013734-1-F

THE UNIVERSITY OF MICHIGAN

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DETECTION OF INCIPIENT TORNADOES BY A SPACEBORNE DOPPLER RADAR - A LITERATURE SEARCH

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31 December 1975

Final Report
Purchase Order S-54214A

1817

Prepared for

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

13734-1-F = RL-2264

Ann Arbor, Michigan

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Introduction

This report is to summarize the results of a limited effort literature search for information needed for the construction of a simplified model of a tornado vortex such as would be seen by a Doppler radar. The project was initiated as a result of our interest and that of NASA Goddard to develop the information needed to design a spaceborne radar system for the detection of incipient tornadoes. Hence, in our literature search, we have placed more emphasis on radar observables as seen from a satellite. It is interesting to note that none of the several dozen papers reviewed had as its major emphasis the use of satellite borne radars for the early detection of tornadoes. Several papers, however, made reference to the subject. Many papers have been written on the use of ground based radars in the detection and study of tornadoes.

With respect to the space platform, two choices are possible—a synchronous satellite or a low orbit vehicle. The synchronous satellite would have the advantage of long looks at chosen areas of interest and the much greater field of view. On the negative side, the power required would be much greater even with the larger antennas which would be required, the resolution would be less and perhaps of greatest importance, the near-vertical viewing angle would make it difficult to properly observe some of the important tornado signatures. In addition, the decrease in radial motion in the storm system as viewed from the synchronous altitude would seriously limit the advantages of the Doppler detection system.

A Doppler radar system on a low orbit satellite would have the obvious advantages with respect to power required, antenna size,resolution, Doppler returns and the improved aspect of the viewing angle. Even so, several difficulties are evident. These include the following:

1. The transmitted and reflected signals must penetrate 5 to 10 km or more of turbulent cloud cover. It may be possible to compensate for the resulting attenuation and noise in the data processing system.

2. If interest is restricted to the North American continent, viewing time efficiency will be less by 75 percent or so while the satellite is over the oceans and other continents.

3. Once the satellite is in orbit, there is little or no opportunity for changing the area viewed (the footprint of the radar.) Thus it is frequently not possible to view a particular area as long or as frequently as desired. It is possible that a tornado would develop and become destructive while the satellite was outside of the U.S. viewing area.

4. It will be difficult to discriminate between the ground and weather targets of interest since there is little difference in their velocities relative to that of the satellite. This problem can be alleviated to some extent by using a narrow beam antenna and by limiting the zone covered. With this limitation it should still be possible to observe the top of a tornado vortex and this may be an important clue for discriminating between tornadoes and other storms.

5. The height of the satellite and the associated long range introduces range ambiguities if the PRF (pulse repetition frequency) is high enough to provide the desired number of looks and resolution.

Despite these somewhat formidable problems, it is believed that the overall advantage is with the low orbit satellite. Methods of solving the above problems have been outlined in the study made by those who prepared the Active Microwave Workshop Report (Matthews, 1975). Radar engineers are confident of their ability to design a satellite borne radar that could collect information that would be effective in detecting the presence of tornadoes (R. Larson, 1975, personal communication).

The results of the literature search are discussed in the following sections. Section II contains a general description of tornadoes. Section III discusses the electromagnetic observables associated with a tornado as seen by both a passive and an active system. In Section IV some of the pertinent Doppler radar systems are discussed and conclusions are presented in Section V.

Since this is a report on a literature search, frequent use is made of quotations, some of which are direct quotations.

II. Tornado Characteristics - General

To add to the background information, it may be helpful to have a brief nonelectromagnetic description of a tornado. Donn (1965) says, "Tornadoes are by far the most destructive manifestations of all nature. Nothing else is comparable to their fury." The power required to drive a tornado vortex has been estimated to exceed 10^8 kw (Vonnegut, 1960). A more complete description is quoted from Petterssen (1969):

> ... A tornado is a vortex of small horizontal extent and great intensity which extends downward from a thundercloud. It is usually visible as a funnel-shaped <u>tuba</u> cloud, with a broad base in the cumulonimbus and a narrow tubular extension down to the ground.
>
> The lower part of the tornado cloud is often surrounded by an ugly column of dust and debris, which are sucked up from the ground and thrown outward by the centrifugal force in the whirl. At the time of inception the funnel is more or less vertical, but as the mother cloud moves on, the upper portion of the whirl becomes slanted and sometimes detached. On occasion several funnels may build down from the mother cloud, and some of these may not reach the ground.
>
> The diameter of a tornado may vary from a few meters to a few hundred meters, with an averabe of about 250 m. The winds are strong also outside the funnel cloud, and the width of the path, as determined by the destructive effects on the ground, may be two to four times as wide as the funnel cloud. The passage of a tornado is accompanied by a sudden pressure drop of the order of 25 mb, though sometimes much larger pressure changes have been observed. The decrease in pressure from the rim to the center of the tornado represents a tremendous force, which few buildings can withstand. As a tornado goes over a building, the outside pressure drops so suddenly that the pressure within cannot follow suit. Much of the damage caused by tornadoes is due to the pressure differential through the walls and roof: buildings tend to "explode" rather than to be "blown over".
>
> The circulation of the wind around a tornado is almost always in a counterclockwise (cyclonic) direction. The wind speed near the core varies within wide limits. Since no anemometer has survived the passage of a severe tornado, no reliable measurements of the wind speed have been made. Estimates, however, indicate that the wind speed is of the order of 100 m/sec, or about 225 mph, and may be twice as high in extreme cases. From the formula given on page 303 it follows that, in extreme cases, the wind pressure may be as large as 800 lb/ft^2. Only few structures can withstand such wind pressures.

> The life of a tornado varies within wide limits. On the average, the length of the path, as determined from the destructive effects on the ground, is about 5 to 10 km (3 to 6 mi). On occasion paths as long as 300 km have been observed.
>
> The majority of the tornadoes in the United States occur in connection with squall lines or severe cold fronts. These tornadoes often occur in families and move in the direction of the wind in the warm air; they usually have long paths. Tornadoes are observed also in connection with scattered thunderstorms of great intensity. Such tornadoes are usually short-lived and have irregular paths. Although tornadoes may occur anywhere, except in the polar regions and over cold northern continents in winter, they are most frequent to the east of the Rocky Mountains, to the east of the Andes, and in eastern India. This suggests that the influences of mountains on the air currents and the distributions of temperature and moisture along the vertical are important, but little is known about the mechanisms that produce tornadoes. In the United States about 95 percent of all tornadoes move from a direction between south and northwest, with a strong preference (61 percent) for a southwesterly direction.
>
> Most of the tornadoes in the United States occur in connection with squall lines and cold fronts when there is a layer of warm and moist air near the ground overlain by a layer of dry air.

Gray (1971), who has emphasized the importance of the statistical approach in the study of tornadoes and tornado genesis states that the individual tornado will always be underobserved and often misrepresented. Based on his studies and those of his colleagues, he concludes that tornadoes, funnel clouds and many lesser intense micro-scale vortices form under conditions when strong cumulus updrafts penetrate lower tropospheric layers of large vertical wind shear. The combination of a strong buoyant updraft and vertical shear are the important environmental requirements. The great plains area of the United States leads the world in having these conditions a relatively high percentage of time and in the production of tornadoes.

Based on the studies made by Ludlam (1963), tornado funnels appear to protude from the arch cloud in the forward right flank of severe storms and outside the precipitation region.

III. Tornado Electromagnetic Observables

Emphasis in this study is on the use of active electromagnetic systems, i.e., radars. Hence, in this section, most interest will be on the scattering and reflection of electromagnetic waves by tornadoes. However, one should also be aware of the electromagnetic radiation generated by a tornado. This subject will be discussed first.

Tornado observables as viewed by passive electromagnetic systems

It is rather obvious that the usual high level of lightning and thunder associated with a tornado would result in electromagnetic radiation. The frequencies commonly associated with a spark discarge extend from near dc values to those approximately equal to the reciprocal of the rise time of the pulse discharge. Frequency components as high as many megahertz are known to be associated with tornadoes. According to Scouten et al. (1972), the parent thunderstorm associated with the tornado and not the vortex is the likely source of the intense electrical activity. Taylor (1973) states that the electrical charges within a thunderstorm cloud are usually dispersed throughout the cloud and are discharged to the earth by the discrete current surges of lightning strokes. The electromagnetic fields radiated during lightning strokes are called atmospherics or sferics. Again, quoting Taylor, "The response of receivers tuned to frequencies less than about 30 kHz are discrete and are easily associated with a return stroke in a cloud-to-ground discharge. As the observing frequency increases, the number of responses increased to several thousand at frequencies above 10 MHz." The higher frequencies are thought to be associated with the rapid occurrence of short-distance dispersive processes within the parent storm cloud.

In his 1973 paper Taylor reports on his investigation of electromagnetic radiation from tornado-producing severe storms occurring in Oklahoma in 1970. He observed the rate of occurrences of atmospherics at frequencies from 10 Hz to 3 MHz using short time constant circuits to preserve the burst nature of the received impulse signals. He concluded that the parameter most indicative of tornadic activity was the number of bursts of high atmospherics rates at frequencies above 1 MHz. His findings are supported by the work of Hughes and Pybus (1970) and by Stanford et al. (1971).

Radar observables

Battan (1973) states that the identification of a tornado by means of conventional radar is not easy. It has frequently been noted that tornadoes are associated with thunderstorm echoes having protruding fingers, V-shaped notches or doughnut shapes, i.e., small dry holes or non-echoes within fairly intense echoes. However, these echo shapes are frequently seen when no tornadoes are present and tornadoes frequently occur when the above echo shapes are not seen.

The presence of a hook-shaped echo in association with a severe thunderstorm is believed by several observers to be a reliable indication of the presence of a tornado. Bigler (1956) described a series of radar observations in association with a tornado that occurred near College Station, Texas. He was able to observe a completely developed hook before the tornado touched the ground. Although the hook echo appears to be a good positive tornado indicator, many radar observers have followed the development of tornadoes in which no such echoes were seen. Freund (1966) examined the radar echo signatures of 13 tornadic storms occurring near Norman, Oklahoma in 1964. He found no definite radar signature common to all of the tornadoes. He concludes that the hook echo might belong to a special class of tornadoes and states that the classic hook might be more characteristic of the severe storm literature than of real tornadic phenomena. Donaldson et al. (1975) conclude that no more than half of all tornadoes, under the best of conditions, indicate their existance with an unmistakable hook echo. This is based on their own experience and information gained from other workers in the field. Battan (1975) states that most of the time the shape of the echo is of little value in identifying tornadoes. In the same paper he states that long-lasting thunderstorms extending to great altitudes and producing intense echoes are likely to have associated violent weather such as hail storms or tornadoes.

The intensity of a radar echo is thus another clue to the presence of a tornado. Donaldson (1961) reports that the echoes from New England thunderstorms which produce tornadoes are more intense than the tornado-free storms. If the effective reflectivity factor is greater than 10^5 mm^6/m^3 at an altitude greater than 10 km as seen by a 3 cm radar, this is a good indication in New England that the thunderstorm will produce a tornado. (The effective reflectivity factor, Z_e, is $(6\lambda^4 \sigma M)/(\pi^6 |k|^2 \rho D^3)$ where M is the liquid water content with particles of diameter D and density ρ. σ is the radar cross section of the particles and $|k|^2$ is a function of the index of refraction conventionally taken as .93 for water.)

The maximum height of the radar echo associated with a storm is an important signature. For example, cyclonic storms occurring in the middle latitudes have maximum height echoes of 5 to 8 km. Thunderstorm echoes reach heights of 10 km or so; hail storms have echoes up to 13 km in height while severe storms with tornadoes commonly have echoes up to 20 km in height (Katz, 1975).

Atlas (1963) proposes a method of tornado detection based on fluctuation analysis based on radar returns. The fluctuations are due to two or more scatterers moving in and out of phase due to the wind velocity and the rotational motion. Higher fluctuation rates are an indication of greater wind speeds. According to Atlas, fluctuation frequencies greater than 2 kHz should provide a unique indication of a tornado, assuming a 10 cm radar system. Such a detection system would, unfortunately, require a pulse repetition frequency of 4000.

The radar signature which, without doubt, is the most reliable means of identifying the presence of a tornado is that which shows the characteristic wind vorticity. Donaldson (1971) makes the following statement: "Tornadoes and other damaging winds in severe local storms provide destinctive features for their remote identification by Doppler radar. Smith and Holmes (1961) demonstrated the capability of a cw Doppler radar for detection of a tornado, and Lhermitte (1964) considered techniques for presentation of unique pulse Doppler velocity patterns associated with tornado vortices." Velocities are most easily measured with a Doppler radar; mean wind velocities are determined from the Doppler returns from the scatterers carried by the wind. Doppler velocity information is, of course, limited to that component which is in the radial direction with respect to the radar system. Hence, special techniques are required to obtain rotational information with a single Doppler radar. Dual Dopplers have been used for this purpose, but that technique is not adaptable to a space platform.

Donaldson (1970, 1971) and Donaldson et al. (1975) were successful in developing a very effective method for recognizing a vortex signature. They found a scanning Doppler radar has capability for measurement of the tangential shear of radar velocity. This is defined as the gradient of the radial component of velocity in the direction normal to the radial vector. This type of shear is an indication of vorticity and its presence is determined by scanning the radar beam in azimuth while its elevation is fixed. Elevation angles between 0^{0} and 10^{0} are selected to observe quasi-horizontal wind components at various heights within the storms. Donaldson et al. (1975) found that high shear values generally were first found at middle altitudes in a storm and then progressed downward.

They found that a shear value of 0.02 sec^{-1} proved to be a reliable threshold criterion for identifying severe storms. Storms were characterized as severe if they deposited hail with diameters of 3/4 inch or larger and/or inflicted wind damage by tornadoes or other means. These criteria enabled them to detect all but three in a series of 48 observed severe storms and the criteria were present in only six of more than 150 nonsevere storms which the group studied. Brown et al. (1973), Kraus (1973 a, b) and Burgess et al. (1975) have made use of similar or related techniques using a single Doppler radar to determine rotational characteristics of tornadoes and tornado cyclones.

Doppler radars have other advantages over conventional radars: they are able to locate a tornado vortex with greater precision and, by suitable signal processing, stationary ground clutter can be eliminated making it more feasible to track storm echoes at short ranges and over hilly terrain.

IV. Doppler Radar Systems

As indicated earlier, there appear to have been few, if any, investigations of the possible use of satellite borne radars for the detection of incipient tornadoes. However, Battan (1975) mentions the idea and states that specialized radars carried on satellites should play a part in the identification of violent weather in future years. He believes that research on the use of satellites for the observation of severe local storms and for use in communication of forecasts and warning deserves generous support. He mentions one example where a strong vortex was detected in the middle levels of a storm area about 23 minutes before an associated tornado touched the ground (with a ground-based system). Detection well before touchdown is, of course, quite important as a means of saving lives and minimizing destruction.

The most intensive and also the most recent study relevant to our objective was that performed by a working group assembled by NASA (Lyndon B. Johnson

Space Center). The group, approximately 70 in number, met at the Space Center in July 1974 to consider the utilization of active spaceborne microwave systems in application programs concerned with observations of (1) the land areas of the earth, (2) the oceans and (3) the atmosphere. Our present interest is in the work of the 16-member panel on the atmosphere. A summary of this work appears in a paper by Isadore Katz (1975) who was one of the two co-chairmen. The complete report is contained in the recently released NASA report, number SP-376, edited by R. K. Matthews (1975).

The charter of the atmospheric panel called for their investigation of the meteorological applications of a satellite borne radar. The following applications and objectives were considered feasible:

map maximum echo heights in rain to provide and indication of storm intensity and rainfall production

tropical storms, size and location

mapping precipitation and drop size spectra

height of the melting level

surface winds

phenomena associated with the formation of sea ice

cirrus cloud detection.

Radar types considered for satellite borne meteorological applications included a more or less conventional pulsed radar, multiwavelength and dual polarization radars, a cw Doppler radar operating at the CO_2 laser frequency ($\lambda = 10\ \mu m$) and a microwave pulsed Doppler radar. The last system appeared to have the most potential and it will be discussed in more detail later.

Both synchronous and low orbit satellites were considered as possible platforms for these systems. Each had some advantages, but for several reasons the lower orbit is to be preferred. A satellite in a near polar orbit with an inclination angle of 58^{o} and a height of 556 km was proposed. Such a satellite would have an orbit period of 1.6 hours. With the antenna beamwidth and scanning arrangement proposed, the complete earth surface between $\pm 68^{o}$ latitude would be covered every 12 hours.

The parameters for a pulsed Doppler radar system were developed by the workshop members. It was emphasized that the specifications were listed only as an example of a radar system having a coverage roughly equal to that of existing meteorological satellite systems. The system specified was considered to be a fairly conventional Doppler radar. The selected specifications were not proposed as the optimum but the panel believed that they could serve as a take-off point for further discussion and development.

It should be noted also that the system was designed with general meteorological applications as the objective and was by no means designed exclusively for the detection of incipient tornadoes. It is the opinion of this writer, however, that the design has many or most of the characteristics and capabilities that would be required for tornado detection. Since it may be difficult to obtain the needed funds for a satellite borne radar to be used exclusively for studying tornadoes, it may be prudent to have as one's objective a system with two or more meteorological applications in mind.

The system parameters are set forth in Table 4-VI of the Active Microwave Workshop Report and that table is reproduced here:

Tentative Specification for a Multibeam Doppler System

Radar wavelength, cm	5.6
Peak power (per beam), kw	5
Average power, w	100
PRF (stability better than 10^{-4}), kHz	2.5
Pulse width, μsec	10
Antenna beamwidth, deg	0.3
Beam footprint on the ground, km	5 by 15
Beam nadir angle, deg	60
Grazing angle, deg	20
Conical scan, beam scan time, sec	40
Satellite displacement during complete scan, km	280
Angular displacement of the antenna beam during echo round trip, deg	0.13
Satellite orbit	polar inclined

(cont.)

Satellite altitude, km	∼500
Satellite orbit time, hr	1.6
Satellite groundspeed, km/sec	∼7
Forward-groundspeed Doppler shift, kHz	∼200
6-dB Doppler smearing (max), m/sec	35
Nonambiguous velocity interval, m/sec	70

An additional specification, not indicated in the table, is a requirement for multiple beams; a 5 to 10 beam system was suggested. With a single beam, the scan rate needed to cover the desired ground swath does not allow sufficient time on each target area for the radiated pulses to return to the antenna. A parabolic reflector antenna is envisaged; it would be suspended below the satellite with its beam at a nadir angle of 60°. A spiral scan on the earth's surface is obtained by spinning the satellite and dish about a vertical axis as the satellite moves forward in its orbit. A swath width (perpendicular to the orbit direction) of 2000 km is obtained.

The bases for the choice of wavelength, beam size, scan rate, pulse repetition rate, etc., are discussed in the Workshop Report and that discussion will not be repeated here except for a few comments. One of the most important considerations was to choose parameters that would provide Doppler information on the atmosphere with a minimum of contamination by ground or sea return. The narrow beam (0.3°) and proper range gating help to eliminate this problem and makes it possible to effectively probe the horizontal and vertical distribution of atmospheric targets.

Another problem inherent with satellite borne Doppler radar systems is due to the high ground speed of the system (7 km sec^{-1}). This causes an undesirably large spread in the Doppler due to the variation in range of the meteorological targets with respect to their position in the beam. The spreading or smearing of the Doppler makes it impossible to obtain useful meterological data from the spectrum width. By using already available signal processing techniques it is possible, however, to obtain values for the mean Doppler. With the mean Doppler data one can monitor mean wind velocities within a precipitation system. Since the target area is viewed from two directions as the satellite approaches and as it recedes, two Doppler velocity components can be measured.

Another critical part of the system specification is the maximum usable PRF. The workshop panel reports that if the antenna pattern is free of sidelobes and with a grazing angle of 20°, the maximum time between successive pulses is 400 to 500 μseconds. A PRF of 2000 Hz places the forward Doppler in the 100th ambiguity region and in the opinion of the panel this would still allow discrimination between atmospheric and ground clutter speed with 35 m sec^{-1} or less Doppler smearing.

Katz (1975) makes a 9 point list of the expected capabilities of a spaceborne radar system in a low altitude orbit. All nine points should be considered by those who would decide on the cost effectiveness of such a system. Here, however, we list only the two capabilities which would tend to increase our ability to detect incipient tornadoes. Comments in parentheses have been added by this writer.

1. Ability to map the maximum echo heights in rain to provide an indication of storm intensity and rainfall production. (As stated earlier, storm heights above 13 km or so almost always indicate the presence of a tornado.)

2. Measure horizontal motion within a storm system. (This capability is to a large extent made possible by the forward and backward look provided by the proposed system. Information on radial and horizontal wind motion should indicate the presence of a vortex and hence the existence of a tornado. The possibility of using the "plane-shear indicator" technique developed by Donaldson and his colleagues (Armstrong and Donaldson, 1969; Donaldson, 1970) should also be investigated. With this scheme it is possible to locate quickly, at least with a ground-based Doppler radar, regions in a thunderstorm echo where circular motions exist.)

The microwave workshop panel concluded that a Doppler radar operating at a wavelength of 10.6 μm (CO_2 laser frequency) had good potential for meteorological applications. It offers an attractive alternative to a 6 cm radar system in its ability to detect and resolve speed and location of cloud particles. Their report states that such a system should be able to survey areas of the atmosphere larger than is possible with a microwave radar. Further, the 10 μm wavelength radar would have range and velocity information in a single pulse, several microseconds long, sufficient to provide mean velocity information at a much higher rate than can be had with a microwave system. As with the microwave system, use could be made of the return as seen in both the forward and reverse direction so that vector wind direction can be determined.

The possibility of using a microwave radar imaging system with a synthetic aperture as an alternate to the radar system with the very large antenna as specified in the above table should be considered. Highly sophisticated imaging systems have been developed by the personnel of the Environmental Research Institute of Michigan (ERIM) and others. Larson (1975) makes the following statement: "Based on the present state of the art in imaging (or synthetic aperture) systems it would appear feasible to design a spaceborne velocity detection and mapping system (for tornado study) having roughly the following capability:

1. velocity resolution 1 mph
2. range resolution < 10 m
3. azimuth resolution (in imaging mode) < 1 mile
4. reacting time: near real time.

These capabilities would be heavily influenced by the data processing required for the Doppler signature determination and image-forming roles of the system. The extent to which these capabilities could actually be achieved would require a detailed investigation."

V. Conclusions

In this literature search, we have found no reports of an investigation seeking to determine the feasibility of a satellite borne radar tornado detection system as the prime objective. As indicated in the body of the report, we found numerous reports on the use of ground-based radars for the detection of incipient storms. In those few studies which have been made on satellite borne meteorological radar systems, very little attention was given to tornado detection. We have examined, however, several reports that are quite relevant to our objective.

Several reports have been reviewed which describe the electromagnetic observables associated with a tornado. Our emphasis has been on those which would be the most reliable signatures for an active radar system. Of these the best are the rotational characteristics of the winds, the echo height, the echo intensity and possibly the "hook" shape.

The most complete source of information on a satellite borne meteorological radar system which we were able to find was the recent report of the active microwave workshop panel (Matthews, 1975). Information from this report which appears to be most relevant to tornado detection is reported in some detail.

Based on the advances made in satellite load capabilities and in advanced radar systems, we believe that a properly designed spaceborne Doppler system would be a valuable tool for use in the detection of incipient tornadoes. We have no estimate of the cost effectiveness of such a system. We believe this could be enhanced by designing a system with two or three or possibly more meteorological applications. We believe also that in the design of a satellite borne microwave Doppler radar system, consideration should also be given to the inclusion of a 10 μm cw Doppler system such as was mentioned by Matthews (1975). To enhance the tornado detection system, the satellite system might also include passive sferic detection systems (Taylor, 1973).

One objection made to the use of spaceborne radars for tornado detection was the undesirable length of time between successive searches of specific areas (Dennis, 1963). If the system would prove successful and cost effective, the time between looks can be reduced by a factor of 2, 3 or 4 by adding additional satellites in corresponding numbers.

We quit again the recent statement by Battan (1975), "Research on the use of satellites for observation of severe local storms and for use in communicating forecasts and warning deserves generous support."

We quote also Dr. David Atlas (1975), President of the American Metcorlogical Society, in a presentation made to the House Subcommittee on the Envionment and Atmosphere at the AMS Conference on Severe Local Storms, 23 October 1975, Norman, Oklahoma: "Among all the observation needs, however, I am sure we are in unanimous accord with Professor Battan (Battan, 1975) who emphasized the need for and potential of remote sensing techniques—especially for Doppler radar—for the unambiguous detection and pinpointing of tornadoes. Here is a tool whose time has come. With the exception of a modest amount of applied research to determine its possible limitations, such as false alarm and miss-rates, I believe it is ready for deployment. ... The phenomenal advances which have been made in remote sensing of clouds and temperatures from satellites over the last 15 years indicates one of the most promising directions to take."

REFERENCES

1. Armstrong, G.M. and R.J. Donaldson (1969),"Plane Shear indicator for real-time Doppler radar identification of hazardous storm winds", J. Appl. Meteor., 8, pp. 376-383.

2. Atlas, D. (1963), "Radar analysis of severe storms", Meteorological Monographs, September 1963, pp. 177-223.

3. Atlas, D. (1975), Overview: The prediction, detection, and warning of severe storms. AMS Conference on Severe Local Storms, 23 October 1975, Norman, Oklahoma.

4. Battan, L.J. (1973) Radar Observation of the Atmosphere. The University of Chicago Press.

5. Battan, L.J. (1975) Detection of Severe Local Storms. Presented at the October 1975 Conference on Severe Local Storms, Norman Oklahoma.

6. Bigler, S.G. (1956) "A note on the successful identification and tracking of a tornado by radar", Weatherwise, pp. 198-201.

7. Brown, R.A., D.W. Burgess and K.C. Crawford (1973)"Twin Tornado Cyclones within a Severe Thunderstorm: Single Doppler Radar Observations", Weather, April 1963, pp. 63-69.

8. Burgess, D.W., L.R. Lemon and R.A. Brown (1975) Evolution of a tornado signature and parent circulation as revealed by single Doppler radar. Radar Meteorology Conference, Vol. 16, April 1975, published by the American Meteorological Society, pp. 99-106.

9. Dennis, A.S. (1963) Fundamental limitations on precipitation observations from satellites. Proceedings of the Tenth Weather Radar Conference of the American Meteorological Society, Boston 1963, pp. 348-354.

10. Donaldson, R.J., Jr. (1970) "Vortex signature recognition by a Doppler radar," J. of Amer. Meteor., pp. 661-670.

11. Donaldson, R.J., Jr. (1971) Doppler radar identification of damaging convective storms by plan shear indicator. Seventh Conference of Severe Local Storms, October 1971, pp. 71-89.

12. Donaldson, R.J., Jr., R.M. Dyer and M.J. Kraus (1975) Operational Benefits of Meteorological Doppler Radar. Report AFCRL-TR-75-0103 21 February 1975, Bedford, Massachusetts.

13. Donn, W.L. (1965) <u>Meteorology</u>, Third Edition. McGraw-Hill Book Co., New York, N.Y.

14. Freund, R.F. (1966) Radar Echo Signature of Tornadoes. Twelfth Radar Meteorological Conference, Norman,Oklahoma, pp. 362-365.

15. Gray, W.M. (1971) Research Methodology, Observations, and Ideas on Tornado Genesis. Seventh Conference on Severe Local Storms, October 1971, Kansas City, Missouri, pp. 292-298.

16. Hughes, W.L. and E.J. Pybus (1970) Severe Storm Sferics-Stroke rate. Fourteenth Conference on Radar Meteorology, American Meteorological Society, November 17-20.

17. Katz, I. (1975) Active Microwave Sensing of the Atmosphere from Satellites. Preprints of the Sixteenth Radar Meteorology Conference, Houston, Texas, April 1975, pp 1-7.

18. Kraus, M.J. (1973a) Calculating Air Flow from Single Doppler Radar Velocity Components. Preprints of the Eighth Conference on Severe Local Storms, pp. 44-47.

19. Kraus, M.J. (1973b) "Doppler radar observations of the Brookline, Massachusetts tornado of 9 August 1972", <u>Bull. Amer. Meteor. Soc.</u>, <u>54</u>, pp. 519-524.

20. Larson, R.W. (1975) Private correspondence (included in 20 January 1975 proposal submitted by the University of Michigan to NASA Goddard Space Flight Center).

21. Lhermitte, R.M. and D. Atlas (1961) Precipitation Motion by Pulse Doppler Radar. Proceedings of the Ninth Weather Radar Conference, pp. 218-223.

22. Lhermitte, R.M. (1964) "Doppler radars as severe storm sensors", <u>Bull. Amer. Meteor. Soc.</u>, <u>45</u>, pp. 587-596.

23. Ludlam, F.H. (1963) "Severe local storms: a review", <u>Meteorological Monographs</u>, <u>5</u>, No. 27, pp. 1-27.

24. Matthew, R.K., Ed. (1975) Active Microwave Workshop Report. NASA Report S P-376. U.S. Government Printing Office, Washington, D.C. 20402 Stock No. 033-000-00624-1, $5.60.

25. Petterssen S. (1969) *Introduction to Meteorology*. Third Edition. McGraw-Hill Book Company, New York, N.Y.

26. Scouten, D.C., D.T. Stephenson, and W.G. Biggs (1972) "A sferic rate azimuth-profile of the 1955 Blackwell, Oklahoma tornado", *J. Atmos. Sci.*, *29* (5), pp. 929-936.

27. Smith, R.L. and D.W. Holmes (1961) "Use of Doppler radar in meteorological observations", *Mon. Weather Rev.*, *89*, pp. 1-7.

28. Stanford, J.L., M.A. Lind and G.S. Takle (1971) "Electromagnetic noise studies of severe convective storms in Iowa: the 1970 storm season", *J. Atmos. Sci.*, *28* (3), pp. 436-418.

29. Taylor, W.L. (1973) "Electromagnetic radiation from severe local storms in Oklahoma during April 29-30, 1970", *J. of Geophys. Res.*, *78* (36), pp. 8761-8777.

30. Vonnegut, B. (1960) "Electrical theory of tornadoes", *J. Geophys. Res.*, *65* (1), pp. 203-212.

GENERAL REFERENCES

1. Biggs, W.G. and P.J. Waite (1970) "Can T.V. really detect tornadoes?", Weatherwise, June 1970, pp. 120-124.

2. Brown, R.A., W.C. Bumgarner, K.C. Crawford and D. Sirmans (1971) "Preliminary Doppler velocity measurements in a developing radar hook echo", Bull. Amer. Meteor. Soc., 52, pp. 1186-1188.

3. Chalmers, J.A. (1954) Atmospheric Electricity. Reports on progress in Physics, Vol. 17, pp. 101-134.

4. Fett, R. W. and S. Brand (1975) "Tropical cyclone movement forecasts based on observations from satellites", J. of Appl. Meteor., 14, pp. 452-465.

5. Fujita, T.T. (1970) "The Lubbock tornadoes: a study of suction spots", Weatherwise, August 1970, pp. 161-173.

6. Fujita, T.T. (1971) Proposed Mechanism of Suction Spots Accompanied by Tornadoes. Seventh Conference on Severe Local Storms, October 1971, Kansas City, Missouri, pp. 208-213.

7. Fujita, T.T. (1973) "Tornadoes around the world", Weatherwise, April 1973, pp. 56-62.

8. House, D.C. (1963) "Forecasting tornadoes and severe thunderstorms", Meteorological Monographs, September 1963, pp. 141-156.

9. Kropfli, R.A. and L.J. Miller (1975) Thunderstorm Flow Patterns in the Three Dimensions from Dual-Doppler Radar. Sixteenth Radar Meteorological Conference, April 22-24, 1975, Houston, Texas, pp. 121-127.

10. Lhermitte, R. (1974) "Real-time monitoring of convective storm processes by Dual-Doppler radar", Atmospheric Technology, Winter 1974-1975, pp. 26-33.

11. Miller, L.J. and R.G. Strauch (1974) "A Dual-Doppler radar method for the determination of wind velocities within precipitating weather systems", Remote Sensing of the Environment, 3, pp. 219-235.

12. Pierce, E.T. (1968) Sferics. Proceedings of the Scientific Meetings of the Panel on Remote Atmospheric Probing, April 18-20, May 16-17, 1968.

13. Purdom, J.F.W. (1971) Satellite Imagery and Severe Weather Warnings. Seventh Conference on Severe Local Storms, Kansas City, Missouri, October 1971, pp. 120-127.

14. Segman, R. (1970) "ESSA Doppler radar system", Weatherwise, April 1970, pp. 70-73, 83 and 103.

15. Serafin, F.J. (1974) "Information extraction from meteorological radars", Atmospheric Technology, Winter 1974-1975, pp. 46-54.

16. Smith, P.L., Jr. (1973) "Weather radar: achievements, promises and problems", Atmospheric Technology, 2, June 1973, pp. 57-65.

17. Strauch, R.G., A.S. Frisch, and W.B. Sweezy (1975) Doppler Radar Measurements of Turbulence, Shear and Dissipation Rates in a Convective Storm. Radar Meteorology Conference, Vol. 16, April, 1975, published by the American Meteorological Society, pp. 83-88.

18. Taylor, W.L. (1972) Atmospherics and severe storms from remote sensing of the troposphere. Edited by V.E. Derr, Chapter 17, U.S. Government Printing Office, Washington, D.C. pp. 17-1 to 17-17.

19. Zrnic, D.S. and R.J. Doviak (1974) Velocity Spectra of Vortices Scanned with a Pulsed Doppler Radar. URSI Spring Meeting, Atlanta, Georgia, June 10-13 (Abstract p. 24). (Complete report obtained from D.S. Zrnic.)