MICROBURST DETECTION WITH AIRPORT SURVEILLANCE RADARS

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INTRODUCTION

With the advent of fully digital signal processing for new airport surveillance radars (ASR-9), terminal air traffic control displays will be largely free of clutter from precipitation and ground scatterers [1,2]. Early acceptance testing of the ASR-9, however, indicated that working air traffic controllers actually made considerable use of the weather echo information on their displays. To reinsert weather data in a non-interfering manner, the ASR-9's signal processor was augmented with a dedicated channel for processing and displaying six quantitative levels of precipitation reflectivity (i.e. rain rate) [2,3]. This processor does not utilize the radar's coherency, other than for Doppler filtering of ground clutter echoes.

In this paper, we describe processing techniques that would allow airport surveillance radars to extend their weather measurement capability to the detection of microburst-generated low altitude wind shear. The two principal technical challenges are the development of:

- (i) signal processing to suppress ground clutter and estimate the near surface radial wind component in each radar resolution cell;
- (ii) image processing to automatically detect hazardous shear in the resulting velocity field.

The techniques have been evaluated extensively using simulated weather signals and measurements from an experimental airport surveillance radar in the southeastern United States. Overall our analysis indicates that microbursts accompanied by rain at the surface -- the predominant safety hazard in many parts of the U.S. --could be detected with high confidence using a suitably modified ASR. In the following section we describe briefly the background and potential operational role of an ASR-based wind shear detection system. We then discuss the primary technical issues for achieving this capability and our evaluation of processing methods that address these issues.

BACKGROUND AND OPERATIONAL MISSION

During the last two decades, microburst generated low-altitude wind shear has been identified as the primary cause of twelve major air-carrier accidents. Seven of these accidents involved fatalities, resulting in the loss of 575 lives.

As illustrated in Figure 1, a microburst is an intense, thunderstorm downdraft which encounters the earth's surface producing a brief outburst of highly divergent horizontal winds [4]. Aircraft penetrating a microburst experience headwind-to-tailwind velocity shear compounded by the downdraft in the microburst core. The resulting loss of performance can be critical in the take-off or final approach phases of flight.

In response to microbursts and other wind shear hazards, the FAA has initiated a two-part enhancement to its terminal area weather information system. The on-airport network of surface wind-speed and direction sensors -- Low Level Wind Shear Alert System (LLWAS) -- is being expanded from six stations to eleven or more and its wind shear detection algorithm reworked [5]. In addition, a dedicated, microwave Terminal Doppler Weather Radar (TDWR) [6] will be deployed at approximately 50 airports to measure the radar reflectivity and radial velocity signatures associated with low-altitude wind shear.

Airport surveillance radars were initially rejected as candidate wind shear detection sensors, owing to perceived deficiencies in sensitivity and ground clutter suppression, and inability to resolve near-surface thunderstorm outflows with their broad elevation beams. To the extent that these problems could be overcome, however, ASRs would complement the dedicated wind shear detection sensors in three areas.

- (i) Airports with low traffic volume or in regions with infrequent thunderstorm activity may not warrant a dedicated TDWR or enhanced LLWAS. A modified ASR could provide wind shear protection at these airports at an incremental cost small relative to that of the dedicated systems.
- (ii) At airports equipped with LLWAS but lacking a TDWR, data from an airport surveillance radar could be used to reinforce LLWAS wind shear reports and to detect wind shear in operationally significant areas not covered by the surface station network.
- (iii) At airports slated to receive a TDWR, additional radar wind measurements from an ASR could help to reduce headwind-tailwind shear estimate inaccuracies resulting from outflow asymmetry. The siting of the ASR will often provide a better viewing angle for headwind-tailwind shear measurements along some runways. Alternately, data from the two radars may be combined to compute the total horizontal component of the wind vector over areas where radials from the two radars intersect at approximately right angles. In addition, the rapid scan rate of an ASR (12.5 per minute) would provide more frequent updates on wind shear than are currently planned for in the TDWR scanning schedule.

Recognizing these potential benefits, the ASR-9 program office has sponsored investigation of the radar's wind shear detection capability. Initial work used data from meteorological Doppler radars and operational ASRs to develop candidate signal processing sequences and to analyze their expected performance [7,8]. Favorable results from these analyses led us in 1986 to deploy an experimental ASR-8 near Huntsville, Alabama. The radar transmitter was modified to provide better stability and the capability to transmit either a constant pulse repetition frequency (PRF) waveform or the alternating PRF sequence used by the ASR-9. A time-series data acquisition system allowed for simultaneous recording of inphase and quadrature signals out to a maximum instrumented range of 60 nmi. This broad band recording capability has facilitated comparative evaluation of various signal processing techniques. To provide reference measurements of thunderstorm reflectivity and wind patterns, a pencil-beam Doppler weather radar was colocated with the ASR-8.

INTERFERENCE REJECTION AND ESTIMATION OF LOW-ALTITUDE VELOCITY

Parameters of the ASR-9 are outlined in Table 1. Vertically displaced feedhorns produce two antenna patterns, shifted in elevation angle by 4.5°. The aircraft detection channel utilizes the higher beam at short range to reduce ground clutter, with a switch over to low beam usage beyond about 10 nmi. While the radar's transmitted power, operating frequency and receiver parameters are wellsuited to weather sensing, its broad elevation beam pattern and rapid azimuthal antenna scanning have significant impact on wind shear detection as described below.

Table 1: ASR-9 Parameters				
Transmitter				
Frequency	2.7-2.9 GHz			
Polarization	Linear or Circular			
Peak Power	1.1 MW			
Pulse Width	$1.0 \ \mu s$			
Block-Staggered CPI lengths	8 pulses/10 pulses			
PRFs (Example)	$972 \ s^{-1}/1250 \ s^{-1}$			
Receiver				
Noise Figure	4.1 dB (max)			
Sensitivity	-108 dBm			
A/D Word Size	12 bit			
Antenna				
Elevation Beamwidth	4.8° (min)			
Azimuth Beamwidth	1.4°			
Power Gain	34 dB			
Rotation Rate	12.5 RPM			

One issue is the ability of an ASR to measure echoes from wind shear events with low radar cross-section densities. The reflectivity density of meteorological targets is normally expressed in terms of the *radar reflectivity factor*. Expressed in decibel units (dBz) the reflectivity factor for clear air scatterers such as insects or refractive index inhomogeneities is 10 dBz or less. Mist or light rain return echoes of 20-30 dBz while maximum reflectivities in severe thunderstorms can exceed 70 dBz. Microbursts in most parts of the country occur in association with heavy rain so that at least part of the outflow wind region is associated with high radar reflectivity. In the high plains of the U.S., however, "dry" microbursts may occur when rain falls through a deep, dry sub-cloud layer before reaching the ground. Reflectivity factors associated with these events are in the range 0 to 30 dBz.

Airport surveillance radars employ sensitivity time control (STC) to prevent large targets such as ground clutter from saturating the receiver or A/D converters at short range. The limit for detection of low reflectivity thunderstorm outflows is therefore a function of the chosen STC setting as well as radar transmitter, antenna and receiver characteristics. Figure 2 plots the minimum detectable weather reflectivity factor (assuming 0 dB SNR requirement) versus range for an ASR-9. The calculation assumes STC attenuation which varies as the inverse square of range, with a cutoff at 23 km. We have shown [9] that, for representative ground clutter environments, this setting is a reasonable choice for minimizing saturation in the low beam receiving channel. The curves also include "beamfilling" loss which accounts for that portion of the transmitted energy which does not intercept shallow, near-surface thunderstorm outflows. The different curves are for high (dashed) and low (solid) receiving beams, assuming outflow depths of 300 m or 500 m. Such values are representative of the depth of microburst outflows [10].

Given the on-airport location of ASRs, microburst detection is operationally relevant only over the range interval 0-12 km. Throughout this area, microburst outflows with reflectivity factor greater than about 10 dBz will be measurable with the low receiving beam. Using the same STC function, high beam sensitivity is about 10 dB poorer at 12 km range, owing to greater beamfilling loss. We conclude that in environments such as the high plains, inadequate sensitivity might prevent an ASR from detecting some microbursts that are not accompanied by rain at the surface. However, for the large areas of the U.S. where essentially all microbursts occur in heavy rain, an ASR's sensitivity would be sufficient.

The need to maximize power received from near surface outflow layers relative to scatterers aloft dictates that the low receiving beam of an ASR be used for wind shear detection, even at short range. This would result in intense ground clutter. Ground clutter measurements from our Huntsville ASR have been analyzed [8] to quantify the performance of a specific clutter suppression scheme. A bank of FIR high-pass filters was used to allow "adaptive" selection of the filter transfer function based on the intensity of clutter and of weather in each resolution cell. This procedure minimizes distortion of the weather echo spectrum in the filtering process. The clutter filters operate coherently across the PRF transitions of the ASR-9's waveform [7].

Figure 3 illustrates conclusions from the analysis. Here, simulated signals from a "microburst" have been combined with the measured ground clutter distribution at our Huntsville test site to map out areas where the wind shear signature could be successfully extracted from clutter. The simulation took into account the stochastic nature of echoes from ground clutter as well as the described signal processing approach. The area obscured by ground clutter is plotted assuming microburst reflectivity factors varying from 10 to 30 dBz. When the reflectivity factor exceeds about 20 dBz, areas of clutter-induced obscuration are sufficiently fragmented that a microburst signature would normally be recognizable. Conversely, recognition of very low reflectivity microbursts at ranges less than 6 km may be difficult owing to ground clutter residue.

A third problem for accurate low altitude velocity measurement with an ASR results from the bias introduced when energy is scattered into the elevation fan beam from precipitation aloft. This overhanging precipitation normally has a radial velocity markedly different from that in the outflow layer. As a result, the power-weighted mean Doppler velocity -- the conventional weather radar radial wind estimator -- would be intermediate between the outflow velocity and winds aloft.

Figure 4 shows examples of velocity spectra measured with the testbed ASR at the point of strongest outflow winds in Huntsville microbursts. Both high (dashed) and low (solid) beam spectra are displayed. The plots in the left column are for the approaching core and those in the right for the corresponding receding core. The spectra have been normalized to have the same integrated area. For reference, low elevation angle (0.7 degree) radial velocities measured at the same locations and times with the colocated pencil beam radar are indicated by dashed vertical lines. Relative to the pencil beam measurements, these spectra show significant RMS width (2-10 m/s) owing to the ASR's elevation beam pattern and the strong vertical shear in the wind field above microbursts. As a result, power weighted mean velocity estimates are significantly displaced from the pencil beam measurement; the result is an underestimate of wind shear as measured by the ASR which is greater for the high beam than the low beam, and which generally increases with range.

Signal processing techniques to overcome this problem separate spectral components associated with low elevation angles from those produced by winds aloft. This can be accomplished by comparing the amplitude and/or phase of signals received in the low receiving beam with those in the high beam. As shown in Figure 5 an ASR's low and high beam amplitude patterns differ significantly at elevation angles below 5° with the difference increasing monotonically towards the horizon. In addition, the vertically displaced feedhorns produce an "interferometric" phase difference between signals in the two channels which varies roughly linearly with elevation angle.

Comparison of the measured power spectra in Figure 4 with the antenna gain patterns in Figure 5 immediately suggests one method for discriminating between signal components from low and high elevation angles. As would be expected, the power spectrum density (PSD) of low beam signals significantly exceeds that of high beam signals for velocity components at the measured near-surface radial velocity. One algorithm [11,12] for exploiting this difference involves:

- (i) transforming high and low beam signals into the frequency domain followed by incoherent averaging in range to generate acceptably stable PSD estimates;
- (ii) subtracting the high from the low beam PSD;
- (iii) identifying that positive lobe in the difference spectrum with the greatest integrated power;
- (iv) calculating the power weighted mean of this lobe.

An analogous procedure [13] eliminates the computationally expensive timefrequency transformation required above. Consistent with many of the measured spectra, the power spectrum of ASR weather signals is modeled as a summation of two Gaussian-shaped components with unknown amplitude, center frequency and width. Solutions for these parameters can be obtained from measurements of lower order lags of the low and high beam signal autocorrelation functions. The center frequency of the "low altitude" Gaussian spectrum component gives the desired near surface radial velocity estimate.

A third approach [14] exploits the elevation angle-dependent phase difference between high and low beam signals to determine the height associated with each measured spectrum component in received signals from an ASR. The crossspectral density of high and low beam signals provides the appropriate frequency resolved phase measure. As seen from Figure 5, the high-low beam differential phase is single-valued for the elevation domain from 2.5° below to 11° above the nose of the low beam. Examination of the antenna gain patterns suggests that ambiguities at higher angles can be resolved up to about 20° by comparing low and high beam power spectrum densities.

AUTOMATIC RECOGNITION OF HAZARDOUS VELOCITY DIVER-GENCE

An algorithm for computer recognition of hazardous divergence in a single-Doppler radial velocity field is described by Merritt [15]. The algorithm initially searches along radials to identify segments of sustained increase in velocity, corresponding to a headwind loss for a penetrating aircraft. These segments are grouped in azimuth and subjected to loose temporal continuity requirements before declaring a microburst alarm.

Initial end-to-end testing of ASR-based microburst detection has applied this algorithm to radial velocity fields estimated as in the preceding discussion. To reduce off-line data processing time, our evaluation sampled the available data from the experimental ASR sparsely; typically only one or two of the 12.5 scans per minute were passed through the data processing sequence of clutter-filtering, low-altitude velocity estimation and automatic microburst recognition. Alarms from the detection algorithm were then "scored" using a simple hit-miss criterion with respect to microburst locations determined manually from the pencil beam weather radar data.

Table 2 summarizes results of scoring on a scan by scan basis using the dual Gaussian parametric method described above for velocity estimation. All microbursts during 1988 that were centered within the operationally significant region extending 12 km from the radar were scored. The analysis treated 35 different microbursts using 600 scans of data from the experimental ASR. Listed performance metrics are:

- (i) probability of detection -- the number of detected microburst signatures divided by the total number of microburst signatures;
- (ii) probability of false alarm -- the number of algorithm alarms not associated with microbursts divided by the total number of alarms;
- (iii) bias -- the average difference between ASR-based and pencil beam radar microburst differential velocity estimates;
- (iv) root mean squared (RMS) difference between the pencil beam radar and ASR-based velocity differential estimates;

These metrics are tabulated separately for all microbursts and for the subsets of more operationally significant microbursts with differential velocities greater than 15 and 20 m/s. As with almost all Huntsville microbursts, the events considered were characterized by high radar reflectivity.

TABLE 2	. Microburst detecti	on algorithm	·	
performan	ce for ASR-based v	elocity fields.		
Dual Gaussi	an Parametric Velo	city Estimator.		
1988 Data				
	$\Delta V_R > 10 m/s$	$\Delta V_R > 15 m/s$	$\Delta V_R > 20 m/s$	
Detection Probability	0.91	0.90	0.96	
False Alarm Probability	0.05	0.04	0.0	
$\Delta V_{\rm P}$ Bias (m/s)	2.4	0.9	0.5	
RMS ΔV_{\bullet} Discrepancy (m/s)	4,8	3.8	3.7	

These statistics indicate a highly useful "wet" microburst detection capability for a modified airport surveillance radar. Detection and false alarm probabilities are uniformly within the 0.9/0.1 limits of the FAA's TDWR system requirements statement. Estimates of radial velocity divergence in the detected microbursts differ on average by 3 to 5 m/s from the closest (in time) available measurements with the pencil beam weather radar. Similar results apply to detection algorithm performance using the spectral differencing based ASR velocity estimates [13] and for data collected during the 1987 thunderstorm season [12]. Statistical analysis of the performance of the coherent cross-spectral velocity estimator is ongoing and will be reported in a future publication.

REQUIRED RADAR MODIFICATIONS

Figure 6 is a schematic of the current signal paths in an ASR-9 from the antenna to the A/D converters. When the radar is transmitting linearly polarized (LP) signals, both the aircraft detection processor and the six-level weather reflectivity channel receive signals from the same-sense polarization ports on the antenna feeds. Both high and low beam signals are brought through the rotary joint in waveguide and a single set of A/D converters are switched between the beams in a range-azimuth gated (RAG) mode. When circularly polarized (CP) signals are transmitted, the target channel continues to receive same-sense polarized data while weather processing is accomplished using signals from the orthogonal antenna ports. Only one RF path through the rotary joint is available for the opposite-sense signals so that RAG switching between the high and low beams must be accomplished on the antenna.

Figure 7 shows modifications to these paths that would allow for acquisition of low beam signals at short range as required for wind shear detection. For LP operations, the single-pole, double-throw switch between the high and low beams would be replaced by a double-pole, double-throw switch. This would shunt lowbeam signals to the wind shear processor for the range interval over which the target channel employs high beam signals. A separate STC module, receiver and A/D converter pair would be installed for this path. High beam data would be simultaneously available to the weather processor from the target channel A/Dconverters. If the target channel's RAG program required a switch to low beam data within the range of operational concern for wind shear measurements, the indicated paths would reverse; the dedicated weather receiver would accept high beam data whereas low beam signals would enter the wind shear processor via the target channel A/D converters.

When the radar transmits CP signals, the weather channel receiver would be switched to the single RF path from the orthogonal-sense antenna ports. High or low beam signals could be acquired over any range interval desired. Without a change to the rotary joint, it would not be possible to simultaneously access high and low beam orthogonally polarized signals, thus precluding the use of the phase differencing method described above. However, amplitude comparisons -- such as the spectral differencing and autocorrelation based methods -- could be accomplished by switching between the high and low beams on alternate antenna scans.

The radar hardware needed to implement the necessary changes consists therefore of switches, a receiver chain and A/D converters. Local oscillator signals must be extracted from the exciter chain and suitable microwave plumbing provided.

As part of our field measurement program we have deployed a real-time signal

processing system at the testbed ASR that implements the processing sequence described in this report. The system uses VME compatible single-board computers for control and microburst detection algorithm processing. Signals from the resolution cells of interest are distributed among six array processing boards, each of which can achieve computational loads of 20 million floating point operations per second. Displays are generated of the reflectivity and radial velocity fields to a range of 30 km with overlays indicating the location and intensity of automatically detected microburst outflows. The system was built from commercially available computing equipment at a cost of roughly 120 thousand dollars.

SUMMARY

Analysis and a field measurement program have demonstrated that a suitably modified airport surveillance radar could provide high confidence detection of microbursts associated with surface rain. Since these "wet" microbursts have been involved in all fatal wind shear-related air-carrier accidents to date, this capability would represent a significant safety benefit for airports not protected by other systems. At high priority airports, integration of wind measurements from an airport surveillance radar with data from TDWR or LLWAS could in some circumstances improve the quality and/or timeliness of wind shear alarms from the dedicated sensors.

Our current efforts are directed towards refined understanding of an ASR's wind shear detection capability and eventual implementation in the ATC system. Field measurements with the experimental ASR will continue at sites near Kansas City (1989) and Orlando, Florida (1990). Data to quantify the capability of an ASR to measure the strong, operationally significant gust fronts that occur in the mid-western and western U.S. have been obtained at the Kansas City site. In addition, we are simulating ASR signals from low-reflectivity microbursts observed during data collection with Lincoln Laboratory's TDWR test radar in Denver; these will allow for a better understanding of the extent to which an ASR could detect dry microbursts.

Ongoing discussion involving the FAA and supporting research organizations is attempting to clarify the extent to which ASR-based wind shear detection will be used within the National Airspace System (NAS). Possible implementations are as a retrofit to the new ASR-9's and/or a built-in capability for the nextgeneration ASR-10s, with the operational mission described previously. In our opinion, the obvious benefits and demonstrated wind shear detection capability justify deployment on both current and future ATC terminal radars.

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Figure 1: Vertical cross section of microburst wind field.

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Figure 2: ASR-9 system noise level expressed in terms of the equivalent weather reflectivity factor. Beamfilling losses for a 300 m or 500 m deep thunderstorm outflow are included.



Figure 3: Calculated area of obscuration for a microburst, assuming weather reflectivity factors of 10, 20 and 30 dBz.



Figure 4: Power spectra measured with ASR in approaching (left) and receding (right) radial velocity cores of example microbursts. The ordinate is relative power in linear units. Solid and dashed curves are from low and high receiving beams respectively. The Dashed vertical lines show the radial velocity measured by the pencil beam radar at 0.7° elevation angle at the same locations and times.

ASR-9 AMPLITUDE AND PHASE PATTERNS









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Figure 6. Simplified diagram of current signal paths from ASR-9 antenna to airplane target processor and existing weather reflectivity processor.

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Figure 7. Diagram of modified ASR-9 signal path configuration to allow for low altitude wind shear processing.

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