Radar for Storm Forecasting and Weather Hazard Warning

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The fields of the three principal Doppler moments are related to weather events hazardous to safe flight. Detection of the phenomena that may cause the hazard may be as important or more important than detection of the hazard itself. Some Doppler radar limitations in providing accurate and detailed observations of weather hazards are highlighted.

Introduction

THE Doppler radar is the only remote sensing instrument that can detect tracers of wind and measure their radial velocities, both in the clear air outside precipitation and inside heavy rainfall regions veiled by clouds—clouds that disable lidars because optical radiation can be completely extinguished in a few meters of propagation distance. This unique capability supports the Doppler radar as an instrument of choice to survey the wind and water fields traversed by aircraft. On the other hand, the radar has limitations. Its proven capabilities, anticipated applications, and critical deficiencies are discussed.

For the past decade, Doppler weather radars have been employed extensively in research projects to probe stormy and clear skies. It now seems likely that in the late 1980s a national network of Doppler radars (NEXRAD) will replace the present network of incoherent WSR-57 radars. Doppler radars are valuable not only for locating thunderstorms but also for pinpointing hazardous regions containing high liquid water content, tornadoes, wind shear, and turbulence. Furthermore, they can provide quantitative estimates of weather hazard intensity based upon measurements and maps of the three principal moments of the reflectivity-weighted Doppler velocity spectrum: the zeroth moment or echo power S, the first moment or mean Doppler (radial) velocity v_r, and the square root of the second moment about the mean or spectral width σ_v.

Figure 1 shows schematically the radar's resolution volume V_6, within which the antenna pattern and range weighting functions are at least ¼ of their maximum values. The scatter cross section per unit volume (reflectivity η) is proportional to the size and density of precipitation particles and v_r depends on the weight that the η distribution gives to the radial velocities within the resolution volume. In addition, σ_v is proportional to the intensity of swirls within the volume.

Because radar meteorologists need to relate the reflectivity η, which is general radar terminology for the scattering cross section per unit volume, to factors that have meteorological significance, they have introduced a term called reflectivity factor, designated by the symbol Z, which is the product of the number of drops per unit volume (in cubic meters) and the average sixth power of their diameter expressed in millimeters. Usually Z values span many orders of magnitude, so the base 10 logarithmic unit of dBZ, equal to 10 log Z, is used. However, the radar cannot measure Z accurately because it is proportional to the radar-observable η only when drops are spherical and have diameters small compared to the radar wavelength (i.e., in the Rayleigh approximation), conditions that are not usually met in storms where rain contains a significant number of drops of diameter exceeding 1 or 2 mm or when radars operate at short wavelengths (i.e., <10 cm). On the other hand, dual polarized radars can estimate the nonsphericity of raindrops[2] and thus make more accurate measurements of Z. Weather radars presently used in the national radar network have wavelengths (10 cm) long enough that all raindrop diameters satisfy the Rayleigh condition.

The width σ_v of the Doppler velocity spectrum is normally a measure of turbulence within V_6 although shear, antenna scan rate, and differential terminal velocities of the falling drops contribute to a lesser degree to the measured value. Dimensions of the resolution volume are determined by the angular pattern of the radar antenna's radiation field as well as the shape of the transmitted pulse and the receiver's finite bandwidth. Furthermore, the apparent beamwidth increases as the beam scan rate increases, thus worsening the resolution for faster scanning radars.[3]

Hazard Forecasting

Forecasting hazards by extrapolation of the observed hazard (nowcasting) is often quite limited because the lifetimes of many of these phenomena (e.g., shear) are short. Lifetimes of weather phenomena increase roughly with their scale or wavelength Λ_0 and decrease as their characteristic velocity increases (i.e., the rms velocity of turbulence on scales $<\Lambda_0$)[4] if they are turbulent phenomena; otherwise, lifetimes can be considerably longer. Furthermore, the level of threat of a meteorological event is conditioned by the response characteristics of the aircraft being threatened. For example, a Boeing 727 aircraft has enhanced response to wind perturbations of frequencies near its phugoid frequency of 3×10^{-2} Hz (period ~30 s). Thus by considering takeoff and landing speeds, it can be deduced that wind swirls of about 3-km wavelength can have a more deleterious effect on the performance of the aircraft than other wavelengths of similar amplitude. Assuming a characteristic velocity of 10 ms^{-1} for this eddy, a lifetime of about 5 min is to be expected. On the other hand, if wind perturbations are associated with ordered flow (e.g., tornadoes, downdrafts), much longer lifetimes are found even though the size of the hazardous phenomenon is small. For example, typical horizontal dimensions of microbursts are 1 to 3 km and lifetimes range from 5 to 15 min, whereas the period of severe wind shear lasts from 2 to 4 min with an average velocity difference of 25 ms^{-1} across the divergent flow.[5]

Because pilots can take evasive action to avoid storm hazards, timely and accurate warnings should increase flight safety. But because pilots have many tasks to perform during the critical stages of landing and takeoff, it is unrealistic to expect them to monitor weather data continuously in order to thread their way among weather hazards. Furthermore, since

Received Dec. 12, 1985; presented as Paper 85-0092 at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, Jan. 14-17, 1985; revision received July 16, 1985. This paper is declared a work of the U.S. Government and therefore is in the public domain.

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it takes time for a radar to survey a volume of space (at least a minute or two for a pencil beam radar) and additional time to arrive at a decision concerning the threat and to communicate it, it seems unlikely to expect a response to hazards whose lifetimes are only a few minutes or less. Even worse, if the radar is committed to scan a large volume of space to provide surveillance of entire thunderstorms from near the surface to their tops, as planned for the NEXRAD radar, several minutes could pass before the radar's beam cycles back to probe any specific location. On the other hand, NEXRAD antenna scans can be altered to decrease significantly the time required to cycle through areas of hazards at low altitudes, where aircraft are particularly vulnerable.[6] Thus, even if the Doppler radar detects these transient hazards, it may be more prudent to use information on larger-scale, more persistent phenomena (e.g., gust fronts, mesocyclones) to identify regions of potential hazard.

Usually hazards are small-scale events embedded in larger-scale weather systems that are more easily detected and monitored. For example, although the planned NEXRAD Doppler radar will not resolve tornadic circulations at all operating ranges, it will more often resolve the mesocyclones from which tornadoes frequently evolve. Furthermore, with Doppler radar we are no longer tied to thunderstorm-scale analyses of reflectivity fields to infer hazards generated by wind or shear; now we can monitor such wind phenomena as mesocyclones and outflows and estimate their intensity to determine their potential for generating hazards. For example, turbulence and short-lived intense downdrafts are found in convection initiated along the leading edge of thunderstorm outflows whose depth and speed can be estimated by the Doppler radar.[7] Larger-scale phenomena that spawn small-scale hazard potential, determined by extrapolation in time, would provide longer lead time. For example, observations indicate that many thunderstorms are initiated along boundaries and intersecting flows.[8-10] Furthermore, Bedard and LeFebvre[11] present evidence indicating that the larger-scale gust fronts are preferred regions for microburst occurrence. Among similar observations are those of Hobbs and Persson,[12] who suggest that a preferred region for the development of tornadoes and downbursts is the gap between precipitation cores on narrow cold-frontal rainbands.

Probably the most significant transient weather phenomenon is the explosive growth of some thunderstorms. Storms can grow from innocuous congestus clouds to mature thunderstorms in about 10 minutes. A study of four thunderstorms in Oklahoma showed that the growth rate of maximum reflectivity factor is about 5 dBZ/min and updraft velocities can increase as rapidly as 6.7 ms^{-1}/min.[6]

Storm Hazards

Hail, excessive water, shear, and turbulence are some of the hazards threatening life and property. With accurate and timely warning, lives and property can be saved. Warnings of intense rain and hail are based on reflectivity factor fields estimated from echo power measurements; Doppler velocity fields are used to locate shear generated by vortices, downdrafts, waves, etc., whose sizes are large compared to the resolution volume V_6, whereas spectral width is used to locate regions of shear and/or turbulence with dimensions small compared to V_6.

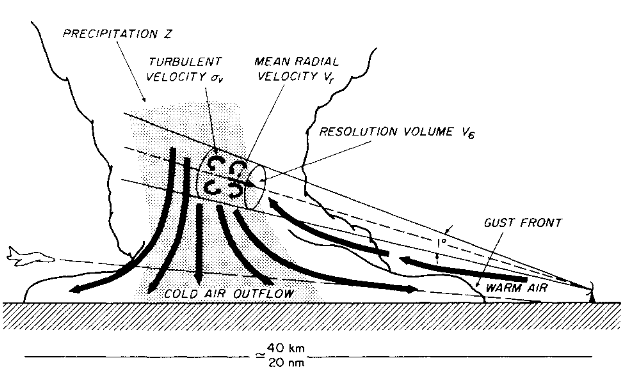

Fig. 1 Schematic showing the relationship between the meteorological variables (precipitation, wind, and turbulence) and the Doppler spectral moments (Z, v_r, and σ_v).

Hazards Resolved from Reflectivity Factor Fields

Fields of reflectivity factor Z are estimated from echo power measurements, range, and radar calibration constants. Storm structure, as depicted by dBZ fields, has undoubtedly been the single most studied meteorological parameter. High values of Z roughly locate the regions of intense rain and/or hail. However, it is important to note that although the radar accurately maps reflectivity (η) fields, it may not necessarily reliably map reflectivity factor, the liquid water content (grams of water per unit volume), nor the rainfall rate fields. Nevertheless, the storm's most intense precipitation and also its strongest dynamics (updrafts and downdrafts) are not too far from the regions of highest reflectivity; so, using liberal criteria, hazards due to thunderstorms can usually be avoided. For example, aircraft at low altitude are advised to remain 20 km away from the edge (usually the 20 dBZ contour) of the storm's dBZ field in order to avoid moderate to severe turbulence.[13] Unfortunately, these criteria are often ignored—sometimes with devastating consequence. The failure to heed such advice may be due to the unacceptably high false alarm rates. If so, then it becomes imperative that more precise criteria be found to pinpoint hazardous regions without compromising flight safety. There is no doubt that the safest path is one that avoids storms by a wide margin, but often this is impractical, particularly around airports congested with aircraft and storms. Present guidelines for flights around thunderstorms claim so much useful and safe air space that pilots may be tempted to ignore these advisories in the interests of timely arrival at their destination. Doppler radars should help to increase the credibility of the warnings without losing valuable air space, time, and margin of safety.

Hail

One cannot reliably detect hail from dBZ fields even though hail is often associated with high dBZ values. However, the reflectivity structure of the storm can often be used to forecast hail. Lemon[14] showed that the position of the echo top relative to the low-level weak echo region and peak reflectivity factor (≥45 dBZ) at midaltitudes are well correlated to the occurrences of large hail. A probability of detection (POD) of large

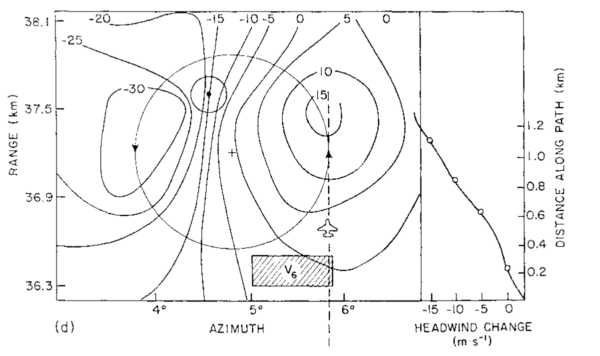

Fig. 2 The mean radial (Doppler) velocity field of a mesocyclone showing the couplet of positive and negative isodops aligned azimuthally. Large and small circles indicate diameters of maximum winds for the mesocyclone and tornado, respectively. Aircraft headwind change for the hypothetical flight path (dashed line) is sketched on the right.

hail in Oklahoma storms using these criteria was 0.98, whereas the false alarm rate (FAR) was about 0.30. The average lead time between warning issuance and the first reported severe hail event was 23 minutes. Similar algorithms applied to Colorado hailstorms gave a 0.90 POD.[15] Because hail-producing storms may have somewhat different reflectivity structure in different regions of the world, and because ambient conditions vary from one location to another, hail algorithms may need to be site-specific or have parameters adjusted for changing environmental conditions. Furthermore, the above statistics are for hail on the ground; because en route aircraft are most susceptible to hail aloft, algorithms may need to be modified to maintain a high POD and low FAR in those cases in which hail melts before reaching the ground. On the other hand, aircraft en route have more latitude to skirt around storms and can easily avoid hail.

The probabilistic inference of the occurrence of hail might not be as meaningful as the remotely sensed direct detection of hail. Dual polarization radars have shown promise for reliable hail detection.[16] Present-day operational radars transmit and receive a single sense linear polarized wave. However, the difference in reflectivity between echoes received from horizontally and vertically polarized transmissions is related to the shape of the hydrometeor; this information, along with reflectivity and its location in the storm, can be useful in identifying hail. On the other hand, direct detection of hail does not give lead times, whereas hail prediction based upon a storm's reflectivity structure can. Furthermore, the storm's Doppler velocity fields could provide additional information useful in determining storm intensity and the probability of hail. For example, Witt and Nelson[17] show high correlation between maximum hailstone diameter and the strength of divergent flow at the top of thunderstorms. Coordinated observations of storm structure and hailfall, coupled with numerical models of severe storms, will help improve accuracy of hail forecasts and warnings.

Liquid Water Content

Radar cannot measure directly the amount of liquid water within its resolution volume. Assumptions of drop size distribution and water phase must be made before reflectivity measurements can be related to liquid water content or rainfall rate. It is entirely possible to have high reflectivity values and yet low values of liquid water. Errors as large as 10 have been found when in situ measurements of rainfall rate are compared to the rate estimated from radar. Dual polarized and dual wavelength radars offer promise of improved accuracy in estimating liquid water content and rain intensity.[18] However, the increase in accuracy may not be significant if other measurement errors (e.g. radar calibration) are larger than the uncertainties caused by an incorrectly assumed drop size distribution.[19]

Hazards Resolved from Doppler Velocity Fields

Mean Doppler (radial) velocity v_r fields are now receiving the greatest attention from radar meteorologists. Even though the radial component of wind is weighted by the reflectivity field and the radar antenna's radiation pattern, the presence of many phenomena can be inferred from Doppler velocity features or signatures. We discuss several such phenomena (e.g., circulating and divergent flows, gust fronts, and solitary waves) that can generate hazardous shear and turbulence.

Shear

The couplet of closed contours of Doppler velocity (isodops) of receding and approaching air is a signature of circulation and/or divergence, and many authors, starting with Sirmans et al.,[20] have shown plan position indicator (PPI) displays of these patterns. An azimuthal alignment of the couplet signifies rotating flow, whereas a radial alignment signifies divergent or convergent flow. Figure 2 shows a con-

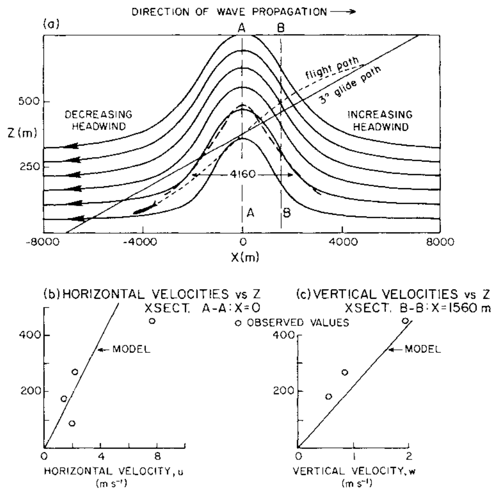

Fig. 3 Comparison of observed and numerically evaluated (solid lines) streamlines and velocities in a solitary wave. Streamlines are for wind in a frame moving with the wave. Dashed streamline in (a) is from measurements, and circles in (b) and (c) are observed velocities. The numerically evaluated streamlines are from figures in a publication of Christie and Muirhead.[23]

toured v_r field of a tornado cyclone. The large circle is the diameter of maximum circulating winds of the tornado's parent mesocyclone, and its parameters (e.g., tangential velocity $\simeq 20$ ms^{-1}; diameter $\simeq 1.3$ km) are calculated from the v_r-field. The parameters of the tornado (tangential velocity $\simeq 30$ ms^{-1}; diameter $\simeq 0.3$ km) are deduced from the shape of the Doppler spectra for the resolution volumes V_6 located in and near the tornado. Note that the peak tornadic wind of 30 ms^{-1}, although seen in the Doppler spectra, cannot be resolved in this V_r field. It is the intense shear associated with these flows that threatens safe flight. Although the tornado is the most intense vortex, its diameter is usually much smaller than that which can be resolved in the v_r field (Fig. 2); but because tornadoes are usually accompanied by a larger parent circulation from which these whirlwinds are often spawned, successful inference of tornado potential is made from observations of the larger-scale mesocyclone isodop couplet. However, isodop couplets do not always indicate mesocyclones, and only if these signatures have a continuity in height, an intensity above a certain threshold, and a lifetime equal to at least one turn of the circulating flow, is there convincing evidence for the potential of a tornado.

Vortices are potentially hazardous because of the shear associated with them. The presence of a vortex can produce a large decrease in headwind if the flight path is tangent to the circle of maximum wind (Fig. 2). Intense circulations are often found along gust fronts. Intense shears are also generated by downdrafts. The radial alignment of an isodop couplet indicates the presence of divergent flow produced by vertical currents impacting the ground. Experiments[21,22] indicate that intense small-scale divergent flow is quite common in Colorado thunderstorms and, as with vortices, it is the smaller-scale downdrafts (i.e., microbursts) that appear to produce the strongest shear. Resolutions of a few hundred meters or less are required to resolve these small-scale circulating and/or diverging flows. Thus, radars with high angular resolution (≤ 1 deg) and observations close to the radar are required to resolve the shear produced by these phenomena. Even though these small-scale hazards may be difficult to detect, they are usually embedded in larger-scale phenomena (e.g., gust fronts), which have a longer lifetime and can be more easily tracked.

A solitary wave (Fig. 3) is probably the most clandestine hazard to aircraft because it can exist in the clear air many tens of kilometers away from the thunderstorm that spawned it.[23,24] Yet it can harbor shear that can be destructive to aircraft and crew unaware of its presence. Furthermore, thunderstorms are not the only source of these waves. In a recent study of 93 meteorologically related wind shear incidents in Australia, only 16% could be attributed with any certainty to frontal and thunderstorm activity.[25,26] Considering the ubiquitous nature of solitary waves and their frequency of occurrence, Christie and Muirhead[25,26] proposed that many aircraft incidents could be attributed to these waves. Solitary waves appear on the PPI displays as thin lines in the reflectivity field because radar targets are created by either turbulent mixing of air in the inversion along which these waves propagate or by debris and insects caught up in the gust of wind that accompanies these waves.

Turbulence

Turbulence on scales larger than the radar's resolution volume can be resolved in the v_r field. In regions of low reflectivity, as in the clear air boundary layer and edges of storms, velocity measurements are subject to significant error due to targets such as birds, aircraft, fast-flying insects, and ground clutter or error due to echo power received through side lobes from high reflectivity regions. Thus, high variance velocity fields in low reflectivity regions need cautious interpretation.

In precipitating regions of higher Z, error sources are less likely to be present, and better estimates of turbulence can be made. Brewster,[27] observing a thunderstorm with a vertically pointed Doppler radar, showed excellent agreement (Fig. 4) in turbulent energy dissipation rates ϵ (a parameter whose values are popularly used to indicate turbulence intensity and, consequently, a measure of its hazard to aircraft) computed from spatial spectra of velocity fields with those ϵ computed from Doppler spectral widths. Thus, it can be argued convincingly that the larger scales and spacial spectra are within the inertial range of isotropic turbulence in which kinetic energy is transferred to smaller-scale eddies and to eventual dissipation when viscous forces act on these eddies. However, at long ranges the radar's resolution volume may be larger than the outer scale of isotropic turbulence; then, neither the mean Doppler velocity nor spectral width fields may give accurate estimates of ϵ and turbulence intensity. Nevertheless, the large swirls depicted by the v_r field may be indicative of hazards to aircraft. But then there is a chance that they will not be detected because they are no longer isotropic and, thus, the v_r field, which shows only one component of the velocity vector field, may not exhibit all turbulence. Furthermore, an accurate estimate of ϵ from Doppler spectral width σ_v measurements requires the outer scale of isotropic turbulence to be larger than the radar's resolution volume.[28] On an encouraging note, Brewster's study indicates that in a thunderstorm the outer scale is larger than 1 or 2 km, in which case measurement of ϵ from σ_v may be accurate for narrow beam radars (i.e., ≤ 1 deg) for ranges to 60 km.

Hazards Resolved from Doppler Spectral Width Fields

The second spectral moment is more difficult to estimate than the other two and is more prone to error. Nevertheless, fields of spectral width σ_v can be related to shear and turbulence. If regions of high reflectivity do not contribute (through antenna side lobes), significantly to the Doppler velocity spectrum the spectral width is then a measure of the spread of radial velocities within the radar's resolution volume V_6, weighted by reflectivity distributions inside V_6. The spectrum is primarily broadened by differences in the terminal velocities of hydrometeors, turbulence, and shear. However, it is also broadened by nonmeteorological causes.[29] For nearly horizontally directed beams, the contribution from spread in terminal velocities is usually negligible compared to that from shear and turbulence.

The separation of wind-related causes of Doppler spectral broadness into shear and turbulence terms is made in order to sort out the contributions to spectral width σ_v (Fig. 1) caused by shear of the nonturbulent or ordered flow, so that one can estimate turbulence and eddy dissipation rates. The Federal Aviation Administration has spurred interest in relating Doppler spectral width to turbulence severity because if the intensity and location of turbulence can be routinely and reliably detected, aircraft can then be safely routed around these hazardous regions. This information should reduce FAR and minimize loss in airspace caused by overwarning. However, because shear sometimes generates turbulence, it may not always be necessary to separate the two. Moreover, detailed analyses of Doppler radar observations of a severe thunderstorm suggest that turbulence contributes much more to spectral broadening than ordered flow shear.[4] Only in a very small portion of the storm is shear responsible for nearly all spectral broadening.

Shear

Strongest shear usually is present near the ground over which strong winds blow and in circulations and outflows of thunderstorms. When the shear is confined to regions small compared to the resolution volume of the radar, it produces large spectral widths that could be confused with turbulence. The mesocyclone is a region of large spectral width due in major part to strong shear associated with the circulating currents (Fig. 2). Regions of large spectral width have been observed by Istok[30] downstream from the mesocyclone location, and evidence suggests that the strong circulations, acting as a block to environmental flow, cause a wake vortex as identified by Lemon.[14] Even though warnings based on spectral width dominated by shear contributions may produce false alarms, we suggest that warnings to aircraft in stormy environments be based partly on spectral broadening because shear regions, although not necessarily hazardous in themselves, have the potential to create turbulence.

On the other hand, in planetary boundary layers, vertical shear of horizontal wind can be the dominant contributor to Doppler spectral width for vast areas of airspace and, in this case, it may be important to estimate both shear and turbulence so that unreasonably large regions of safe airspace are not tagged as hazardous. For example, Fig. 5 shows measured spectral width exceeds 5 ms^{-1} in nonstormy regions of the planetary boundary layer (i.e., altitudes less than 1 km) for the entire observed azimuth sector of 60 deg. Lee's analysis[31] of thunderstorms suggests that when σ_v exceeds 5 ms^{-1}, moderate to severe turbulence can be expected. However, in

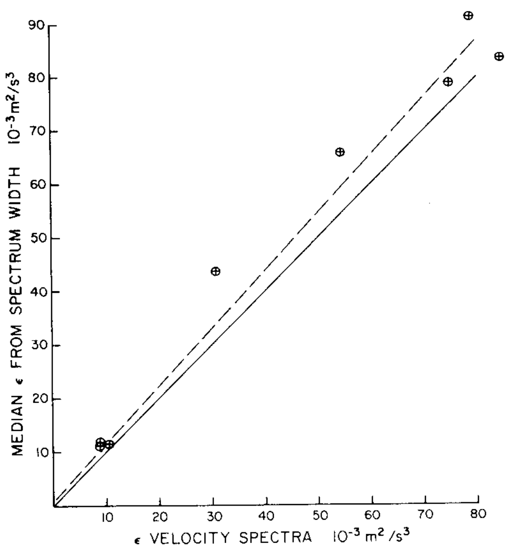

Fig. 4 Eddy dissipation rate computed from Doppler velocity spectral width regressed against those values estimated from the spatial spectrum of mean Doppler velocities.

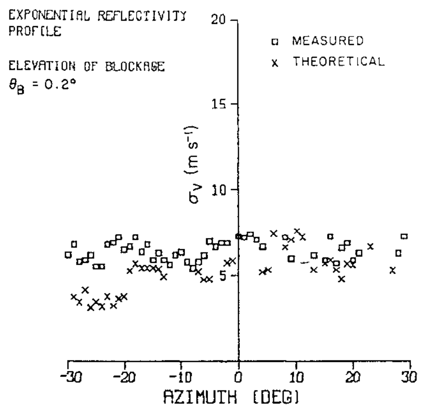

Fig. 5 Comparison of measured spectral width (squares) and that computed from vertical shear of radial velocities (crosses) for a radar beam scanning nonprecipitating regions of the planetary boundary layer.

the data in Fig. 5, nearly 100% of the width values are contributed by vertical shear of the radial velocities, which in itself would not be hazardous to safe flight if pilots were made aware of its presence.

Turbulence

Analysis by J.T. Lee[31] suggests a strong connection between spectral width and aircraft measurements of turbulence. His data show that when aircraft-derived gust velocities exceeded 6 ms^{-1}, corresponding to moderate or severe turbulence, the spectral width exceeded 5 ms^{-1} in every case for aircraft within 1 km of the radar resolution volume. Furthermore, when σ_v was less than 4 ms^{-1}, the aircraft experienced only light turbulence in over 50 thunderstorm penetration flights. Not all storm regions containing large spectral width produce turbulence that affects aircraft.

Doppler Radar Limitations

In the preceding sections we have mentioned, whenever appropriate, limitations in radar measurements. There are other important restraints as yet not discussed. The most significant limitations on radar observation of weather hazards are antenna sidelobes, attenuation, and range-velocity ambiguities. Furthermore, angular resolution finer than a degree or two and sensitivity to detect targets in low reflectivity regions and in clear air require large antenna diameters and high-powered radars operating at nonattenuating wavelengths (e.g., ≥ 10 cm). Unlike aircraft or missile detection, weather hazard detection by Doppler radar imposes a more severe constraint on the antenna side-lobe level, mainly because of the distributed nature of weather targets and the large dynamic range (≥ 80 dB) of their echo power. Because echo power is proportional to the angular integral of the reflectivity field weighted by the antenna radiation pattern, the power received through side lobes, which subtend practically the full spherical volume, can be comparable to that in the main lobe, especially when the latter is in a weak reflectivity region. Important wind information can be found in regions of weak reflectivity such as is observed along gust fronts. Side lobes can be controlled better, although not eliminated, by use of array antennas. However, for a fixed-diameter antenna there is always a compromise between side-lobe level and main-lobe resolution. On the other hand, Sachidananda et al.[32] have come up with a novel technique to eliminate errors in velocity estimates due to echoes entering side lobes without resorting to this compromise.

Augular resolution can be increased without increasing antenna size by use of synthetic aperture techniques. However, these techniques are not effective for weather targets because their echoes lose coherence in a few milliseconds.

Range and velocity ambiguities are also a coupled problem: reduction of range ambiguities increase the number of velocity ambiguities, and vice versa. Although there are techniques to mitigate the deleterious effects of Doppler ambiguities, there is no known solution that can eliminate them.[3]

Conclusions

Doppler radar, the only remote sensing instrument that can identify hazards both in the clear air as well as inside heavy rainfall regions veiled by clouds, is the instrument of choice to survey the wind and water fields for weather hazardous to aircraft. However, Doppler radars have limitations due to side lobes, attenuation, and range-velocity ambiguities. New techniques in antenna design and signal coding hold promise to mitigate some of these limitations.

Weather hazards that usually affect aircraft are of small scale and have short lifetimes, making difficult the task of detecting the hazard by scanning a pencil beam. Nevertheless, the authors suggest that detections of the larger-scale phenomena that spawn the smaller-scale hazards may be as important or more important than detection of the hazard itself.

Symbiotic working relationships between the research and radar applications communities are needed in order to improve safety of flight during hazardous weather conditions. Researchers can advance weather science that leads to improved physical models of the phenomena causing hazards. Applications-oriented people can exploit the relationships between the model and the Doppler moment fields using automated methods to search for features of hazardous phenomena.

Acknowledgments

The authors thank Joy Walton, Michelle Foster, Joan Kimpel, and Bob Goldsmith for their assistance in the preparation of this paper. Special thanks go to Keith Brewster and Steve Smith of the Cooperative Institute for Mesoscale Meteorological Studies at the University of Oklahoma, who kindly provided us with Figs. 4 and 5, respectively. This work has been partially supported by FAA Grant DTFA01-80Y-10524.

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