Echo Size and Asymmetry: Impact on NEXRAD Storm Identification

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ABSTRACT

The effects of echo shape and radar viewing angle on detecting small thunderstorms with the NEXRAD storm identification algorithms are examined. The amorphous low level echo shapes are modeled as ellipses with major axes ranging from 5-15 km and minor axes varying between 2-5 km. The model echoes are then used to create a "probability of detection" chart that demonstrates the impact of storm asymmetry on cell identification. Moreover, we examine the algorithm performance on small thunderstorms observed near Huntsville, Alabama and Kennedy Space Center, Florida. The two thunderstorms observed near Huntsville also produced microbursts. The probability of storm detection using the NEXRAD default values for both Huntsville cases is less than 0.5 at the time of the first lightning discharge and less than 0.4 at microburst onset. The Kennedy Space Center storms were already electrically active when the probability of detection was 0.5 or less. A new algorithm based on the analysis of 15 storms observed in Florida, Alabama, and New Mexico is proposed that would identify storms as having lightning if 40 dBZ reflectivity is present at the -10°C level and the echo top exceeds 9 km. This algorithm would have a 100% probability of detecting lightning producing storms 4-33 min before the first flash, a 7% false alarm rate and a critical success index of 93%.

1. Introduction

Early identification of storms is important for a number of nowcasting and warning applications. Even small, short-lived storms can produce dangerous phenomena such as microbursts; violent wind sheer hazards to aircraft caused by strong thunderstorm downdrafts that spread out upon impacting the ground (Fujita 1979; Wakimoto and Bringi 1988). A microburst is defined as a wind speed differential of $\geq 10$ m s$^{-1}$ occurring over a distance of $\leq 4$ km as observed by Doppler radar (Wilson et al. 1984). These storms can also generate frequent lightning (Goodman et al. 1988), which poses a major hazard for many aerospace and ground operations at airports and space launch complexes such as Cape Canaveral, Florida (NRC 1988). Thus, early storm identification enables a more timely assessment of a potential storm hazard so appropriate actions can be taken.

NEXRAD (Next Generation Weather Radar) is a network of Doppler weather radars that is being deployed across the United States and overseas to permit more timely warnings of severe weather (Leone et al. 1989). NEXRAD contains a number of algorithms designed to automatically track and characterize individual storms (NEXRAD, 1985). These algorithms are usually adequate for identifying and tracking larger storms such as those that cause severe weather in the Great Plains. However, while trying to use these algorithms to analyze the evolution of a small microburst producing thunderstorm, we discovered that the storm was not identified until the microburst began, nearly 11 min after the first lightning discharge (Goodman et al. 1988). An algorithm must first identify a storm (i.e., know the storm exists) before predictions of significant weather events originating from the storm can be made.

NEXRAD can be thought of as an additional tool that allows skilled mesoscale meteorologists to select products and information to help properly diagnose the current weather situation. Hence, it is important that users understand any algorithm limitations. Studies of microburst outflow structure (Hjelmfelt 1988; Ellts and Doviak 1987; Wilson et al. 1984) reveal that the wind shear along the maximum shear axis can be six times that along the minimum shear axis. A single Doppler radar then may not be in the correct position to observe the maximum shear. Similarly, the storm identification technique employed by NEXRAD depends critically upon the radial length of 30 dBZ reflectivity seen at the base scan elevation by the radar. Since storms generally are not symmetric, echo orientations that present a shorter storm dimension to the radar decrease the probability of detection. In this pa-
per, we explore the ability of the NEXRAD algorithms to identify small thunderstorms.

2. Simulated probability of detection

The NEXRAD storm identification procedure (Bjerkaas and Forsyth 1980) is briefly described. The identification process begins by searching along each radial for storm “segments,” defined as contiguous reflectivity values above a threshold (NEXRAD default value is 30 dBZ) spanning a threshold distance (NEXRAD default is 5 km). A “dropout” criteria allows lower reflectivity values (25–30 dBZ) to exist in the interior of a segment. Located segments are then grouped together if sufficient overlap with adjacent segments is found. Finally, grouped segments that correlate vertically are identified as storms. However, to be identified as a storm, a group of adjacent segments must be found in the lowest elevation scan. We therefore focus our attention on the low level echo structure and morphology.

An idealized 30 dBZ echo shape in the form of an ellipse was chosen to determine the probability of detection of a storm by the NEXRAD algorithms. An ellipse, for example, describes the first harmonic in the Fourier series representation of a reflectivity contour (Blackmer and Duda 1972). Zittel (1976) used this elliptical Fourier approximation of echo shapes to track cells and determine warning areas for extrapolated storm positions. The smooth elliptical shape (or 30 dBZ contour) also represents an echo having a fractal dimension \( D = 1 \). The fractal dimension expresses the complexity of the contour and relates the perimeter \( P \) of the contour to the area \( A \) enclosed such that \( P \propto A^{D} \). Contour lines lie in the range \( 1 < D < 2 \), with \( D \) increasing with contour complexity. The fractal dimension ranged from 1.0–1.07 for three base scan observations of one of the small Huntsville storms \( (P < 16 \text{ km}) \) examined. Rys and Waldvogel (1986) found the fractal dimension of hail storm echoes at 45 and 55 dBZ thresholds is 1.0 for storms having a perimeter less than about 12 km. However, their regression curves indicate that \( D \approx 1 \) is valid in the range \( 1 < P < 20 \text{ km} \). Thus, for small storms the elliptical echo model is a reasonable approximation of the real world complexity.

Figure 1 illustrates the viewing angle problem. Suppose two radars, labeled A and B, are located along the major (a) and minor (b) axes, respectively, of an elliptical echo. Due to the placement of the radars with respect to the storm, Radar A will view a greater contiguous span of 30 dBZ reflectivity along a radial than is observable from Radar B. If the echo major axis has a length of 5 km (the NEXRAD default segment length), a NEXRAD system located at Radar A will be able to identify this as a segment. Radar B however, viewing across the minor axis, detects a maximum radial length of 30 dBZ reflectivity that is less than 5 km and thus does not identify a segment. Similarly, a radar situated anywhere along an arc between radars A and B will also observe a radial length of 30 dBZ that is less than 5 km and also not identify a segment. The radial resolution of an actual radar is determined by its gate spacing such that the radar observed 30 dBZ length may not equal the true storm length.

We now sample this simulated storm from radar positions situated in \( 1^\circ \) increments \( (1^\circ - 360^\circ) \) around the storm and count the number of view angles that will see a contiguous radial length of 30 dBZ of at least 5 km (i.e., a segment). For purpose of discussion, we assume that if a segment is observed, a storm will be identified by NEXRAD (i.e., the adjacency criterion is neglected). The results are shown in Fig. 2 for ellipses with values of \( a/b \) ranging from 1.0 to 3.0, and major axes ranging from 5–15 km. Thus far we have observed approximate values of \( a/b \) varying from 1.2–2.8 during the life cycles of the four storms studied (33 scans).

A storm will always (100%) be identifiable from all angles if the minor axis is at least 5 km. For a circular storm \( (a/b = 1.0) \), the major axis (or diameter) must be at least 5 km to be identified at all. For the most extreme elongation considered, \( (a/b = 3.0) \), the major axis would need to be 15 km (such that the minor axis would equal 5 km) for the echo to always be detected. If \( b < 5 \text{ km} \), then 100% probability of detection is unattainable for any value of \( a/b \). Given \( b = 4.8 \text{ km} \), for example, the probability of detection asymptotically approaches only 80%.

The effect that varying the segment length threshold has on the probability of detection is considered next. The ratio of the long to short dimension (described later) from observed echoes was computed from each
low level scan of all storms to get an average storm ratio of 1.8. We assume this is approximately equivalent to an ellipse with $a/b = 1.8$. We then sample this elliptical echo from vantage points around the storm and calculate the probability of detection using 1, 2, 3, 4, and 5 km segment thresholds. The result is shown in Fig. 3. Consider the case of a storm with its long dimension ($\approx a$) equal to the NEXRAD default segment length of 5 km for the case where the ratio of $a/b = 1.8$ (i.e., the short dimension $\approx b = 2.8$ km). A radar using a segment threshold of 4 km would have about a 35% probability of identifying the storm given a random echo orientation. A segment threshold of 3 km would increase the probability of detection to near 70%. To achieve 100% probability of detection, the segment threshold would need to be reduced to the length of the short dimension. For a typical storm with $a/b = 1.8$ its long dimension must be 9 km (short dimension of 5 km) to always be detected.

Specifying shorter default segment lengths can cause fragmentation of larger storms due to the reflectivity distribution. The problem of using threshold reflectivity contours to define cells has been discussed by Austin (1978) who found that small "fringe" areas of reflectivity slightly more than the threshold commonly occur near the main echo. These "fringe" areas may be identified as separate cells if the default segment length is reduced, an effect seen in the storms of the present study. Storms then had a tendency to be identified differently from one scan to the next, resulting in the loss of valuable storm trend information.

3. Observations

a. Huntsville, Alabama storms

Radar observations of two small storms were taken on 19 and 20 July 1986 by the National Center for Atmospheric Research (NCAR) CP2 Doppler radar during COHMEX (Cooperative Huntsville Meteorological Experiment) (Dodge et al. 1986). Volume scans were taken every 2–3 min throughout the life cycle of each of these storms while lightning data were obtained continuously by an instrumented mobile laboratory operated by the National Severe Storms Laboratory situated under the storms. Data taken from this S-band, 1° beamwidth radar (gate spacing of 200 m) were interpolated onto an evenly spaced grid (0.25 × 0.25 km) for analysis. To determine the low level dimen-
Fig. 4. Methodology for determining actual storm dimensions using the CP2 base scan of the 20 July 1986 storm at 1923:49 UTC. A fictitious radar is placed around storm approximately 20 km from the center of the storm. Radials are shown emanating from two different radar positions. The extent seen from each radar position is dashed (long storm dimension) or dotted (short storm dimension).

sions (0.5°) of the actual storms, a fictitious radar was positioned 20 km from the storm center at various angles; two of which are shown in Fig. 4. From each position, a number of beams from the fictitious radar would contain lengths of 30 dBZ reflectivity. The length of the maximum contiguous span of 30 dBZ reflectivity seen along a radial at each radar position is noted and is referred to as an “extent.” For example, in Fig. 4 a number of radar beams are shown intersecting the 30 dBZ echo of a storm from radar position A₁. The extent (dashed) is the greatest length of contiguous 30 dBZ reflectivity seen from this position. Similarly, the extent observed from position Aₙ is dotted. The maximum extent for each echo is called the long dimension of the storm, while the minimum extent is called the short dimension. In Fig. 4, a radar at position A₁ is viewing across the long dimension, while from Aₙ the short dimension is being viewed. An extent of 5 km or greater is equivalent to a segment and is assumed to be identifiable as a storm (the adjacency criteria are ignored) from this radar position. The probabilities of detection computed from the elliptical echo shape are similar to those obtained from actual observations, because the higher probabilities caused by neglecting the adjacency and vertical correlation criteria are offset by the fact that irregularly shaped actual storms may have a greater chance than an ellipse of being detected. Unlike the elliptical echoes, the angle between the long and short dimension is not necessarily orthogonal.

Figure 5 illustrates the use of this method for the 20 July case. For example, using the base scan at 1920:34 UTC (microburst onset for this storm), the longest extent is 5.6 km (from a radar with the most favorable viewing angle) while a radar at the least favorable viewing angle would observe an extent of just 3.6 km. Assuming that these are the major and minor axes of an ellipse (a/b = 1.6), Fig. 2 reveals that there is only about a 30% probability of identifying the storm from this base scan. Allowing for the 5 min required for NEXRAD to complete a volume scan and process the data means that if the storm is identified, it will not be displayed to the user until about 1925 UTC, or nearly 2 min after the maximum outflow was observed.

Figure 6 shows the relationship between the long and short storm dimensions, lightning activity, and microburst outflows for the 20 July storm. The time history of the long dimension shows that this storm could not be identified until the 1920:34 UTC base scan (assuming that a 5 km segment length was needed for detection) or about 11 min after the first lightning flash occurred. The long dimension had a length of only 2.2 km at 1909:02 UTC, the base scan nearest in time to the first flash. To attain 100% probability of

20 July 1986

1909:02  1914:52  1920:34  1926:28  1932:37

To Radar

5 km

Fig. 5. Contours of 30 dBZ radar reflectivity for the 20 July 1986 storm. The long (dashed) and short (dotted) dimensions are shown along with the observed (arrows pointed toward CP2) extent. Time is UTC.
detection at 1909:02 UTC, the segment threshold would need to be reduced to the length of the short dimension (1.2 km). In addition, a short dimension of at least 5 km (or 100% probability of detection) occurred only at the time of peak microburst outflow (1923:48 UTC), when nearly 85% of the lightning produced by the storm had already occurred. Since the orientation of the long dimension axis was continuously changing (Fig. 5), it is likely the storm could be identified for at least some portion of its life cycle. This points out another identification liability: a storm initially in a favorable orientation could be "lost" as it moves and its orientation changes, resulting in the loss of important storm trend and tracking information.

Figure 7 shows the evolution of the long and short axis dimensions of the 19 July storm. Radar scans were available for most of the storm life cycle. This echo differs from that of 20 July in that the long dimension first attained a length of 5 km at the 2306:00 base scan, 5 min prior to the first lightning flash. At this time, based on the ratio of the long and short dimensions, there is about a 25% probability of identification. Again, even if the storm is identified from this scan, the user will not be notified until 2311 UTC, or about the time of the first lightning flash. The short dimension on 19 July never attained a length of 5 km so the storm was never 100% identifiable. Its maximum probability of detection of 40% occurred at the 2308:45 UTC scan. This storm produced a microburst beginning at 2314:48 UTC, when there was only a 38% probability of storm identification.

b. Kennedy Space Center storms

Two small storms that occurred over Kenendy Space Center (KSC), Florida have also been examined. Lightning was measured by an LDAR (lightning detection and ranging) system (Lhermitte and Krehbiel 1979). Complete life cycle dimensions were not available from these storms; however, they represent examples of storms that are producing lightning yet may not be identified given the NEXRAD 5 km default segment length. Figure 8 shows the 30 dBZ reflectivity contour of a storm observed on 8 August 1977 at 1818 UTC, with a C-band radar having a beamwidth of 1° and a gate spacing of 150 m. At this time the storm was producing about 1.4 lightning flashes per min (Lhermitte and Williams 1985). For this scan the long dimension was 6.8 km and the short dimension was only 3.6 km (a/b = 1.9), resulting in a probability of detection near 35% (Fig. 2).

The second KSC storm occurred on 11 July 1978 (Fig. 9) and was observed at 1925 UTC by a C-band radar with a beamwidth of 1° and a gate spacing of 300 m. Lightning flashes were occurring at a rate of 8 per minute at this time (Lhermitte and Williams 1986). The long and short dimensions were 7.2 and 4.2 km, respectively (a/b = 1.5), yielding a 50% probability of
identification. These two cases illustrate the important impact of storm orientation on NEXRAD storm identification, since both storms occurred in the same general location. Concerning the 11 July case, a NEXRAD radar at the Melbourne, Florida site would have seen the echo along its short dimension, and thus would not be able to identify the storm from this scan. However, the 8 August storm (Fig. 8) could have been identified from Melbourne, where NEXRAD would view the storm approximately across its long axis.

4. Summary and conclusions

We have shown that the current default thresholds for storm identification for NEXRAD are inadequate for identifying small, potentially hazardous thunderstorms. One solution might be to change the reflectivity and storm segment length thresholds. Although the algorithms will be modified and improved with time, a simple change of the segment length will affect the performance of other algorithms. Also, NEXRAD can only keep track of a limited number of storms, and displays only a fraction of these to the user. Thus, if a number of storms are in progress, smaller storms may be ignored. Since these storms can produce damaging winds and lightning, it is important to display and track them.

One of the drawbacks of the NEXRAD algorithms in identifying lightning producing storms is their dependence on the base scan. Lightning can occur before convective rainfall is heavy and extensive enough at low levels to produce reflectivity values sufficient to trigger identification (Goodman et al. 1988; Dye et al. 1989). This is particularly true of high base storms in dry environments where the reflectivity at the radar base scan can be much less than the reflectivity at cloud base due to evaporation of the falling precipitation (Rosenfeld and Mintz 1988). An algorithm that uses volume scan information without the base scan segment constraint would undoubtedly improve detection efficiency. Such algorithms have been developed by Crane (1979) and Rosenfeld (1987). The increased
complexity of these algorithms, however, increases the computational load needed to provide timely storm identification to the forecaster.

Studies of initial storm electrification (Larsen and Stansbury 1974; Marshall and Radhakant 1978; Chernia and Stansbury 1986; Goodman et al. 1988, Dye et al. 1989) suggest keying on the vertical growth of clouds and the enhancement of reflectivity at −10°C (the inferred height of the main negative charge region in the thunderstorm central dipole). Hence, an improved algorithm might simply identify storms by looking for areas of high reflectivity (40 dBZ) at the −10°C level, obtainable from a nearby sounding or climatology. Based on 20 storms, using the results of Dye et al. (1989) and the present cases (11 July 1978 was excluded due to insufficient data), such an algorithm would identify all (100% probability of detection or POD) lightning producing storms 4–33 min before the first flash with a false alarm rate (FAR) of 20% and a critical success index (CSI) of 80% (Donaldson et al. 1975). The FAR and CSI are improved to 7% and 93% (still 100% POD), respectively, by further constraining identification to storms whose echo tops exceed 9 km (15 cases). However, more cases are needed where both lightning and radar data are available to further refine an algorithm like this.

Although NEXRAD may not automatically identify all echoes, some of its products will be useful for small thunderstorm detection by forecasters. This can be done within the current framework of NEXRAD, for example, by looking for expanding regions of high reflectivity values (≈40 dBZ) (growing storms) near the −10°C level. However, this procedure is not automated. To prevent natural and triggered lightning strikes to the Space Shuttle, for example, various launch commit criteria have been developed to avoid launching when cloud echo heights exceed the 0, −10 and −20°C levels (NRC 1988), although a study is currently under way to see if these restrictions can be relaxed. Whatever the outcome, the current NEXRAD echo tops product would be useful to the forecasters who would determine if the launch constraints are violated.

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