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Three-dimensional storm motion detection by conventional weather radar

Knowledge of the kinematic structure of storms is important for understanding the internal physical processes. Radar has long provided information on the three-dimensional structure of storms from measurements of the radar reflectivity factor alone. Early users of radar gave total storm movement only, whereas later radar data were used to reveal internal motions based on information related to cloud physics such as the three-dimensional morphology of the storm volume. Such approaches have continued by using the increasingly finer scale details provided by more modern radar systems. Both Barge and Bergwall[2] and Browning and Foote[3] have used fine scale reflectivity structure to determine airflow in hailstorms. Doppler radar added a new dimension to our capabilities through its ability to measure directly the radial component of motion of an ensemble of hydrometeor particles. Two[4] or three[5] Doppler radars collecting data in conjunction, the equation of mass continuity, and an empirical radar reflectivity–terminal velocity relationship have enabled the estimation of the full three-dimensional airflow fields in parts of storms. Because of the inherent advantage of Doppler radar in motion detection, little effort has been directed toward developing objective schemes of determining internal storm motions with conventional meteorological radars. Pattern recognition schemes using correlation coefficient techniques[6], Fourier analysis[7], and gaussian curve fitting[8] have been used with radar and satellite data, but primarily for detecting overall storm motions, echo merging and echo splitting. Here we describe an objective use of radar reflectivity factor data from a single conventional weather radar to give information related to the three-dimensional motions within a storm.

The basic technique uses the correlation coefficient approach for pattern recognition. An initial array of radar reflectivities is correlated with later arrays. By locating the second array with the best correlation, a motion vector for the initial array is determined. This objective tracking of radar echo with correlations (TREC) is done by computer.

Consider, for example, the storm depicted in Fig. 1. The storm is scanned in azimuth by a radar located at P with measurements of storm intensity made at range rates along each given radial (azimuth ray). Consider an array of radar reflectivity factors n range gates long and n azimuth rays across at time t_1, lying on a conical surface. Some time later (t_2) we can compare our initial array of reflectivities with a second array located on the same surface, and calculate a correlation coefficient. We then shift this second array and repeat the calculation. This procedure continues until all possible second arrays have been searched over a specified area, the size of which is based on the known storm velocity, rawinsonde wind data or some other criterion. An arrow is then drawn from the centre of the initial array to the centre of the best correlated second array, provided the radar reflectivity factor at each centre location exceeds a preselected reflectivity. In our case we require a reflectivity of $10 (zdB_z \equiv 10 \log z\ (\mathrm{mm^6\ m^{-3}}))$. Motion vectors at other locations are determined by systematically examining initial arrays throughout the storm and repeating this entire correlation procedure for each.

Figure 2 shows the results of this procedure applied to a hailstorm observed near Grover, Colorado, on 22 June 1976 by the S-band, narrow-beam radar of the National Hail Research Experiment. Data were collected starting at 1625 MDT for the initial arrays and 1627 MDT for the second arrays, both at an elevation angle of 3.3°. Because of known storm motions on this day (average cell speed of $14\ \mathrm{m\ s^{-1}}$), the search area was restricted to ±5 gates and ±5 rays from the initial position. Five rays may be too few near the radar and too many far from the radar, so in the future a specified size (in kilometres) of the search area is planned. Initial arrays were 15 gates long by 15 rays across and are spaced 5 gates and 5 rays apart. Thus, adjacent points in Fig. 2 have a 2/3 overlap with immediate neighbours, 1/3

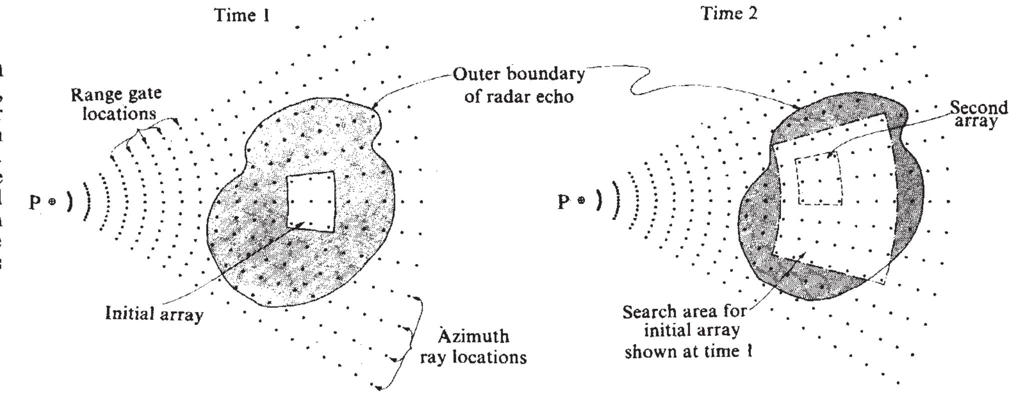


Fig. 1 Representation of a storm scanned by a radar located at P, where a measurement of radar reflectivity factor is made at each range gate/azimuth ray location. The initial n by n array at time 1 (where $n=3$ here) is compared with all n by n second arrays in the search area at time 2, where one of these second arrays is depicted.

overlap with their second nearest neighbours, and are completely independent of their third nearest neighbours. Figure 3 shows the flow field 2 min later. While there are some differences, the general features are quite consistent from one time to the next. Similar continuity is evident when looking at the patterns from one tilt angle to the next.

Several points can be made about the results in Figs 2 and 3. First, the procedure detects tangential motions as easily as radial. This should be true in the vertical as well as the horizontal. Second, the total area covered is fairly large, approximately five times that of the triple-Doppler system collecting data on the same storm at the same time. Third, the procedure can sometimes give vectors which are inconsistent. An example of this is the pair of crossing arrows in Fig. 2, 50 km east and 28 km north of the radar. Erroneous vectors might be eliminated by using the rate of change of available reflectivity information, by requiring that the correlation coefficients exceed some value, or by some other optimisation procedure which can be applied to TREC.

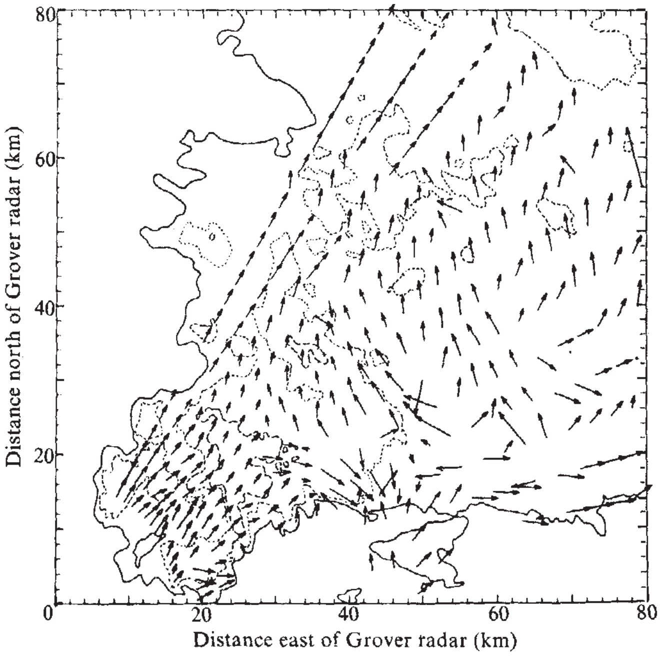


Fig. 2 Reflectivity motion field for data collected on 22 June 1976 at 1625 MDT and 1627 MDT at an antenna elevation angle 3.3° above the horizon. Dots indicate that the initial and final arrays were best correlated at the same locations. Superimposed are the 15, 35 and 55 dB_z radar reflectivity contours for the 1625 MDT data.

Tracking reflectivity patterns may not give the same information as the direct measurement of airflow. A triple-Doppler radar system does yield airflow and can be compared with the results of TREC. Such a system, operated jointly by NCAR and the Wave Propagation Laboratory of the National Oceanic and Atmospheric Administration, was collecting data on the same storm system. None of the three Doppler radars used was located at the Grover radar site. Also, the output of the triple-Doppler processing is on horizontal (or vertical) planes while TREC processing is on constant tilt conical surfaces. As the elevation steps used by the Grover radar were quite large on this day, conical surfaces were reconstructed from the Doppler data, rather than by attempting to construct constant altitude surfaces from the Grover radar data.

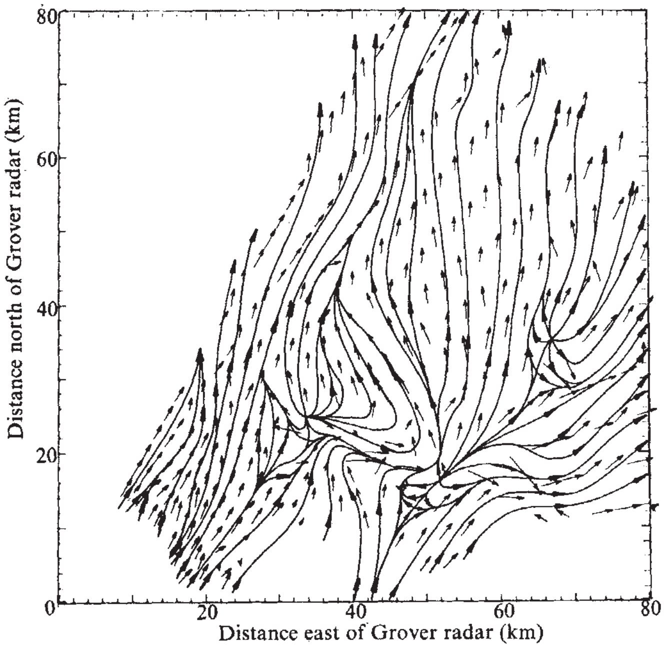


Fig. 3 Reflectivity motion field for data collected on 22 June 1976 at 1627 MDT and 1629 MDT also at 3.3° elevation angle. A subjective streamline analysis is superimposed.

Figure 4 is a reconstructed conical surface at 3.3° tilt centred at the Grover radar. Data for this Doppler analysis were collected from 1625 to 1629 MDT and were obtained from six constant altitude surfaces at 0.5 km height intervals. For clarity, only every third vector from the Doppler data is shown, although the subjective streamline analysis uses all the data.

A comparison of the streamline analyses in Figs 3 and 4 shows reasonable agreement in some locations and considerable difference in others. The agreement at the southwest edge of the storm is quite good in both direction and speed. Large differences exist in regions of rapid change. The main source of difference is caused by the velocity-measuring schemes. Doppler analysis gives instantaneous air motion while TREC determines reflectivity pattern motion. The reflectivity patterns being tracked will often be precipitation generated at a higher altitude. Thus, the pattern may move with the speed and direction of the generating region rather than the velocity appropriate to the area being examined. Figures 3 and 4 show another difference caused by the velocity-measuring schemes. During the two minutes between data scans used in the TREC analysis the whole storm was moving north-northeastwards at approximately 20 m s^{-1}, accounting for some difference in position of the streamline patterns. One of the areas of investigation using the TREC technique is to study the causes and information content of the differences between motion fields detected by the triple-Doppler radar system and TREC. Harris *et al.*[10] give further Doppler analyses from this time period in the 22 June 1976 case which may be compared to the results presented here.

The method clearly may be generalised so that the search for an optimum correlation can be made in three dimensions, utilising data points obtained at a range of tilt angles. Using data from volume scans at different times, vertical velocities might be determined, and data from a single volume scan of the radar where data at adjacent tilt angles are collected nearly simultaneously, enables a streamline pattern to be constructed which would show the slope of the storm at each point.

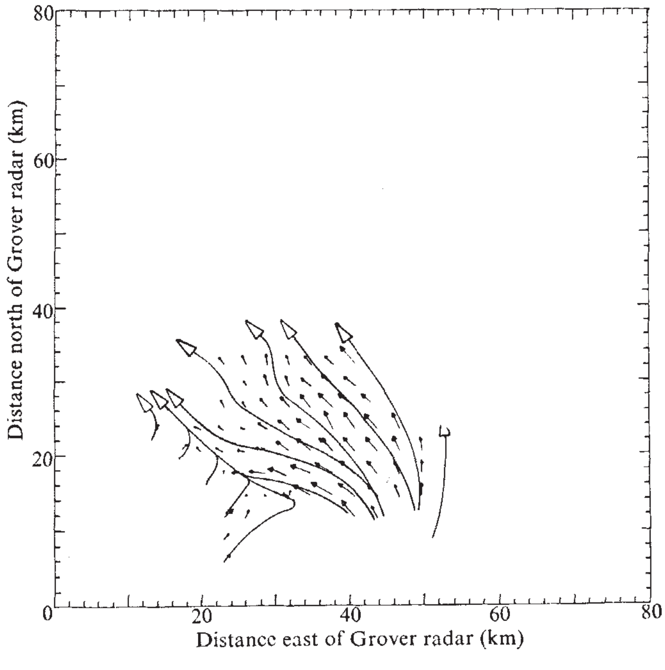
The procedure outlined above has several possibilities. A first area of development is to optimise the procedure for the phenomena being studied. The 15 by 15 arrays now used are probably not optimal for convective storms. But when the array size is specified in kilometres it will allow various scales of motion to be determined more easily.

A second area of development is to determine vertical motions. We intend to continue using the r, θ, φ coordinate system as far into the processing as possible, waiting until after the full motion field has been determined before transforming to x, y, z coordinates. While we could first interpolate reflectivities into Cartesian coordinates and then try to follow the patterns, we feel that the reflectivity patterns are better conserved in the natural radar coordinate system; attempting to follow these patterns in an x, y, z system would increase the error rate unnecessarily. Additionally, the equation of mass continuity and $V_t - Z$ relationships can be used for this scheme just as they are in dual- and triple-Doppler processing. TREC's ability to measure vertical motions depends upon trackable reflectivity features being present in the storm. For a true steady-state storm, TREC would not be able to detect any motion. In supercells[3], inhomogeneities in reflectivity exist which should provide trackable features most of the time. The extent to which TREC can provide vertical velocity measurements will be investigated in the future.

There may be more efficient means of pattern recognition that can be incorporated into the tracking procedure. The simple correlation coefficient procedure seems to work but it does require numerous calculations, thus adding to the expense.

In conclusion, TREC is an objective technique for obtaining quantitative and qualitative information on the three-dimensional motion fields within storms. Arrays of radar reflectivity factor data are correlated from one time or elevation to another. TREC follows reflectivity patterns rather than airflow and these patterns may be moving with the velocities of the generating regions rather than the velocities of the regions being observed. Thus these results should be interpreted with caution. Nevertheless, this technique seems capable of yielding much more information about internal kinematic structure than has previously been obtained with a single conventional weather radar.

Fig. 4 Air motion field for data collected on 22 June 1976 at 1625 MDT to 1629 MDT by a triple-Doppler radar network. The original Doppler data at 0.5-km intervals were reconstructed into a 3.3° tilt conical surface centred at the Grover radar. A subjective streamline analysis is superimposed.



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Global fallout of curium

THE search for ^{242m}Am ($t_{1/2}$=152 yr) in environmental samples has involved detection of its daughter ^{242}Cm ($t_{1/2}$=163 d) (refs 1–3). These samples were contaminated by transuranium nuclides either from a nuclear fuel reprocessing plant or from a thermonuclear test fallout. A logical consequence was then to analyse global fallout-contaminated samples for ^{242}Cm and ^{244}Cm to establish the present distribution and global contamination of our environment by these transuranium elements. We have chosen the lichen *Cladonia alpestris*, which is an excellent bio-indicator for atmospheric fallout and we present the results here. The samples have been stored in the laboratory for 5–16 yr. Thus, ^{242m}Am and ^{242}Cm were in sequelar radioactive equilibrium. The ^{242}Cm present in the aged samples therefore represents the ^{242m}Am present in the fallout. The results indicate a ^{242m}Am/$^{239+240}$Pu activity ratio of about 0.003% in global fallout.

In nuclear power reactors the production of transuranium elements with mass number exceeding 240 can be very substantial. The total activity of ^{241}Am, ^{242}Cm and ^{244}Cm will be a hundred- to a thousandfold greater than that of ^{239}Pu. The highest activity is produced by ^{242}Cm and the activity ratio of ^{242m}Am/^{242}Cm in waste from nuclear fuel reprocessing is less than 1% (refs 4,5). Thus, it is very difficult to record the activity of ^{242}Cm supported by ^{242m}Am in samples contaminated by discharges from nuclear fuel reprocessing plants.

In nuclear explosions the transuranium nuclides with mass number exceeding 240 are produced in multiple neuron-capture by ^{238}U. The most prominent activity is ^{241}Pu, which decays to ^{241}Am, but small activities of ^{242m}Am ($t_{1/2}$,152 yr) and ^{242}Am ($t_{1/2}$,16 h) can also be produced, of which the latter decays rapidly to ^{242}Cm. A transient equilibrium between ^{242}Cm and ^{242m}Am is reached after 3.0 yr. Attempts have been made to show the presence of ^{242m}Am in 12 yr old samples contaminated by fallout by measuring the ^{242}Cm activity[3]. Observations indicate a ^{242}Cm/$^{239+240}$Pu activity ratio of 0.1%, and in one sample a ^{244}Cm/$^{239+240}$Pu activity ratio of 0.005% is derived. However, Beasley[1] investigated sediment samples from Bravo Crater in the Bikini Lagoon