AIRPORT SURVEILLANCE RADAR BASED WIND SHEAR DETECTION

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1. INTRODUCTION

The Federal Aviation Administration is deploying over 100 next-generation airport surveillance radars (ASR-9) at major airports. To meet the requirements of the Advanced Automation System (AAS), additional digital radars must be acquired, either through purchase of additional ASR-9s or through upgrade of existing ASR-7s and ASR-8s. Given this widespread deployment, improved weather sensing capabilities for airport surveillance radars will have significant operational benefits.

This paper provides an update on the development of an ASR-based system for detection of thunderstorm generated low-altitude wind shear. Achieving this capability will require:

1. addition of radio-frequency couplers, amplifiers, switches and receiving chains to extract the signals necessary for wind shear detection;
2. a digital signal processing channel that implements algorithms for estimation of the low-altitude radial wind field and for automatic recognition of the signatures associated with hazardous wind shear;
3. additional interfaces and displays to disseminate the wind shear information to controllers in the airport tower and TRACON.

Our discussion will focus on wind shear detection using the ASR-9, although most of the technical issues would also apply in including this capability in a digital processing upgrade to earlier ASR-7s and ASR-8s. Sections 2 and 3 provide background and an overview of technical issues. In section 4, results of an initial operational test of ASR-based wind shear detection at the Orlando International Airport are described. We conclude by discussing interface of a wind shear processor to the ASR-9, and the status of ongoing development activities.

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2. BACKGROUND

During the last two decades, thunderstorm generated low-altitude wind shear has been identified as the primary cause of a number of air-carrier accidents, involving almost 600 fatalities. In response to this hazard, the FAA has initiated programs to improve nowcasting and forecasting of phenomena such as microbursts and gust fronts. Terminal Doppler Weather Radars (TDWR) will be deployed at 45 major airports, augmented by extended low-level wind shear alert systems (LLWAS, Phase III).

In 1985, the ASR-9 program office initiated an investigation to determine whether a suitably modified ASR-9 could provide an operationally useful wind shear detection capability (Weber and Anderson, 1985); this would provide coverage at second-tier airports not slated to receive a TDWR. An algorithm development testbed (hereafter designated ASR Wind Shear Processor or ASR-WSP) was fabricated using an ASR-8, modified to emulate the essential features of an ASR-9. The antenna beam pattern, scanning rate, range resolution, transmitted power, instability residue and signal waveform are nearly identical to those of an ASR-9.

The ASR-WSP testbed was operated at Huntsville, Alabama during 1987 and 1988 and at Kansas City, KS in 1989. Data collected during nearby thunderstorm activity were used to develop and evaluate algorithms for radial velocity estimation and for detection of microbursts and gust fronts. A real time data processing and display system was implemented to provide automatic detection of wind shear hazards. The testbed was moved to the Orlando International Airport in 1990 where an operational test and evaluation was conducted.

3. OVERVIEW OF TECHNICAL ISSUES

3.1. Radar Sensitivity

The broad elevation beam of an ASR has substantially less antenna gain than a pencil beam weather radar. "Beam-filling loss", which accounts for that portion of the transmitted energy which is not intercepted by shallow, near-surface thunderstorm outflows, and the use of sensitivity time control attenuation (STC) also reduce the signal-to-noise ratio (SNR). Over the range of operational concern for wind shear detection (10 km for microbursts, 25 km for gust fronts) the reflectivity factor equivalent to 0 dB SNR varies from 0 to about 15 dBz for an ASR's low receiving beam. (See Figure 5 in Weber (1989a)).

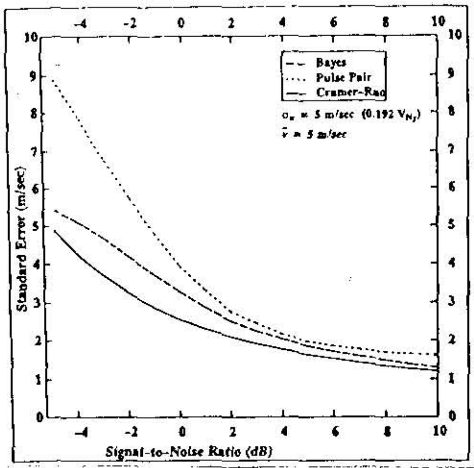

Figure 1. Velocity estimate standard error versus SNR for pulse-pair estimator and "Bayes" estimator. These are compared to the Cramer-Rao minimum variance bound. Monte Carlo simulations assumed Gaussian shaped weather spectra with spectrum width of 5 m/s. Twenty samples were used in generating the velocity estimates.

Detection of low reflectivity wind shear events such as gust fronts is improved by the ability to make reasonably accurate velocity estimates at low SNR. Our efforts to extend the capability of ASRs to measure radial winds at low SNR are focussed on:

1. implementation of instantaneous automatic gain control to reduce the sensitivity loss associated with STC in resolution cells without strong clutter;
2. velocity estimation algorithms that provide lower variance estimates than the "pulse-pair" algorithm under low signal to noise conditions.

Figure 1 compares pulse-pair estimate standard error (square root of sum of squared bias and standard deviation) to the Cramer-Rao minimum variance bound. The calculation assumes that the twenty pulses transmitted as an ASR-9 antenna scans one beamwidth are used for the velocity estimate. The comparison indicates that, if the Cramer-Rao bound were achieved by algorithms other than pulse-pair, velocity estimate variance reductions equivalent to as much as a 4 dB SNR increase would be attained. An example is the "Bayes" estimator shown by the chain-dashed curve. This takes the form of a windowed discrete Fourier transform of the autocorrelation function and achieves minimum standard error under the assumptions of Gaussian shaped signal spectrum and Gaussian signal statistics. Other estimators tailored to low SNR conditions are described by May and Strauch (1989) and Anderson (1989a). Additional reduction in variance by a factor of four or more can be achieved by data averaging over multiple scans of the antenna and over adjacent range-azimuth resolution cells.

3.2. Ground Clutter

Detection of low-altitude wind shear with an ASR requires processing of data from the low receiving beam, even at short range where aircraft detection is performed using high beam data. This results in intense ground clutter.

Weber (1987) used clutter data from the ASR-WSP testbed in Huntsville to analyze the impact of the ground clutter on velocity estimation. As in the ASR-WSP testbed, FIR high-pass filters providing up to 50 dB clutter suppression were assumed. The measured ground clutter was combined with signals from a simulated microburst to map out areas where the wind shear signature could be successfully extracted from the clutter. The reflectivity factor of the microburst was a parameter of the simulation. The analysis showed that when the microburst reflectivity factor exceeded 20 dBz, the fractional area where clutter residue prevented detection of the microburst's radial velocity shear was less than 0.3, even at short range. The microburst signature would be recognizable over at least part of its aerial extent in this circumstance. Conversely, recognition of very low reflectivity microbursts or gust fronts (10 log Z << 20) at ranges less than 6 km may be difficult owing to ground clutter residue.

3.3. Estimation of Low Altitude Radial Velocity

The wind speed and direction in microbursts varies rapidly with altitude, with the strong outflow confined to a shallow layer extending only a few hundred meters above the surface. The microburst echo spectrum received in the broad elevation beam of an airport surveillance radar reflects this vertical shear, consisting of components covering a substantial fraction of the Nyquist interval. Even at the relatively short ranges of operational concern for wind shear detection, signal components scattered into the the beam from higher altitudes must be rejected in order to reliably retrieve the microburst velocity signature.

Discrimination between spectral components scattered from low altitude thunderstorm outflows and those produced by winds aloft can be performed by comparing signals received simultaneously in an ASRs high and low receiving beams. Figure 2 shows the elevation gain patterns of an ASR-9's high and low receiving beams and the elevation angle dependent phase difference between signals received in the two beams.

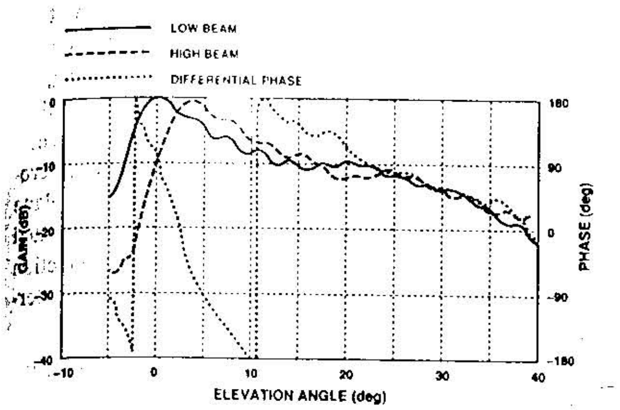

Figure 2. Amplitude and phase patterns versus elevation angle for ASR-9 antenna.

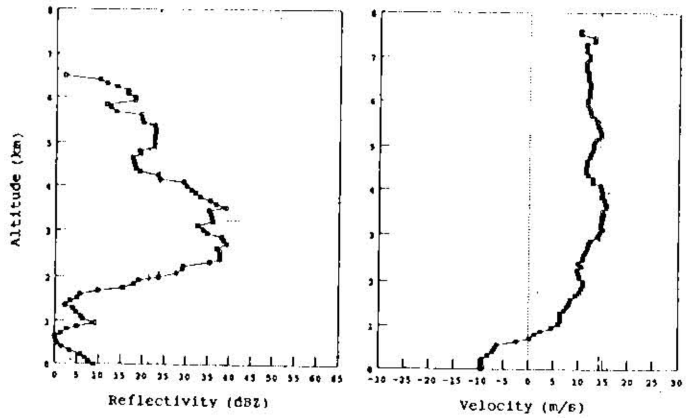

Figure 3. Profile of reflectivity and radial velocity on downshear side of a line thunderstorm near Kansas City, Kansas.

The algorithm implemented in the ASR-WSP testbed has been a simple, time-domain algorithm (Weber, 1989b) based on the assumption that the echo spectrum received in the broad elevation beam of an ASR consists of two components that correspond respectively to scattering from near the surface and from aloft. The center frequency of the near-surface spectral component is estimated using the zeroth and first autocorrelation lags of signals in the high and low beams.

Evaluations of dual-beam velocity estimators using data collected by the ASR-WSP testbed in air mass thunderstorms in the Southeastern U.S. (Weber (1988,1989), Anderson (1989b)) indicated accuracy supporting reliable detection of microbursts in this environment.

Measurement of the near-surface radial velocity component can be more difficult in an environment where thunderstorms form under conditions of strong, vertical shear in the ambient wind. Tilting of reflectivity structures in the downshear direction can result in strong, positive gradients in reflectivity with altitude as shown in the profiles of Figure 3, measured in a line thunderstorm near Kansas City. For the example shown, the Doppler spectrum component associated with the near surface radial wind was measured by the ASR-WSP to be 15 dB smaller than the component scattered from aloft. The time domain algorithm implemented on the ASR-WSP testbed cannot resolve this small a signal component, resulting in a velocity estimate reflecting the higher level winds. Juxtaposition of areas where the low altitude wind is correctly measured with regions where velocity estimates correspond to winds above the surface can produce a false-microburst divergence pattern. Using the time domain velocity estimation algorithm, this phenomenon resulted in an unacceptable number of false microburst detections in strongly sheared thunderstorms at the Kansas City site.

As illustrated in Figure 4, however, careful comparison of the amplitude and/or phase of signal spectra acquired simultaneously from the low- and high-beams of an ASR can resolve the signal components arising from near surface scattering. The plot shows spectra corresponding to the profiles in Figure 3. Owing to the relatively high reflectivity above 2 km altitude, most of the received power is in the Doppler velocity interval associated with winds aloft (+10 to 15 m/s). Near surface scattering produces the much

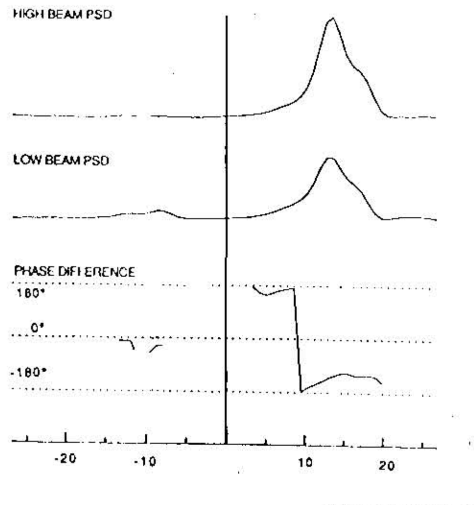

Figure 4. High and low beam power (linear units) and differential phase spectrum of weather echo from strongly sheared environment.

smaller spectral component at -10 m/s. Note that the low-beam PSD significantly exceeds that of the high beam near -10 m/s, and that the phase difference approaches 0, the value associated with near surface scattering. Signal processing hardware has been acquired for the ASR-WSP testbed that can support frequency-domain processing and testing of appropriate algorithms is underway using the Kansas City time-series data.

3.4. Microburst Detection Algorithm

The microburst detection algorithm implemented on the ASR-WSP testbed is derived from the TDWR microburst divergent outflow detection module (Merritt, 1987). Radial segments of generally increasing radial velocity are detected, subjected to tests as to minimum slope, length, total radial wind speed change, then grouped azimuthally to produce loss regions. These are subjected to temporal persistence requirements before a microburst alarm is issued. An alternative algorithm, based on thresholding of radial velocity gradient estimates has also shown good performance in off-line evaluation (Noyes, this conference).

3.5. Gust Front Detection Algorithm

The gust front detection algorithm implemented on the ASR-WSP testbed is based on recognition and tracking of the thin-line echo frequently observed at the leading edge of gust fronts. The algorithm first identifies potential thin-line features in the reflectivity field. Thin-line features are then merged to form gust front detections, based on proximity, shape and orientation. Detected gust fronts are tracked over time to estimate propagation direction. The speed of propagation is estimated using the underlying radial velocity measurements.

The gust front algorithm used in the ASR-WSP testbed was derived from work on the Advanced Gust Front Algorithm for the TDWR (Olson et al., this conference). Efforts are underway to improve the performance of the thin-line detection algorithm, and to incorporate detection of convergent shear that will be made possible by more accurate velocity estimates at low SNR.

4. OPERATIONAL TEST AT ORLANDO INTERNATIONAL AIRPORT

In August and September 1990, an operational test of the ASR-WSP was conducted at the Orlando International Airport. Air traffic controllers and supervisors in the tower and TRACON had access to five distinct products in graphical and alphanumeric formats: microburst alarms, gust front detections, ten- and twenty-minute forecasts of gust front position, six-level precipitation reflectivity and estimates of storm movement.

The 1990 test was the first evaluation of ASR-derived wind shear products in an operational setting. The test had two basic objectives: quantitative assessment of the performance of the signal processing and wind shear detection algorithms in the moist, convectively unstable environment of the Florida peninsula and obtainment of feedback from users (air traffic controllers and supervisors) on the strengths and weaknesses of the system.

4.1. Real Time Wind Shear Processor

Signals from the testbed ASR-8's low and high receiving beams were shunted to Lincoln Laboratory built receivers, digitized and distributed simultaneously to the real-time data processor and to a high density data recording system. Signal processing operations -- ground clutter filtering, reflectivity measurement, radial velocity estimation and data editing were performed using six commercial array processing cards interconnected via a VME-bus backplane (Pieronek, 1991). Single-board computers in the same backplane managed data I/O and processor control, and implemented the microburst detection algorithm. Gust front detection and the storm motion algorithm were implemented on external SUN workstations.

The algorithm outputs were disseminated to users via the display types developed for the TDWR. Ribbon (alphanumeric) displays provided runway-specific hazard messages when microbursts or gust fronts impacted runways or approach/departure corridors. These were relayed verbally to pilots by the local controller at the time of issuance of landing or takeoff clearance. A geographic situation display (GSD) for the tower and TRACON supervisors showed the location and size of the wind shear regions, six-level precipitation reflectivity data and vectors indicating storm movement. Figure 5 shows the GSD during an active weather period.

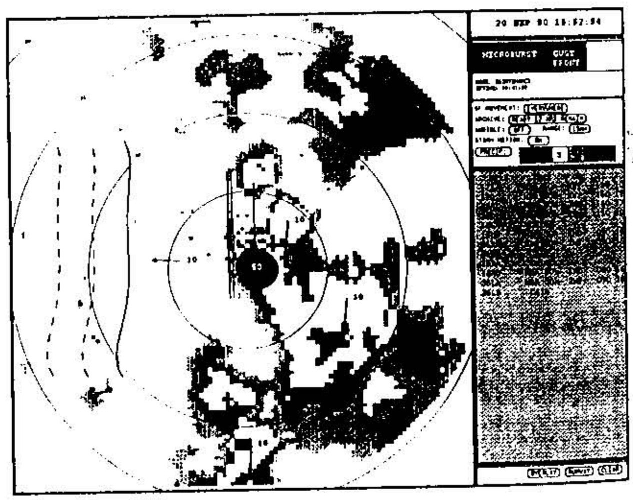

Figure 5. Geographic Situation Display for ASR-WSP during thunderstorm activity at Orlando International Airport. Filled circle is location of microburst with measured velocity differential of 50 knots. Solid and dashed north-south oriented lines to the west of the airport show current and predicted locations of a gust front. Vectors on storm cells show estimated direction of storm movement.

4.2. Data Verification

Figure 6 shows the locations of the three pencil beam Doppler weather radars available to support verification of the ASR-derived wind shear products. Lincoln Laboratory's TDWR testbed, denoted by FL-2C, operates at C-band with peak power of 250 kW, 120m (1 usec) range resolution and

0.5 degree beamwidth. Two additional C-band meteorological Doppler weather radars were operated by University of North Dakota (UND) and Massachusetts Institute of Technology (MIT) to provide complimentary viewing angles for asymmetric microburst outflows. The three radars executed coordinated volume scanning on an approximately four minute cycle with near-surface scans inserted each minute to provide more rapid updates on microburst outflows.

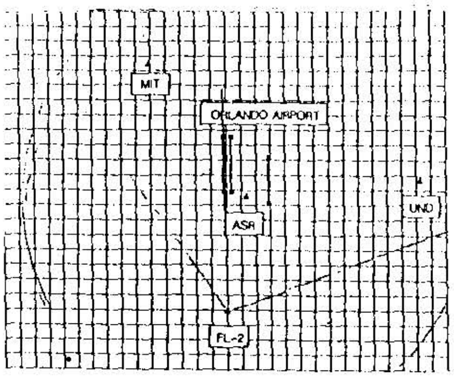

Figure 6. Map showing location of ASR-WSP testbed and meteorological Doppler radars used for performance assessment.

4.3. Microburst and Gust Front Detection Performance

Table 1 summarizes microburst and gust front algorithm detection and false alarm probabilities for the Orlando test. The data base used for microburst detection includes the near- and on-airport wind shear activity occurring during the period 20 August to 30 September. Data from all moderate and strong gust fronts (wind shift greater than 15 knots) from July through September were included since only one strong gust front occurred during the operational test period.

TABLE 1. Algorithm Performance Summary

	Detection Prob.	False-alarm prob.
MB (>30 kts)	0.97	0.14 (0.06)
GF (>15 kts)	0.57	0*

The detection probabilities for microbursts are consistent with previous analyses of ASR-WSP performance in the southeastern U.S. indicating that the high-reflectivity outflows characteristic of this region can be reliably detected. False alarm probabilities during the test period, however, were higher than measured in earlier offline experiments. A significant fraction of these false alarms occurred during one brief period of strong gusty winds and heavy rain behind a line thunderstorm. Operations at the airport were curtailed anyway at this time owing to the wind and heavy rain. When this period is excluded from the scoring (parenthetical number), the false alarm probability is below 10 percent, consistent with previous evaluations.

During the operational period, the gust front detection algorithm successfully identified 15 gust fronts, one of which exhibited convergent shear in excess of 15 kts. Although some gust front false alarms occurred (caused, for example, by second trip weather) none impacted the airport and none had shear estimates greater than 10 kts. Of the seven stronger gust fronts scored for the analyses in Table 1, four were detected by the algorithm; the other three did not exhibit recognizable thin-lines.

4.4. Controller and Supervisor Evaluations

The FAA Technical Center distributed questionnaires on the ASR-WSP system to all Orlando tower air traffic controllers and supervisors at the conclusion of the test period. Forty-nine controllers responded, although some indicated that they had not been able to assess all aspects of the system owing to the lack of severe weather during their on-duty time.

Overall, user response as assessed by the numerical ratings was favorable. About 80% of the respondents indicated that the system helped them in their job of controlling local traffic and 85% indicated that the system was suitable for widespread operational deployment.

Individual comments, however, voiced concerns that the microburst product was overly conservative, and sometimes impeded traffic flow in situations where the controller's felt they could have safely worked around or through the weather. This sense of "overwarning", also raised during the earlier TDWR test at Orlando, arose from the combination of actual false alarms and the conservative alarm-generation strategy employed. Use of the phraseology "microburst alert" in relaying warnings to the pilots was flagged as a "scare tactic" by some controllers: it was suggested that a better procedure would be to always issue the messages as "wind shear alert" and allow the stated loss value to convey the severity of the loss. Several respondents indicated that uplink of the windshear information on the GSD directly to pilots was preferable to relay by controllers.

The gust front prediction product, six-level storm intensity product and storm motion products were received favorably. All of these products provide advisory information that is used at the discretion of the controllers. Several comments emphasized the value of advanced prediction of gust front arrivals at the airport.

5. ASR-9 INTERFACE FOR WIND SHEAR PROCESSOR

Integration of the wind shear processor in the ASR-9 must be achieved without a measurable degradation of the aircraft surveillance capability of the radar. As mentioned above, the ASR-9 has two fan beams which, for the

* As discussed in the text, some false gust fronts were detected with estimated convergent shear less than 15 knots. These are not considered to be safety hazards and do not result in issuance of wind shear alerts to pilots.

ASR-WSP, should be accessed simultaneously and processed by separate receivers to produce digitized time series. To attain a large dynamic range and the ability to achieve inter-clutter visibility, a pair of instantaneous automatic gain controlled (IAGC) receivers are required which employ logarithmic amplifiers to develop control signals for digital attenuators at the input to linear amplifiers. Each linear amplifier output is processed by a quadrature video detector whose outputs are sampled and quantified into pairs of 14-bit words. These are then combined with the attenuator value and sent as floating-point numbers to the array signal processor. Oscillator, timing and antenna position signals are obtained from the ASR-9 for use by the ASR-WSP. A Doppler-shifted, amplitude-controlled test signal is also available from the ASR-9 for use in monitoring and calibrating the system.

Integration of the ASR-WSP is further complicated by the dual-channel architecture of the ASR-9. Redundancy for the critical aircraft detection function is achieved by incorporating two complete transmitter/receiver and target processor subsystems. The two subsystems are used alternately, i.e., only one subsystem is connected to the antenna and produces aircraft reports. Since a single ASR-WSP is planned for installation, provision will be made to access the received signals and the local oscillator signals required for operation with either radar channel. The facts that each channel operates with its own radiated frequency and that it is desired to maximize the detection performance of the ASR-WSP have lead to the installation of the microwave components directly on the low-loss waveguides of the ASR-9. This approach minimizes modifications within the existing ASR-9 cabinets, since the wind shear digital processor will be a free-standing module.

Integration of the ASR-WSP with the existing ASR-9 can be accomplished at moderate cost and with no interruption or degradation to aircraft surveillance capability.

6. PROGRAM STATUS

Additional operational testing of the ASR-WSP will be performed at the Orlando International Airport which is located in the United States region of maximum thunderstorm activity. Design validation and refinement will be based upon the insights obtained from controllers who use the ASR-WSP-generated wind shear and gust front information in terminal area traffic control.

7. SUMMARY

Analysis and on-line testing of ASR-based wind shear detection indicates that these radars can support detection of microbursts and gust fronts. While ongoing algorithm development will improve wind shear detection capability, the baseline system tested in Orlando was viewed by controllers as providing an operationally useful capability.

We are currently modifying a production ASR-9 to demonstrate that interfaces to the WSP can be achieved without degradation to the ASR-9's aircraft detection channel. This ASR-9 testbed will be employed for further operational testing of the wind shear processor and will serve as a "test bench" for implementation and validation of radar interfaces.

References

Anderson, J., personal communication, 1989a.

Anderson, J.,*Techniques for the Detection of Microburst Outflows using Airport Surveillance Radars*, 3rd International Conference on the Aviation Weather System, Anaheim, Ca., January 30-February 3, 1989b.

Merritt, M., *Automatic Detection of Microburst Wind Shear for Terminal Doppler Weather Radar*, Digital Image Processing and Visual Communications Technologies in Meteorology, Cambridge, Ma., 26-28 October, 1987.

Noyes, T., *Detection of Hazardous Divergence in Wind Fields Estimated by an Airport Surveillance Radar: A Deterministic Approach*, 4th International Conference on Aviation Weather Systems, Paris, France, 24-27 June, 1991.

Olson, S., A. Abrevaya, S. Troxel and D. Klingle-Wilson, *The Use of Reflectivity Thin Lines to Detect Gust Fronts*, 4th International Conference on Aviation Weather Systems, Paris, France, 24-27 June, 1991.

Pieronek, J., *New Parallel Signal Processors for the FAA/Lincoln Laboratory Doppler Testbed Radars*, 25th International Conference on Radar Meteorology, Paris, France, 24-28 June, 1991.

Weber, M. and J. Anderson, *Evaluation of the ASR-9 Weather Reflectivity Product*, 2nd International Conference on the Aviation Weather System, Montreal, P.Q., Canada, June 19-21, 1985.

Weber, M., *Ground Clutter Processing for Wind Measurements with Airport Surveillance Radars*, Project Report ATC-143, Lincoln Laboratory, MIT, FAA-PM-87-21, 1987.

Weber, M., *Weather Sensing with Airport Surveillance Radars*, 3rd International Conference on the Aviation Weather System, Anaheim, Ca., January 30-February 3, 1989a.

Weber, M., *Dual-Beam Autocorrelation Based Wind Estimates from Airport Surveillance Radar Signals*, Project Report ATC-167, Lincoln Laboratory, MIT, FAA-PS-89-5, 1989b.