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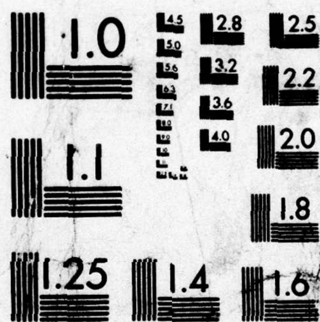

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ANALYSIS OF AN ASYMMETRIC DOPPLER VELOCITY PATTERN

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1. A PUZZLING PATTERN

Following the development and installation of a Pulse Pair Processor (Novick and Glover, 1975) and a color display (Jagodnik et al., 1975) for analysis and presentation of Doppler spectral moments, we have routinely acquired velocity patterns in all available storms, using the 5.5-cm Porcupine Doppler radar. The usual procedure for taking data requires the antenna to scan in azimuth at a constant elevation angle. After each complete rotation, the antenna elevation is stepped up to a new value. The elevation increments are generally 1°, commensurate with the antenna half-power beamwidth of 0.9°, but often larger increments are used above an elevation of 10°. The output of the Pulse Pair Processor, containing information on reflectivity, velocity mean, and velocity variance in each resolution cell, is recorded on tape for subsequent analysis and is presented in real time on the color display in PPI-format. The color display of data taken at any elevation angle above 0° is not, strictly speaking, a plan view of the storm. It is, instead, a conical surface with apex at the radar, slicing across the storm at heights defined by range and elevation angle.

The summer of 1975 in eastern Massachusetts was notable for its scarcity of severe thunderstorms and for occasional intrusions of widespread, winter-type precipitation. A small coastal northeaster, a weak cousin of the producers of heavy winter-time snow along the Atlantic seaboard, visited our area briefly during the morning of August 7. Precipitation was light, with an average rate of only 0.6 mm/hr, but was sufficient to provide detectable tracers of velocity for our Doppler radar. The storm was scanned in 1°-increments of elevation angle from 1° to 10°.

A photograph of the velocity pattern at elevation 8°, displayed in color, is reproduced as Figure D of the color plate in the preceding paper by Kraus and Donaldson. As in the other figures of this plate, the colors represent contours of velocity, in accordance with the scale on the right of the photograph, ranging from +22 m/s away from the radar (red), down through yellows and greens to black (± 1.3 m/s) and on to negative velocities, toward the radar, represented in succession by white, ever-deeper shades of blue, and finally purple indicating velocities up to -22 m/s. The narrow black band separating advancing and receding velocities not only eliminates the stationary ground clutter, but also serves as an indicator of locations where motions within the storm are normal to the radar beam. The two range rings are located at 16 and 32 km.

The puzzling feature of Figure D, and its neighbors at nearby elevation angles, is the asymmetry of the color patterns. Maximum positive and negative velocities are sensed by the Doppler radar when its antenna beam is pointing downwind and upwind. In a horizontally homogeneous wind field, archetypical of widespread stratiform storms, we would expect Doppler-sensed velocities to decrease uniformly on either side of a maximum, in accordance with the cosine of the directional change of the beam from the velocity maximum. Curiously, though, Figure D shows a concentration of velocity contours near each peak, but each has a long tail trailing clockwise. The pattern resembles the Yin-Yang symbol of Chinese cosmology, or, in a less traditional orientation, two tadpoles chasing one another in a circle.

2. SOLUTION OF THE PUZZLE BY FOURIER ANALYSIS

No rawinsonde winds were available on August 7, 1975 for comparison with the Yin-Yang Doppler velocity pattern. Consequently, we generated a wind field from the recorded velocity data, using the precipitation as tracers and following the scheme for Fourier analysis of harmonics developed by Browning and Wexler (1968). Our aim was not only to derive a vertical profile of average wind, but also to gain some knowledge of the uniformity of the wind at each height. At the time of this writing, the harmonic analysis is confined to a quasi-cylindrical section through the storm with a radius of 8.325 km around the radar. This section extends up to a height of 1.45 km, using integral values of elevation angle from 1° to 10°.

Browning and Wexler suggested that the Fourier coefficients of order 0, 1, and 2, which give the horizontal wind field properties of divergence, mean wind velocity, and deformation, respectively, may be computed with sufficient accuracy by summations of Doppler velocities at 10° intervals of azimuth. Accordingly, we sampled the velocities at 36 equally-spaced azimuths around the scanning circle, for each of the eight elevation angles from 2° through 9°. At elevations 1° and 10° we could obtain data at only 30° azimuth intervals, owing to a data gap at elevation 10° and several places at 1° where ground clutter strongly contaminated the precipitation echo. At these two extremes of the elevation angles we computed only the mean wind vector, because we felt that a 30° azimuth spacing was much too coarse for meaningful estimates of divergence and deformation. We will not lay out the computational details here; the reader who may be interested in performing harmonic analyses of Doppler velocities will find all the instructions he needs in the treatise of Browning and Wexler.

Estimates of divergence using Doppler velocities acquired at elevation angles above 0° are contaminated by a small component of precipitation fall speed moving toward the radar. We did not measure the vertical speed of the raindrops, but on the basis of the rain rate (0.6 mm/hr) we estimated a minimum value of 3 m/s for fall speed. Since all divergence values were negative by an amount greater than the fall speed contamination, we feel we have made maximum estimates of convergence. Although this procedure lacks the rigor requisite for a dynamic analysis of the wind field, we feel it is more than sufficient for our purpose in assessing the uniformity of the wind.

Results of the wind field analysis are listed in Table I, and wind vectors are plotted in hodograph form in Fig. 1. We now have the answer to two questions: What is the vertical profile of mean wind, and how homogeneous is it at any given height?

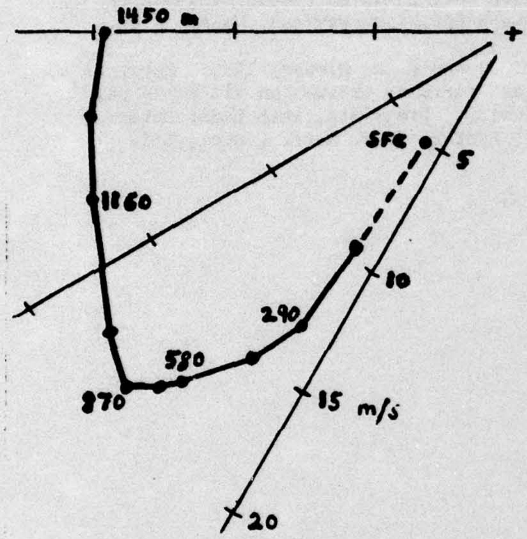

Fig. 1. Hodograph representation of wind field of 7 August 1975 computed by Fourier analysis of Doppler velocity components. Numbers adjacent to every other dot show heights in meters above ground level. The surface datum was recorded by anemometer.

Considering the second question first, we see that values of divergence and deformation are in the vicinity of 10^{-5} to 10^{-4} s^{-1}, typical of widespread precipitation occurring in synoptic-scale disturbances, and at least two orders of magnitude less than shear values associated with severe thunderstorms. The average value of deformation, multiplied by the radius of the area for which it was computed, is only 7.4% of the average wind speed. For divergence, the comparable value is only 3.6% of average wind speed. We are, therefore, satisfied that we have a wind field which is rather close to a condition of horizontal homogeneity. For the purpose of explaining the arresting features of the color display, we need consider only the vertical profile of mean wind.

The wind speed increased from 5 m/s at the surface (measured by anemometer) up to a maximum of 18.8 m/s at the 870 m level. The direction of the wind was nearly constant from slightly north of northeast over the lowest 290 m. From that level

Table I
Wind Field Properties of 7 August 1975 Storm
Computed by Fourier Analysis

Elevation Angle	Hgt. (m)	Wind Speed (m/s)	Direction From	Divergence (10^{-5} s^{-1})	Deformation (10^{-5} s^{-1})
1°	145	9.5	36°	--	--
2°	290	12.9	35.7°	- 4.4	2.8
3°	435	14.9	38.5°	- 4.4	12.2
4°	580	17.1	43.3°	-11.1	16.3
5°	725	17.9	44.6°	-15.3	12.4
6°	870	18.8	47.8°	- 4.9	17.7
7°	1015	18.0	53.4°	- 8.9	21.0
8°	1160	16.2	68.3°	- 4.8	17.8
9°	1300	15.4	78.8°	- 3.6	17.0
10°	1450	14.6	90°	--	--

up to the speed maximum at 870 m, the wind veered about 12°, averaging a direction change of 2.1°/100 m. Above the speed maximum the wind veered much more sharply, at a rate of 7.3°/100 m, until at 1450 m it was blowing directly from the east. At higher altitudes the wind eventually became westerly, indicated by the green (outbound) patch in Fig. D toward the east between the 16 and 32 km range rings. Examination of the recorded velocities directly east of the radar at elevation angles 7° through 10° showed velocities changing from inbound to outbound at a height of 2.7 to 2.8 km. This altitude caps the easterly regime and is the base of the overlying westerlies.

We now have all the information we need to decipher the kinematics, if not the cosmology, revealed in the color display of velocities. At any elevation angle α where the radar can locate targets *above the windspeed maximum, there will be a locus*, or spine, of maximum velocities in both the outbound and inbound halves of the picture. The absolute maximum, or if you will, the peak of the spine, occurs at a particular range, r_m, where $r_m \sin \alpha = 870$ m, and at azimuth angles toward the northeast (inbound) or northwest (outbound), which are directions where the radar beam lies along the peak wind. Clockwise from the peaks, the radar encounters winds which are moving along the same azimuth as the beam at a greater height (as indicated in Fig. 1) and hence at a greater range. Since wind speeds are decreasing slightly in this altitude interval, the indicated maximum will be at a compromise range (height) somewhere between the wind direction at that height and the somewhat greater speeds found at a lower height. The spine of maximum velocities consequently spirals outward, toward higher ranges, with increasing azimuthal distance clockwise from the absolute peak velocity.

On the other side, i.e., counter-clockwise from the absolute peak velocity, the same general structure is found but in a strikingly asymmetrical manner. In this region the radar beam is directed along winds at heights below the absolute velocity peak, so the velocity spine tends to continue its inward spiral with counterclockwise direction. However, the wind field is radically different here: with a small decrease of azimuth the height of maximum wind in that direction and its maximum speed both decrease precipitously. Accordingly, the velocity contours in this region are crowded.

In sum, our two tadpoles have tails because the wind profile has a marked asymmetry on either side of its speed maximum. On the "tail" side the speed shear is small but the directional shear is large. Note, however, that the tadpoles are not aligned in a circle, which would be out of character with a horizontally homogeneous wind field. Rather, they are spiralling inward. Note also that at any given range the measured velocity components are symmetric with respect to azimuth angle on either side of a velocity maximum. This condition is required by a uniform wind field at any height.

3. COLLATERAL ANALYSES

Contemplation of the asymmetries in the Yin-Yang velocity pattern played a part in inspiration of the Kraus and Donaldson (1976) work on generation of velocity patterns from model wind fields. Figure 6 in that study, showing the velocity pattern associated with veering wind direction and speed increasing up to a maximum and then decreasing above it, comes closest to a depiction of our Fig. D. However, our pattern is much less symmetric because of the strikingly different character of our wind field above and below the speed maximum.

Novick (1976) was also intrigued by the novel appearance of our velocity pattern. He focussed his concern on the nature of the S-shaped zero velocity line, which appears as a black band separating the inbound and outbound colors in Fig. D. He derived an analytical solution for the equation of this line, under the assumption of constant wind speed and a linear change in wind direction with height. He found that the zero-velocity curve can be expressed simply as a spiral with distance from the origin linearly proportional to azimuth angle. This is certainly very similar to the picture we see at heights above the speed maximum, where our computed wind speed decreased by only 22% while the wind direction veered 42°.

In the course of our study another thought occurred to us. A complex pattern of velocity may be interesting not only for what it may reveal, but also for what it may conceal. In a situation amenable to Fourier analysis of the Doppler velocities, or one where environmental winds are available from another source, we could, in principle, generate a display which would present the observed Doppler velocities minus the horizontally uniform wind components along the radar beam. Whatever remains on display after such treatment would be solely a function of anomalous winds indicative of distortions such as vortices, jets, waves, reactions to obstacles, and the like. These anomalies, having special value for severe storm forecasting, would stand out in isolation once the masking uniformities are removed.

4. ACKNOWLEDGEMENTS

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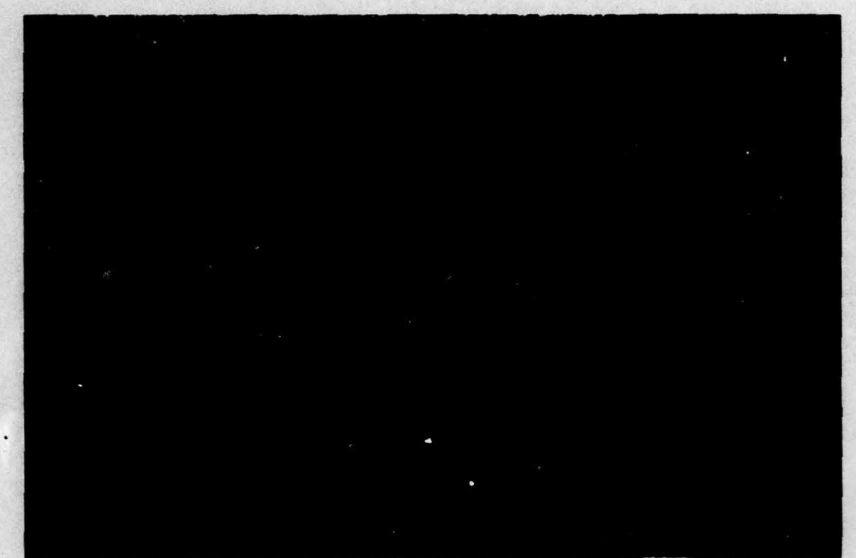

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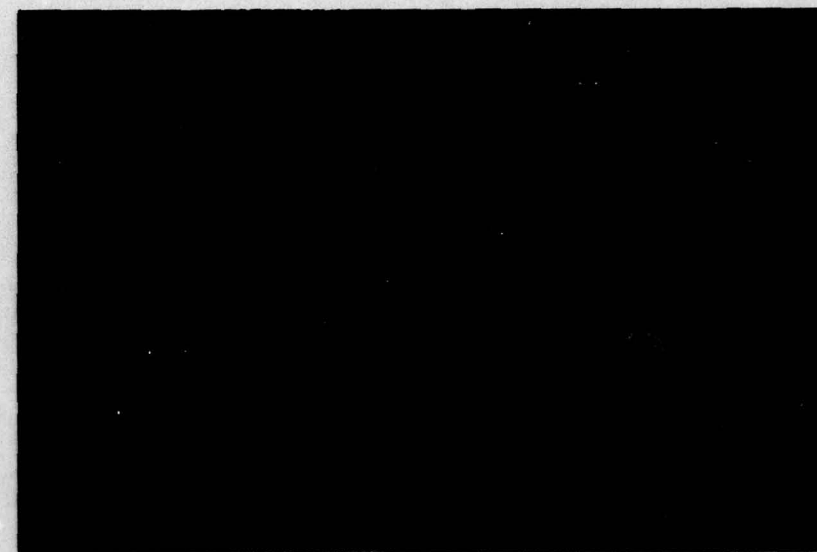

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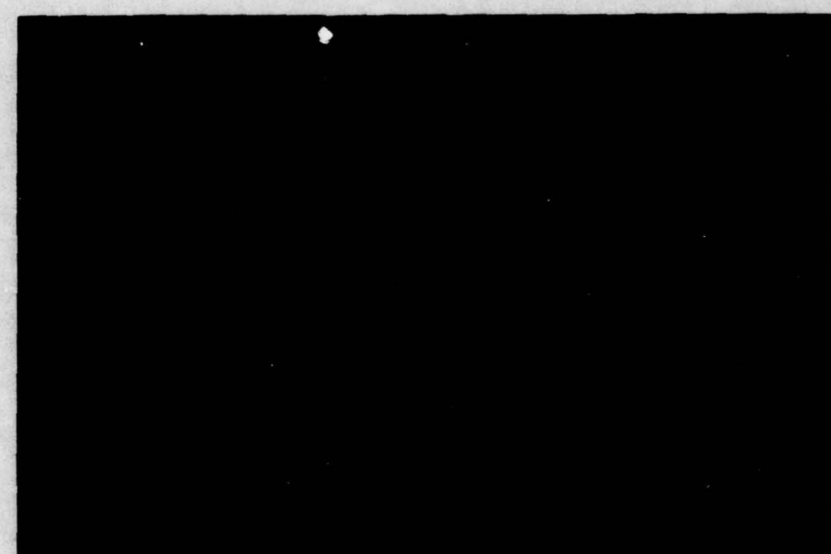

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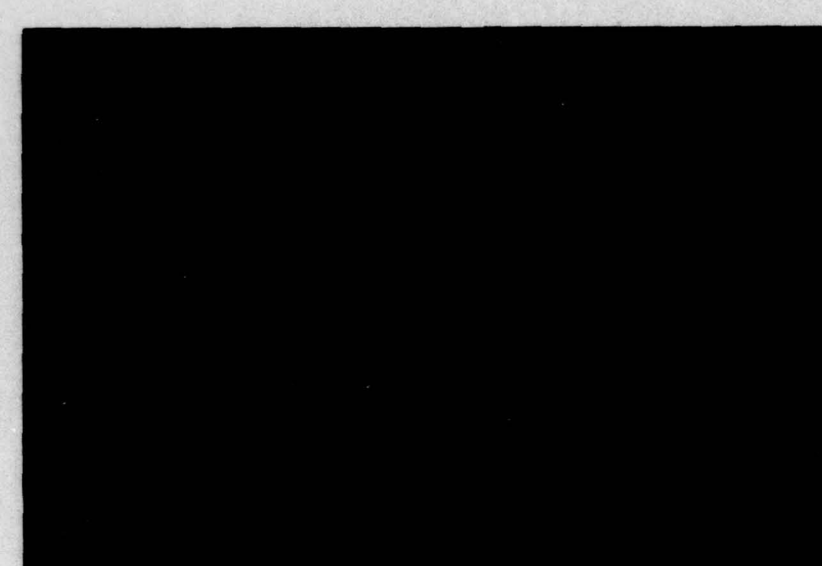

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13. ABSTRACT

Plan-view velocity contours of storms are routinely obtained on the color display of the AFGL Porcupine Doppler radar as its antenna rotates in azimuth with a fixed elevation angle. After each azimuth scan the elevation angle is stepped to a new value and a refreshed velocity pattern is displayed. In a widespread stratiform storm the elevated contours of Doppler velocity were remarkably asymmetric, producing a pattern strikingly similar to a Yin-Yang symbol. Fourier analysis of the variation with azimuth of the recorded velocities, however, revealed azimuthal symmetry of velocity components at any given range and elevation angle, indicating at each height an essentially homogeneous wind field which veered appreciably with increasing altitude and displayed a speed maximum well below the top of the precipitation. There were also a number of minor small-scale perturbations superimposed on the major wind field.

KEYWORDS: Doppler radar-radial velocity, Pattern, Pulse pair processor, Color display, Wind field