Velocity Characteristics of Some Clear-Air Dot Angels

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ABSTRACT
The nature of the targets responsible for certain clear-air dot angel echoes, and their suitability as wind tracers, are deduced from pulse Doppler radar observations of their velocity characteristics. The angel echoes were observed during a six-hour period in the lowest few thousand feet of the atmosphere. They were all discrete point targets and probably had discrete Doppler velocities as well (i.e., they were coherent). The angel populations showed well-defined swarm velocities with superimposed random deviations. Three types of dot angels were distinguished according to their mean deviation from the swarm velocity and their average vertical motion. Type 1, in the early afternoon, showed mean velocity deviations of 1-15 m sec\(^{-1}\) and average downward motions of up to 4.5 m sec\(^{-1}\). Type 2, in the late afternoon, showed mean deviations of less than 1 m sec\(^{-1}\) and average downward motions of less than 1.8 m sec\(^{-1}\). Type 3, after sunset, showed mean deviations of 1-4 m sec\(^{-1}\) and average vertical motions that were mainly upward at up to 3.7 m sec\(^{-1}\). The small back-scattering cross sections of individual angels (<10\(^{-4}\) cm\(^2\)), their discreteness in space and velocity, their often quite large mean deviations from a uniform velocity, and the fact that the only major upward velocities occurred after sunset, at a time when the lapse rate was becoming increasingly stable, all suggest insects rather than atmospheric inhomogeneities as the source of the angels. The Type 1 angels had mean swarm velocities differing from the wind by less than 2 m sec\(^{-1}\); Type 2 probably differed by even less than this and are judged to have been good tracers of the wind. The Type 3 angels, on the other hand, had swarm velocities of up to 5 m sec\(^{-1}\) relative to Type 2 and hence to the wind as well, and thus they were poor tracers of the wind.

1. Introduction
Dot or point angels may be defined as radar echoes associated with visually undetected targets whose size is small compared with the resolution of the radar. Some dot angels are thought to be due to special configurations of atmospheric refractive index gradients (Atlas, 1965a) while others are thought to be due to birds and insects [see Geotis (1964), for example]. One way of deciding which of these explanations is the more likely is to study the dependence of the angle cross sections upon radar wavelength (Geotis, 1964; Hardy et al., 1966), another is to study their persistence and trackability (Hardy et al., 1966), and a third is to study their velocity characteristics (Battan 1963; Chernikov 1966).

The purpose of the present paper is to analyze the velocity characteristics of some clear-air dot angels as determined using a simple Doppler radar technique. In addition to inferring the probable nature of the dot angels, an attempt is made to assess the accuracy with which populations of dot angels can serve as wind tracers.

At the very outset, the writers would like to acknowledge that the direct impetus for this study were the similar observations of Dr. R. M. Lhermitte made in Oklahoma who furnished them before publication (Lhermitte, 1966).

2. Observational technique
The radar used in this study was a 5.42-cm pulse Doppler (called Porcupine) having a pulse repetition frequency (PRF) of 3300 cps and a conical beam 1° between half power points. For these observations it was operated at a peak power of 20 kW with a pulse length of 2 μsec.

The Velocity Azimuth Display (VAD) technique of Lhermitte and Atlas (1961) was used, in which the radar beam is elevated at a fixed angle α (30° in this case) and rotated continuously in azimuth. The phase-detected bipolar video was range gated (with a 0.5-μsec gate) at a succession of ranges corresponding to heights of interest, and was fed into an audio frequency analyzer (Rayspan Model 30-2). This analyzer has 420 filters each with a bandwidth B of 32 cps. The radial velocity of targets detected by the radar is related to Doppler frequency shift f\(\nu\) by the well-known relation \(f = 2V_c/\lambda\), where \(\lambda\) is the radar wavelength. The bandwidth thus corresponds to a velocity resolution of 0.9 m sec\(^{-1}\). As discussed shortly, however, most velocity determinations are based upon the velocities of large populations of targets and they can thus be made with much greater precision than this.

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Private communication reported by Atlas (1965b).
The frequency analyzer is capable of providing a Doppler frequency (or velocity) spectrum within the build-up time \((1/B)\) of a single filter, i.e., within 0.03 sec. The output of the entire filter bank was scanned by a commutator at a rate of 30 sec\(^{-1}\) while the antenna was rotated at 4 rpm, thus providing a spectrum readout every 0.8°, i.e., 1.2 readouts per beam width. A synchronizing signal was generated after each revolution of the commutator and this permitted the horizontal displacement of the spot on an oscilloscope display to be made directly proportional to Doppler frequency or velocity. The vertical displacement of the spot was determined by a signal directly proportional to azimuth. The filter output was then used to intensify the scope at the velocity \(x\)-azimuth \(y\) position being sampled at any given moment. The resulting Velocity Azimuth Displays were then photographed. In this paper all figures based upon the VADs are depicted with velocity as ordinate.

Series of VAD photographs were obtained with the range gate located at a succession of ranges (see Figs. 3, 4, and 5). The closest permissible slant range \(R\) was 2000 ft, corresponding to the 4-μsec recovery time of the receiver (even after this the receiver was not quite at full sensitivity); with the elevation angle \(\alpha\) at 30° this was equivalent to a minimum altitude of 1000 ft. Other VADs were obtained at successive 500-ft altitude intervals up to the highest level of detectable echoes. At times when echoes were sparse, multiple-exposure photographs were taken while the beam was permitted to make repeated revolutions.

3. Analytical technique

The interpretation of VADs has been discussed in detail by Atlas (1964). It is repeated here briefly in a form appropriate to the present data. Fig. 1 shows the geometry of the VAD scan, with the radar at O viewing a target at some instant at B along an azimuth \(\beta\). If the target is traveling with a vertical velocity component \(V_f\) (positive downward) and a horizontal velocity component \(V_h\) from a direction \(\theta\), then the radial component of velocity \(V_r\) sensed by the radar is given by

\[
V_r = V_f \sin \alpha + V_h \cos \alpha \cos (\theta - \beta).
\]

In the event that the entire scanning circle is filled with targets with a horizontally uniform field of velocities, the VAD will show a sine curve as depicted by the heavy curve in Fig. 2. The direction of travel \(\theta\) of the targets is then given by the phase of the sine curve, and the velocity components \(V_h\) and \(V_f\) of the targets are given by

\[
V_h = (V_1 - V_2)/2 \cos \alpha,
\]

\[
V_f = (V_1 + V_2)/2 \sin \alpha,
\]

where \(V_1, V_2\) are the magnitudes of the maximum and minimum of the sine curve.

VAD techniques have been used to obtain fairly reliable wind soundings within widespread or so-called stratiform precipitation (Lhermitte and Atlas, 1961; Boucher et al., 1965). This is possible because of the absence of major horizontal inhomogeneities in the wind fields accompanying widespread precipitation and also, of course, because precipitation elements are good tracers of the horizontal wind. In the present paper, however, a study is made of the VAD patterns obtained when the sky was clear and the only echoes were discrete dot angels. As will be shown, the individual angels often had significant velocities relative to the mean wind. Consequently, the VAD patterns were not perfect sine curves, and so it has been necessary to match best-fit sine curves in order to estimate the parameters \(\theta, V_1\) and \(V_2\).

Although the best-fitting sine curve was always determined without regard to its vertical location in the velocity azimuth display, all further measurements were made with the sine curve centered at \(V_r = 0\) (see the lighter sine curve in Fig. 2). Departures of the velocity of individual dot angels from this curve are denoted by \(\tilde{V}_r\) (see Fig. 2 for clarification); of course \(\tilde{V}_r = V_f \sin \alpha\).
(see footnote)\(^4\). Non-zero values of \((V'_r - \overline{V}_r)\) may be attributed either to inhomogeneities in the wind field due to wind shear and turbulence or to the velocity of the angels themselves relative to the wind.

One of the best parameters for characterizing the entire spectrum of angel velocities at any time is found to be the mean deviation of their velocity departures, given by

\[
\overline{\Delta V'_r} = \frac{\sum |V_{r}' - \overline{V}_r'|}{n}. \quad (4)
\]

\(^4\) Because the angels did not always follow the wind, a significant part of \(\overline{V}_r\) might be due to horizontal convergence of the angels as well as to their vertical motion \(V_r\); in this paper, however, \(\overline{V}_r\) will be interpreted in terms of an effective vertical velocity derived on the assumption that the horizontal convergence is negligible.

Another useful parameter is the maximum velocity departure among the angel population, and is taken as

\[
V_{r_{\text{max}}'} = \frac{(V_{r_{\text{max}}} - V_{r_{\text{min}}})}{2}, \quad (5)
\]

where \(V_{r_{\text{max}}}\) is the largest positive departure and \(V_{r_{\text{min}}}\) is the largest negative departure.

4. The data

The data were collected at Bedford between 1300 and 2000 EST on 27 September 1965. At the time, New England was having a light to moderate northerly flow at low levels ahead of an eastward-moving anticyclone. Temperature soundings showed that the lower atmos-
phere was stable during the entire period. The air was dry with surface dew points a few degrees Celsius below zero and clear skies throughout. Daytime surface temperatures in the Bedford area were somewhat above 10°C, dropping to close to 0°C by the end of the night, with surface winds diminishing to calm.

Series of VAD soundings were obtained at 500-ft altitude intervals about half to one hour apart, with a total of ten such series in all. Photographs of the raw VAD patterns for three of these series are displayed in Column a of Figs. 3, 4 and 5. Although the character of the angles changed during the day, it appears that they all were due to discrete targets, each signal being displayed over an azimuth range equal to one or two half-power beam widths (depending on the amount of bloom on the oscilloscope display) and over a velocity range equal to 1–6 m sec\(^{-1}\) (depending on the backscattering cross section of the target—see Section 5).

The radar was operated at short ranges and hence strong ground clutter echoes were detected by the beam side lobes even though the main lobe was directed 30° above the ground. Since, however, the ground echoes were always centered around the zero of velocity (as shown by the echoes along the axes in Figs. 3, 4 and 5), Doppler spectral analysis permitted separation of the moving targets from the ground clutter except where the radial components of the former were quite small.

Individual angel echoes could not always be resolved from their neighbors; however, as far as possible, the midpoint of each angel echo has been plotted in column b of Figs. 3, 4 and 5, together with the best-fit sine curve. The best fitting amplitude was chosen by eye; it turned out to minimize the mean deviation \(\Delta v'_r\) rather than the standard deviation \(\bar{v}'_r\), since the latter gave undue weight to a few very large deviations. There was found to be no difficulty in estimating the best fit to the nearest 1 m sec\(^{-1}\), sometimes even to the nearest 0.5 m sec\(^{-1}\). As mentioned earlier, although the best fitting sine curve was determined without regard to its vertical location, all curves in column b have been centered to \(V_r = 0\). Thus, any tendency for most of the angels to be on one side of the curve is symptomatic of a mean vertical velocity \(V_r\) of the entire angel population. Number distributions of angels as a function of \(V_r\) are plotted in column c of Figs. 3, 4 and 5.

Surface winds were reported hourly at a site within 1 mi of the radar. Also, at 1433 EST (at the same time as the series of VAD soundings in Fig. 3), a balloon was released and tracked from the radar site which gave wind measurements every half minute, at approximately 300-ft altitude intervals. The 1433 wind hodograph is plotted in Fig. 6a.

Fig. 6b-g has been prepared to facilitate comparison of the balloon-measured winds with the mean horizontal velocity \(V_h\) of the population of angels at corresponding altitudes. In order to guard against possibly unrepresentative individual measurements, VAD soundings made within half an hour before and after the balloon ascent are plotted in addition to those made during the ascent; moreover, at each level for which a comparison is made, balloon-measured winds are plotted for the three levels nearest the reference level. Although
5. The nature of the dot angles

Using all ten series of VAD soundings analyzed as in Figs. 3, 4 and 5, it has been possible to derive time-height patterns of several parameters describing the motion of the angels from 1300 until 2000 EST. While the mean horizontal velocity $V_h$ and direction of travel $\theta$ are shown later in Figs. 11 and 12, the present section is more concerned with the mean deviation $\Delta V_r$ (Fig. 7) the maximum relative velocity $V_{rel}$ (time-height section not shown) and the mean (effective) vertical velocity $V_z$ (Fig. 8).

Three kinds of angel population can be identified during the course of data acquisition; they are labeled in Fig. 7 as Types 1, 2 and 3. Type 1 angels, exemplified in Fig. 3, occurred for much of the afternoon. They had mean deviations $\Delta V_r$ between 1 and 1.5 m sec$^{-1}$ and maximum relative velocities $V_{rel}$ between 3 and 7 m sec$^{-1}$. Type 2 angels, exemplified in Fig. 4, occurred for a period of two hours or so before dusk having mean deviations between 0.2 and 1.0 m sec$^{-1}$ and maximum
relative velocities between 0.5 and 3 m sec\(^{-1}\). Type 3 angels, exemplified in Fig. 5, occurred after dusk, with mean deviations of 1 to 4 m sec\(^{-1}\) and maximum relative velocities between 4 and 13 m sec\(^{-1}\).

A part of the velocity deviations of the angel populations, plotted in Fig. 7, will have been due to the wind shear itself, over the depth sampled by the pulse volume. The altitude interval sampled during each VAD scan was about 620 ft, given by \(\frac{1}{2}(h_t + h_p)\) sin\(\alpha\), where \(h_t\) and \(h_p\) are the lengths of the pulse and range gates, respectively. Fig. 11 shows that, except for the VAD scans made at 1000 ft after 1830 EST, the change of \(V_t\) over a 620-ft height interval is seldom likely to have exceeded 1 m sec\(^{-1}\) and was usually much less. Evidently, therefore, all velocity deviations greater than this must be attributed to some other effect.

According to Atlas et al. (1966), angel echoes with variable velocities may sometimes be detected from refractive index gradients embedded within a turbulent airstream. Indeed, Gorelik (1966) has measured root mean square velocity fluctuations ranging between 5 cm sec\(^{-1}\) and 1.8 m sec\(^{-1}\) for radar signals returned from the clear atmosphere. It is important, therefore, to examine the possibility that the above velocity deviations were associated with turbulence.

Using the equilibrium theory of isotropic homogeneous turbulence (Obukhov, 1949), the one-dimensional energy spectrum of velocity perturbations may be expressed as

\[
E(k) = A_1 k^{-4/3},
\]

where \(\epsilon\) (cm\(^2\) sec\(^{-1}\)) is the rate of viscous dissipation of turbulent energy per unit mass, \(k\) is equal to \(2\pi/L\), where \(L\) (cm) is the scale of turbulence and \(A_1\) is a constant whose value has been found to be about 0.64. Now the mean square turbulent velocity, equal to twice the kinetic energy per unit mass, is given by

\[
\sigma_v^2 = \int_0^\infty E(k)dk,
\]

so that

\[
\sigma_v^2 = \left(\frac{4}{3}A_1\right)\left(\frac{L_0}{2\pi}\right)^{4/3} \epsilon^{1/3},
\]

where \(L_0\) is the largest limiting scale sensed by the radar (i.e., twice the pulse length or the outer scale of the turbulence spectrum, whichever is the smaller).

A fairly typical value for the mean deviation \(\Delta V_t\) of the angels in the present study is 1 m sec\(^{-1}\). The histograms of \(V_t\) shown in column c of Figs. 3, 4 and 5 are approximately Gaussian in form so that this is equiva-
lent to a mean square deviation $\sigma_v^2$ of about $1.6 \text{ m}^2 \text{ sec}^{-2}$. Eq. (6) then shows that this corresponds to an $\epsilon$ of order $10^2 \text{ cm}^2 \text{ sec}^{-1}$. According to Atlas et al. (1966), such a value would be produced only by moderate turbulence, which is most unlikely in view of the stable lapse rate and the generally small wind shear. Taken together with the $2 \text{ m sec}^{-1}$ discrepancy between the mean angel motion and the wind, noted in the previous section, this effectively rules out turbulence as a possible explanation.

Another meteorological explanation for dot angels is that they are reflections from sharp refractive index gradients at the caps of thermals (Atlas, 1965a). Since the sharpest gradients are maintained while thermals are actively rising, this mechanism is expected to produce a preponderance of rising angels. This kind of reasoning led Battan (1963) to infer that the predominantly rising dot angels observed by him were due to thermals. Although the mean vertical velocity $V_\phi$ of the angel populations in the present study was quite variable, it was almost always downward during the daytime, occasionally reaching $1.5 \text{ m sec}^{-1}$ for the Type 2 angels and even several $\text{ m sec}^{-1}$ for the Type 1 angels. Therefore, it seems unlikely that the daytime angels were due to thermals.

In sharp contrast to the daytime angels, the Type 3 angels had mean vertical velocities that were usually upward. By 1900 EST these upward velocities were exceeding $1 \text{ m sec}^{-1}$ at most levels; moreover, between 1820 and 1920 the highest level at which angels could be detected increased from 3500 to over 4500 ft. Even then, however, the angels are still unlikely to have been due to thermals because the low levels of the atmosphere
after sunset were becoming increasingly stably stratified with the onset of radiational surface cooling.

Although the velocity characteristics of the angels appear to be inconsistent with the expected behavior of natural atmospheric targets, they are consistent with behavior that might be expected from many insects. In particular, the upward motion of the Type 3 angels, and also their large relative velocities, is consistent with the initial ascent of relatively strong-flying nocturnal insects. A few of the Type 3 angels even had relative velocities exceeding 10 m sec⁻¹, which according to Houghton (1964) is close to the airspeed of some slow-flying birds. However, since the number of these very fast-flying angels was small, it is reasonable to disregard this possible explanation and to assume that practically all of the angels were due to insects of one kind or another.

Although there was some uncertainty as to the sensitivity of the radar receiver during the present study, the minimum back-scattering cross section $\sigma_{\text{min}}$ detectable at a range of 6000 ft (3000 ft altitude) is likely to have been between $10^{-4}$ and $10^{-2}$ cm². According to Stephens (1961), at a radar wavelength of 5.42 cm, such cross sections would be produced by water spheres between about 3 and 6 mm in diameter, corresponding to the kind of cross sections expected from insects rather than birds. Assuming that the radar cross section of an insect is rather similar to that of a water sphere of the same mass, insects just detectable at a range of 6000 ft would have weighed between 14 and 110 milligrams. Using the dimensional relationships of Greenewalt (1960), this corresponds to insects with total wing spans of from 1 to 7 cm.

If the angels were indeed due to individual insects then the intrinsic velocity spectrum for each one should have been very narrow. In fact, as already mentioned,
Fig. 6. Comparison of balloon-measured winds with mean horizontal velocities of the angel population where (a) shows the hodograph for the 1433 EST wind sounding and (b) through (g) show angel velocities at 500-ft altitude intervals from 1000 to 3500 ft compared with winds at three levels close to the appropriate levels. Angel velocities obtained from the VAD series concurrent with the balloon sounding are depicted by circles, those obtained from the preceding and succeeding series being depicted by triangles and squares, respectively.

Fig. 7. Time-height pattern of the mean deviation of the radial velocity $\Delta V_r$ relative to the mean velocity of the overall population of angels. Velocities are plotted in m sec$^{-1}$, with decimal points giving the locations of the VAD soundings.

A substantial velocity spread of up to 6 m sec$^{-1}$ was detected. Some of this will have been due to the motion of one edge of the radar antenna toward the target and the other away from it; however, for the 16-ft Porcupine antenna rotating at 4 rpm, this is estimated to have produced a spread of only about 1 m sec$^{-1}$. The major contribution to the velocity spread is thought to be due to the back-scattering cross section of the angels being considerably in excess of the minimum detectable, thereby leading to detection on the skirts of neighboring filters in the frequency analyzer. Such an interpretation is consistent with the abrupt increase in the velocity spread of individual angels that was associated with the appearance of the Type 3 angels after sunset. The Type 3 angels have been identified as strong-flying nocturnal insects and it is, therefore, quite understandable that they should have had relatively large cross sections.

The transition from a population of Type 2 angels to a population of Type 3 angels can be seen in the 1500-ft
VAD pattern for 1806 EST (Fig. 9a). Here a few Type 3 angels with velocity spreads typically 5 m sec⁻¹ (190 cps) are beginning to be detected among Type 2 angels with velocity spreads only about 3 m sec⁻¹ (110 cps). A calibration of the response of the frequency analyzer filters using signals of known power has shown that such spreads are produced by signals 13 and 2 db above minimum detectable, respectively. Thus, although most of the Type 2 angels, and the Type 1 angels before them, seem to have had back-scattering cross sections only a little above minimum detectable, the Type 3 angels had cross sections some 20 times greater than minimum detectable, i.e., between $2 \times 10^{-8}$ and $2 \times 10^{-7}$ cm⁴. According to Stephens (1961), such cross sections are equivalent to those produced by water spheres between 5 and 8 mm in diameter.

Actual radar measurements of back-scattering cross sections are available for a few insects and, although there is no reason to believe that the same kinds of insects were responsible for the angels in the present study, it is still illuminating to compare their cross sections. Hajovsky and LaGrone (1965) have suspended a number of anesthetized insects within the beam of a 3.2-cm radar. With the exception of a locust, all of the

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**Fig. 8.** Time-height pattern of the mean vertical velocity $V_r$ of the population of angels. Velocities are plotted in m sec⁻¹, with positive velocities downward. The decimal points give the locations of the VAD soundings.

**Fig. 9.** (a) VAD pattern for 1500 ft at 1806 EST, at a time when a few Type 3 angels were beginning to be detected among the Type 2 angels. This is a hand-drawn copy, because the original photograph was poorly reproduced. (b) Schematic drawing obtained from (a). Individual Type 2 angels all lay within ±0.5 m sec⁻¹ of the dotted curve; the midpoints of individual Type 3 angel echoes are identified by circles, the best-fit curve for these being drawn solid. (c) Mean horizontal velocity vectors $V_h$ for the Type 2 and Type 3 angels. The relative velocity of the Type 3 angels with respect to the Type 2 angels is 5 m sec⁻¹, 035 deg. (Direction of Type 3 angels in (b) should be 355 deg.)
insects that they studied had characteristic body dimensions of 1 cm or less. Although some of them were a little large to be treated as Rayleigh scatterers, their cross sections at 5.42 cm can still be estimated to a reasonable approximation assuming a \( \lambda^{-4} \) dependence. Adjusted accordingly, the cross sections that they obtained fell in the range \( 10^{-3} \text{ cm}^2 \) to \( 10^{-4} \text{ cm}^2 \), except for the locust which had a cross section exceeding 1 cm² when viewed longitudinally. More recently, Glover et al. (1966) released individual large insects from an aircraft and tracked them simultaneously with radars at 3.2, 10.7- and 71-cm wavelength. Interpolating between the cross sections measured at the two shorter wavelengths, it is possible to infer the following cross sections at 5.42 cm wavelength: dragonfly, \( 3 \times 10^{-4} \text{ cm}^2 \); worker bee, \( 7 \times 10^{-5} \text{ cm}^2 \); Hawk moth, \( 5 \times 10^{-4} \text{ cm}^2 \). With the exception of the locust and Hawk moth, all of the above cross sections fall within the range of values obtained for the angels in the present study, thereby leading further credence to the view that the angels were, in fact, due to insects.

Since received echo power \( P_r \propto R^{-4} \) for point targets, the velocity spread for individual angels within a population of identical angels should diminish with range. A factor 2 increase in \( R \) should cause \( P_r \) to diminish by a factor 16; for the particular analyzer used, this should cause the velocity spread to decrease by 2 m sec\(^{-1}\). The fact that a diminution of velocity spread with increasing range (i.e., altitude) was barely perceptible suggests that any given large insects were present at greater heights. However, this does not appear to have led to greater values of \( \Delta V_r \) at the higher levels.

Fig. 10 shows a time-height plot of the number concentration of angels within the volumes swept by the radar. Although the concentrations are liable to be underestimated at times when the angels were difficult to resolve from one another (as in Fig. 4), the pattern in Fig. 10 is thought to be valid in a broad sense. Two factors stand out. First of all, there is an overall diminution of the concentration of angels at all levels until half an hour after sunset, this being followed by an abrupt increase in concentration above 2000 ft associated with the appearance of the Type 3 angels. Secondly, as Chernikov (1963) has found, the concentration of angels diminishes rapidly with height which may be due in part to a decrease in \( P_r \), with range, but is mainly due to an actual decrease in the concentration of targets with height.

The highest measured concentration, at 1406 EST at 1250 ft, was 170 per 10^9 ft^3 (6 \times 10^9 km^-3). Although this is comparable with the maximum summer concentration of clear air dot angels observed in the Soviet Union by Chernikov (1963), it is some two orders of magnitude smaller than the concentration of dot angels observed by Lhermitte (1966) on a clear summer day in central Oklahoma, and also some two orders of magnitude smaller than the concentration of insects collected by Glick (1939) during aircraft flights in Louisiana and Mexico at altitudes from 1000 to 4000 ft above the ground. The discrepancies may simply be due to differences in location and weather.

Finally, an interesting feature of Fig. 9 is that the Type 3 angels do not lie on the same best-fit sine curve as the Type 2 angels. Whereas the latter all lay within \( \pm 0.5 \text{ m sec}^{-1} \) of a sine curve corresponding to \( V_r = 8 \text{ m sec}^{-1} \) and \( \theta = 335 \text{ deg} \), the former were clustered about a sine curve corresponding to \( V_r = 11 \text{ m sec}^{-1} \) and \( \theta = 355 \text{ deg} \) (Fig. 9b). In view of the small deviations of the Type 2 angels from the best-fit sine curves and their generally rather small vertical velocities, it appears that they followed the wind fairly closely, within \( \pm 0.5 \text{ m sec}^{-1} \), say. Therefore the vector difference between the velocities of the two classes of angels is a measure of the mean airspeed, or drift relative to the wind, of the population of Type 3 angels. According to Fig. 9c this was as much as 5 m sec\(^{-1}\) from 035 deg. Although this velocity is only approximate, it definitely indicates that the Type 3 angels had a substantial airspeed, and it is one more piece of evidence to corroborate the earlier inference that they were due to strong-flying nocturnal.

Table 1. Characteristics of angel populations, 27 September 1965.

<table>
<thead>
<tr>
<th>Type</th>
<th>Approximate times (EST)</th>
<th>Mean drift velocity (m sec(^{-1}))</th>
<th>Mean deviation ( \Delta V_r ) (m sec(^{-1}))</th>
<th>Maximum relative velocity ( V_{rm} ) (m sec(^{-1}))</th>
<th>Mean vertical velocity ( V_{r} ) (m sec(^{-1}))</th>
<th>Back-scattering cross section ( \sigma ) (cm(^2))</th>
<th>Diameter of equivalent water sphere at 3000 ft altitude (mm)</th>
<th>Probable identity of angels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>~1530 1530-1800</td>
<td>&lt;1</td>
<td>1-1.5</td>
<td>3-7</td>
<td>0-2.4-4.5</td>
<td>10^4-10^2</td>
<td>3-6</td>
<td>Insects</td>
</tr>
<tr>
<td>Type 2</td>
<td>1800-</td>
<td>~8</td>
<td>1-4</td>
<td>4-13</td>
<td>0-1.8</td>
<td>10^4-10^2</td>
<td>3-6</td>
<td>Weak-flying insects</td>
</tr>
<tr>
<td>Type 3</td>
<td>~1530 1530-1800</td>
<td>5-8</td>
<td>3.7-1.4</td>
<td>2 \times 10^2</td>
<td>5-8</td>
<td>2 \times 10^2</td>
<td>5-8</td>
<td>Strong-flying insects</td>
</tr>
</tbody>
</table>

* Positive downward.
insects. Characteristics of the dot angels are summarized in Table 1.

6. The use of dot angles as wind tracers

Lhermitte (1966) has proposed that observations of clear-air dot angels using the VAD Doppler technique might constitute accurate measurements of the horizontal wind velocity. He has demonstrated by means of a detailed case study that this is a potentially powerful technique for describing the vertical wind structure in the lowest few thousand feet, particularly since it can provide a time and height resolution better than that previously attained by other means. In his study Lhermitte does not attempt to infer the nature of the targets; however, he does feel justified in regarding the targets as being good tracers of the air motion. While this may have been valid for the occasion studied by Lhermitte (1966), the analysis in the present paper has shown that this certainly is not always the case. It is important, therefore, to evaluate the usefulness of dot angel populations as tracers of the wind in situations such as the present one in which the individual angels often have a significant velocity relative to the wind.

Time-height patterns of the mean horizontal velocity $V_A$ and direction of travel $\theta$ of the angel populations on 27 September 1965 are presented in Figs. 11 and 12. They represent a velocity field that varies in a remarkably smooth and orderly fashion. There is no sign of the erratic behavior that might have been expected in view of the occasionally large relative velocities of the individual angels. It almost seems as though, in the mean, the angel population were following the horizontal winds. That this was not true is shown by the systematic 2 m sec$^{-1}$ vector difference between $V_A$ and the balloon-measured winds at the lower levels (Fig. 6). It is also shown by the large 5 m sec$^{-1}$ difference between the two angel populations in Fig. 9 as discussed in the previous section. Indeed, this last discrepancy is so large that one is even led to wonder whether a large part of the apparent low-level nocturnal jet in Fig 11 was due to the strong-flying Type 3 insects traveling in a preferred direction. Obviously, therefore, it is necessary to be selective in using dot angels as wind tracers. It would be wise, for example, to discard all data for which the mean deviation $\Delta V_A^r$ significantly exceeds a value that can be reasonably attributed to turbulence and wind shear.

Although, in the present study, it was impossible to measure the mean wind accurately to the nearest m sec$^{-1}$ on the basis of either the Type 1 or the Type 3 angels, it seems reasonable to expect that such an accuracy might have been achieved using the Type 2 angels, for which $\Delta V_A^r$ was always less than 1 m sec$^{-1}$. It is to be hoped that further studies of this kind will reveal that there are many occasions when there are populations of dot angels having velocity characteristics similar to the Type 2 angels especially at certain times of the day and year, and in certain localities. If this is found to be so, then this could become an important low-level wind sounding technique.

Finally, it should be mentioned that Lhermitte (1966) has also raised the possibility of using this technique to investigate vertical as well as horizontal air motions. This seems less promising, however, since even the Type
2 angels were often observed to be descending in excess of $1 \text{ m sec}^{-1}$, a velocity which is large enough to obscure most vertical air motions likely to be encountered in the clear air.

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