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OPERATIONAL BENEFITS OF METEOROLOGICAL DOPPLER RADAR

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Operational Benefits of Meteorological Doppler Radar

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A comparison is made between Doppler and conventional radar as a tool in operational forecasting of hazardous weather. Estimates are given of the cost increment of Doppler capability above the basic radar cost. The advantages and limitations of dual-Doppler and multi-Doppler networks are also considered. The evidence leads to the firm conclusion that, for operations in areas subject to the threat of tornadoes, hurricanes, and other damaging windstorms, the cost increment of single-Doppler radar capability is more than justified by

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its advantages over conventional radar. On the other hand, dual-Doppler capability is not recommended for operational use, although it is an excellent research tool.

Preface

We are deeply grateful to Kenneth M. Glover, Chief of the Weather Radar Branch of the Meteorology Laboratory, AFCRL, for preparing the discussion on the advantages of a coherent transmitter for calibration of a radar receiver. We are also pleased to acknowledge a number of helpful suggestions and the encouraging interest given by Dr. Paul L. Smith, Jr., Chief Scientist of the Air Weather Service.

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Operational Benefits of Meteorological Doppler Radar

1. INTRODUCTION

Radar has been used for many years by forecasters, both military and civilian. This report is intended to provide up-to-date information on the capability of Doppler radar information, over and above conventional weather radar data, to contribute toward improvement of operational weather services. There is fairly wide agreement that radar techniques are highly successful in locating areas of precipitation within a radius of about 200 km and in providing a general characterization of the nature of the storm. Only modest success has been claimed for measurement of precipitation intensity, for prediction of storm motion, and for identification of hazards to aircraft in flight and to people and their artifacts on the ground. Research studies using Doppler radar have indicated significant improvements are possible in forecasting storm dangers associated with air motion—tornadoes, damaging winds, and turbulence. Such improvements would be expected with Doppler radar since it can measure air motion directly, while conventional radar techniques must rely on the probabilistic association of destructive winds with those storm features which it can observe, such as echo height, intensity, and shape. Accordingly, this report will concentrate on research evidence pertinent to severe convective storm hazards. Meteorological research using Doppler radar is in its early stage and limited to a very few

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installations; therefore, research programs have concentrated on exploration of the possibilities of this relatively new tool and on the development of techniques, rather than comparative studies of the value to forecasters of Doppler vis-a-vis conventional radar. Nevertheless, the available evidence definitively and credibly demonstrates a significant improvement in the operational utility gained through use of Doppler radar.

2. ASSESSMENT OF CONVENTIONAL RADAR CAPABILITY FOR SEVERE STORM IDENTIFICATION

We have examined all of the evidence we could find for quantitative estimates of success of conventional radar techniques for identification of hailstorms and tornadoes. We wanted to find a fair method of comparing various techniques which could also be used with the very limited experience acquired so far with Doppler radar. Furthermore, we wanted our method to be as independent as possible of the climatological representativeness of the observations sampled. Even in the most conscientious investigations of techniques for identification of infrequent severe weather events, there exists an unknown but probably large bias against observations of the much more common non-events: the storms with no hail or no damaging winds. Accordingly, we selected data for analysis from which it was possible to obtain both false alarm ratios and probabilities of detection.

Explanation of our terminology is in order. Identification of severe weather by radar has always been a statistical exercise, because we do not obtain a unique and distinctive signature of the severe weather event. We find, rather, that inhazardous events tend to occur more frequently in the larger, taller, more intense, better organized convective storms. Assume we have found an indicator of hail, for example echo top height in excess of a certain threshold. It is a good indicator, from the standpoint of assurance that we will rarely be subjected to the unpleasant surprise of the failure of our technique to identify hail, if the number of hail occurrences correctly identified (x) exceeds the number of hail occurrences which are not identified (y) by a comfortable margin. We define the probability of detection (POD) = $x/(x+y)$ as the proportion of hail which our technique identifies. There is also a second measure of performance: false alarms. The number of storms exceeding our identification threshold which do not contain hail (z) strains the credibility of our technique. False alarm ratio (FAR) = $z/(x+z)$.

Adjustment of an identification threshold can enhance the probability of detection but at the expense of a greater false alarm ratio, or vice versa. For example, if we are penalized for low probabilities of detection but not high false alarms, we can lower our threshold to a ridiculous value (for example, echo tops of 5 km). In this case, our technique will never fail to identify hail, but our false alarms will be excessively high, displaying no skill above that provided by climatology.

Consequently, we feel that comparative assessment of various techniques must take into account both the failures to identify and the false alarms. We have given equal weight to errors of both kinds by proposing a simple Critical Success Index (CSI) = $x/(x+y+z)$. CSI is the number of successful identifications (x) of a severe event, divided by the sum of the total number of severe events (x+y) and the false alarms (z). Consideration of the relative consequences of the two kinds of error could lead to a more elaborate success index.

What does the evidence show? The greatest success of conventional radar is in identification of hail, using S-band (10-cm) radar. Dennis et al,[1] operating in the high plains of Western Nebraska, adjusted their thresholds for a fixed 0.90 POD and found an amazingly small FAR of 0.13 for S-band reflectivity threshold of 50 dBz at a height of 3 km. This gives an excellent CSI of 0.80. For X-band (3-cm) radar, their best hail indicator was a reflectivity threshold of 39 dBz at an altitude of 9 km, with FAR = 0.32 and CSI = 0.63. Excellent results were also obtained by Morgan and Mueller,[2] who identified hail by a recently developed parameter of the 10-cm reflectivity, vertically integrated liquid water (VIL) and its time derivative. Although their preliminary sample of only six cases is extremely small, the technique looks promising indeed, with a 100 percent POD, FAR = 0.33, and CSI = 0.67. Techniques using 3-cm reflectivity in New England[3,4] give POD and FAR both close to 0.5 with best CSI of 0.33.

Echo top heights are not as successful as reflectivity for indicating hail. The most successful experience was found in New England[5] where penetration of the tropopause by echo tops yielded, for hail identification, POD = 0.59 with FAR = 0.66 and CSI = 0.27. Higher POD's but very high FAR's were computed from

1. Dennis, A.S., Smith, P.L., Jr., Boyd, E.I., and Musil, D.J. (1971) Radar Observations of Hailstorms in Western Nebraska, South Dakota School of Mines and Technology, Final Report, NSF Grant GA-1518.

2. Morgan, G.M. and Mueller, E.A. (1972) The total liquid water mass of large convective storms, Preprints, 15th Radar Meteorology Conf., pp. 39-40.

3. Donaldson, R.J., Jr. (1961) Radar reflectivity profiles in thunderstorms, J. Meteor. 18:292-305.

4. Donaldson, R.J., Jr. (1965) Methods for identifying severe thunderstorms by radar: a guide and bibliography, Bull. Amer. Meteor. Soc. 46:174-193.

5. Donaldson, R.J., Jr., Chmela, A.C., and Shackford, C.R. (1960) Some behavior patterns of New England hailstorms, Physics of Precipitation, Am. Geophys. Union, pp. 354, 368.

the work of other investigators,[6,7] reducing their CSI's to about 0.1. Subjective impressions of intense echoes and line echo shapes provided by operational rareps[7] were the least successful hail indicators, with CSI's of 0.06 and 0.08, respectively.

Conventional radar is significantly less successful in identifying tornadoes and windstorms, in comparison with hail. The best indicator found for tornadoes[4] was an increase of 3-cm reflectivity above the melting level (taken as 4.5 km) by more than 5 dB, which yielded POD = 0.57, FAR = 0.69, and CSI = 0.25. This method has the great advantage of not requiring an absolute calibration. For echo heights exceeding the tropopause,[6] POD's were higher but so were FAR's, and CSI = 0.10 for tornadoes and 0.05 for other damaging windstorms. For the rarep indices[7] (intense echo, line echo, and echo tops above 45,000 ft) POD's were sometimes good (for example, 0.92 for identifying tornadoes by "intense" echoes) ranging down to 0.57 for identifying windstorms by high echo tops, but all FAR's were very high (0.89 to 0.96), so CSI's were only 0.08 to 0.10 for damaging windstorms and 0.04 to 0.06 for tornadoes. These results are presented in Table 1.

The hook echo has long been used as an indicator of tornadoes. However, we have not found any quantitative evaluations of its effectiveness. Perhaps this is so because the subjective nature of hook identification is not amenable to objective statistical treatment. The more classical hook echoes can be recognized by any weather radar operator, but a great deal of skill and experience is required for successful identification with hook shapes deteriorating toward more ambiguous notches and extensions. Therefore, both POD and FAR of tornado detection by hook recognition will depend to a great extent on the informed judgment of the radar analyst. The decision that a hook echo exists does not lend itself to automation.

A brief survey[8] of Oklahoma tornadoes observed by radar during one season revealed "apparent" hook echoes in nearly half the cases. There is no justification to generalize this very limited result. However, our experience gained in watching a radar scope for echo patterns associated with tornadoes, and in discussions with others engaged in this activity, would support the idea that no more than half of all tornadoes, under the best conditions, betray their presence with an unmistakeable hook echo.

6. Pautz, M. E. and Doloresco, F. (1963) On the relationship between radar echo tops, the tropopause, and severe weather occurrences, Proc. 10th Radar Meteorology Conf., pp. 51-56.

7. Bonner, W. D. and Kemper, J. E. (1971) Broad-scale relations between radar and severe weather reports, Preprints, 7th Conf. on Severe Local Storms, pp. 140-14[illegible].

8. Freund, R. F. (1966) Radar echo signature of tornadoes, Proc. 12th Radar Meteorology Conf., pp. 362-365.

Table 1. Identification of Severe Weather by Radar

a. Conventional Radar

Severe Event	Probability of Detection	False Alarm Ratio	Critical Success Index	Reference No.	Criterion
HAIL	0.90	0.13	0.80	1	10 cm, 50 dBz at 3 km
	0.90	0.32	0.63	1	3 cm, 39 dBz at 9 km
	1.00	0.33	0.67	2	10 cm VIL
	0.46	0.45	0.33	3	3 cm, 45 dBz at 9 km
	0.52	0.57	0.31	4	3 cm, reflectivity increase above 0°C level
	0.59	0.66	0.27	5	Tropopause penetration by echo top.
	0.88	0.91	0.09	6	Tropopause penetration by echo top.
	0.72	0.89	0.11	7	Echo tops > 45 k ft
	0.91	0.94	0.06	7	Echo tops > 35 k ft
	0.87	0.94	0.06	7	Echo intensity
	0.73	0.92	0.08	7	Line echo shapes
WINDSTORMS	0.75	0.95	0.05	6	Tropopause penetration by echo top
	0.57	0.89	0.10	7	Echo tops > 45 k ft
	0.84	0.92	0.07	7	Echo tops > 35 k ft
	0.85	0.92	0.08	7	Echo intensity
	0.78	0.90	0.10	7	Line echo shapes
TORNADOES	0.5	0.1 to 0.25	0.43 to 0.47	rough optimistic estimate	Hook echo
	0.57	0.69	0.25	4	3 cm, reflectivity increase above 0°C level by > 5 dB
	0.83	0.89	0.10	6	Tropopause penetration by echo top
	0.63	0.94	0.06	7	Echo tops > 45 k ft
	0.98	0.96	0.04	7	Echo tops > 35 k ft
	0.92	0.96	0.04	7	Echo intensity
	0.83	0.95	0.05	7	Line echo shapes

b. Doppler Radar

Severe Event	Probability of Detection	False Alarm Ratio	Critical Success Index	Reference No.	Criterion
SEVERE WEATHER	0.94	0.12	0.83	9	Tangential shear $> 0.02\ sec^{-1}$
TORNADOES	0.94	0.38	0.60	11, 12	Vortex signature

Using the classic tornado hook as a criterion, we estimate very roughly that perhaps one-tenth to one-quarter of these are false alarms, in which no tornado ever touches down. The magnitude of the FAR will certainly decrease as the skill and experience of the radar operator increases. It is also likely that POD of tornadoes can be increased by highly sophisticated interpretation of shallow echo indentations and protrusions which scarcely appear hook-like to the uninitiated observer; but in all fairness, one must expect an escalation of FAR as POD is pushed to the limit. Therefore we propose, as a reasonably attainable goal, that identification of tornadoes through recognition of hook echoes can achieve a POD = 0.5 and FAR = 0.1 to 0.25, yielding CSI = 0.43 to 0.47. This is considerably more successful than the indicators using echo top height or reflectivity. However, it must be emphasized that our figures are very rough estimates, not much better than wild guesses. Perhaps a real artist at scope interpretation could achieve more satisfactory results, and certainly the average radar operator, under the press of a variety of weather station duties, would not do as well.

Many other types of qualitative echo patterns (for example, LEWP's or waves in lines, converging echoes) have been identified in connection with severe weather, but none of them is regarded with the same respect as hook echoes. In conclusion, then, we commend reflectivity measurements by non-attenuating conventional radar as a useful technique for identifying hail, but find this type of radar less than satisfactory for identification of tornadoes and other damaging windstorms.

3. DOPPLER RADAR CAPABILITY FOR SEVERE STORM IDENTIFICATION

Meteorological Doppler radar can measure precipitation particle motion as well as reflectivity. Since the particles follow the air motion with fidelity, Doppler capability adds a whole new dimension to storm diagnosis and offers a direct method to sense storm hazards arising from high winds and turbulence.

Measurements of disturbances in the horizontal Doppler velocities in New England thunderstorms revealed a clean distinction between severe and non-severe storms (Figure 1).[9] Disturbed wind fields in this study were characterized by measurement of tangential shear, defined as the gradient in Doppler velocity normal to the radar beam. This type of shear contributes to vorticity and is obtained by scanning the radar beam in azimuth while its elevation is fixed.

9. Donaldson, R. J., Jr. (1971) Doppler radar identification of damaging convective storms by plan shear indicator, Preprints, 7th Conf. on Severe Local Storms, pp. 71-74.

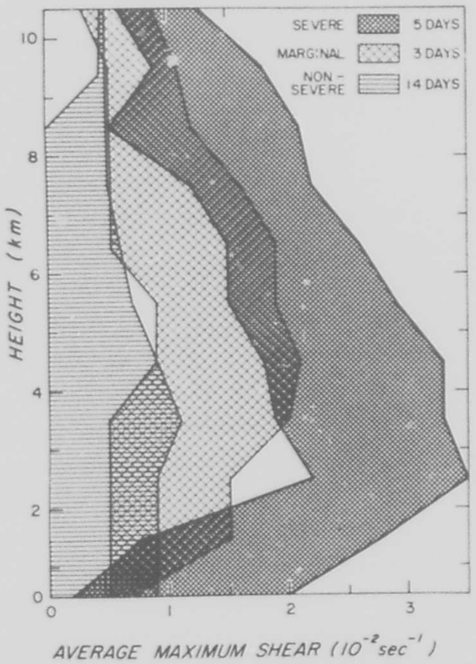

Figure 1. Vertical Profiles of the Spread of Maximum Tangential Shear of Radial Velocity, Averaged Over All Doppler Observations Taken During a Storm Day for Severe, Non-severe, and Marginal Storm Days. The data demonstrate a clear distinction between severe and non-severe storm days, particularly at heights above 1 km

typically, at some value between 0° and 10°, in order to observe quasi-horizontal wind components at various heights within the storms. Generally, the high shear values initially appear at middle altitudes in a storm and progress downward.

A tangential shear value of 0.02 sec^{-1} proved to be an excellent threshold for identifying severe storms. (This is equivalent to a change in the Doppler component of velocity of 20 m sec^{-1} along a distance of 1 km normal to the radar beam.) Storms were characterized as severe if they deposited hail of at least 3/4 in. diam and/or inflicted wind damage by tornadoes or other means. The shear value of at least 0.02 sec^{-1} was observed somewhere in all except 3 of 48 severe storm profile observations but in only 6 of more than 150 profile observations in non-severe storms. These observations yield POD = 0.94, FAR = 0.12, and a very satisfying CSI of 0.83.

A single Doppler radar suffers a handicap in observing a wind field in storms because only motions along the radar beam are observable. Cross-beam components go undetected. Nevertheless, a mesoscale vortex (size larger than radar resolving power but smaller than a storm) has a characteristic and easily recognized signature on Doppler radar, and Donaldson[10] has proposed criteria for credible validation of the vortex signature. The National Severe Storms Laboratory conducted a search for mesoscale vortex signatures in the tornado-prone area of Oklahoma. During the spring of 1973, several tens of storms were scanned for evidence of a vortex.[11] Only 9 revealed a resolvable vortex; tornado reports accompanied 7 of these 9. Storms that did not show the vortex signature did not produce any confirmed tornadoes. This sample, although small, yielded very impressive results: 100 percent POD, FAR of only 0.22, and a very healthy CSI of 0.78. Addition of 1974 results, from data supplied by Burgess,[12] reduced the success somewhat, but in view of the increased sample size our confidence in the Doppler technique is undiminished. The combined set of 1973-74 Oklahoma data have POD = 0.94, FAR = 0.38, yielding CSI = 0.60 for tornado identification by Doppler radar detection of a vortex. The one failure to detect, incidentally, was not a complete bust because it occurred in a storm with a series of tornadoes in which a vortex was first observed after the initial tornado appeared. Also, three of the false tornado alarms produced damaging straight-line winds, so with respect to destructive winds of any curvature, the two-year experience with Doppler radar in Oklahoma shows a CSI of more than 0.7. Not only are vortex signatures more objective (and thus more amenable to automated data processing techniques) than the classical hook echo identification, but the Doppler method eliminates false hooks and reveals vortices within the main body of the storm, or where the hook has wrapped around the weak-echo notch and filled it in. Doppler radar results are included in Table 1.

An excellent example of success in tornado identification by Doppler, where conventional methods failed, was given by Kraus[13] in his study of the Brookline, Massachusetts tornado. Although small in size, this tornado caused one fatality. During the tornado a mesoscale cyclonic vortex was clearly evident (Figure 2), but a hook echo which had appeared over 2 hr earlier had just about disappeared.

10. Donaldson, R. J., Jr. (1970) Vortex signature recognition by a Doppler radar, J. Appl. Meteor. 9:661-670.

11. Sirmans, D., Doviak, R. J., Burgess, D., and Lemon, L. (1974) Real time Dopper isotach and reflectivity signature of a tornado cyclone, Bull. Am. Meteor. Soc. 55:1126-1127.

12. Burgess, D. W. (1974) Private communication. Data to be published in 1975, Bull. Am. Meteor. Soc. 56.

13. Kraus, M. J. (1973) Doppler radar observations of the Brookline, Mass. tornado of 9 Aug 1972, Bull. Am. Meteor. Soc. 54:519-524.

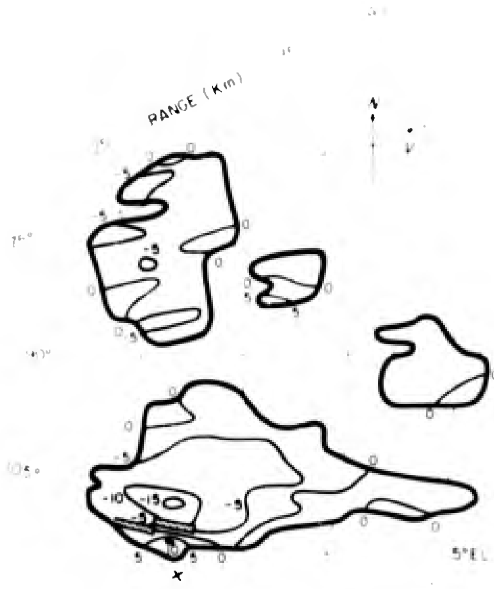

Figure 2. The Within-Storm Radial Velocity Pattern of the Brookline, Mass. Storm While a Tornado Was in Progress. Flow is relative to the storm and is seen at 5° elevation angle with a height range of 2.3 to 3.8 km, due to the tilt of the beam. Contours show component of flow along the radar beam, positive outbound, in m sec^{-1}. Arrow "V" shows direction of storm motion. The hatched portions represent areas of unattainable mean velocity values due to a large spectral variance. X shows location of tornado at the ground

Storm height never reached 12 km and maximum reflectivity was below 50 dBz, both rather modest values for New England thunderstorms, and well below tornado thresholds.

One of the more attractive possibilities offered by Doppler radar is a substantial warning of severe events on the ground through earlier detection of wind disturbances and vortices aloft. Two heavily damaging Massachusetts windstorms (but apparently without tornadoes) provided warnings of 55 and 60 min from the first appearance of high shear aloft until destructive winds hit the surface. A weak vortex signature was first noted at altitudes of 5.4 to 8.0 km, 40 min before the earliest wind damage, in the Union City, Oklahoma tornado of 24 May 1974.[14] Other Doppler observations in Oklahoma show a vortex signature 40 min before

14. Donaldson, R.J., Jr. (1975) History of a tornado vortex traced by plan shear indicator, Preprints, 16th Radar Meteorology Conf., pp. 80-82.

a funnel cloud[15] and 50 min before the first of several tornadoes which dropped from the same storm during a 2-hr period.[16] We do not know of any documentation of comparable reliable warning times provided by conventional radar.

The ability to detect the base altitude of the vortex aloft by Doppler radar provides an opportunity to track the descent of a tornado and observe the timing of its touchdown. In the Union City tornado, for example, the vortex intensified as its base descended, offering a more precise target to follow as the danger of a serious tornado became increasingly obvious.

Still another advantage of a Doppler radar is the opportunity for more precise location of the severe event. The severe weather, particularly wind damage, may occur many kilometers removed from projections to the ground of the reflectivity core or echo top. A classical tornado hook is a better locator of severe weather, but a well-formed hook may cover a swath of 10 km (in extreme cases up to 20 km), and it is not easy to pick out the center of circulation from a reflectivity pattern which is the resultant of precipitation formation and fallout as well as mesoscale vortex circulation. Doppler radar can pinpoint the vortex with much greater precision. The Union City tornado, for example, had a vortex diameter of up to 5 km when first detected, which contracted to a diameter of 1 to 2 km during its descent toward the ground, and was 0.7 to 1.0 km near the ground after tornado touchdown. During this period the storm width grew from 30 to more than 50 km and had a slightly greater length. Accordingly, Doppler radar not only identified this storm as a dangerous one, but located the dangerous region which was two to four orders of magnitude smaller than total storm area.

4. ADDITIONAL OPERATIONAL APPLICATIONS FOR DOPPLER RADAR

The major operational advantage of Doppler over conventional radar, as we have discussed in some detail, is in the task of identification and warning of tornadoes and other heavily damaging windstorms. We suggest three other applications of Doppler radar which would be of operational advantage. These applications, taken alone, may (or may not) be considered of sufficient importance to justify the additional expense of Doppler capability. However, as an increment of usefulness over and above severe storm applications, they sweeten the cost/benefit ratio.

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15. Brown, R.A., Bumgarner, V.C., Crawford, K.C., and Sirmans, D. (1971) Preliminary Doppler velocity measurements in a developing radar hook echo, Bull. Am. Meteor. Soc. 52:1186-1188.

16. Brown, R.A., Burgess, D.W., Carter, J.K., Lemon, L.R., and Sirmans, D. (1975) NSSL dual-Doppler radar measurements in tornadic storms: a preview, to be published, Bull. Am. Meteor. Soc. 56.

The most economically advantageous and most widely applicable of these dividends is the opportunity for a more reliable calibration of the receiving and data processing equipment. This task is of vital significance in view of the excellent success of 10-cm reflectivity in identifying hail. If the advanced weather radar system is to provide accurate quantitative measurements over the entire range of signal amplitudes that are normally encountered, a correspondingly accurate means of calibrating the system must be provided. A Doppler (coherent) transmitter offers several advantages in this regard. These advantages arise from the fact that there is a point in nearly all coherent transmitters where there is a CW signal at the transmitter frequency and at a level of from 1 to 10 watts. This signal can be tapped to provide a gated or ungated RF calibration signal source which (1) always falls in the center of the receiver pass-band, (2) is quite stable in both power level and frequency, and (3) is of sufficient power to enable the calibration of wide dynamic range receivers using RF attenuation techniques. Conventional RF test sets do not have sufficient power levels to calibrate most wide dynamic range weather radars; all of the power measured at the test set frequently does not fall within the receiver pass-band; and the conventional sources are known to drift in both frequency and level. We are indebted to our chief, Mr. Kenneth Glover, for pointing out these important features of a Doppler radar.

Another use of Doppler capability is the elimination, with suitable processing, of stationary ground clutter. This may be helpful in tracking storm echoes at nearby ranges or over hilly countryside.

Finally, Doppler radar can obtain wind vectors and divergence in a widespread storm at any height where precipitation particles are located. This technique, called Velocity-Azimuth Display or VAD, was developed many years ago by Lhermitte and Atlas.[17] The method is very simple and has an accuracy comparable to or better than a rawinsonde. Doppler radars which are employed for tornado and severe windstorm identification during spring and summer could be used during winter to monitor the development of widespread storms by obtaining winds-aloft observations with tighter spatial and temporal resolution than the upper-air network provides. Such additional wind coverage could have application to forecasting of snow on airfield runways.

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17. Lhermitte, R. M. and Atlas, D. (1961) Precipitation motion by pulse Doppler radar, Proc. 9th Wea. Radar Conf., pp. 218-223.

5. PROMISING DIRECTIONS OF FUTURE DOPPLER RESEARCH

Decisions affecting meteorological radar employment during the next two or three decades should factor in the possibility of significant improvements in the operational capability of Doppler radar which may be provided by research during this period. There appear to be four or five areas of investigation which are likely to contribute to the usefulness of Doppler radar in the 1980's.

Lhermitte suggested many years ago that an abnormally wide spread of Doppler velocities within a range gate could identify a small, very intense vortex.[18] Convincing verification of Lhermitte's idea was obtained by Kraus[13] in his study of the Brookline, Mass. tornado and by Brown and his colleagues[16] in a more recent tornado situation in Oklahoma. Both investigations showed a small region of Doppler spread covering the entire velocity capability of the radar, located within the resolvable mesoscale cyclone. It is reasonable to expect that quantitative measurements of Doppler velocity variance may enable more precise detection of tornado development within a mesoscale vortex.

Observations of Doppler velocity variance may also contribute to flight safety within clouds and more economical use of airspace around terminals. Preliminary results of experiments by Lee and Kraus[19] indicate an association of severe turbulence encountered by storm-probing aircraft with larger-scale shear measured by Doppler radar. It seems reasonable that further experiments, employing quantitative real-time measurement of Doppler velocity variance, will indicate closer coupling with turbulence sensed by aircraft, which is affected by wind variability on a scale more nearly commensurate with Doppler-measured variance than with shear. Turbulence associated with thunderstorms is a major flight hazard in civil aviation.[20] In normal times military aircraft may have sufficient flexibility of scheduling to enable avoidance of nearly all thunderstorms, but a national emergency may require the fullest utilization of airspace by military vehicles consistent with successful mission performance. Remote turbulence sensing by Doppler radar could be very helpful in these circumstances.

Prediction of storm motion should improve as more knowledge is gained of circulations within storms and the effects of their interaction with the environmental wind field. Current techniques for predicting storm motion depend on

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18. Lhermitte, R.M. (1964) Doppler radars as severe storm sensors, Bull. Am. Meteor. Soc. 45:587-596.
19. Lee, J.T. and Kraus, M. (1975) Plan shear indicator and aircraft measurements of thunderstorm turbulence: experimental results, Preprints, 16th Radar Meteorology Conf., pp. 337-340.
20. Ellingsworth, R.K. (1974) NTSB seeks better pilot weather data, Aviation Week and Space Technology, May 6, 1974, p. 34.

linear extrapolation of past positions of the storm.[21] Unfortunately, severe storms tend to curve and change speed. Sometimes there is a dramatic shift in direction; the Union City tornadic storm, for example, made nearly a 90° turn to the right. Violent storms frequently display erratic motions. If a realistic estimate is to be made of the threat by tornado or damaging windstorm to an air base, a rather small target in comparison with the large standard errors expected by current extrapolative techniques, it appears that a breakthrough is required in prediction of storm motion. We believe that information on air circulation within the storm, which can be obtained by Doppler radar, contains important clues on deviations from simple drift of the storm with the mean winds. Splitting storms, for example, sometimes show cyclonic circulation in the right-moving half and anticyclonic circulation in the left-moving half.

The ability to predict the descent rate of a violent vortex toward the earth's surface, or whether it will fail to reach the ground, is another research problem of critical significance in estimating the threat of destructive winds. Research with Doppler radar has revealed that intense disturbances in the wind field of a convective storm occur much more extensively and frequently at middle heights than near the ground. The boundary layer seems often to act as a protective shield. However, occasionally a tornado or damaging windstorm will poke through. Perhaps there are indications of probability of touchdown in the nature of the vortex itself, such as its vertical profile of size and intensity, its tilt, or its location with respect to the reflectivity structure of the storm. This undoubtedly will become a lively research topic in future years, and one with a big payoff if successful.

The detection and tracking of high winds and tornadoes within hurricanes is another unexploited research topic with important operational significance. No success has yet been reported in identifying tornadoes within hurricanes by conventional radar. This would seem to be a task ideally suited to Doppler radar. Aside from tornadoes, the high winds of hurricanes sometimes leave surprisingly narrow paths of damage with sharp gradients. Not far from swaths of heavy damage there are regions with only light damage. The decision to evacuate an air field would be much better informed if there could be advance warning of the location and probable track of hurricane winds above a critical danger threshold. There is much research to be done, because until recently there has not been any meteorological Doppler radar located in regions subject to frequent threat of hurricanes.

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21. Blackmer, R.H., Duda, R.O., and Reboh, R. (1973) Application of Pattern Recognition Techniques to Digitized Weather Radar, Stanford Research Inst., Final Report, Contract 1-36072, SRI Project 1287.

6. CONSIDERATION OF THE DUAL-DOPPLER MODE

The velocity information acquired by a single Doppler radar is limited to components of motion along the radar beam. Motions across the beam are not sensed by the radar. Lhermitte[22] proposed an observational scheme to overcome this limitation, employing two Doppler radars at different locations, viewing the same storm from different directions. In this manner, the complete velocity field in the plane defined by the two radars could be synthesized by combining the components of velocity measured separately by each radar for every point within the common field. Shortly thereafter, Lhermitte demonstrated his technique by mapping the complete horizontal velocity field at low levels in a convective storm.[23] The dual-Doppler mode has proved its worth as a powerful research tool for investigating the complexities of previously inaccessible winds within storms.

In view of the success of dual-Doppler observations in contributing to storm research, it is reasonable to consider whether this mode is feasible for operational applications. We advise against it for two reasons: single-Doppler radar, despite its limitations, is better adapted for severe storm identification and warning service, and dual-Doppler equipment is too costly and requires a high degree of coordination to operate properly.

Earlier in this report we have discussed the success of single Doppler radars in detecting wind shear and turbulence within storms, and in identifying and measuring mesoscale vortices which are frequently accompanied by tornadoes. In these crucial aspects of motion pattern recognition, the additional contribution of a second Doppler radar would have very little effect on forecasting skill. The dual-Doppler technique would excel in mapping vector wind fields throughout an entire storm, and the information so derived might have a bearing on the prediction of anomalies in storm motion. However, Kraus[24] has developed a technique for deriving information on the vector wind field in thunderstorms from single-Doppler velocity components, under circumstances wherein the major features of the velocity field maintain identity for periods of about 10 to 20 min. Kraus' method would provide useful information in storms of great operational significance, the class of severe storms characterized by a persistent phase of well-organized, quasi-steady circulation.

22. Lhermitte, R.M. (1968) New developments in Doppler radar methods, Proc. 13th Radar Meteorology Conf., pp. 14-17.
23. Lhermitte, R.M. (1970) Dual-Doppler radar observation of convective storm circulation, Preprints, 14th Radar Meteorology Conf., pp. 139-144.
24. Kraus, M.J. (1973) Calculating airflow from single Doppler radar velocity components, Preprints, 8th Conf. on Severe Local Storms, pp. 44-47.

A dual-Doppler system operating in real time would cost considerably more than two single-Doppler radars. In order to take full advantage of dual-Doppler capability, care would be required to assure that both radars scanned the same region of space at the same time. Furthermore, synthesis and display of the vector wind field in real time would be required for operational applications, so a sophisticated, high-capacity computational facility would have to be available on a priority basis. Finally, the common area in which the two radars could obtain velocity without unacceptable errors contaminating the resultant vector wind field synthesis is considerably less than the area which can be covered by either radar alone in single-Doppler mode. The optimum distance between radars operating in the dual-Doppler mode is about half the maximum usable range of either radar, giving a dual-Doppler scanning region of 46 percent of the area which can be covered in the single-Doppler mode. Because of cost escalation and diminished coverage of dual-Doppler, and suitability of a single-Doppler radar for meeting the most urgent operational requirements, we recommend against planning to incorporate dual-Doppler capability in an operational system.

7. INCREMENTAL COST OF DOPPLER CAPABILITY

Estimates of radar costs were furnished through the courtesy of two engineers employed by Raytheon Company. One of them was manager of a program which produced conventional (non-Doppler) radars for meteorological applications. The other is concerned with development of processing and display techniques for our meteorological Doppler radar. Both engineers emphasize that the data provided are approximate estimates for planning purposes only but are believed to represent in gross terms the unit purchase price of typical hardware items, assuming quantities of ten items are procured. Larger quantities might lower the unit costs slightly. Costs are given in late 1974 dollars.

The cost of a conventional meteorological radar, similar to the National Weather Service WSR-57 but with some modernized features, would be in the neighborhood of $300,000. Following is an approximate breakdown:

(a) Console – $50,000. Includes RHI, PPI and A + R monochrome scopes and a digital video integrator.

(b) Receiver-Transmitter – $45,000. Meets MIL-STD-469, has 500 kw peak power at S Band, STC, log and lin receivers, precision IF attenuators and 8 dB noise figure.

(c) Antenna Pedestal – $60,000. Includes a 12-ft dish (giving 2.2° half-power beam width at S Band), solid state servo amplifier, 0 - 6 azimuth rotations per minute, and 0° to 60° elevation travel, with RHI scan capability.

(d) Installation Materials – $75,000. Includes radome, tower, waveguide, interconnecting cabling, and installation field support. Does not include building and prime power.

(e) Spares – $30,000.

The minimum total hardware cost of an incoherent radar with the listed features would be about $260,000. Not included are costs of such efforts as design, handbooks, reliability predictions, reliability and maintainability demonstration tests, and prototype production. With sharing of these costs over several tens of production models, the unit cost would end up somewhere in the neighborhood of $300,000. Special color displays and data processing for parameterization and transmission of information to a central analysis facility are not included in this cost estimate.

The cost increment required to add Doppler capability is quite reasonable. For about $10,000 to $20,000 a coherent channel (exclusive of processing) could be incorporated in the system. This increment is modest because it is assumed that the stringent requirements of MIL-STD-469 for the incoherent radar already assure the necessary stability in the receiver-transmitter. A pulse pair processor which will furnish estimates of velocity mean and variance from the basic Doppler data would cost about $30,000 to $40,000 per unit, and the two additional displays would add $20,000. The employment of color coding in these displays would cost perhaps $50,000 extra.

In conclusion, from a basic incoherent radar cost of $300,000, coherent Doppler capability (without processing) could be provided for an average increment of 5 percent, a workable Doppler system with processing and display of velocity mean and variance would cost about 25 percent more than a conventional radar, and a system with color Doppler displays would run about 40 percent higher than the basic radar.

8. RECOMMENDATIONS

The 5 percent incremental cost of providing a coherent channel in the receiver-transmitter is a very good investment for two reasons. First, as we have discussed in Section 4, a coherent channel will enable significant improvements in the reliability and accuracy of system calibrations. Therefore, even if the radar is never used for velocity measurement, a coherent channel will be a valuable feature to maintain the credibility of reflectivity measurements. Second, if a radar has the coherent channel in its receiver-transmitter, Doppler processing and display can be easily added on at any time. If future research results and/or more favorable funding enable the future addition of Doppler capability, it can be provided economically. If, however, the decision is made to upgrade an incoherent radar to Doppler capability, the basic receiver-transmitter would have to be replaced with a correspondingly higher unit cost.

Current research experience shows decisively that hail can best be identified by radar through the measurement of reflectivity. On the other hand, even the limited research accomplished so far indicates that Doppler radar techniques are clearly and significantly superior to conventional radar for identifying tornadoes and other damaging windstorms. Consequently, we recommend the following courses of action:

(1) In any advanced meteorological radar procurement, allow a 5 percent cost increment to incorporate the coherent channel in the receiver-transmitter system in all of the radars, because all of them will require capability for accurate, reliable reflectivity measurement and some will sooner or later be used as Doppler radars.

(2) Provide Doppler processing and display capability for radars destined to serve regions subject to the threat of tornadoes, hurricanes, and other damaging windstorms, and in addition, at air bases where mission requirements during a national emergency may impose such a high traffic load that identification of airspace free of dangerous in-cloud turbulence could be a crucial factor in mission success.

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