Forecasts of gust front/wind shift impact at an airport are generated by extrapolating the front's current position using this motion estimate.

## 2.3 Scoring Methodology

### 2.3.1. Microburst Algorithm

The performance scoring utilized in this report characterizes the end-to-end capability of the WSP microburst detection system (i.e., sensor, base data generation algorithms and meteorological product generation algorithms) to automatically detect loss-inducing wind shear. Truth is generated through manual examination of the base data fields generated by the supporting sensors (principally pencil-beam weather radars such as the Lincoln/FAA TDWR testbed) described in Section 3. User-interactive software allows the analyst to draw, with a mouse, arbitrarily shaped polygons over the displayed data to enclose microbursts or wind shears with loss. Coordinates defining these polygons are entered into the truth database for automatic comparison with the corresponding shapes that define detections from the WSP. Note that the supporting radars often scanned only a portion of the area covered by the WSP and typically updated their near-surface data at intervals of one to three minutes. WSP detections that were outside the areas covered by the truth radars or were displaced by more than 30 seconds from the nearest truth radar scan were not scored.

A hit is defined as a WSP-generated microburst shape that overlaps a truth polygon. Should more than one WSP-generated shape overlap a truth, only one hit is tabulated. A false alarm is tabulated for each WSP-generated report that does not intersect a truth polygon. Probability of detection (Pd) is defined as the ratio of the number of hits to the total number of wind shear polygons in the truth database. Probability of false alarm (Pfa) is the ratio of the number of false alarms to the total number of WSP reports (i.e., the sum of hits and false alarms). In this report, both statistics are presented for categories of increasing microburst intensity. The categories for Pd refer to the differential velocities of the events considered in the truth database. Thus, for the " $\geq 15$  m/s" category, wind shear events with true differential velocity of less than 15 m/s are effectively deleted from the truth database in calculating Pd. For Pfa, these categories refer to the differential velocity reported by the WSP algorithms. Thus, again considering the " $\geq 15$  m/s" category, WSP reports with differential velocity less than 15 m/s would not be considered in tabulating false alarms.

### 2.3.2. Gust Front Algorithm

Gust front hit-miss statistics are tabulated analogously to those presented for the microburst algorithm. Truth polygons in this case are taken as elongated eight-kilometer-wide corridors centered on the line of maximum velocity convergence and/or thin line intensity as determined from the truth radar data. Hits, false alarms, Pd and Pfa are then calculated as above based on whether the WSP's reported gust front lines intersect or miss truth polygons. The relatively broad width of the truth polygon accounts for the finite extent of the region of convergent shear associated with a gust front and for time differences between available near-surface data from the truth radar and the WSP reports. A maximum time difference of two minutes is allowed before the WSP reports are not scored.

## 3. WIND SHEAR DETECTION PERFORMANCE AT PROTOTYPE OPERATING SITES

### 3.1 Huntsville, Alabama, 1987-1988

#### 3.1.1 Testbed Configuration

One channel of a Navy ASR-8 was deployed to a site just west of the airport in Huntsville, Alabama in the summer of 1986. The radar and associated quadrature video recording system were operational by autumn, and the first Doppler weather imagery from the testbed was generated (off line from the recorded raw radar data) over the winter. Based on the successful summer 1987 off-line demonstration that microburst and gust

front signatures could be extracted from the testbed signals, a first implementation of a real-time signal processor was deployed in 1988. This facilitated effective data collection, monitoring, and scoring.

The net effect of the ASR-8 parameters and the WSP receive chain configuration was to substantially reduce receiver sensitivity relative to that of the eurrent prototype and the production WSP. Net reduction in low-beam sensitivity was 16 dB at 5 km and 6.5 dB at 15 km. In Huntsville, this would not likely have affected results for the microburst detection function since essentially all microbursts at this site are "wet" and therefore exhibit high radar reflectivity. Detection of the much less reflective thin-line signatures associated with gust fronts is substantially degraded, with the net lowering of system sensitivity. For these reasons we have not attempted to quantify WSP gust front detection capability at the Huntsville site. The later Orlando data sets, collected with a more appropriate set of radar and receive chain parameters, provide gust front detection results representative of what would likely be achieved at Huntsville with the WSP.

### 3.1.2 Truth Sensors

An essentially co-located C-band 1.4° pencil-beam weather radar (operated under subcontract to the MIT Center for Meteorology) provided the primary source of truth for evaluation of the WSP algorithms. This is a coherent-on-receive magnetron system, providing good sensitivity. We estimate that the radar can measure reflectivity and Doppler velocity to 30 km for weather exceeding 0 dBz reflectivity.

### 3.1.3 Environmental Characteristics

The combination of significant low-level moisture and strong daytime surface heating in the absence of significant vertical wind shear leads to the occurrence of "air-mass" thunderstorms in the southeastern U.S. during the summer months. From fall to early spring, however, thunderstorms here are induced by strong frontal systems associated with considerable vertical shear due to the proximity of the polar jet stream. Microbursts in Huntsville are "wet", i.e., characterized by core radar reflectivities greater than 30 dBZ and measurable surface precipitation.

### 3.1.4 Microburst Detection Performance

Storm data from five different days in Huntsville were scored to characterize microburst detection algorithm performance in the Huntsville environment. This relatively small database (approximately 3-1/2 hours total, involving nearly 30 separate microburst events) was chosen as representative of the storms that occurred near the prototype over the two-year operating period.

Approximately 2500 images of WSP and radar imagery were scored for the evaluation. Difficulties in recovering Huntsville data, caused by aging digital tapes and subsequent changes in our prototype's processing hardware/software, precluded scoring over the larger databases employed at subsequent operating sites.

Table 1 lists microburst detection (Pd) and false alarm (Pfa) probabilities for this data set. Given uncertainty in exactly measuring these parameters using finite wind shear databases, the statistics in Table 1 are consistent with those derived from the very similar Orlando environment where wet microbursts associated with air mass thunderstorms are also predominant. For the overall population of divergent shears, the Pd was 84 percent, increasing to 95 percent for events exceeding the 15 m/s "microburst alert" threshold. False-alarm probability decreases from 20 percent for all "loss" alerts to 13 percent for "microburst" alerts.

Note that the majority of "misses" and "false alerts" tabulated for the weak shear strength category are the result of relatively small discrepancies between the loss intensities reported by the WSP and the pencil-beam radar employed as "truth". For example, a WSP differential velocity report of 11 m/s in association with a truth radar reading of 9 m/s would be tabulated as a false alert and reversed readings would constitute a miss. Operationally, it is doubtful that this class of "erroneous" WSP report would be perceived as incorrect. For this data set as for those at subsequent prototype operating sites, the arbitrary 10 m/s alert/no-alert threshold somewhat distorts (in a pessimistic direction) the extent to which measured performance statistics for weak divergent shears reflect the "operational" reliability of the product.

TABLE 1  
ASR-9 Microburst Detection Algorithm  
Scoring Results for Huntsville

| Event Strength | Pd   | Pfa  |
|----------------|------|------|
| ≥10 m/s        | 0.84 | 0.20 |
| ≥15 m/s        | 0.95 | 0.13 |
| ≥20 m/s        | 1.00 | 0.11 |

## 3.2 Kansas City, Kansas, 1989

### 3.2.1 Testbed Configuration

The WSP testbed was re-located to a rural site overlooking the Missouri River valley some 15 km southwest of Kansas City International Airport. The site was characterized by relatively intense ground clutter from the bluffs of the Missouri River valley and the rolling terrain. As in Huntsville, the radar parameter settings

significantly reduced sensitivity relative to later WSP designs, with the primary expected impact being on gust front detection. For this reason we again do not present a statistical analysis of the WSP's gust front detection capability in Kansas City.

### 3.2.2 Truth Sensors

The WSP testbed was essentially co-located with the FAA/Lincoln Laboratory Terminal Doppler Weather Radar (TDWR) prototype, FL-2. At that time, this radar operated at S-band, producing a 1° pencil beam. Over the range of concern for evaluation of the WSP products (30 km), FL-2 had sensitivity sufficient to reliably measure reflectivity and Doppler velocity for wind shear phenomena with reflectivity of approximately -5 dBz or greater. The Klystron transmitter provided excellent stability, thereby supporting ground clutter suppression approaching -50 dB. In most cases, FL-2 performed a 120° sector scan centered on the airport. Full PPI scans at the surface were performed only once every five minutes. Unfortunately, the University of North Dakota pencil-beam radar that was also deployed to support the FAA wind shear measurements at Kansas City likewise performed a sector scan over the airport and did not provide significant coverage in this back sector. Thus, full scoring of the WSP testbed's products was limited to about one-third of the area that would be of operational concern for an on-airport WSP.

### 3.2.3 Environmental Characteristics

The prevalence of nocturnal low-level jet streams over the midwestern U.S. often sustains thunderstorm development (non air-mass) into the nighttime hours. Thus, a more significant difference relative to the southeastern U.S. sites is the presence of strong, vertical speed and directional shear in the ambient horizontal wind field in which Midwestern thunderstorms form. This shear serves to organize the convection into long-lived, meso-scale complexes that propagate rapidly and for long distances. Associated "sloping" of precipitation shafts is a significant issue for low-altitude wind shear detection with the ASR-9's fan beams. In some circumstances, reflectivity aloft may exceed that at the surface by many orders of magnitude, making it virtually impossible for the radar to measure the near-surface wind field accurately. This circumstance does not directly affect the ability to detect microbursts since, as indicated above, these are predominantly associated with surface rain. However, false divergent velocity signatures may result when changes in wind with altitude are "interpreted" by the fan beam as horizontal wind shear.

Data collected by the TDWR testbed indicates that about one-half of all Kansas City microbursts are haz-

ardous to aviation (stronger than 15 m/s) and that they are predominantly wet. Median reflectivity factor (~45 dBz), however, is substantially less than was observed in either Huntsville or subsequently in Orlando (~50dBz) [Evans, 1990; Bernella, 1991].

### 3.2.4 Microburst Detection Performance

False divergence signatures generated by the sloping storm structures described above are most prevalent near the edges of storm cells, or in other regions where the vertically integrated reflectivity seen by the ASR's beam has a significant horizontal gradient. To reduce the occurrence of false alarms from this mechanism, the verification stage of the WSP's microburst detection algorithm aggressively filters out divergence signatures that are centered outside the significant reflectivity contours in a storm cell. Although this and other image processing techniques are effective in holding false alert probabilities down, occasionally they may also eliminate alerts for true divergent shears.

Detection and false-alarm statistics from the Kansas City database are listed in Table 2. Data are from a representative set of thunderstorm episodes, acquired on ten different days. The database encompasses six hours in total, and approximately 45 discrete microbursts. Forty-three hundred WSP images were scored against truth. These periods include most of the significant convection that occurred at the test site during the Kansas City campaign.

TABLE 2  
ASR-9 Microburst Detection Algorithm  
Scoring Results for Kansas City

| Event Strength | Pd   | Pfa  |
|----------------|------|------|
| ≥10 m/s        | 0.67 | 0.21 |
| ≥15 m/s        | 0.87 | 0.15 |
| ≥20 m/s        | 0.99 | 0.09 |

Relative to southeastern U.S. air-mass thunderstorm environments, the Pd at Kansas City was lower, particularly for divergent wind shears below the "microburst alert" threshold. Overall, about two-thirds of all divergent shears were detected by the prototype, rising to almost 90 percent at the 15 m/s "microburst" threshold. Higher detection probabilities in this environment could readily be attained if Pfa were allowed to rise.

## 3.3 Orlando Florida, 1990-1992

### 3.3.1 Testbed Configuration

The WSP testbed was moved to Orlando, Florida in the spring of 1990, along with the TDWR prototype and other supporting sensors [Noyes et al., 1991]. The WSP

testbed occupied the former on-airport site of the FAA's operational radar (ASR-8) which had been vacated upon commissioning of its ASR-9. During the Orlando field program, the host radar for the WSP prototype was upgraded from an ASR-8 to an ASR-9, and the WSP receiver's dynamic range was increased substantially. Gust front detection was identified as a system requirement so that, in contrast to previous operations, a database was acquired that was appropriate for quantitative evaluation of WSP gust front capability.

### 3.3.2 Truth Sensors

As in Kansas City, the FL-2 TDWR prototype was generally the preferred reference for scoring of WSP products. For operations in Florida, this radar was converted to the C-band operating frequency used in the production TDWR. Because FL-2 was not co-located with the WSP testbed, radar viewing angles for some wind shear events differed significantly between the two radars. When there was concern that asymmetry in the strength of microburst outflow winds might be a factor in differences between WSP and TDWR testbed measurements of a microburst, we examined data from either the University of North Dakota or MIT C-band weather radars (whichever had a viewing angle to the event most similar to the WSP testbed) to arbitrate.

### 3.3.3 Environmental Characteristics

Air-mass thunderstorms form almost daily during the summer months in Orlando, often aided by the propagation of sea-breeze fronts that migrate eastward and/or westward across the Florida peninsula. Since these phenomena are instigated by daytime surface heating, most summertime microbursts in Florida occur during the daylight hours, with a few lingering into the early evening. As mentioned previously, all microbursts in the southeastern U.S. are classified wet. Median core reflectivities in Orlando microbursts were measured to be 50dBz.

Gust fronts observed in Orlando were characterized by low to moderate thin line reflectivity values and weak convergence strengths. Median gust front thin line reflectivity was 15 dBz. Seventy-two percent of Orlando gust fronts exhibited maximum convergence strength less than 10 m/s.

### 3.3.4 Microburst Detection Performance

Table 3 lists detection and false-alarm statistics for the WSP's microburst detection function operated over the three years of the Orlando field program. The database is from thunderstorm episodes on 34 days during this period, encompassing approximately 30 hours of convective storm activity and 200 discrete microburst events. Twenty-one thousand single-scan images from

the WSP were scored against truth radar data.

As in Huntsville, the prevalence of air mass (weakly sheared) thunderstorm cells, high radar cross sections in microbursts and the benign clutter environment contribute to a high overall probability of detection and low to moderate false-alarm probabilities for all strength categories. The Pd at the microburst alert threshold is 91 percent, with an associated false-alarm probability of six percent.

**TABLE 3**  
ASR-9 Microburst Detection Algorithm  
Scoring Results for Orlando

| Event Strength | Pd   | Pfa  |
|----------------|------|------|
| $\geq 10$ m/s  | 0.80 | 0.12 |
| $\geq 15$ m/s  | 0.91 | 0.06 |
| $\geq 20$ m/s  | 0.96 | 0.04 |

### 3.3.5 Gust Front Detection Performance

Data from eight thunderstorm days during the 1991 and 1992 storm seasons were evaluated to estimate WSP gust front detection performance in the Orlando environment. Approximately 630 images of WSP and TDWR data were compared, encompassing more than 25 hours of data collection. Statistics summarizing detection performance are presented in Table 4. Detection probability for fronts with associated convergent velocity differential exceeding 10 m/s was 67 percent, increasing to 73 percent for fronts with  $\Delta V \geq 15$  m/s.

**TABLE 4**  
ASR-9 Gust Front Detection Algorithm  
Scoring Results for Orlando

|    | $V \geq 10$ m/s | $V \geq 15$ m/s | Pfa  |
|----|-----------------|-----------------|------|
| Pd | 0.67            | 0.73            | 0.11 |

## 3.4 Albuquerque, New Mexico, 1993-1995

### 3.4.1 Testbed Configuration

The testbed was relocated to Albuquerque International Airport (ABQ) in the spring of 1993 for data collection and operational demonstrations in an arid, High Plains environment. An on-airport site with unobstructed viewing to the runways and principal approach and departure corridors was chosen. Our testbed siting choices differ significantly from those the FAA employed in siting its ASR-9 at Albuquerque. The FAA's radar is sited in a natural depression (serving as a clutter fence for the radar), and its antenna is tilted up-

wards  $0.5^\circ$  relative to the normal ASR setting. These choices reduce interference from the severe ground clutter at ABQ but also reduce radar illumination at low altitude where wind shear phenomena are most manifest. It is unclear whether the differences in our siting and antenna tilt, relative to those used for the FAA's radar at Albuquerque, would lead to a net increase or decrease in wind shear detection performance.

#### 3.4.2 Truth Sensors

The MIT C-band radar used previously in Orlando and Huntsville was deployed at a site approximately 3 nmi south of the WSP testbed as our primary source of truth for the WSP's wind shear products. As noted previously, this radar's sensitivity is adequate to detect wind shear with reflectivity of 0 dBZ or greater. However, limited clutter suppression capability associated with the radar's magnetron transmitter makes accurate measurement of low reflectivity weather echoes problematic in intense ground clutter areas around ABQ. In most cases, the spatial extent of the wind shear phenomena is sufficiently large relative to the clutter-obscured area that a human data interpreter can adequately truth the event. In the circumstance where actual wind shear events were invisible to our truth radar – an event we believe was rare, based on visual observations of wind shear cues and wind data from a MESONET array – the effect would have been to undercount the occurrence of missed detections (if the WSP likewise did not detect the event) or over count false alarms (if the WSP did detect the event).

#### 3.4.3 Environmental Characteristics

Albuquerque International Airport is located on a plateau south of the city of Albuquerque. The terrain rises steadily to the east and northeast before reaching the shear faces of the Sandia Mountains. These extend at their highest elevation more than 1800 m above the altitude of the airport. To the west, the terrain falls off 100 meters or more to the Rio Grande River Valley, then rises steadily over many miles to a level approximately 120 m higher than that of the airport. Ground clutter resulting from this significant topographic relief is extreme. In addition to the topography, large hangars and buildings on Kirtland Air Force Base to the northeast of the testbed produce intense discrete clutter sources at short range. The median equivalent weather reflectivity factor for clutter within 15 km of the testbed is 32 dBZ, and in 10 percent of the resolution cells within this range, equivalent clutter reflectivity exceeds 60 dBZ.

More than one-half of Albuquerque's annual thunderstorm days occur in late summer (July–August) in conjunction with the monsoon season in the desert

Southwest. Summertime thunderstorms are air-mass type, but peak occurrence is in early evening, possibly delayed by a “deficit” of atmospheric moisture, relative to other testbed locations. This relative lack of moisture is also evident in the frequent occurrence of dry microbursts in Albuquerque which have relatively low radar reflectivities and little or no surface rainfall. During our testbed operations approximately 25 percent of Albuquerque microbursts exhibited core reflectivities of less than 30 dBZ. Such events exhibit radar cross sections that may be many orders of magnitude smaller than the severe ground clutter sources that are prevalent at this site. Compounding the difficulty of radar-based microburst detection at this site is the presence of significant vertical shear in the ambient wind field caused by topographic effects and the frequent proximity of synoptic fronts. We described the effects of vertical shear on WSP microburst detection capability in discussing the Kansas City results.

The arid ABQ environment is also manifest in the radar reflectivities of gust front thin lines. Essentially all of the gust fronts observed had reflectivities less than 10 dBZ, and 35 percent had reflectivities less than 0 dBZ. The speed of movement and convergence strength associated with many of these fronts were strong, however. In particular, “Canyon Wind” events – outflows from thunderstorms east of the Sandia Mountains, which are funnelled through the Tijeras canyon onto the airport – are normally very strong, with maximum convergence strengths greater than 15 m/s. Radar detection of these events is extremely difficult until they clear the intense ground clutter from the mountains.

#### 3.4.4 Microburst Detection Performance

Table 5 summarizes detection and false-alarm probabilities for the WSP prototype's microburst detection function at ABQ. Data evaluated were from 38 representative thunderstorm days during the 1993 and 1994 storm seasons. Approximately 35 hours of data are included, involving 120 separate microburst events. Twenty-five thousand scans of WSP data were scored in generating these statistics.

The environmental challenges of this site – severe ground clutter, low cross section microbursts and a vertically sheared ambient atmosphere – resulted in significant reduction in Pd relative to the other sites evaluated. Two-thirds of all divergent wind shears were detected by the WSP prototype, rising to approximately 80 percent at the microburst alert threshold. Higher false-alarm probabilities also were incurred, particularly for weak shear alerts near the 10 m/s threshold.



**TABLE 5**  
ASR-9 Microburst Detection Algorithm  
Scoring Results for Albuquerque

| Event Strength | Pd   | Pfa  |
|----------------|------|------|
| $\geq 10$ m/s  | 0.66 | 0.29 |
| $\geq 15$ m/s  | 0.78 | 0.18 |
| $\geq 20$ m/s  | 0.92 | 0.13 |

#### 3.4.5 Gust Front Detection Performance

Gust front detection results from Albuquerque are summarized in Table 6. This data set was drawn from six representative days in 1994. (The WSP receive chain configuration was improved following the 1993 ABQ storm season to realize increased sensitivity for the very low radar cross section gust fronts prevalent at this site, resulting in a substantial improvement in gust front detection performance.) Fifteen hours of data, encompassing 422 comparisons of WSP and truth radar imagery, are included in the database.

As with the microburst detection algorithm, the sensitivity constraints of the ASR-WSP and the presence of strong clutter regions inhibited the gust front algorithm's detection ability. Due to the low reflectivity associated with many of the gust fronts, the events were often barely visible in the base data, especially those located near clutter regions. In spite of these challenges, the algorithm did very well with the stronger gust fronts, detecting 74 percent of the gust fronts having  $\Delta V > 15$  m/s. Weaker gust fronts were more difficult to observe by the WSP. The Pd for all fronts with  $\Delta V$  exceeding 10 m/s was 50 percent.

**TABLE 6**  
ASR-9 Gust Front Detection Algorithm  
Scoring Results for Albuquerque

|    | $V \geq 10$ m/s | $V \geq 15$ m/s | Pfa  |
|----|-----------------|-----------------|------|
| Pd | 0.50            | 0.74            | 0.11 |

#### 4. INTERPRETATION OF RESULTS RELATIVE TO WSP NATIONAL DEPLOYMENT PLANS

Estimates of WSP wind shear detection performance at all sites scheduled to receive the WSP can be achieved via a climatology-based extrapolation of the testbed scoring results reported here. Analysis of climatological data for the proposed WSP locations permits separation of the sites into groups of homogeneous climatology that can be used to project ASR-WSP wind shear detection performance at locations for which we

have not collected testbed data. The climatological data used for this analysis included 30-year normals for annual number of thunderstorm days, measurable-precipitation days and the average hour of maximum thunderstorm occurrence. In Table 7 below we project detection performance for the major safety hazard addressed by the WSP, divergent shears with differential velocity exceeding 15 m/s (microburst alerts).

Thunderstorms in the northeast U.S. occur mainly during the summer months in late afternoon and are often triggered by fronts associated with low-pressure systems traversing southern Canada. In these situations, significant vertical shear in the ambient wind is likely to be present, possibly leading to contamination of the ASR-WSP surface velocity estimates from above-ground storm features as in Kansas City. In other instances, conditions favor air-mass-thunderstorm development typical of the southeastern U.S. Given this knowledge, we would expect wind shear detection performance to fall between the Kansas City and southeastern U.S. testbed results. Ten proposed WSP sites fall into this environmental regime.

Another distinct climatological region exists in the upper-midwestern U.S. and includes the ASR-WSP sites of Madison, Cedar Rapids and Des Moines. These locations exhibit slightly more thunderstorm days than those in the northeastern U.S. and a nocturnal peak in thunderstorm frequency. The nocturnal peak is attributable to this region's closer proximity to the main jet stream and nocturnal low-level jets during the summer months. The strong dynamics associated with these features sustain thunderstorm development beyond the hours of daytime surface heating. Consequently, vertical wind shear is likely to be significant in this regime during thunderstorm periods as was observed when the ASR-WSP testbed collected data in Kansas City in 1989. Therefore, we would expect microburst detection performance at these three WSP locations to mirror the Kansas City testbed results cited earlier.

The southeastern U.S. comprises a third climate zone. The 11 ASR-WSP sites in the Southeast have approximately the same number of days with measurable precipitation, but the hour of maximum thunderstorm frequency is slightly earlier on the Southeast coast and Florida peninsula, primarily due to sea-breeze enhancement. Cities here also have more thunderstorm days, while those farther north experience significant snowfall ( $>1''$ ) on at least one day annually. However, the predominant type of thunderstorm throughout the Southeast is the air-mass thunderstorm driven by diurnal surface heating during the summer months and promoted by sea-breeze fronts if near the Southeast coast. Hardly any vertical shear in the ambient wind is present in both regimes during the summer.

so interference with ASR-WSP surface-velocity estimating capability is minimal. We would expect wind shear detection performance statistics at the northern-tier WSP Southeast sites (RIC, ORF, GSO, TYS, BHM and HSV) to be well represented by data gathered at the Huntsville WSP testbed site, and performance at the southernmost sites (CHS, JAX, GNV, DAB and SRQ) to be similar to that of the Orlando testbed.

The ASR-WSP sites in southern Texas are distinct from other Southwestern sites in their early hour of maximum thunderstorm frequency (high convective available potential energy) and absence of vertical wind shear most of the year. Summertime thunderstorms are usually air-mass type, with Gulf of Mexico moisture fueling the activity. Therefore, we would expect wind shear detection performance for the three south Texas sites to reflect Orlando/Huntsville performance.

The second climatological group of Southwest sites (Lubbock, El Paso, Tucson and Albuquerque) will experience atmospheric moisture conditions representative of Albuquerque, although vertical wind shear and ground clutter may be significantly lower than ABQ. As mentioned previously, the operational issue unique to this region is the occurrence of dry microbursts, mainly in late spring/early summer, which ASR-WSP may not detect if the events are very dry. Most thunderstorm activity occurs during the later summer months when moist monsoonal flow enters the region. Vertical shear in the ambient wind has been evident in Albuquerque during the summer months, although this may be less of an issue at more southerly sites owing to greater distance from polar fronts and rugged topography. Expected WSP performance at these sites would be similar to Albuquerque, although Southwest sites with less ground clutter might show improved results.

Finally, thunderstorm frequency in southern California and Hawaii is lowest of all the ASR-WSP sites. Cold fronts associated with coastal-Pacific winter storms are often the cause of those in the Los Angeles area. We would suspect sea breezes and terrain induce most thunderstorms in Hawaii. Vertical wind shear should not pose a problem for surface velocity estimation at either location, except during the winter months in Los Angeles when the polar jet stream occasionally dips southward toward the area. Our best estimate is that detection performance in southern California would be in the range of that demonstrated at the prototype's southeastern and midwestern U.S. sites, and that Hawaii's would closely resemble Orlando's since both locations are tropical.

TABLE 7

Projected WSP Microburst Detection Performance  
Within Climatological Regimes ( $\Delta V \geq 15$  m/s)

| Region            | Total Sites | Expected Pd | Expected Pfa |
|-------------------|-------------|-------------|--------------|
| Northeast         | 10          | 0.85 - 0.90 | 0.10 - 0.15  |
| Midwest           | 3           | 0.85 - 0.90 | 0.15 - 0.20  |
| Southeast/Florida | 11          | 0.90 - 0.95 | 0.05 - 0.15  |
| SouthCentral      | 3           | 0.90 - 0.95 | 0.05 - 0.15  |
| Southwest         | 4           | 0.75 - 0.85 | 0.15 - 0.20  |
| So. California    | 2           | 0.85 - 0.95 | 0.10 - 0.15  |
| Hawaii            | 1           | 0.90 - 0.95 | 0.05 - 0.15  |

## 5. SUMMARY

In this report, we have provided background and a quantitative performance summary for the wind shear detection functions (microburst and gust front) of the Airport Surveillance Radar Weather Systems Processor. The current prototype WSP hardware and algorithms are viewed as largely representative of what will be deployed in the production version of the WSP, although some improvements in performance may accrue from refinement efforts that will be ongoing up to the time of full-scale development (FSD) contract award. The algorithms will be provided at that time by the Government to the FSD contractor for implementation.

Overall, we believe that the analysis in this report supports the contention that the WSP's wind shear detection algorithms - at their current level of performance - will provide operational products sufficient to meet the needs of the aviation community at the airports where the system will be deployed. Challenging environmental conditions - such as those experienced during testbed operations at Kansas City and Albuquerque - may degrade performance relative to the near-TDWR-like capability demonstrated in the southeastern U.S. Operational feedback, however, during our recent Albuquerque demonstrations indicate - as was the case during the earlier Orlando, FL demonstrations - that the wind shear detection performance of the prototype WSP is viewed extremely positively by Air Traffic Controllers and pilots. Informal feedback and questionnaires filled out by users at both airports have documented that the WSP's wind shear products, in combination with its predictions of flight route impact through gust front tracking and storm motion estimation, have significantly improved the safety and efficiency of terminal operations.

## REFERENCES

Weber, M.E., "Ground Clutter Processing for Wind Measurements with Airport Surveillance Radars", Lexington, Massachusetts, M.I.T. Lincoln Laboratory, DOT/FAA/PM-87/21, Project Report ATC-143, 4 November 1987.

Weber, M.E., "Dual-Beam Autocorrelation Based Wind Estimates from Airport Surveillance Radar Signals", Lexington, Massachusetts, M.I.T. Lincoln Laboratory, DOT/FAA/PS-89/5, Project Report ATC-167, 21 June 1989.

Newell, O.J. and J.A. Cullen, "ASR-9 Microburst Detection Algorithm", Lexington, Massachusetts, M.I.T. Lincoln Laboratory, DOT/FAA/NR-93/2, Project Report ATC-197, 22 October 1993.

Delaney, R.L., and S.W. Troxel, "Machine Intelligent Gust Front Algorithm", Lexington, Massachusetts, M.I.T. Lincoln Laboratory, DOT/FAA/RD-93/1, Project Report ATC-196, 4 November 1993.

Noyes, T.A., S.W. Troxel, M.E. Weber, O.J. Newell and J.A. Cullen, "The 1990 Airport Surveillance Radar Wind Shear Processor (ASR-WSP) Operational Test at Orlando International Airport". Lexington, Massachusetts, M.I.T. Lincoln Laboratory, DOT/FAA/NR-91/1, Project Report ATC-178, 17 July 1991.

Evans, J.E., "Results of the Kansas City 1989 Terminal Doppler Weather Radar (TDWR) Operational Evaluation Testing", Lexington, Massachusetts, MIT Lincoln Laboratory, DOT/FAA/NR-90-1, Project Report ATC-171, 17 August 1990.

Bernella, D.M., "Terminal Doppler Weather Radar Operational Test and Evaluation, Orlando 1990", Lexington, Massachusetts, MIT Lincoln Laboratory, DOT/FAA/NR-91-2, ATC-179, 9 April 1991.