Optimum Siting of NEXRAD to Detect Hazardous Weather at Airports

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The Federal Aviation Administration has been concerned for some time about the number of aircraft accidents during terminal flight in which weather has been identified as the cause or a contributing factor. The next generation weather radar (NEXRAD), for which final specifications are being worked out on a multiservice basis, offers the possibility of dedicated and detailed surveillance of hazardous weather in the terminal airspace. This paper outlines considerations for choosing a site for a NEXRAD installation to fulfill this role in an optimum manner. It is shown that the detection of low-level shear without precipitation imposes the most severe constraints on NEXRAD siting. Three general siting areas are considered: 1) within the airport area, 2) within the terminal area, but outside the airport area, and 3) outside the terminal area. When a single NEXRAD radar must cover all hazardous phenomena over the terminal area, siting within the airport area appears to be the best choice. Under certain conditions, a case exists for siting the NEXRAD outside the terminal area.

Introduction

RELIABLE detection of hazardous weather phenomena near terminals has been a matter of continuing interest for the Federal Aviation Administration. A number of reports[1-11] in the last decade have established a strong link between atmospheric convection and aircraft accidents. Also, severe weather phenomena such as thunderstorms have been found to be the largest single cause of air traffic delays in excess of 30 min in recent years.[12] Thus there is a growing need to incorporate into the terminal air traffic control system improved capability to detect and identify elements of weather which are hazardous to aviation.

An aircraft would naturally respond to any disturbances occurring in the air mass in which it flies. However, the hazard potential of atmospheric disturbances is highest during the initial and terminal phases of an aircraft flight. This is so because during takeoff and landing an aircraft has very little airspeed and altitude to spare, and since the aircraft is in a high-lift configuration, it is more vulnerable to rapid changes in airspeed than it is under cruise conditions. Also, the effect of disturbances is greater at low altitude, where the air density is larger.

The problem of terminal area hazard detection is rendered rather complex by the fact that threats to flight safety come from a number of dissimilar atmospheric processes, such as thunderstorms, tornadoes, downdrafts, low-level shear, hailstorms, etc., affecting air flight in basically different ways. A successful hazard warning system must be capable of observing as many of these diverse phenomena as possible. To achieve economy in installation and operation, a maximum amount of common equipment should be used for the various tasks.

Detailed specifications and system configurations are being currently worked out for a multiservice next generation weather radar system (NEXRAD) based on the pulsed-Doppler principle and employing advanced techniques for signal processing and display. The Federal Aviation Administration, which is a participant in the NEXRAD project, is interested in using this system for improving the safety of terminal area air navigation and has instituted a number of studies toward that end. One study includes generation of data for evolving system specifications such as scan rate and scan pattern, and another part involves the determination of an optimum position of the NEXRAD system relative to the airport area—the so-called "siting" problem.

This paper deals with the factors that must be considered to determine an optimum siting for the next generation weather radar system from the point of view of detection of hazardous weather in air terminal areas.

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Weather Environment in Air-Traffic Terminal Areas

Several atmospheric phenomena affect air safety in terminal area (Table 1). The most familiar and easily observable among these are thunderstorms carrying heavy precipitation and often accompanied by strong winds. Turbulence, reduced visibility, and improper combustion (partial extinction) in jet engines, due to excessive water in intake air, are major hazards associated with thunderstorms. Precipitation may also occur as hail. Although as of now there is no foolproof method of identifying hail by radar, it usually involves high reflectivities. Since hailstorms have the same order of spatial extent and temporal stability as rainstorms, the discussions in the following sections apply as much to the former as to the latter.

Another class of phenomena of serious concern in terminal navigation consists of downbursts, low-level shear, and gust fronts. Precipitation may or may not be present. A downburst is a downdraft which causes damaging winds on or near the surface and may have a lifetime of only a few minutes. It is hazardous to aircraft if vertical speeds exceed the local ascent speed of the aircraft. There is no way of directly detecting the downburst shaft with a Doppler radar unless it is observed at high elevation angles. However, the parent convective cell usually has a longer lifetime and can be detected far more easily. It is therefore safest to avoid active cells rather than wait for the detection of downburst through the Doppler signatures of their outflow at low levels. Gust fronts often are associated with, and stay attached to, the thunderstorms that cause them. However, it is not uncommon to find gust fronts detaching themselves and propagating independently over considerable distances. A scenario depicting the hazard posed by low-level shear to aircraft in terminal maneuver (landing or takeoff) is shown in Fig. 1. Cold air downflow from a thunderstorm has a very well-defined boundary with the

Table 1 Atmospheric phenomena affecting air safety in terminal areas

Hazard	Reason	Most critical location
Heavy precipitation	Reduced visibility Possible aerodynamic effects Turbulence	Along the glideslope
Short-lived vertical downdrafts (downbursts) and horizontal shears	Forces airplane to ground	Glideslope less than 300 ft altitude
Gust front	Loss of airspeed, increased descent rate	Glideslope near the ground
Hail	Aircraft damage Turbulence	Entire area
Wake vortices	Unsafe for small aircraft to penetrate	Immediate vicinity of runway <300 ft altitude
Turbulence	Passenger safety and comfort Increase accident potential/hard landing	Along the glideslope

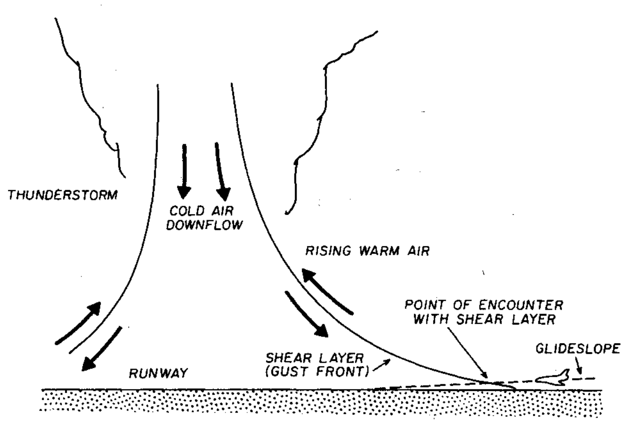

Fig. 1 Scenario depicting encounter of aircraft with low-level shear.

warm air inflow, causing a sharp shear layer to form at the interface. A low-flying aircraft would experience a sudden jump in airspeed while passing through the shear layer. This would cause large departures from the nominal flight path, or even instabilities, without prompt corrective pilot input. If this occurs too close to the ground, such perturbations can be fatal. The importance of wind shear as a hazard factor in terminal areas is borne out by the large number of recent studies based on both radar remote sensing[13-16] as well as direct airborne measurement.[17,18] Although methods have been suggested to minimize the hazardous effects of wind shear by modifying the flight procedure and/or flight instrumentation,[19,20] these methods are still experimental and are likely to be limited in application because of the limited airspeed margin (airspeed in excess of local stall speed) available when the aircraft is close to landing or takeoff. The best approach, at present, seems to be to detect any hazardous shear along runways and glideslopes and warn the pilot so that he may avoid the hazards or remain alert for corrective action.

An atmospheric turbulence phenomenon of great interest to terminal area navigation is the shedding of powerful wake vortices by large jet aircraft. These vortices can often be strong enough to affect the flight of other aircraft, especially the smaller ones, within the wake region, and thus force a minimum separation between aircraft taking off or landing. A reduction in this separation would lower operating costs and fuel expenditure owing to greater traffic handling by airports and reduced waiting time. Fortunately, such a reduction is possible because wake vortex turbulence is often dissipated faster or deflected from the flight path by crosswinds (which might be measured by Doppler weather radar). Thus the spacing between aircraft need not be maintained at a worst-case value, but may be altered in each case. The needed observations can, in principle, be conducted by weather radars,[13,21,22] although wake vortex turbulence is not a phenomenon of weather origin.

Next Generation Weather Radars

Weather radars operate essentially by transmitting bursts of microwave energy and detecting the energy backscattered by the weather phenomena. In order to return detectable amounts of energy, weather phenomena must contain sufficient numbers of scattering agents of appreciable size. These scatterers are called "tracers" because they help trace the motion of the air mass which carries them. In severe weather phenomena, solid or liquid particles such as hail or raindrops usually serve as tracers. When these particles are absent, and the air is optically clear, small-scale (several centimeters) pockets of turbulence containing refractive index gradients act as tracers. In general, the latter type of tracers return less signal than the former. It is thus more difficult to observe clear-air weather phenomena than to observe precipitation.

At present, routine radar observation of weather in the U.S., conducted by the National Weather Service using the WSR-57 radar, relies almost entirely on reflectivity measurement, i.e., the estimation of power returned from scatterers in individual radar resolution cells weighted by certain radar parameters such as antenna pattern, pulse shape, receiver response, etc. The underlying assumption here is that the higher the echo strength, the higher the water content and, hence, the higher the severity of a weather phenomenon. However, with increasing demands on weather radars to monitor different types of phenomena and/or observe more attributes and details of the more familiar types, it is becoming clear that reflectivity measurement alone is not enough. Thus future weather radars must be "Dopplerized," i.e., provided with capability to process echo returns coherently from pulse to pulse so as to estimate the radial velocity of the tracers (relative to the radar site) contained in different resolution volumes.

Radar observation of weather phenomena differs substantially from observation of point targets such as aircraft. The latter type causes a Doppler shift which is essentially a single frequency, while the former generates an ensemble of frequencies, caused by the motion of numerous individual scatterers within the resolution volume. Thus, in weather observation, one deals with a "Doppler spectrum" (Fig. 2) instead of Doppler frequency, and estimates the moments of the spectrum that are related to the attributes of the weather process. The zeroth moment, or the area under the power spectrum curve, is a measure of reflectivity indicative of the intensity of precipitation in the resolution cell. The mean Doppler frequency, the first moment of the power spectrum [about the power spectral density (PSD) axis] normalized with respect to the zeroth, indicates the mean radial velocity of the air within the resolution cell. The square root of the normalized second moment of the Doppler spectrum, usually referred to as "spectrum width," corresponds to the level of turbulence and shear within the radar resolution cell.

Moments of higher orders can be defined, but they not only progressively lose correspondence with reality, but are increasingly difficult to evaluate and have diminishing accuracies. For almost all applications, it will suffice to measure and display the first three spectral moments.

Coherent radar processing to extract Doppler information requires that time series data obtained from the receiver be in complex form, containing both the amplitude and phase of the echo return from each resolution cell. Also, coherent processing requires a much higher stability of transmitter and local oscillator frequency (phase) than is necessary for incoherent processing. These special features are reflected in the block diagram (Fig. 3) of a typical Doppler weather radar. The NEXRAD system, for which specifications are being worked out and design studies are in progress, is likely to be a variant of the system shown in Fig. 3.

There are two basic methods for spectral moment computation: the spectral or Fourier transform method and the autocovariance or pulse-pair method. In the former, calculations are performed in the frequency or spectral domain, whereas in the latter they are carried out in the time domain. The formulas used for moment estimation are given elsewhere.[23] The estimation of moments in the spectral domain is conceptually straightforward; its chief advantage associates with a more familiar and easier interpretation of echoes that produce multimodal spectra, i.e., spectra with multiple peaks. Such complex spectra can be produced when weather signals are mixed with echoes from other interfering targets, such as aircrafts and ground clutter, that may be in the same resolution cell or other cells at the same range. Weather phenomena occurring at a cell different from the one under observation, but at the same range, also constitute interference. The pulse-pair method, in contrast, is effective only when spectra are nearly unimodal, as in part (i) of Fig. 2b, but offers the advantage of much lower complexity of computation, permitting efficient real-time implementation at an affordable price.

The final specifications of the NEXRAD system are yet to be worked out. However, in order to study the siting problem, a set of baseline characteristics, as given in Table 2, may be assumed.[24] It is generally believed that these parameters are close to optimum for an operational Doppler weather radar.

After the three spectral moments are computed for all the resolution cells covered by a scan, they may be displayed on separate color/black-and-white cathode-ray tube displays with color codes/shades of gray representing various quantized levels. Alternatively, features from each of the three moment fields may be combined on a single display. Such a composite display may delineate the hazardous areas with a possible option of color coding hazard types. This holds potential for terminal area radars since it adds the least to the already overcrowded display panels aiding air traffic controllers.

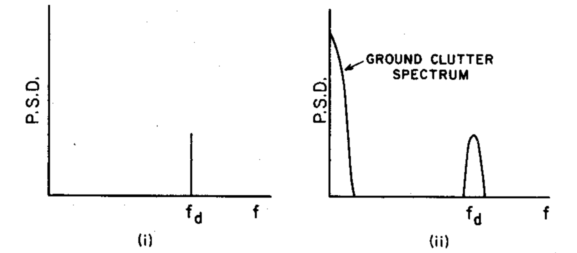

Fig. 2a) Doppler frequency shift by point target; i) a moving point target ideally produces a spectrum with zero width; ii) actual spectrum has finite width and may be accompanied by a ground clutter spectrum component. f_d is the Doppler shift due to target motion.

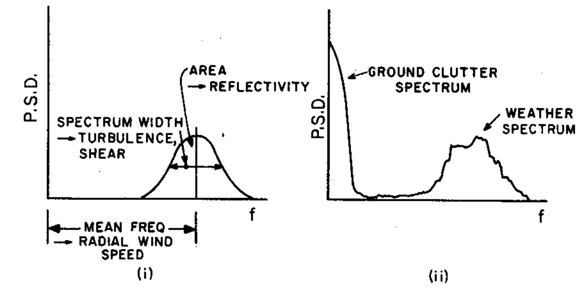

Fig. 2b) Doppler spectra of distributed targets, e.g., weather: i) ideal, showing the three moments and their significance, ii) actual, showing distortions and ground clutter contamination. f is the Doppler shift.

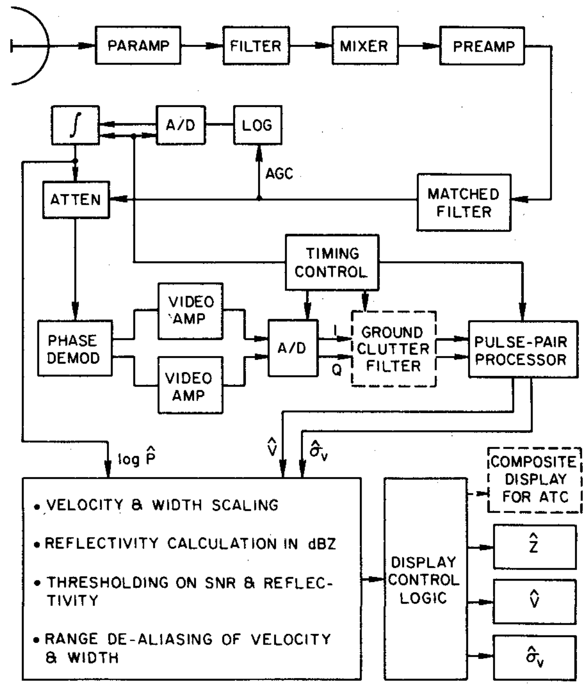

Fig. 3 Schematic of a Doppler weather radar receiver.

Definition of the Siting Problem

Terminal area is defined as an area of radius 30 n.mi. (56 km) around the airport's runway complex. The siting problem is stated as[24]: "Where, and for what reasons, should a single Doppler weather radar be sited within the area identified as the 'terminal area' such that optimum identification, measurement and tracking of those convective attributes termed 'hazards' can be accomplished from the surface to 20,000 ft above MSL."

Table 2 Clear-air gust fronts

Date	Maximum height, km	Peak reflectivity,[a] dBZ	Radial speed difference, $m \cdot s^{-1}$	Width of front,[b] km	Length, km
4/10/81-11/30/81	1.2	8	40	1-4	50-80
4/13/81	1.3	9	35	1-5	25-110
4/30/81	1.6	11	36	2-7	120
5/9/81	2	7	30	7	120
5/13/81	0.6	2	21	0.4-1.0	80-100

[a]The radar reflectivity factor Z is the average sum of the sixth powers of particle diameter per unit volume. It is customary to express Z in units of $mm^6 m^{-3}$ and then convert it to the decibel system, resulting in the dBZ notation.
[b]The difference in the peak radial velocities in the gust and the radial velocity of the environmental flow immediately in advance of the front. The gust front width is measured from the peak gust velocity location to the leading edge of the front.

Siting Criteria

In deciding a site for locating a radar of the NEXRAD type to detect convective phenomena hazardous to terminal area navigation, the following criteria must be considered.

Range Coverage

The radar must be able to detect reliably the weakest phenomenon of interest over the entire terminal area. Among the phenomena that affect terminal flight safety, the weakest from the point of view of radar detection is the low-level wind shear without precipitation. As mentioned before, refractivity irregularities are much weaker scatterers than particulate tracers, making the detection of clear-air convection more difficult than that of precipitation. Thus detection of clear-air wind shear sets the range limit on a hazard detection radar. Characteristics of five clear-air gust fronts are given in Table 2. Wake vortices in clear air usually have considerably lower reflectivity factor Z determined by the refractive index structure constant.

Also of some concern is the minimum range of the radar, which is determined by the following three major factors:

1) The recovery time of the receiver (and/or duplexer) following the transmitted pulse; 2) the distance to which ground clutter returns received via main and sidelobes of the antenna pattern saturate the receiver; and 3) the distance to which the part of the transmitter phase noise reflected by the ground clutter is strong enough to interfere with the weather signal.

For modern radars with very low recovery times, the minimum range is usually decided by factor 2 for strongly scattering weather phenomena and by factor 3 for weak ones.

Altitude Coverage

The radar must be able to cover the entire altitude interval between the highest, stipulated to be 20,000 ft (6.1 km) above MSL, and the lowest at which hazardous phenomena may be found. Covering the higher altitudes seldom poses any problem. Again, the lowest height to be observed is determined by low-level shear, which often has a peak below 500 m. To detect most parts of a gust front with a peak velocity located at, say, 300 m altitude, the radar must be able to "look" down to about 100 m or, preferably, 50 m. The minimum observable height is determined by the radar horizon, surface obstructions, and ground clutter, in addition to range from the radar. The fact that the phenomenon which decides the minimum height is also the weakest, complicates the problem of hazard detection.

Range Ambiguities and Overlaid Echoes

The problem of range and/or velocity ambiguities (aliasing) is inherent in pulsed-Doppler systems and in the case of pulsed-Doppler weather radars such as NEXRAD, the problem is very real. There is a tradeoff between choices of unambiguous range and velocity defined in

$$r_a v_a = c\lambda/8 \tag{1}$$

where r_a is the unambiguous range of the radar; v_a is the unambiguous velocity along a radial from the radar; c is the propagation speed, 3×10^8 m/s; and λ is the radar wavelength. If, as given in Table 3, a 10-cm wavelength is chosen from the consideration of antenna size, severe weather penetration, etc., Eq. (1) reduces to

$$r_a v_a = 3750 \tag{2}$$

where r_a is expressed in kilometers and v_a in meters per second. To observe most severe weather phenomena without undue velocity aliasing, an unambiguous velocity up to ± 30 $m \cdot s^{-1}$ must be used. Then, relation (2) gives an unambiguous range of 125 km. NEXRAD requirements[25] stipulate a range of 230 km for velocity and spectrum width measurement. Thus the NEXRAD must have coherent measurement capability over a two-pulse interval.

Although an unambiguous range of 125 km seems large compared to the 56 km radius of the terminal area, the problem of overlaying of features can, nevertheless, be quite serious in the context of terminal area surveillance because of the extremely large dynamic range of the phenomena of interest. Also, unlike point targets such as aircraft and ships, for which the strength of the return signal decreases as the fourth power of range, the return from weather phenomena diminishes only as the square of the range. Thus, if precipitation of strength 40 dBZ (which is quite common) occurs at a range of 175 km, it will be overlaid into the unambiguous range and appear as a patch of strength 29 dBZ located at 50 km, which is less than the radius of the terminal area. This apparent feature can completely overshadow all clear-air phenomena coinciding with it, including severe low-level shear, which usually have reflectivities of the order of 10 dBZ or less.

Table 3 Typical characteristics of a pulsed-Doppler weather radar

Characteristics	Specification or specification range
Wavelength	10 cm
Beam width	0.75-1.25 deg
Number of beams	1 or 2
Pulse widths	0.15-0.45 km
Pulse repetition rate	300-900 pulses/s
Update rate	2-5 min
Antenna rotation rate	Commensurate with update rate
Processing equipment	Commensurate with real-time display of reflectivity and Doppler attributes individually and collectively

Zone of Blindness

A radar system is blind to a volume of space directly above it, depending on its scanning scheme. If e_{max} is the elevation angle of the highest level of scan in degrees, then the overhead blind zone is an inverted vertical cone with a semivertical angle of $90 - e_{max}$ deg and vertex located at the radar, as shown in Fig. 4. When the radar is required to observe only up to a specified height, the maximum radius r_b of the overhead blind zone is given as

$$r_b = H \, ctn \, e_{max} \tag{3}$$

where H is the maximum height of observation.

Studies have been conducted at NSSL on the lifetime and spatial extent of significant storm features and their influence on a scan strategy for NEXRAD.[26] It appears that as a good figure of compromise between excessive scan time and too large a blind zone, the highest scan elevation should be about 25 deg. Substituting this value for e_{max} and the stipulated height of 20,000 ft (6.1 km) for H in Eq. (3), the maximum radius of the blind zone is 13 km.

To decrease the blind zone, the elevation of the highest scan level must be raised further. However, since the scan time increases in proportion with the maximum elevation angle (keeping the spacing between scan levels fixed), this would amount to a considerable reduction in information update rate in exchange for only a modest increase in the scan volume. In the NEXRAD context, where a case exists for actually speeding up data update, any increase in scan cycle time may not be acceptable. Thus any siting scheme must take into account the existence of a blind zone of maximum diameter of 26 km centered at the radar.

Resolution

In general, it may be said that the resolution requirement of terminal area weather radars must be finer than en route radars since terminal airspace is more crowded than en route airspace, and also because large trajectory deviations may not be permissible for an aircraft close to takeoff or landing. However, for observing large features such as thunderstorms, an overly fine resolution is not necessary, since, in any case, aircraft must be sufficiently separated from the storm to take into account its gradual edge definition as well as its motion between successive scan cycles of the radar. The radar resolution need not be much finer than this separation.

Considerations are, however, different with regard to the observation of phenomena of smaller spatial extent. For example, in the case of low-level shear occurring within a height of 500 m or less, a linear beam width of the order of 200 m should be used so that the lowest two or three scans of the scan cycle would pass through the part of the shear layer above the radar horizon. With a 1-deg beam (Table 2), this means that the radar should not be located more than about 12 km from the point where the existence of a shear layer is to be determined. It is clear that this requirement conflicts directly with the blind zone consideration and that either one of these or both would have to be compromised.

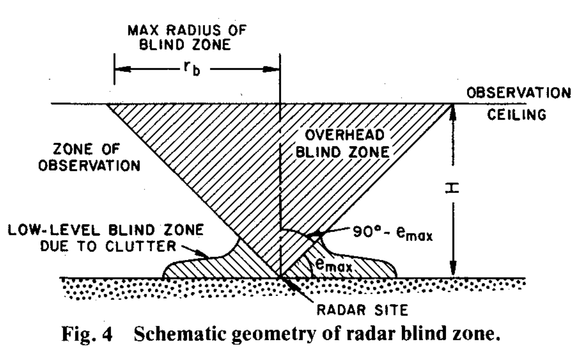

Fig. 4 Schematic geometry of radar blind zone.

Information Updating Interval

New information concerning the weather situation within the scan volume is obtained once every scan cycle. The scan cycle time currently being considered for NEXRAD is 5 min. The Federal Aviation Administration is exploring the possibility of cutting down the cycle time by a half—to 2.5 min—in case there are fast-growing hazardous phenomena that may be missed by using a slower scan rate. One way of achieving this is to locate the radar at some distance from the area surveyed so that scanning of a limited azimuthal sector gives the desired coverage. In such a case, the cycle time can be brought down to 2.5 min or less, while scanning all the levels of interest, at the penalty of coarser resolution and higher radar horizon.

There are other possible approaches to the problem of missed detection of short-lived or fast-growing phenomena. These include scanning alternate elevation angles in alternate scan cycles (the so-called "interlaced scanning"), interposing a decimated scan cycle (covering one or a few of the more important levels) within a full scan cycle, etc. Each approach has its own strong points. The sector scan has the advantage that the maximum time interval between data update at any level in a scan cycle is a minimum, if the total number of scan levels is kept the same in all approaches.

Airport Configuration

Since the Doppler radar measures only the radial component of windspeed, it should be located along the runway if estimates of headwind/tailwind are to be obtained. In larger airports, which have a number of runways, the radar should be located as close as possible to the common intersection of all the runways. However, such a point may not exist or may not be available for radar installation. In such a case, the location should be as close as allowed (height limitations, blockages, etc.), so that a component of headwind/tailwind will be measurable. One of two assumptions may be used to derive the absolute windspeed from the radial component: 1) the wind direction is normal to the local tangent to the gust front, 2) the wind direction is along the runway being observed (worst case).

It should be mentioned here that it is not essential to measure the headwind/tailwind to establish the hazard potential of a phenomenon. The severity of a phenomenon can, in most cases, be inferred from nearly all aspects of view. For example, a downdraft perpendicular to the surface has a nearly omnidirectional outflow. Similarly, a gust front, which may not show up too well in the velocity field if seen along the direction of the front, will appear in the Doppler spectrum width field owing to increased turbulence.

Other Functions

Although the present discussion concerns the use of NEXRAD for terminal area surveillance, it must be remembered that the NEXRAD system is not being designed solely for this purpose, but with a much wider application in mind. In fact, it is expected to eventually replace the current generation of non-Doppler radars for routine weather coverage as well as en route air weather monitoring over most of the conterminous U.S. (CONUS). Thus the terminal area surveillance function of the NEXRAD should not conflict seriously with its broader role as a weather radar.

Discussion of Specific Siting Alternatives

Depending on the distance of the NEXRAD site from the runway complex, three broad siting alternatives are considered: the airport area, the air terminal area, and outside the air terminal area. The relative merits and demerits of each of these alternatives are discussed in the following subsections.

Siting in Airport Area

Airport area is defined as an area of 10.8 n.mi. (20 km) radius around the runway complex. Locating a NEXRAD radar within this area offers several advantages:

1) Since the detectability of a weather feature improves as R^{-2} (R is the range from radar), a closer location helps the detection of weakly scattering phenomena, such as those occurring in clear air, over the runway complex.

2) Observation at close range minimizes the probability of overlaid echoes from strong features obscuring weak scatterers. This is so because multiple-trip echoes are attenuated by the square of the ratio between the actual and apparent (ambiguous) ranges. Thus, if a weak feature lies at a range of 10 km and a strong feature at 135 km folds over it (unambiguous range = 125 km), then the strong feature will be attenuated by a factor $(135/10)^2 = 182$, or 23 dB, and hence it will have less chance of overpowering the weak feature.

3) Because of the above two reasons, close siting provides measurement of vertical profile of wind shear where it is most needed—on the runways and the parts of glideslopes closest to runways.

4) Since linear beam width is small at close ranges, airport siting provides excellent resolution for mapping wind shear phenomena along critically important glideslope approaches to runways.

5) Problems of beam blockage may not be severe because tall buildings would not be allowed close to the airport.

6) Since the stipulated ceiling height of radar observation is the smallest (10,000 ft or 3.05 km)[24,25] in the airport area, the maximum radius of the blind zone is also the smallest, as seen from Eq. (3).

The disadvantages of siting NEXRAD in the airport area include

1) Loss of flexibility in locating a site, since most parts of the airport area are occupied by runways, airport structures, and accessories; also, the radar installation itself would be subject to height restrictions within the airport area.

2) An overhead blind zone that, although the smallest, is located in a more critical area close to the runway complex.

3) The need for sophisticated clutter rejection techniques.

Ground clutter is the most difficult problem encountered in performing close-range observation of weather phenomena. At low elevation angles (less than the 3-dB beam width), the main beam of the antenna pattern is reponsible for most of the clutter return, while at higher elevation, clutter is caused primarily by sidelobe returns. Thus, at low elevation angles, clutter is more severe. In the NSSL experimental Doppler weather radar at Norman, Oklahoma, the average range of severe clutter interference (i.e., equivalent reflectivity factor, Z_e, of clutter above 45 dBZ) is from about 15 to 20 km for an elevation angle of 0.5 deg and is about 5 km when the elevation is of the order of 2 deg or more. It would be possible to reduce the latter figure by using an improved antenna in the NEXRAD with lower sidelobe level (the NEXRAD specified one-way mainlobe-to-sidelobe ratio of 25 dB may be adequate) and by improving the radome design and construction to minimize the distortion of the basic antenna pattern. A reduced sidelobe level has the added advantage that strongly reflecting precipitation appearing in the sidelobes would have less interfering effect on the main beam observation of weather targets.

The problem of main beam clutter, however, cannot be solved by antenna and radome improvements. This problem is especially severe while trying to observe the lowest levels stipulated by FAA for the airport area; this level is at 200 ft (61 m) above gound.[27] If the radar is to be located 10 km away from the center of the runway complex, the opposite end of the airport area would be 30 km away, and to observe a height of 61 m, the elevation angle of the lower 3-dB point of the beam should be 0.12 deg. At this elevation angle, mainlobe ground clutter can extend to over 30 km in range. By using relatively simple and affordable clutter filtering techniques, the area of severe ground clutter interference can be considerably reduced, but this would impose some constraints on the number of pulses that must be available for processing (which, in turn, regulates the scan rate) and discourage the use of nonuniform pulse spacing to resolve range ambiguities.[28,29]

A very effective, but relatively expensive method of clutter filtering in the reflectivity field is to generate and store a static clutter map of the area around the radar installation and subtract the clutter strength, cell by cell, from the incoming signal. However, a static clutter map has the drawback that if the clutter environment changes with time (as it often does), then cancellation performance will be degraded. A way out of this problem is to use a dynamic mapping scheme in which the clutter map is continuously updated, based on the near-zero frequency component of the most recent observations, but this method again has the disadvantage that stationary or nearly stationary weather phenomena are recognized erroneously as clutter and are included in the clutter map.[13]

The success of any clutter rejection scheme at all is based on the assumption that clutter and weather signals appear additively at the receiver output, which is true only if the receiver operates in the linear region. When the clutter return is so strong that the receiver is saturated, the weather signal component is irrecoverably lost and no clutter cancellation method can retrieve that signal. Although the range to which saturation occurs is a function of several radar parameters and clutter cross section, a probable range, based on experience with NSSL radars, lies between 2 and 5 km. The minimum range based on ground return of transmitter noise, as explained before, is probably longer. If convective phenomena are to be observed at closer ranges, then receiver desaturation methods such as sensitivity-time control (STC) must be employed, along with the attendant complications of hardware and software.

It is thus clear that there is no easy way out of the problem of main beam clutter and that sophisticated clutter cancellation methods are necessary for successful observation of low-level shear at close ranges. At present there are no data on operational effectiveness of ground clutter cancellers on Doppler weather radars. However, engineering experience with other radar systems and theoretical predictions[30] suggest that 50 dB of clutter cancellation is achievable. At sites this would leave only small patches of clutter area.[28,31]

The minimum distance of the radar from the runways is obtained from blind zone considerations. Figure 5 shows the minimum and maximum altitudes of weather radar coverage in different areas, as required by FAA. For a maximum altitude of 10,000 ft (3.05 km) and a maximum scan elevation of 25 deg, the radius of the overhead blind zone is obtained from Eq. (3) as 6.5 km. Thus, to observe the space directly above and in the immediate vicinity of runways and glideslopes, the radar should not be located closer than about 8 km (preferably 10 km) from the nearest runway or glideslope. However, at the altitude of low-level shear

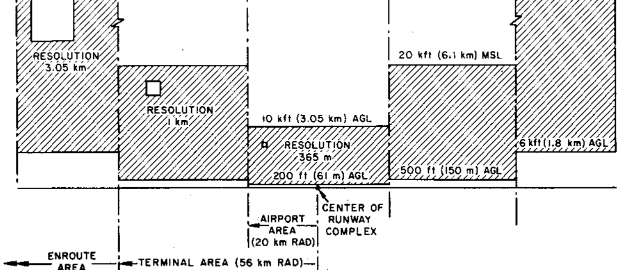

Fig. 5 FAA requirements[24] of altitude limits of NEXRAD coverage and resolution in different flight areas.

phenomena (approximately 500 m) the radius of the blind zone is very small and it may be assumed that the radar can "see" these phenomena over the entire airport area.

Siting in Terminal Area

Locating the NEXRAD radar within the terminal area (30 n.mi. or 56 km radius), but outside the airport area (10.8 n.mi. or 20 km radius), offers the following advantages:

1) The runway complex as well as the critical parts of the glideslopes, where weather observation is of utmost importance, are well outside the range of sidelobe ground clutter. Also, main lobe ground clutter would not be a serious problem in observing these critical areas since they are at a minimum range of about 20 km, and since these areas would return relatively less clutter because of the flatness of terrain and absence of significant man-made structures.

2) By suitably locating the radar, the entire airport area can be kept outside the blind zone of the radar.

3) A greater flexibility in siting the radar is obtained so that coverage can be optimized. This may include minimizing beam blockage from buildings, raised ground or mountains, etc., and close-range coverage of other nearby installations.

4) By locating the radar close to the airport area boundary (within 21 km from the center of the runway complex for a 1-deg beam) the stipulated resolution of 365 m (Ref. 27) can be obtained over the runway complex.

5) Obscuration of the terminal area due to multiple trip echoes from thunderstorm squall lines[29] can be reduced by locating the radar so that the line joining the radar and the runway complex is perpendicular to the most frequently observed orientation of the squall lines in the area.

The chief disadvanages of locating the NEXRAD radar inside the terminal area but outside the airport area follow:

1) Since the stipulated ceiling height of observation for the terminal area [20,000 ft mean sea level (MSL)] is more than that for the airport area [10,000 ft above ground level (AGL)],[27] the maximum diameter of the overhead blind zone would be correspondingly larger for the former. The maximum diameter of the blind zone has a radius of 13 km for the terminal area as compared to 6.5 km for the airport area. This assumes that the airport being considered does not have an appreciable height above the mean sea level.

2) To satisfy the minimum altitude coverage requirement all over the airport area, the beam would have to graze the ground at close ranges. Thus the severe main beam clutter problems mentioned earlier would remain in their entirety. However, because of the relatively distant location of the radar, the runway complex and glideslopes will be outside the zone of strong clutter interference.

With a relatively modest clutter cancellation scheme, the zone of severe clutter interference can be made smaller than the overhead blind zone of the radar. This does not, however, mean that the incentive for further clutter cancellation is lost. The maximum radius of the overhead blind zone is defined only at the highest level. At lower levels, the area of the blind zone gets progressively smaller, and at the height of low-level shear, it is negligibly small. Thus any improvement in clutter performance will result in better coverage close to the radar. Also, to avoid surprise developments within the blind zone of a radar, the zone must be observed, albeit coarsely, by an adjacent NEXRAD system. Since such a system is likely to be far away (as much as 400 km), it can observe only the top part of the next radar's blind zone, the bottom part being below its radar horizon. Thus there is no redundancy available in the observation of low-level phenomena and, hence, reduction in clutter is the only way that low-level phenomena close to the NEXRAD site can be observed.

In relative terms, however, the clutter performance of a NEXRAD located in the terminal area need not be so stringent as that of one located in the airport area. This is because it is possible to choose a location within the terminal area so that the clutter in the surveillance region is weaker. A low-level shear phenomenon, such as a gust front, is likely to be wide enough to have detectable portions outside the clutter region. If it is small enough to be entirely in the clutter zone, it would be detected at a later time as it gets out of that zone and moves toward the runway area, where it can be a source of hazard.

3) If the radar is assumed to be located at a distance of 38 km from the runway area (halfway between the boundaries of airport and terminal areas) then, with a 1-deg beam, the worst resolution within the airport area would be 1000 m and within the terminal area it would be 1600 m. This is much worse than the FAA stipulated values of 365 and 1000 m in those areas, respectively.[27]

Siting Outside Terminal Area

A NEXRAD radar can also be located outside the terminal area, i.e., at a distance greater than 56 km from the center of the runway complex. Such a location has several advantages:

1) It offers the possibility of covering the terminal area by sector scan, rather than full-circle scan. Since the scan cycle time varies almost in proportion to the angular width of the sector being scanned, the information updating interval can be reduced in this manner. This would minimize the possibility of fast-evolving phenomena growing to hazardous levels between successive scan cycles of the radar. Such a possibility has been the cause of some concern on the part of FAA, which has favored a somewhat faster scan rate than the 5 min nominally accepted for NEXRAD and has instituted some studies in this connection.[26,32] The sector-scan advantage of locating the NEXRAD outside the terminal area may not, however, be realizable in practice because of other commitments of the system, such as en route surveillance and general weather monitoring, which may enforce a full-circle scan pattern.

2) The greatest flexibility in siting is obtained because the requirement of terminal area surveillance does not seriously interfere with plans to set up a nationwide network of NEXRAD radars. Studies have been conducted[25] to evolve a siting scheme for optimally covering the CONUS, using a minimum number of radars. Such coverage will be facilitated if the NEXRAD is not constrained to be located within the terminal area.

3) The entire terminal area can be made to lie outside the clutter region and the blind zone of the radar. Thus complete coverage of the terminal area can be obtained and expensive clutter-filtering methods need not be employed.

The following are the disadvantages of locating the NEXRAD outside the terminal area:

1) The stipulated minimum altitude of observation over the airport area falls below the radar horizon even when the radar is located close to the terminal area boundary. Thus, when the radar is close to the ground level at about 20 km from the terminal area boundary, the height of the radar horizon above ground at the runway complex is about 1000 ft (305 m), rather than the stipulated minimum of 200 ft (61 m). Visibility may be improved by installing the radar higher above the ground, but this would have the drawback of increasing the range of clutter interference since the shielding provided by the ground at close range (causing faster main beam rolloff) would be lost.

2) The resolution requirements would not be satisfied. Assuming the radar to be 76 km away from the center of the terminal area (20 km from the boundary) and a 1-deg beam width, the worst resolution in the airport and terminal areas would be 1700 and 2300 m, respectively. As mentioned before, the stipulated resolutions in these areas are 365 and 1000 m, respectively (Fig. 5).

3) The distance of the radar from the runway area would be limited by the range to detect low-level shear. Experiments at NSSL show that observation of clear-air phenomena of moderate strength (of the order of 0 dBZ) within the planetary boundary layer is reliable only up to about 60 km.

4) The interference due to overlaid echoes is stronger than that for a radar located in the airport area.

Comparison of Siting Alternatives

It is clear from the foregoing discussions that no single siting option satisfies all the FAA requirements of weather surveillance over the entire terminal area. The problem of optimal siting therefore reduces to choosing a location that minimizes the compromises.

Resolution requirements over the entire terminal area can be met only by locating the radar very close to (within about 1 km) the center of the terminal area. This condition, together with the advantages of close observation of runways and terminal parts of glideslopes, and minimum risk of range-folded overlay are strong factors favoring location of the NEXRAD radar within the terminal area. The existence of an overhead blind zone and a clutter-limited area close to critical areas, such as runways and glideslopes, are reasons against airport area location.

Locating the radar outside the airport area, whether within or outside the terminal area boundary, violates the resolution requirement. However, these sites offer the important advantage of nearly clutter-free operation over the runway complex, which is the main area of interest. In addition, siting outside the terminal area makes possible complete coverage of the terminal area without any blind zone.

Overall, it appears that if one NEXRAD radar is required to observe all hazardous convective phenomena over the entire terminal area, then it has to be located within the airport area. A preferred range of location would be between 10 and 12 km from the center of the runway complex. Also, a minimum distance of about 8 km must be maintained from the nearest runway or glideslope. With such a location, the blind zone and the clutter area can be kept clear of runways and glideslopes.

It should be remembered, however, that when a radar is located at a range of, say, 10 km from the center of the runway complex, it may be only about 6 or 7 km from the nearest runway, and to keep this runway and its vicinity positively clear of clutter, the clutter zone must be limited to about 5 km in range. This approaches the range at which clutter starts saturating the receiver, and clutter-reflected transmitter noise would also severely compete with weather signal at such ranges. Thus the suggested location still requires efficient anticlutter measures for satisfactory operation. In addition to using transmitters with very good phase stability, signal processing or beam shaping or both may be employed. The former consists of the spectral or time-domain filtering, static or dynamic clutter map generation and subtraction, and sensitivity-time control methods mentioned earlier. The latter may involve antenna shrouds for sidelobe reduction and "clutter fences" which are rf screens erected around the radar installation to provide artificial blockage of the ground-grazing parts of the main beam and thus reduce backscatter from points on the ground beyond the fence. The clutter fence, in effect, causes a faster roll-off of the lower side of the main beam radiation pattern at far field than that which is provided by the antenna.

It must be pointed out here that the location of the NEXRAD as suggested above would somewhat violate the resolution requirement in the terminal and airport areas. The worst resolution in the airport area would be 520 m as against a stipulated 365 m, and in the terminal area it would be 1150 m as against 1000 m. To fully satisfy resolution requirements from the proposed location in the terminal area, a beam width of 0.7 deg would have to be employed. In addition to nearly doubling the aperture area of the antenna, it would slow down the scan rate for a given processing time and the scan cycle time of 5 min would be more difficult to achieve. If beam blurring due to antenna rotation is taken into account, a static beam width of about 0.5 deg may have to be adopted to satisfy the resolution requirements. This would escalate the cost of the radar system rather steeply.

It appears that the resolution requirements of FAA are too stringent and may have to be relaxed at least at the edges of the regions concerned. One suggestion is not to specify constant values of resolution over entire areas, but to express resolution as an increasing function (linear or parabolic, say) of radial distance from the center of the runway complex, subject to a ceiling. This would also make the stipulated resolution continuous across the boundaries of the airport and terminal areas, which appears to be a natural thing to do. A suggested resolution law is

$$\Delta r = \min\left[(350 + 0.45\, r^2),\ 3050\right] \tag{4}$$

where Δr in meters is the required resolution at a distance r (in kilometers) from the center of the runway complex. This law guarantees a resolution of 365 m over the runway complex and 1000 m at 38 km, which is midway between the airport and terminal area boundaries. The suggested radar location 10 km from the center of a runway complex would satisfy the resolution given by Eq. (4) with a 1-deg beam.

In the case of very large and busy airports, a case exists for siting the radar outside the terminal area. This is because a suitable place may not be available in the 10-12 km range interval suggested earlier and, more importantly, such a location offers the possibility of sector scanning, resulting in a faster data update rate. Although a NEXRAD unit tied to the national weather network is most likely to have a full-circular scan pattern, the scale of operations at a large airport may justify the use of a dedicated NEXRAD unit which may then operate in a manner most optimum for terminal area surveillance, without any compromises dictated by other applications.

The use of other instrumentation to aid NEXRAD operation has been mentioned in the literature. Strauch and Sweezy[16] have suggested distributing wind shear sensors, consisting of small antennas and low-power transmitters with receivers located at the intersection of major runways and hooked to a common data system. Such a system would complement the NEXRAD system, which would then be primarily used for storm surveillance. However, in its simplest form, it will be effective only in the presence of precipitation.[16] To detect wind shear in clear air, each of these instruments would have to be a nearly complete radar unit of considerable sophistication, resulting in high cost. While work toward proving the feasibility and economics of such a proposal is worthwhile, the best course for an operational system at present is to extract as much detection capability as possible from a general system such as NEXRAD by suitable parameter design and siting.

Concluding Remarks

The decision regarding siting a radar for the detection of hazardous convective phenomena in the terminal area around a particular airport depends on a large number of factors, among which are the topography and layout of the airport; type, distribution, and severity of the convective phenomena normally encountered in that area; characteristics of the radar to be sited; and the totality of functions assigned to the radar. In the absence of detailed information on all of these, the discussion can at best be a general one, based on average parameters. There is much interplay of the various significant factors involved in choosing a proper site for a NEXRAD radar for terminal area surveillance.

In spite of the seeming uncertainties inherent in the problem, it has been possible in this study to draw definite conclusions regarding the best location for a NEXRAD unit for terminal area weather surveillance. When a single radar system is available, which will be the case for most airports in the forseeable future, the best place to locate it is at a distance of between 10 and 12 km from the center of the runway complex. At such a location, the system would be able to meet almost all of the FAA requirements. The exact spot within this 2-km ring will depend on the airport topography and other operational constraints.

The parameters of the NEXRAD system are still in a stage of evolution and are not yet available in a final form. One of the objectives of the study reported in this paper is to help finalize the NEXRAD system parameters by pointing out cases where the proposed parameters either conflict with, or are inadequate for, one of the proposed functions of the NEXRAD system—terminal area hazard surveillance.

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References

[1] Fujita, T.T. and Caracena, F., "An Analysis of Three Weather-Related Aircraft Accidents," *Bulletin of the American Meteorological Society*, Vol. 58, Nov. 1977, pp. 1164-1181.

[2] Fujita, T.T. and Byers, H.R., "Spearhead Echo and Downburst in the Crash of an Airliner," *Monthly Weather Review*, Vol. 105, Feb. 1977, pp. 129-146.

[3] Aircraft Accident Report, Eastern Airlines, Inc., Boeing 727-225, N8845E, Jamaica, N.Y., June 24, 1975; NTSB-AAR-76-8, March 1976.

[4] Shrager, J., "The Analysis of National Transportation Safety Board Large Fixed-Wing Aircraft Accident/Incident Reports for the Potential Presence of Low-Level Wind Shear," FAA-RD-77-169, Dec. 1977.

[5] National Transportation Safety Board, Annual Review of Aircraft Accident Data, U.S. Carrier Operations (1978), Report NTSB-ARC-80-1, 1980.

[6] *Annual Review of Aircraft Accident Data*, U.S. Carrier Operations (1977), Report NTSB-ARC-78-2, 1978.

[7] *Annual Review of Aircraft Accident Data*, U.S. Carrier Operations (1976), Report NTSB-ARC-78-1, 1978.

[8] *Briefs of Fatal Accidents Involving Weather as a Cause/Factor*, U.S. General Aviation (1978), Report NTSB-AMM-80-5, 1980.

[9] *Briefs of Fatal Accidents Involving Weather as a Cause/Factor*, U.S. General Aviation (1977), Report NTSB-AMM-78-16, 1978.

[10] *Briefs of Fatal Accidents Involving Weather as a Cause/Factor*, U.S. General Aviation (1976), Report NTSB-AMM-78-5, 1978.

[11] *Annual Review of Aircraft Accident Data*, U.S. General Aviation (1978), Report NTSB-ARG-80-1, 1980.

[12] Bromley, E. Jr., "Aeronautical Meteorology: Progress and Challenges—Today and Tomorrow," *Bulletin of the American Meteorological Society*, Vol. 58, Nov. 1977, pp. 1156-1160.

[13] Strauch, R.G., "Applications of Meteorological Doppler Radar for Weather Surveillance Near Air Terminals," *IEEE Transactions on Geoscience Electronics*, Vol. GE-17, No. 4, Oct. 1979, pp. 105-112.

[14] Chadwick, R.B., Morran, K.P., and Campbell, W.C., "Design of a Wind Shear Detection Radar for Airports," *IEEE Transactions on Geoscience Electronics*, Vol. GE-17, No. 4, Oct. 1979, pp. 137-142.

[15] Chadwick, R.B., Moran, K.P., Morrison, G.E., and Campbell, W.C., "Measurements Showing the Feasibility for Radar Detection of Hazardous Wind Shear at Airports," Final Report AFGL-TR-78-0160, Air Force Geophysics Laboratory, Hanscom AFB, Mass., June 1978.

[16] Strauch, R.G. and Sweezy, W.B., "Wind Shear Detection with Pulse Doppler Radar," Final Rept. FAA-RD-80-26, Systems Research and Development Service, Washington, D.C., Jan. 1980.

[17] Krauspe, P., Swolinsky, M., and Vörsmann, P., "Wind Determination and Wind Shear Detection from Flight Test and Airline Flight Data," American Meteorological Society, Montreal, Quebec, Canada, May 4-6, 1981.

[18] Vörsmann, P. and Swolinsky, M., "Wind Shear Detection from PCM-Recorded MLS-Flight Data," *12th Congres of the International Council of the Aeronautical Sciences*, Munich, Federal Republic of Germany, Oct. 12-17, 1980.

[19] König, P., Krauspe, G., and Schänzer, G., "Procedures to Improve Flight Safety in Wind Shear Conditions," *12th Congress of the International Council of the Aeronautical Sciences*, Munich, Federal Republic of Germany, Oct. 12-17, 1980.

[20] Garodz, L., "Measuring Weather for Aviation Safety in the 1980's—Winds and Wind Shear—In-Situ Sensors," *4th Annual Workshop on Meteorological and Environmental Inputs to Aviation Sensors,* The University of Tennessee Space Institute Tullahoma, Tenn., March 25-27, 1980, NASA Rept. CP-2139.

[21] Tinsley, H.G., Coons, F.G., Wood, L.W., and Clark, M.E., "System Research and Development Service Progress Report," FAA-RD-78-90, 1978.

[22] Noonkester, V.R., Richter, J.H., and Jensen, D.R., "Unique Echoes Observed by FM-CW Radar at a Jet Airport," Naval Electronics Lab. Center, Technical Note 2787, Naval Electronics Laboratory Center, Calif., 1974 (information to be considered tentative and unpublished).

[23] Zrnic', D.S., "Estimation of Spectral Moments for Weather Echoes," *IEEE Transactions on Geoscience Electronics*, Vol. GE-17, No. 4, Oct. 1979, pp. 113-128.

[24] "Terminal Area Weather Radar Detection and Convective Prediction Development," Interagency Agreement DTFA01-81-Y-10521 between DOT/FAA and DOC/NOAA, Jan. 7, 1981.

[25] Jain, G.P., "Preliminary NEXRAD Sites," MITRE Corp. Working Paper WP.80W00874 Rev. 1 under Contract No. NA-80-SAC-00650 sponsored by Dept. of Commerce, Project No. 14600, Jan. 1981 (information considered tentative and the paper informal).

[26] Mahapatra, P.R. and Zrnic', D.S., "Scanning Strategies for Air Traffic Control Radars," 37th Annual Meeting of the Institute of Navigation, Annapolis, Md., June 9-11, 1981.

[27] Submission of FAA operational weather requirements to the NEXRAD Joint Systems Program Office, Dec. 14, 1979.

[28] Hamidi, S. and Zrnic', D.S., "Considerations for the Design of Ground Clutter Cancelers for Weather Radars," *Preprints*, 20th Conf. Radar Meteorology, Boston, Mass., Nov. 30-Dec. 3, 1981, pp. 319-326.

[29] Doviak, R.J., Sirmans, D., Zrnic', D.S., and Walker, G.B., "Considerations for Pulse-Doppler Radar Observations of Severe Thunderstorms," *Journal of Applied Meteorology*, Vol. 17, Feb. 1978, pp. 189-205.

[30] Groginsky, H.L. and Glover, K., "Weather Radar Canceller Design," *Preprints*, 19th Conf. Radar Meteorology, American Meteorological Society, Boston, Mass., April 1980, pp. 192-201.

[31] Karp, D., "En Route Weather Data Extraction from RTC Radar Systems," Project Report DOT-FAA-RD-82-5, Lincoln Laboratory, MIT, Cambridge, Mass., March 1982.

[32] Zrnic', D.S. and Mahapatra, P.R., "Lifetimes of Atmospheric Features Hazardous to Aircraft Navigation: A Study Conducted to Determine Scanning Strategies for Air Traffic Radars," interim report submitted to FAA under Contract DTF A01-80-1-Y-10524, April 1981.