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ATMOSPHERIC PROBING BY DOPPLER RADAR

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ABSTRACT

This paper is a survey of the application of Doppler techniques to the study of atmospheric phenomena. Particular emphasis is placed on the requirement of adequate digital processing means for the Doppler signal and the Doppler data which are acquired at a very high rate. The paper also discusses the need of a two or three Doppler method as an ultimate approach to the problem of observing the three-dimensional field of particle motion inside convective storms.

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1. INTRODUCTION

Although conventional radar techniques have been extensively used for years in the study of atmospheric phenomena, Doppler radar techniques were introduced to this field only a decade or so ago. Experiments based on the use of continuous wave Doppler radar were conducted as early as 1958; however, this report will essentially deal with pulse Doppler radar techniques having the same ranging capabilities as conventional pulse radars. The radar wavelengths covered in this report range from X-band (3 cm) to S-band (10 m).

The first papers on the meteorological use of pulse Doppler radar techniques were presented in 1960 at the Eighth Weather Radar Conference and were concerned with the analysis of the vertical motion of precipitating particles using a vertically pointing beam.

Discussion of the earliest experiments, involving the use of a scanning Doppler radar beam for the purpose of analyzing wind field from observation of the motion of precipitation particles, was presented a year later at the Ninth Weather Radar Conference. Since the time of these early experiments, the number of pulse Doppler radars specifically designed for meteorological studies has been steadily increasing. There are now five meteorologically-oriented pulse Doppler radars in the United States, two in England and one in Japan. These radars were designed and built for the purpose of the study of atmospheric phenomena. The use of pulse Doppler radar for atmospheric physics studies has also been mentioned in the Russian literature on meteorological research. However, no information was provided as to the nature of the Doppler equipment involved in these experiments. More sophisticated equipment is now being built such as the Environmental Science Services Administration's planned system of three identical radar sets to be used for the study of the three-dimensional field of particle motion inside convective storms.

Considerable experience on the capabilities and usefulness of pulse Doppler radars has been acquired through their use. These experiments also have revealed the weaknesses and limitations of the single Doppler radar method which need to be overcome in order to increase the capabilities of the Doppler methodology toward its ultimate potential.

This report is a brief review of the meteorological Doppler technique, as well as a summary of the results which have already been acquired in several areas of atmospheric research. We will also propose improvements aimed towards the design of a more elaborate and appropriate Doppler radar methodology. The opinion of the writer is that the potential of the Doppler methods is far from being developed to its full capability and the use of more complex and sophisticated systems will provide us with a methodology capable of solving a large number of problems related to the study of microscale and mesoscale atmospheric phenomena. The design of multi-unit Doppler radar systems and the use of advanced data storing and processing techniques, compatible with large computers, will be an essential part of the proposed effort.

2. THE DOPPLER RADAR SPECTRUM

Numerous discussions of the Doppler radar method applied to the study of atmospheric phenomena have been given in various articles (Lhermitte 1963, Atlas 1964, Lhermitte 1966). It appears only necessary in this report to briefly mention the basic principles of the method. Only pulse Doppler radar techniques, having the same ranging capabilities as conventional radars, will be discussed.

In addition to the conventional radar capabilities of observing backscattered signal amplitude, the pulse Doppler radar provides information on the rate of change of the phase, ϕ, of the backscattered signal returned by the radar-detected target. By use of appropriate design of the Doppler circuits, the phase difference between transmitted and received signals, which is observed by the coherent radar, is a function only of the distance between the target and the radar. The rate of phase change, $d\phi/dt$, will therefore provide knowledge of the radial velocity dR/dt of the target. We can then write $\frac{d\phi}{dt} = \frac{4\pi}{\lambda}\frac{dR}{dt}$ where λ is the wavelength of the transmitted signal. This expression shows that there is a complete cycle of phase change everytime the target moves by $\lambda/2$. The pulse Doppler radar is thus an accurate ranging device which provides knowledge of the rate of change of target range, i. e., the radial velocity. If the target is approaching the radar, the phase of the signal is increasing as a function of time and $d\phi/dt$ is a positive quantity which is equivalent to an increase of the transmitted frequency of the radar. On the other hand if the target is receding $d\phi/dt$ becomes a negative quantity which is equivalent to an effective decrease of the transmitter frequency. The sign of $d\phi/dt$ is opposite to the sign of motion derived from the convention that kinematic divergence is a positive quantity. It therefore appears that it is more appropriate in meteorological work to consider that the receding targets have positive velocity. If the target moves in a direction different from the radar beam axis, only the radial velocity, i. e., the component of the target's vectorial velocity along the axis of the radar beam, will be measured. This statement reveals the ambiguities of dealing with radial velocities, which can partially or completely be overcome in certain ways described in this report.

Since we are discussing the application of Doppler techniques for the study of atmospheric phenomena, we are dealing with volume scattering due to an extended or "distributed" target composed of large numbers of scatterers.

The classical analysis of the backscattered signal received by conventional pulse radars from distributed targets, shows that the signal amplitude at any selected point in the radar range is due to the contribution of the signals re-radiated by scatterers existing inside a scattering volume defined by the cross-section of the radar beam and the pulse length of the radar. The pulse Doppler radar will be concerned with the same type of analysis but also provides information on signal phase.

Assuming the signal backscattered from a scatterer, i, has constant amplitude, α_i and phase, ϕ_i, the total backscatter signal, $A(t)$, will be given by the following expression:

$$A(t) = \sum_{i=1}^{N} \alpha_i \; e^{-j(\omega_o t + \phi_i)} \tag{1}$$

$\omega_o = 2\pi f_o$ with f_o being the transmitted signal frequency.
The signal phase, ϕ, can be split into a component, ϕ_o, corresponding to some conditions at the origin and a variable term $\omega_d t$ where $\omega_d = d\phi/dt$ (Doppler shift); therefore we can write:

$$A(t) = e^{-j\,\omega_o t} \sum_{i=1}^{N} \alpha_i \; e^{-j(\omega d_i \; t + \phi_{oi})} \tag{2}$$

The above relationship implies statistical independence of motion between scatterers and also implies that there is no collision processes between scatterers. It also relies on the fact that scatterers are moving freely for several radar wavelengths therefore leading to a clear definition of the Doppler shift. If the scatterers are submitted to a random displacement limited to a small fraction of the radar wavelength a different and more complicated expression of A(t) will be needed.

In the case of pulse radars, the time function A(t) is sampled at the radar pulse repetition rate. Selection of the signal at any radar range can be done by use of conventional range-sampling units assisted by signal-holding circuits which restore the time continuity of the signal between radar pulses and therefore provide a time function of the form of equation (1). However, the sampling and transformation of the signal in the radar circuits slightly modifies the spectral characteristic of the signal represented in A(t) especially for frequencies approaching half of the radar pulse-repetition rate. This effect is well known and usually is corrected by appropriate means.

Equation (1) shows that the power density spectrum of A(t) is the probability density function for the backscattered power expressed as a function of the Doppler shift and is called the Doppler spectrum. If the radar cross section of the scatterers exhibits time variations, the spectrum of A(t) will include the Fourier components generated by amplitude modulation due to this effect, Brook and Latham (1968).

Figure 1 shows an example of a Doppler spectrum obtained with a vertically pointing radar beam in falling snow conditions. This example illustrates the excellent velocity resolution of the radar system.

3. COHERENT RADAR DESIGN AND SPECTRUM RECORDING MEANS

Radar equipment capable of observing the phase difference between backscattered and transmitted signals is called phase-coherent or simply "coherent".

The simplest method for comparing phases is based on mixing the signal returned by the moving target with the signal reflected by a fixed target at the same range. This "external-coherence" method, which is often used in airborne navigational Doppler radars, has been applied to the study of the motion of precipitating particles, Lhermitte (1960b). However, the usefulness of this method is seriously limited by the need for a fixed target to be at exactly the same range as the moving target under study. The transmitter pulse signal can also be stored in microwave cavities but this technique is limited to short ranges by fast time decay of the stored signal. The above solutions have not been used extensively in the design of meteorological Doppler radars because they can be replaced by more appropriate systems described below.

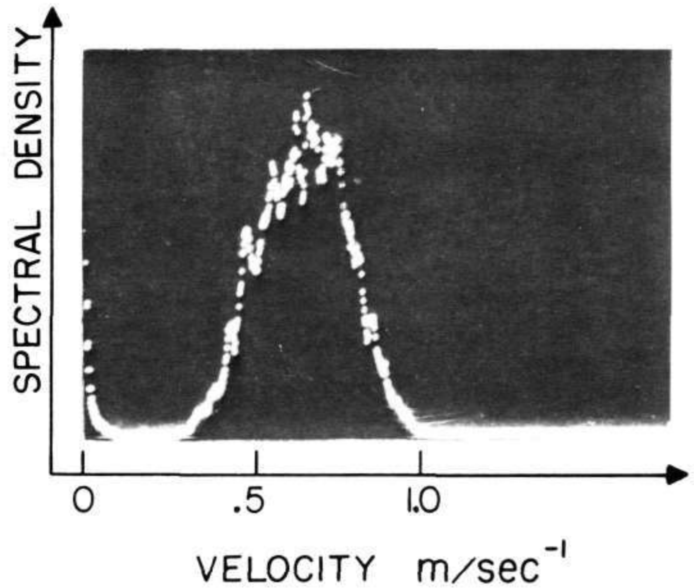


Figure 1. Doppler spectrum obtained in snow with a vertically pointing Doppler radar beam. Note the excellent velocity resolution of the system.

The most effective and accurate system is based on a primary stable microwave source called a STALO (Stable Local Oscillator). The microwave signal generated by the STALO is amplified, pulsed by a phase-coherent amplifier and radiated by the antenna. The scattered signal coming from the moving target is compared to the STALO signal and the signal phase analysis is performed by systems sensitive to the phase difference $\Delta\phi$ between successive pulses. The quality of this system depends upon the frequency stability of the microwave oscillator during the time interval between radiation of a pulse and the return of the scattered signal. Therefore it involves only the "short term" frequency instabilities of the STALO. Relative frequency stabilities of 10^{-10} can be easily achieved for longer than one millisecond and with Doppler phase jitter smaller than 5×10^{-3} radian.

System performance can be analyzed in terms of these estimated random phase instabilities occurring from pulse to pulse. If these phase instabilities are uncorrelated and limited to a small fraction of 2π, they cause the presence, in the radar signal, of a radar-sampled white spectrum superimposed on the signal Doppler spectrum. The Doppler signal to noise ratio is given by the ratio between the signal phase variance (Doppler) and the contribution of the variance due to random phase instabilities, Lhermitte and Kessler (1964). If this is due to STALO phase instabilities, this ratio will typically be better than 50 db. We must emphasize that small STALO frequency instabilities will not limit the ability of the radar to observe very slow target motion which is only limited by the signal dwell time and the stability of the mean index of refraction in the path during this time. The instabilities will only generate a phase noise which limits the dynamic range of the Doppler spectrum, and thereby inhibits the clear definition of the spectrum boundaries. The STALO contribution to phase instability increases systematically with target distance. In a well designed, fully coherent system, the STALO contribution to phase instabilities largely exceeds other contributions.

The need for a coherent microwave amplifier can be overcome by use of a conventional (but stable) magnetron microwave oscillator assisted by a transmitter phase-locked system (COHO) which stores the phase of the transmitter signal. This is the classical MTI radar which has been known and utilized for years. Phase-locking is usually done at the intermediate radar frequency and the basic requirements on the STALO remain the same as they are for fully coherent systems. High quality, commercially available magnetron oscillators have acceptable frequency stability. However, there is more phase noise generated by the magnetron and by the instabilities in phase-locking the COHO than in a system utilizing a STALO and a microwave coherent amplifier. The ratio of signal-phase to phase-noise, better than 50 db for fully coherent systems, is reduced to 30 to 35 db in the case of the MTI system. This phase noise contribution is independent of the radar range.

The above discussion shows that frequency analysis of the Doppler signal must be obtained prior to any reduction of the data. As discussed in section 8 of this report, multirange signal sampling and digitizing followed by digital computations of fast Fourier transforms offer the most flexible and effective means for this requirement. These techniques are, however, in a developing stage and have been temporarily replaced, in the present experimental work discussed in this report, by the following methods:

a. Range-gating associated with either a signal crossing technique which provides the spectrum's second moment, Lhermitte (1963), or a velocity tracking system which essentially processes the spectrum median frequency, Tripp (1964). This technique has the advantage of simplicity but it doesn't provide information on the spectrum width and shape, and is only acceptable in the case of narrow or, at least, symmetric spectra for which only the knowledge of the average frequency is required.

b. Range-gating associated with the use of multifilter frequency analyzer. This method leads to acceptable knowledge of the spectrum shape especially if integration means are provided for the signal at the output of every filter. It is, however, a slow process which doesn't match the requirements imposed by the study of atmospheric phenomena.

c. Coherent memory filter or velocity-indicator coherent integrator (VICI). The application of this device to meteorological work, which was first proposed by Chimera (1960), allows quick display of the distribution of the Doppler velocity as a function of radar range (Range velocity indicator, RVI). The device is extremely fast but it suffers from restricted range and velocity resolutions due to practical limitations of the system. The device is also unable to provide or display the signal power spectral density in a quantitative manner and therefore fails to indicate the Doppler spectrum shape. In its present form, the coherent memory filter also fails to produce data in a digital format which seems to be the only way to cope with the type of information provided by this system. An extension of its use for PPI display has been recently proposed by Armstrong and Donaldson (1968).

d. Time compression scheme. Several range gates can be Doppler analyzed in a short time by use of signal multiplexing techniques and time compression schemes. The digital time compression essentially allows that quick analysis of the spectra be done by use of fast scanning filters. The system is capable of analyzing the Doppler information at ten range gates in a time of the order of a few seconds. The complexity of this system, which involves digital techniques, approaches that of a purely digital system such as the one described in section 8 of this report. However, it doesn't have the flexibility of the digital computations and doesn't provide the digital output which is required for easy handling and processing of the data.

e. If real-time operation is not necessary, the recording of the Doppler signal by aid of a multi-track magnetic tape recorder offers a high rate of data acquisition which matches most of the requirements. Complementary informations can also be recorded on a separate track. The processing of the recorded signals can be done with the aid of specialized digital devices which provide a digital output. This seems to be the closest approach to the sophisticated digital system proposed in section 8 of this report.

4. VERTICAL BEAM METHOD

The method, which was first proposed by Boyenval (1960), Probert-Jones (1960), Lhermitte (1960), relies on the operation of a fixed, vertically pointing, radar beam. The method is attractive from the point of view of data processing in that antenna orientation need not be recorded. The radar observes only the target's vertical motion by aid of a very narrow, perfectly vertical, radar beam. Smearing of the Doppler spectrum by the horizontal wind will occur in the case of a finite size beam. However, this effect is practically negligible for beam widths of the order of 1° if the tangential speed is limited to less than 30 m sec^{-1}.

Let us accept the fact that we are essentially dealing with the vertical velocity of the precipitating particles. The analysis of the data will still be ambiguous since the particles' vertical velocity is due to the contribution of both particle terminal speed and vertical air motion. In the case of stratiform precipitation, vertical air motion may be assumed to be negligible. Furthermore if we are observing raindrops, a relationship between particles' radar cross section and particles' vertical speed can be established thereby allowing the Doppler spectrum to be predicted on the basis of the knowledge of the particles' size distribution. The inverse proposition is true and the size distribution of raindrops have been derived from the vertical velocity Doppler data, Probert-Jones (1960), Rogers and Pilié (1962), Caton (1963), Rogers (1966).

For study of raindrop growth or evaporation in stratiform conditions this method of observing drop-size distribution is excellent. However, the results are very sensitive to the presence of air motion, especially where the speeds correspond to large drops whose terminal velocity is weakly related to drop diameters. In practice, this limits the method to nonconvective precipitation. Also, large particle scattering in case of limited signal dynamic range might overwhelm the weak contribution due to the smaller particles scattering and prevent accurate knowledge of the relative concentration of smaller size raindrops.

Provided that the antenna radiation pattern is excellent, fully coherent radar provides adequate spectrum dynamic range allowing good estimates of the presence of small raindrops. We may also mention that combined study of vertical velocity spectra and signal intensity in stratiform precipitation, Lhermitte and Atlas (1963), may lead to a better understanding of precipitation growth mechanisms.

Although the above comments indicate that the vertical beam method is useful, its systematic application to the study of convective storm processes is still very limited. In these cases it is unreasonable to expect that the altitude-time display of the particles' vertical velocity is significantly representative of the actual, time evolving, three-dimensional structure of the storm. Furthermore the vertical velocity observed by the radar will be difficult to resolve in its two components, the particle terminal speed and the vertical air motion.

To obtain estimates of the vertical air motion Rogers (1963) assumed an exponential (Marshall Palmer) model of raindrops size distribution of the form:

$$n(D).dD = N_o e^{-\Lambda D} .dD \tag{3}$$

where n(D)dD is the number of drops per unit volume in the diameter interval dD, N_o is a constant, and Λ is a parameter that depends upon rainfall rate. By further assuming a relation between terminal fall velocity and size, Spilhaus (1948), and also Rayleigh scattering, Rogers arrived at an expression of the relationship between the average vertical velocity, $\overline{V}_f$, and radar reflectivity, Z, which is the following: $\overline{V}_f = 3.8Z^{1/14}$. He concluded that any departure from the above equation will be due to vertical air speed. The application of the above treatment seems to be only practical in stratiform rain, for average quantities obtained over long periods of time.

Similar assumptions have been made by Donaldson et al (1966) and Donaldson (1967a). In this work the analysis was restricted to regions where Z>10, and the following expression between $\overline{V}_f$ and Z was derived:

$$\overline{V}_f = 2 \log Z - 2 \tag{4}$$

The estimated vertical air speed, $\hat{W}$, was also derived from the following equation:

$$\hat{W} = \overline{V}_f + 2 \log Z - 2 \tag{5}$$

A different method to estimate updrafts has been used by Probert-Jones and Harper (1961) for the study of small convective storms. They suggested that above the 0° C level in the convective storm, precipitation was present in the form of large ice crystals or snow flakes. The assumption of a terminal fall velocity of 1 m sec^{-1} $\pm$ 0.5 m sec^{-1} provided Probert-Jones and Harper with means to estimate vertical air motion. They extended the analysis below the melting level by assuming continuity of air motion through the melting level and by further assuming that there was very little change of the terminal velocity of the drops between the melting level and the ground.

Although numerous assumptions were present in the analysis, the method showed a surprisingly well organized pattern of motion in the convective storm which could be used for a model of the structure of the air circulation within the storm. The model seems to have questionable application to larger convective systems where the melting level is not as clearly defined as in the convective storm analyzed by Probert-Jones and Harper.

A different approach to estimating updraft velocities has been used by Battan (1963a) and Battan and Theiss (1966, 1967). They suggested that the lowest part of the velocity spectrum is related to the small size precipitation particles which can be estimated by assuming a threshold of detection. Since the terminal speed for such precipitation particles was known, updraft could then be determined from this lower boundary of the vertical velocity spectrum. There is, however, some difficulty in estimating the lowest velocity boundary of the spectrum since its dynamic range is limited by the noise generated by or accepted in the radar circuit. This noise is mainly due to the radar phase noise generated by the radar equipment, but also includes contributions due to backscattering received outside the antenna main beam as allowed by the complex nature of the radiation pattern of the radar antenna. The spectrum dynamic range can also be degraded by signal processing such as the single sideband detection scheme used by Battan and Theiss (1966).

In spite of the restrictive assumptions, there is acceptable consistency in the published radar observations of vertical Doppler speed. These have covered a wide range of updraft speeds from 4 m sec^{-1} deduced by Probert-Jones and Harper (1961) in a weak convective storm, to 20 m sec^{-1} deduced by Battan and Theiss (1966). Updraft speeds larger than 16 m sec^{-1} have also been observed by Donaldson et al (1966). These observations reveal that updrafts are found mostly above the 0° C level and downdrafts below this level.

The application of the previous methods to the estimate of updrafts and other processes inside storms is, however, questionable. Noticeable departure of the drop size distribution from the exponential Marshall Palmer mode, which will reduce the applicability of the updraft estimates, will occur in a variety of cases. Sorting of the precipitation particles is a frequent cause of drastic modification of spectrum size. The presence of hail will completely upset the estimated relationship between radar reflectivity and $\overline{V_f}$, presented above.

The validity of the assumptions involved in estimating updraft speeds might be further questioned on the basis of some of the published results indicating very high air vertical velocity gradients dw/dz, Donaldson (1967). One sees that the Donaldson results shown in Figure 2 indicate that, between 1641 and 1642 EST, dw/dz was larger than $10^{-2} sec^{-1}$ at an altitude of 8 kms, therefore requiring that horizontal divergence of the same order of magnitude be present at this altitude. Results recently obtained by Donaldson (1968) indicate that dw/dz can reach a maximum value of $3.10^{-2} sec^{-1}$.

The vertical beam method requires that some stratification or steady state process be realized for a reasonable length of time. These conditions will seldom be met in the case of convective storms.

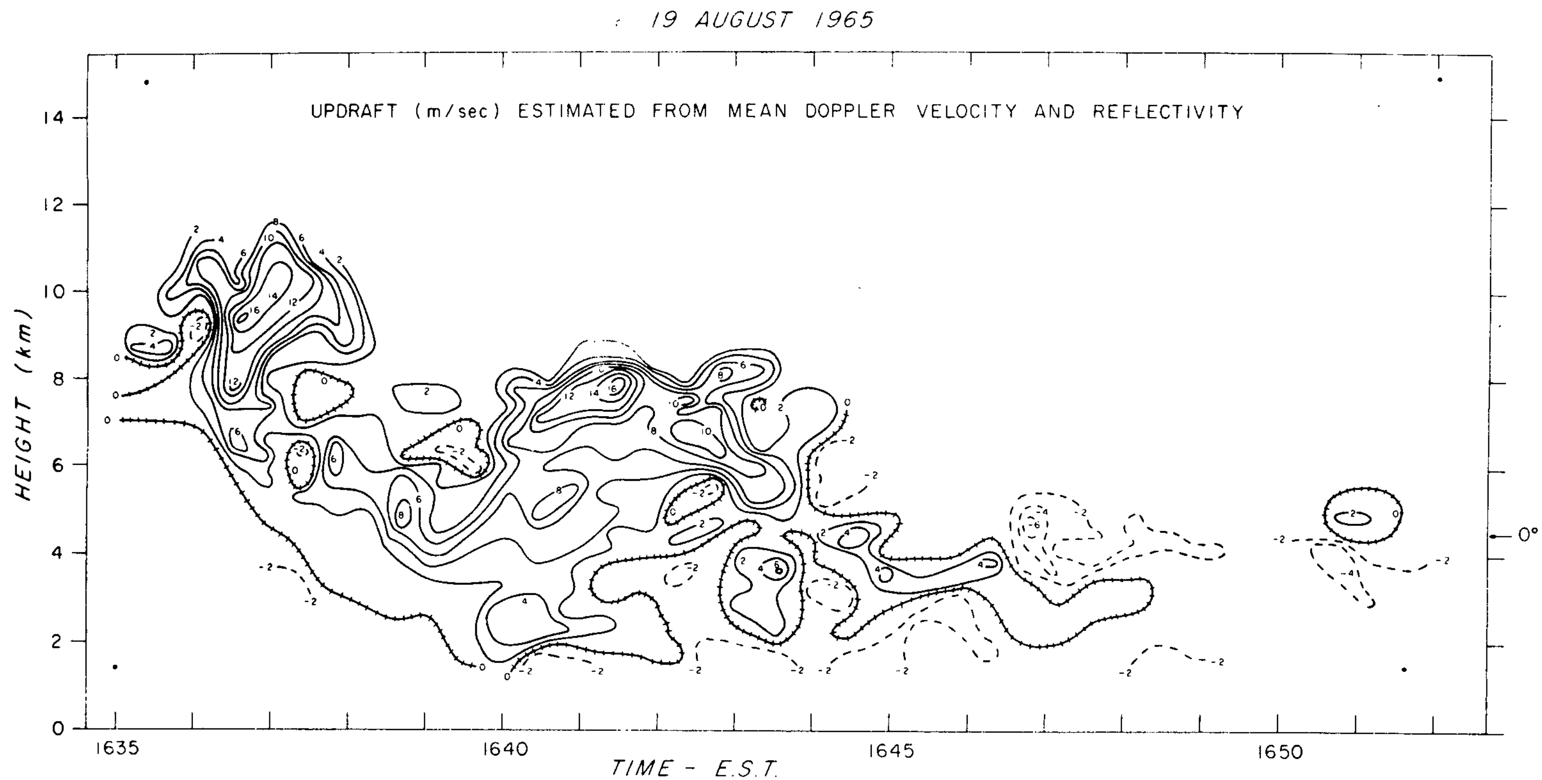


Figure 2. Vertical air motion field estimated from mean Doppler velocity and an assumed relationship between reflectivity and mean particle fall speed. Updrafts are solid contours, and downdrafts are dashed contours, with railroad tracks showing locations of zero vertical air motion. (After Donaldson, 1968).

In order to give meteorological significance to the Doppler data, the experimenter must rely on arbitrary assumptions which are not derived from sound physical reasoning. This attitude is reflected on the controversy surrounding the existence of a "balance level" proposed by Atlas (1966) and its significance as an important part of the storm processes. The balance level is characterized by the altitude at which the mean vertical Doppler velocity is zero. It is adventurous to specify such quantity without some knowledge of the spectrum shape. Furthermore, as indicated by Donaldson and Wexler (1968) the restricted significance of altitude-time cross sections does not allow any firm conclusion as to the presence of an accumulation zone or region of particle growth in the three-dimensional storm structure.

Since critical phases of the analysis of data derived from vertically pointing radar rely on arbitrary assumptions used as a substitute for the lack of knowledge of the storm processes outside of the region observed, the reader is referred to the above mentioned papers for a more detailed discussion on the significance of the balance level.

To summarize, it is the author's opinion that a single, vertically-pointing radar has and will continue to have severely limited application for the study of convective processes inside storms and should be replaced by the multiple Doppler radar method discussed at the end of this report.

5. VAD METHODOLOGY

If we assume statistical homogeneity of the speed of the particles in the area covered by the radar equipment and if we are interested in deriving average properties of the wind field, it is appropriate to observe several radial components of the particle motion obtained in different directions, by means of azimuth scanning of the radar beam and display of the velocity azimuth function (Velocity-Azimuth-Display). With appropriate programming of the radar beam elevation angles and also selected ranges, the data can be representative of a range of altitude levels in the storm, thereby leading to a definition of the vertical distribution of the properties of the motion field.

The method was first proposed, Lhermitte and Atlas (1961), for the purpose of measuring the wind vertical profiles within a snow storm. An example of the method capability is shown in Figure 3. The particle radial velocity, V_R, at a certain altitude level in a snow storm is continuously recorded as a function of the azimuth of the radar beam, β. V_R is expressed as a function of the horizontal motion speed, V_h, and direction, β_o, the radar beam elevation angle, Θ, and the particle vertical velocity, V_f, by the following equation:

$$V_R = V_h \cos \Theta \cos (\beta-\beta_o) + V_f \sin \Theta \qquad (6)$$

V_R is in fact a spectrum whose variance is due to the contribution of V_h variance, σ_h^2, V_f variance, σ_f^2(due mainly to the distribution of particle terminal speed), and the covariance between V_f and V_h. The estimate of the mean velocity V_R (spectrum first moment) collected as a function of radar beam azimuth, offers means to determine a least square fit of equation (6) which permits a prediction of the average quantities: $\overline{V_h}$, $\overline{V_f}$ and $\overline{\beta_o}$.

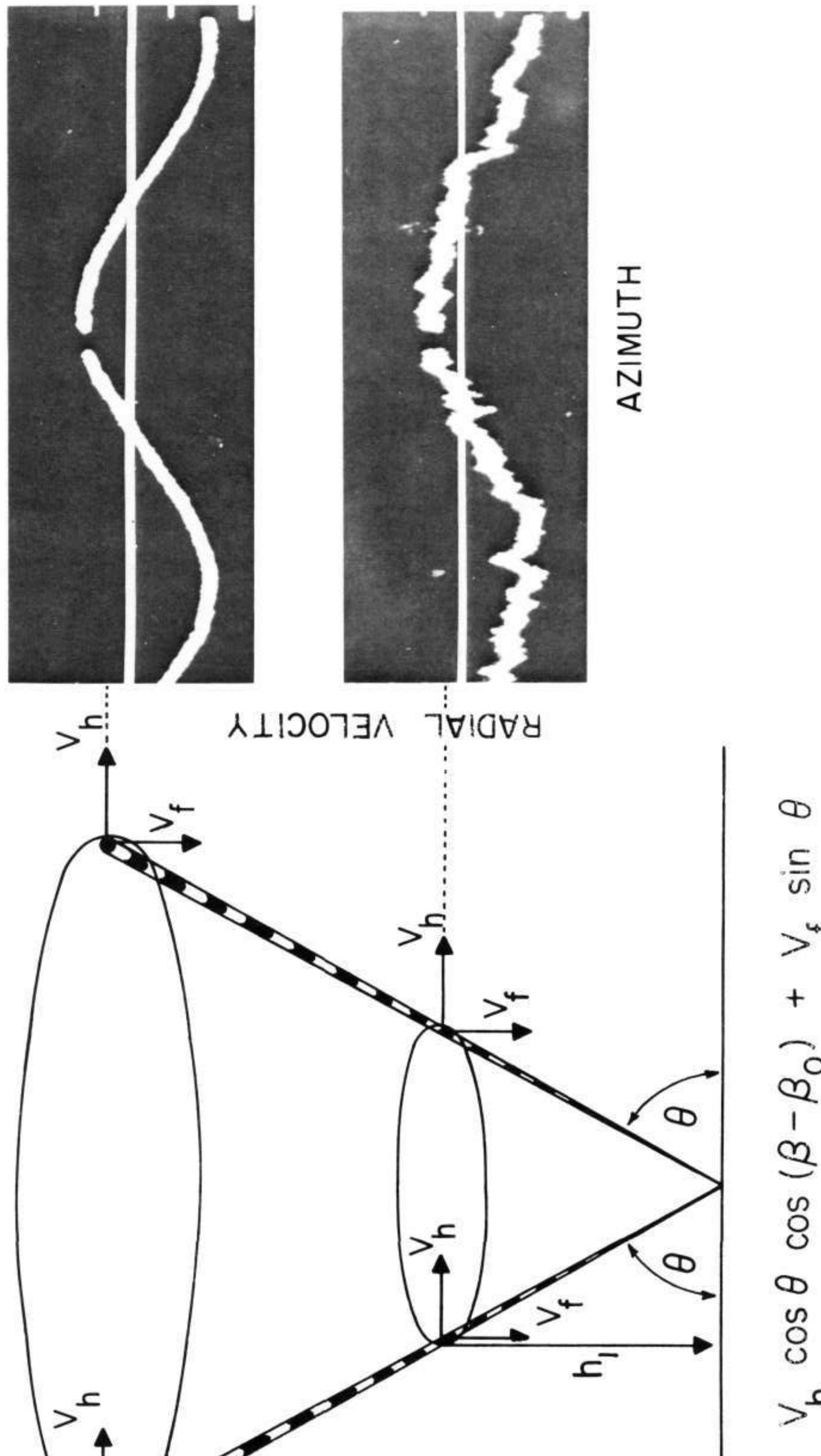


Figure 3. Velocity azimuth display with examples of actual results.

There is, however, an ambiguity in the prediction of $\overline{V}_f$ which is due to the possible presence of wind convergence in the wind field. This is easily shown by integrating V_R as a function of β. We have:

$$\int_0^{2\pi} V_R(\beta)\,d\beta = \cos\Theta \int_0^{2\pi} V_h \cos(\beta-\beta_o)\,d\beta + \sin\Theta \int_0^{2\pi} V_f\,d\beta \qquad (7)$$

The term $\int_0^{2\pi} V_h \cos(\beta-\beta_o)\,d\beta$ will be null only if there is no wind convergence.

We then can write:

$$\int_0^{2\pi} V_R(\beta)\,d\beta = \sin\Theta \int_0^{2\pi} V_f\,d\beta \qquad (8)$$

and therefore estimate $\overline{V}_f$. However, if there is wind convergence the term,

$$\int_0^{2\pi} V_h \cos(\beta-\beta_o)\,d\beta$$

will not be zero and will contribute to the term on the right hand of equation (7). By further manipulating the equations we can estimate the wind divergence, $div_2\vec{V}$ by the following expression:

$$div_2\,\vec{V} = \frac{1}{\pi r}\int_0^{2\pi} \frac{V_R(\beta)\,d\beta}{\cos\Theta} - \left(\frac{2\,\overline{V}_f \tan\Theta}{r}\right) \qquad (9)$$

In this equation, r is the radius of the circle scanned by the radar beam at the selected range or altitude. The method is capable of an accurate estimate of the wind convergence if Θ is small and if the particle fall speed can be estimated accurately,i.e., (snowflakes falling in still air). For instance, if $\Theta = 10^o$ a change of the estimate of V_f by 0.5 m sec^{-1} will modify the convergence estimate by 2 10^{-5} sec^{-1} at r = 15 kms.

This method of measuring wind convergence has been first proposed and applied by Caton (1963). It reliably applies only to snow storms or the region of the atmosphere where the fall velocity of targets is either small or accurately estimated. Browning and Wexler (1966) have extended these computations to the study of other properties of the wind field such as deformation. Vorticity can not be observed with a single Doppler radar since it requires that the tangential component of the motion be known.

Wind fluctuations of smaller scale can also be estimated by classical Fourier analysis of the V_R (β) function and the Fourier components expressed in the following equation:

$$C_n = \int_0^{2\pi} V_R(\beta)\, e^{-jn\beta}\,d\beta \qquad (10)$$

C_n is indeed a complex quantity containing information of the phase and amplitude of the Fourier components.

$C_o = \int_o^{2\pi} V_R\ (\beta)\ d\beta$ is the "DC" term controlled by both the vertical velocity and the wind convergence which was discussed above. The method can bring information on the small scale variability of the wind, Lhermitte (1968b).

The design of the experiments with a program of elevation angles, Θ, provides more flexibility in analyzing the data since the relative contribution of the vertical and horizontal motion to the radial velocity will be modified by varying Θ.

The method is now largely being used for the study of mesoscale phenomena in widespread storms. Its capabilities of analyzing the wind field properties inside snowstorms are excellent. Mesoscale wind properties as well as turbulent eddy sizes and eddy dissipation rate can be observed and analyzed if the data are acquired at a high rate, simultaneously at different altitudes. However, in order to utilize the method to its full capabilities, the data have to be produced in digital form for efficient reduction by digital computers.

6. COMMENTS ON THE USE OF A SINGLE DOPPLER RADAR FOR THE STUDY OF CONVECTIVE STORMS

Attempts have been made to analyze the horizontal wind field in a convective storm system from a slightly tilted Doppler radar beam. Donaldson (1967b) presented such experiments which were made by azimuth scanning of the convective cells, with elevation angle limited to 1^o, 3^o, and 5^o, for which the contribution due to particle vertical velocity was negligible. However, even if restricted to the storm's lowest levels the results are not representative of the storm circulation since only the radial particle velocity is observed. Even with assumptions about mean wind, whose significance is questionable in the strongly perturbed storm environment, the results do not show any convincing pattern leading to estimates of the storm wind field properties such as convergence and vorticity. The results obtained with such a technique will always be inconclusive except in the case where the azimuth scanning is limited to a small range of azimuth. One objective of such experiments might be to specify the scales of variance of the storm particle motion which can be used to assess the optimum sampling interval in future experiments involving the simultaneous use of several radars.

It is the writer's opinion that neither the vertical beam method nor the single radar horizontal scanning beam will provide significant improvements of the storm circulation knowledge. The prospects are much better if the measurements are based on a two radar system from which two radial components of the motion can be observed. By restricting the observations to low elevation angles, i.e., the storm's lowest levels, the analysis will bring a fairly good knowledge of the wind field leading to estimates of kinematic properties such as convergence. Vertical drafts can be estimated in the low levels of the storm by applying the equation of continuity to the wind fields observed at several altitude levels in the storm.

The Environmental Science Services Administration is developing a system of two compatible Doppler radars which will be tested during summer 1968 and should allow an assessment of the logistic problems involved. The two-Doppler radar method is a necessary step towards the design of a three-Doppler method described in section 9 of this report. Since the three-Doppler method retains the continuity of radar scanning it is more appropriate for the probing of the three-dimensional structure of a storm than the use of a network of vertically pointing Doppler radars, which was proposed by Browning (1966)*.

7. DOPPLER STUDY OF CLEAR AIR MOTION

Doppler methods have also been used for the study of clear air targets (CAR) commonly called "Angels". The experiments were concerned with the observation of the speed of these targets for the purpose of identifying their nature and also the motion of the surrounding air. A much better identification of the target is possible with the phase information provided by the Doppler radar. For instance, birds species can be identified on the basis of the characteristics of the Doppler spectrum as related to the motion of their wings. On the other hand, insects which are smaller than the radar wavelength will only provide a small phase modulation of the signal, which can be used as information to recognize their nature. Although this sort of information would be helpful to entomologists and ornithologists interested in the migration of insects or birds species there has not been any real attempt to direct the analysis of the Doppler data to this use. Expected differences between the Doppler spectra might sometime resolve the controversy between the attribution of clear air radar returns to either sharp index of refraction discontinuity or the presence of small physical targets. It is, however, surprising to notice that there has been no published paper devoted to detailed analysis of the Doppler spectrum as means of identifying the targets detected in clear air. Only the mean Doppler frequency is usually observed and analyzed. The first data of this kind have been acquired with a vertically pointing beam, Battan (1960; 1963). The targets' vertical motion was observed as limited to $\pm$ 1 m sec^{-1}. The analysis of the data was based on the assumption that the radar signals were due to air bubbles generated by thermal convection.

By use of the VAD technique described above Lhermitte (1966), Browning and Atlas (1966) were able to analyze the horizontal motion of the clear air targets. The Lhermitte observations, which are illustrated in Figure 5, were obtained in central Oklahoma and showed unambiguously that the targets were moving with the horizontal wind. Furthermore, the analysis showed that the method was capable of providing useful data on the vertical structure of the horizontal wind, almost continuously and over long periods of time. The low level jet frequent in central Oklahoma and northeastern Texas, when analyzed by use of this method, revealed a structure of the jet consistent with the classical studies of these boundary layer phenomena. Correlation between the clear air target horizontal motion and the presence of synoptic features such as cold fronts have been also analyzed by Lhermitte and Dooley (1966) for the spring and summer months in Oklahoma when the concentration of targets is very great. A summary of the observations of clear air target motion showed that vertical profiles of the wind can be often estimated by the method up to 1 or 2 km of altitude. The conclusions as to the nature of

*Private communication.

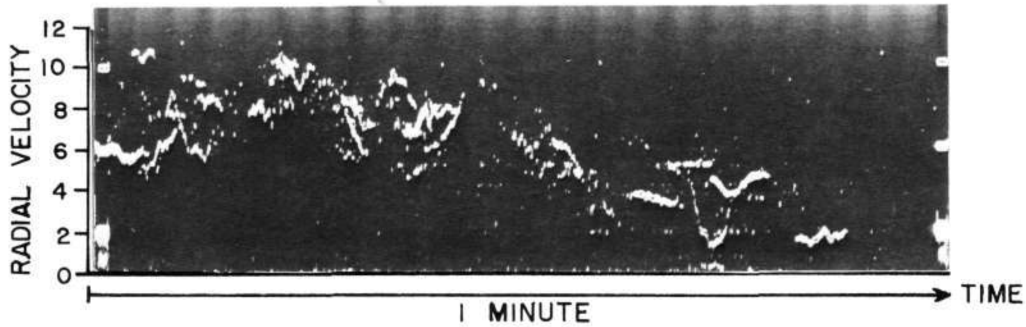


Figure 4. Time velocity variations of clear air target at a fixed point in space. Note the average trend which can be attributed to change of air motion speed.

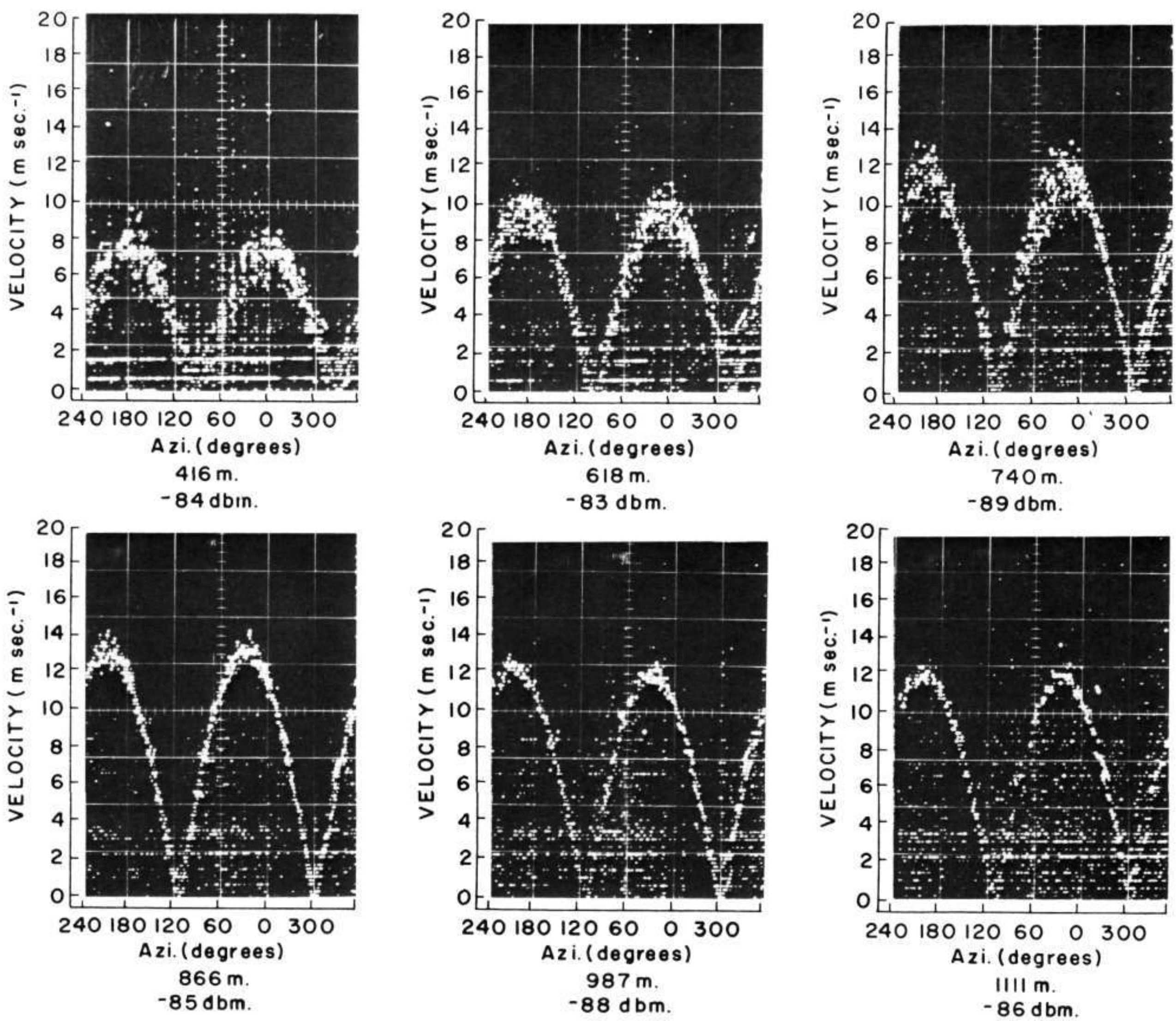


Figure 5. Velocity-Azimuth displays showing the CAR radial velocity at several altitudes. Radar beam elevation angle 20°. Radar site, Norman, Okla. Time 2023 to 2031 CST, 26 June. Signal mean intensity is indicated in -dbm.

the targets was uncertain although there was a high probability that they were insects drifting at air speed. In certain cases the space variance of the motion, with respect to the average wind, was so small that it would indicate very poor ability for these insects to react to the environment. More of these studies should be made to further specify the nature of the target and the capability of using the method for wind sounding techniques.

Tracers, such as "chaff" dipoles, offer an extremely interesting possibility for the probing of steady and turbulent air motion. The Doppler spectrum will be controlled by the turbulent processes and will contain information on turbulent parameters such as the eddy dissipation rate. Furthermore, by extending the observations to different regions of space by means of beam scanning, the study of turbulence homogeneity and large scale wind fluctuation can be performed. The material can be dispersed, either in bundles which will drift with the wind and expand through turbulent diffusion process, or introduced over large areas. The method will provide means to analyze the field of turbulent and steady clear air motion. The variance of the Doppler spectrum obtained under these conditions will be controlled by the variance of the horizontal motion, σ_h^2, the variance of vertical motion, σ_f^2, and the covariance between these two quantities. The covariance can be separated from the other variances by acquiring the Doppler information in such a way that positive and negative signs for the covariance will be available in the data analysis. The observation of the covariance between the horizontal and vertical component of the motion will provide means to probe the vertical transport of momentum in the friction layer, which is due to the interaction between the turbulent atmosphere and the earth's surface acting as a boundary, Lhermitte (1968b). The vertical distribution of the vertical motion variance, σ_f^2, can be easily obtained from a vertically pointing beam. Also the differences between Lagrangian (space variability) and Eulerian (time variability) scales of motion variance can be easily studied by comparing the cross correlation of covariance spectrum of the motion observed simultaneously at two points in space with the time autocorrelation or autocovariance of the individual motion sample. A scheme similar to this was presented by Gorelik (1965) and more recently by Boucher (1968). These methods present an extremely good prospect for the study of turbulent diffusion processes in critical areas where this is becoming an important factor (pollution zone). Surprisingly little work has been done in this research area and we recommend that such activity be included in research projects in the next few years. An X-band Doppler radar (or shorter wavelength) is appropriate for this kind of experiment. If the chaff is released by airplane the method also offers the possibility of probing the high altitude clear air turbulence.

8. ADVANCED DOPPLER SIGNAL PROCESSING AND DOPPLER DATA STORING

Most of the results which have been discussed in the previous section have been obtained through the use of relatively simple signal processing and data storing techniques which have severely limited the analysis of the data and have prevented the use of the method to its full capability. Since most of the data have been hand reduced, an extremely time consuming analysis was needed, which has prevented the statistical treatment of the very large amounts of data provided by the method.

Recently, signal and data processing methods have drastically improved through the use of modern general purpose digital computers and also by the aid of special purpose processing systems based on the use of modern digital hardware such as integrated circuits. The meteorological Doppler radar system, with its high rate of information flow, can benefit dramatically from the introduction of modern digital circuitry and methods for the processing and storing of the Doppler information. This section is devoted to analyzing the problems and predicting solutions which are expected to take place in the next few years for the treatment of the Doppler radar information to such an extent that the potential of the method will be fully realized.

As mentioned in the first part of this report, the Doppler signal which contains backscattering phase and amplitude information, must be processed to provide useful information on the spectrum of radial velocity of the scatterers. The transformation required is a conventional Fourier transform or its equivalent such as the processing of the signal by use of an analog type frequency analyzer.

Although digital computations of the Doppler signal power density spectrum have been involved in some of the experiments mentioned previously in this report, Battan (1964), they have not been widely used because of the time consuming nature of the operation. However, substantial progress has been made in the field of power density spectrum computation by digital computers, and efficient algorithms are now available which match the digital computer methods with the mathematics of the Fourier transform, Cooley, Tukey (1965). This fast Fourier method allows a substantial reduction of the time requirement for the digital computations of Fourier transforms.

The digital Fourier transform is based on the availability of digitized time samples, a_k, of the signal to be analyzed. The spectral power density estimates, S_j, are computed according to the following equations:

$$A_j = \sum_{k=1}^{N} a_k \cos 2\pi K_j/N$$

$$B_j = \sum_{1}^{N} a_k \sin 2\pi K_j/N$$

$$S_j = A^2_j + B^2_j \qquad (11)$$

The method provides N non-redundant frequency samples from N time samples thus requiring that N^2 multiplications be done per complete spectrum. It is usually admitted that 500 time samples are fairly representative of the spectral information in a time signal, requiring that 250,000 multiplications be done for each conventional Fourier transform. With modern fast digital computers the computing time will be on the order of, or less than, one second which is comparable to the signal dwell time required to build an acceptable knowledge of the spectrum. Therefore real-time digital computations by conventional Fourier algorithms are, at least, as effective as the filter bank method. In addition, the digital computer offers complete flexibility in the choice of appropriate frequency filter characteristics and the frequency coverage which is controlled by the signal sampling rate. See Blackman and Tukey (1958). Since it is based on the unambiguous Fourier transform mathematical expression, the digital frequency analyzer provides a well-defined answer for the spectral density estimate which is easier to use in the analysis of the data.

The use of fast Fourier transform algorithms decreases the required number of multiplications to 2 N $\log_2$ N instead of N^2. This will considerably reduce the computation time to much less than signal dwell time and thereby making it feasible to process several radar ranges in a time less than a few seconds. This involves the use of a high speed, elaborate system for multiplexing, and analog-to-digital conversion, of the Doppler signal. It also requires core memories which are organized in such a way that the sequence of the Fourier transforms can be easily computed, range after range, from the stored digital data. Such systems can be built at an acceptable cost by use of modern integrated circuit digital hardware. The expected maximum rate of data which can be processed by the system is on the order of 2,000 (20 ranges, 50 velocities) samples every two seconds. By use of a logarithmic scale only one BCD coded character will be necessary to represent the spectral density at a given range-velocity address. The storing of the Doppler data with range-velocity addresses will be done on magnetic tape with a format compatible with the requirement of general purpose digital computer (BCD format suitable for Fortran IV programming). Figure 6 illustrates the capabilities of the digital method for reducing and even presenting a three-dimensional display of the Doppler radar information. Such displays can be obtained in very short times by use of output devices usually associated with large computers.

The system is capable of processing signals recorded at an average speed of 10 to 20 spectra per second, which is compatible with the scanning capabilities of the radar beam and signal dwell time requirements (one or two beam width per second).

Let us inquire if the method has an acceptable observational speed to define convective storm processes known and anticipated. The evaluation of the number of points, which are needed to adequately sample the field of particle motion inside a convective storm, depends on the scale of the motion variance and the size of the storm. Although this information has to be acquired through actual experiments yet to be performed, it is reasonable to accept a few hundred meters as an appropriate space sampling interval.

This estimate is consistent with the radar angular resolution for nearby storms. If we analyze the problem in terms of the radar polar coordinates we will deduce that, (with a one degree beam width) an adequate description of the storm will be obtained with approximately 50 beam-widths in azimuth and 10 to 20 elevation angles. Assuming as mentioned before that the beam will stay in a fixed position for a time on the order of 0.5 second i.e., 20 to 30 spectra will be processed in one second, the total time required for exploring the storm will be on the order of 250 to 500 seconds or 4 to 8 minutes. This is marginal since the storm will be translating and evolving during this time. This effect can, however, be accounted for in the computation of radial velocity field estimates.

It is important to note that the rate at which the Doppler data are acquired and stored can be increased well beyond the limits expressed above. The expected availability of large scale integration (LSI) digital hardware along with the increasing speed capability of integrated circuits can increase the data acquisition rate expressed above, by one order of magnitude. The capability of the system will still be limited to the scanning speed capabilities of radar antennas, although this, too, might ultimately be overcome by the development of electronic beam scanning techniques; but, isn't it dreaming??

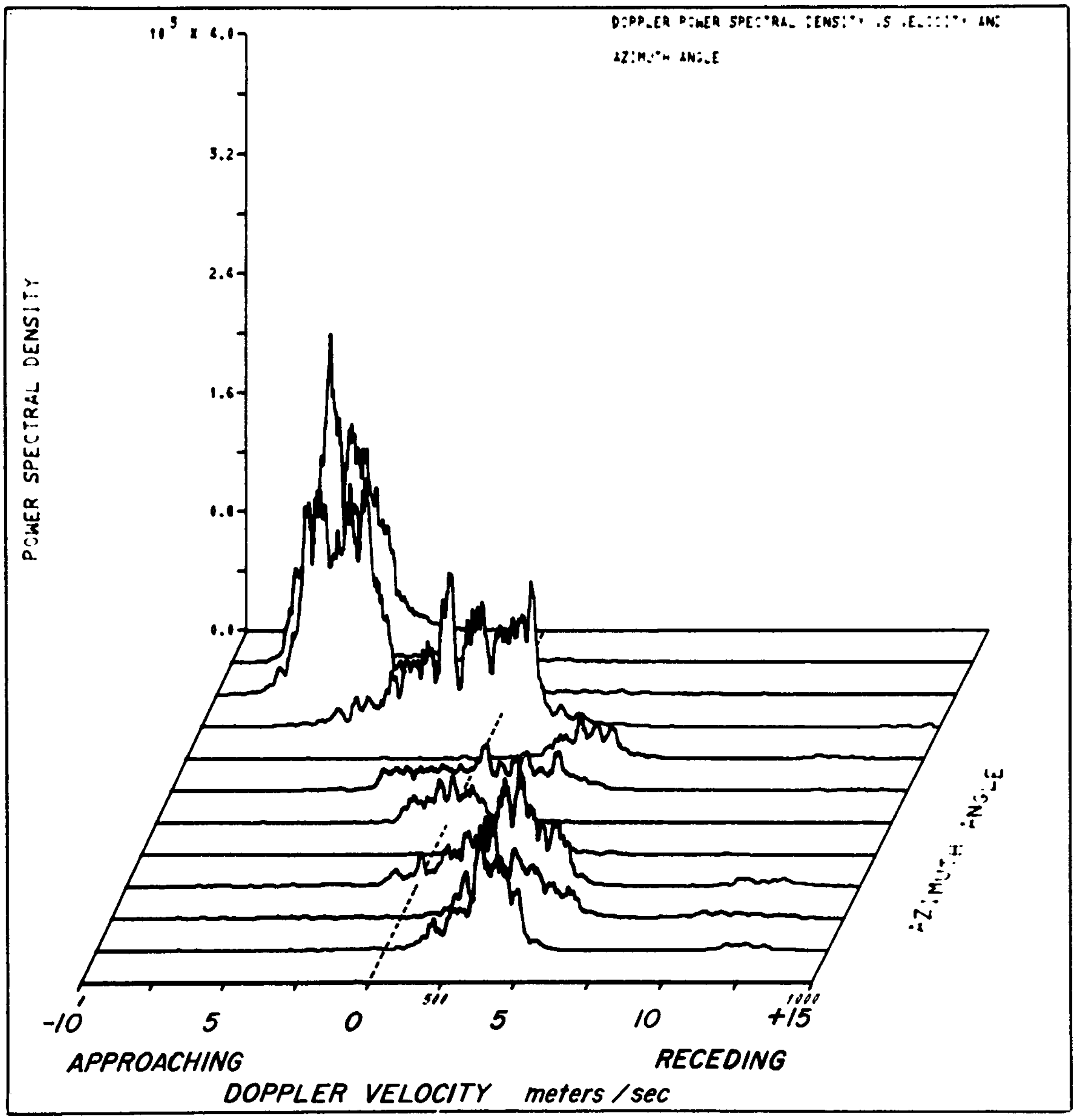


Figure 6. Three dimensional display of Doppler-azimuth patterns obtained with the cathode ray tube plotter of a CDC 3800 digital computer.

9. THE THREE DOPPLER RADAR METHOD

As mentioned in the previous section of the report the real weakness of the Doppler radar method is that it only provides the scatterers radial velocity. Since the vertical beam method is sensitive only to particle vertical velocity, it is less ambiguous and in the case of marked stratification, very useful. But, the method fails to exploit the outstanding capability of the radar, i.e., its ability to acquire data distributed in three coordinates of space. The observation of particle vertical velocity along a vertical coordinate is hardly respresentative of the storm processes except in the case of stratiform storms.

The use of a single radar scanning beam is useful and effective if assumptions about statistical homogeneities of particle motion in the region covered by the radar can be accepted. The most commonly employed scanning scheme is based on continuous azimuth scanning of the radar beam with a programmed elevation angle (VAD). The method, which was discussed in section 5 of the report, has an extremely good potential for the study of the dynamics of widespread storms by providing separate estimates of the mean properties of the horizontal wind field (magnitude, direction, convergence) and the vertical motion of the targets.

However, because of the absence of stratification and the non-uniformities of wind field, neither the vertical beam nor the VAD methods are applicable to observing the particle motion field inside convective storm systems. The understanding of the physical and dynamical processes involved in these storms fall in the most stimulating and unknown areas of meteorological research and have received a large attention from the meteorologist. However, progress on the study of storm dynamics has been slow mainly because of the lack of experimental data at the required scales. Theoretical work has always been limited to crude modeling far from the actual complexity of the storm's circulation patterns.

The main reason for this slow progress is the lack of appropriate means for observing the storm inner processes. The use of airplane as a means to acquire such data has been limited to a poor sampling of the storm environment since penetration of the storm was always questionable. Radiosonde networks have been useful to specify the condition of the storm environment and its link to the mesoscale or synoptic scale but, because of the techniques involved, they again provide only a poor time and space sampling far from the resolution required to adequately define the inner processes and evolution of a convective storm. Conventional radars have brought a much better understanding of the structure of the storm systems, which is still being developed, through the use of more elaborate quantitative processing of the radar signal.

As mentioned in section 6, the use of two Doppler radars, installed at different locations and simultaneously observing the same storm, drastically improves the capability of the single Doppler radar method. Figure 7 illustrates the concept. The same region of a storm is observed by two radars, R_1 and R_2, installed at different locations thereby providing two radial components of the particles' motion, V_1 and V_2. The two components, V_1 and V_2, can be expressed by the following equations:

$$V_1 = V_h \cos\alpha \cos\Theta_1 + (V_t + w)\sin\Theta_1 \tag{12}$$

$$V_2 = \cos(\beta_1 + \beta_2 - \alpha)\cos\Theta_2 + (V_t + w)\sin\Theta_2 \tag{13}$$

In these equations β_1 and Θ_2 respectively are the azimuth and elevation angles for R_1; β_2 and Θ_2 respectively are the azimuth and elevation angles for R_2; V_h is the horizontal motion speed; α is the azimuth angle between the direction of the motion and β_1; $V_t + w$, the particles' vertical velocity (V_t is the terminal speed and w the air vertical motion). If the contribution to the Doppler due to vertical motion can be neglected, i.e., $(V_t + w) \sin \Theta \simeq 0$, equations (12) and (13) can be solved for V_h and α according to the following expressions:

$$V_h^2 = \frac{1}{\sin^2(\beta_1+\beta_2)}\left[\frac{V_1^2}{\cos^2\Theta_1} + \frac{V_2^2}{\cos^2\Theta_2} + \frac{2V_1V_2\cos(\beta_1+\beta_2)}{\cos\Theta_1 \cos\Theta_2}\right] \tag{14}$$

$$\tan\alpha = -\frac{1}{\sin(\beta_1+\beta_2)}\left[\frac{V_2}{V_1}\frac{\cos\Theta_1}{\cos\Theta_2} + \cos(\beta_1+\beta_2)\right] \tag{15}$$

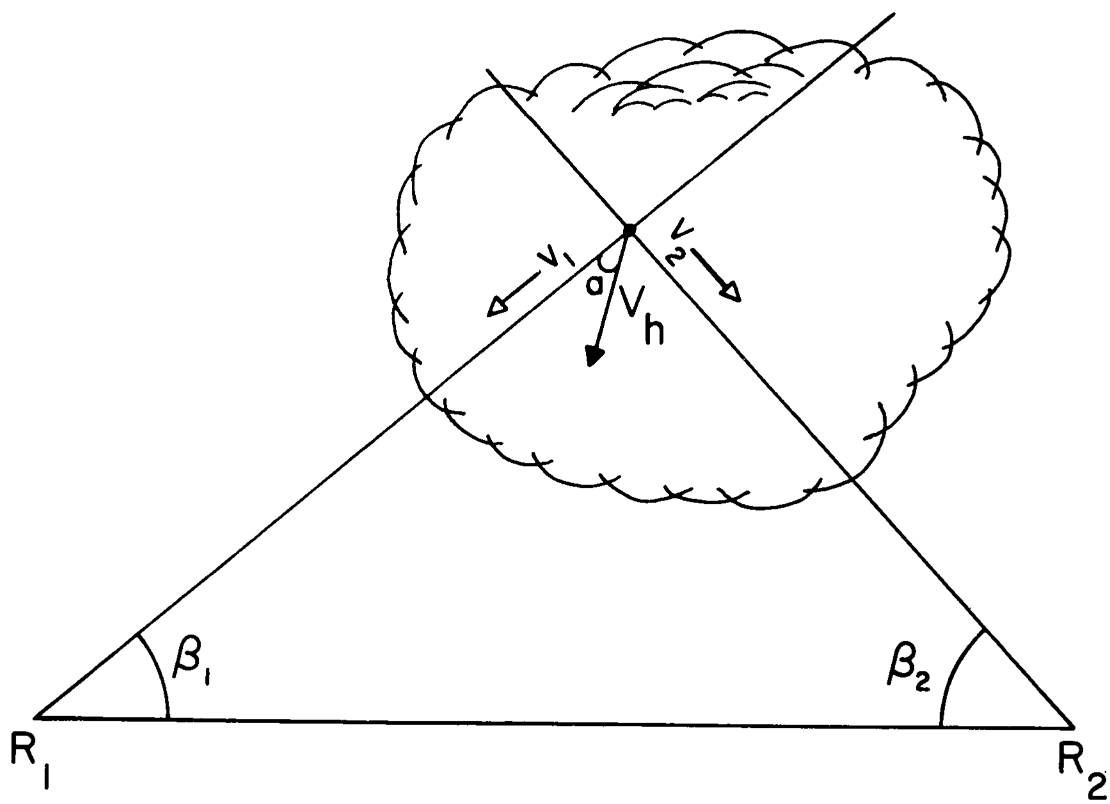
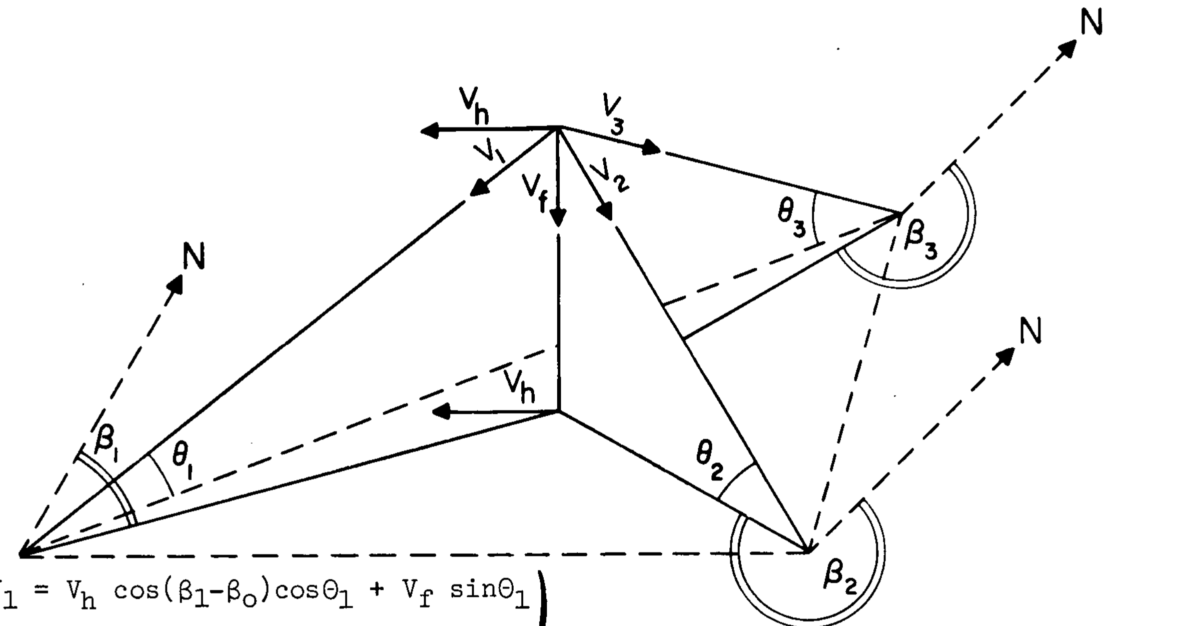


Figure 7. Measuring two-dimensional horizontal particle velocities by use of two Doppler radars observing the same storm from different directions.

The optimum spacing between the two radars depends on their characteristics but it is on the order of 20 to 60 kms.

The method offers excellent potential for mapping the particles' horizontal motion field inside convective cells for nearly horizontal radar beams. However, radar beam elevation angle smaller than 5° to 10° can be accepted in the scheme allowing the observation of the horizontal motion field up to altitudes on the order of 10,000 to 15,000 feet. The only assumption which is needed is to neglect the contribution due to particles' vertical motion. For targets which are outside of the line of sight between the two radars, the method offers accurate and non-ambiguous results which should clearly reveal convergence and vorticity patterns in the low levels of a convective storm.

If assumptions about the terminal velocity of the particles are adopted, the method can be extended to observations from larger elevation angles for which a significant contribution to the Doppler, due to the particles' vertical velocities, is likely. The method is also capable of providing estimates of the vertical air motion from convergence estimates made at several altitudes.



$$\begin{cases} V_1 = V_h \cos(\beta_1-\beta_o)\cos\Theta_1 + V_f \sin\Theta_1 \\ V_2 = V_h \cos(\beta_2-\beta_o)\cos\Theta_2 + V_f \sin\Theta_2 \\ V_3 = V_h \cos(\beta_3-\beta_o)\cos\Theta_3 + V_f \sin\Theta_3 \end{cases}$$

$$V_f = V_t + w$$

$$\underline{\text{w estimated from}} \quad \frac{\partial w}{\partial z} = - \left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right]$$

Figure 8. The three-Doppler radar method

Although it is a reasonable step towards the design of more elaborate systems, the dual Doppler radar method described above fails to provide useful horizontal wind information for targets situated on the line of sight between the two radars. It does not provide a complete knowledge of the three-dimensional field of the V_x, V_y, V_z components of the storm's particles' motion. This objective may be achieved from data collected by a well designed system of three Doppler radars, installed at three different locations which simultaneously observe the same convective storm. Figure 8 illustrates this concept and shows that the radial velocity at a given point in space can be observed from three different directions. The system of three equations indicated in Figure 6 provides the basis for computing the value of the three components of the motion. Therefore, by combining the radial velocity information provided by the three Doppler radars, it is indeed possible to isolate and evaluate the three dimensional distribution, in Cartesian coordinates x, y, z, of V_x, V_y, V_z. This information can be sampled periodically provided that the storm is within the maximum range of the equipment. The time and space sampling capabilities are discussed below.

As an example of the unique capability of the method, the three dimensional field of particles' motion can be analyzed in the following manner:

First, it is assumed that precipitation particles are moving in the same direction and at the same speed as the horizontal wind. This assumption is valid except when particles are falling in regions of strong wind shear which might introduce a lag of the particles' velocity with respect to the environment. This effect is negligible for most of the precipitation particles; large hailstones are a marginal case. If we accept the above assumption, the particles horizontal motion field may be taken as that of the horizontal wind. The mean speed (first moment of the velocity spectrum) must be computed to provide basis for interpreting the two dimensional field. Theoretically, the estimated horizontal motion components do not include the variance due to particles' vertical speed distribution. The data are sorted according to their x, y and z coordinates evaluated from radar polar coordinates R, β and Θ. The two dimensional estimates of the two quadratic components u and v of the estimated "wind" can then be defined at selected altitudes in the storm. The application of the equation of continuity, within the assumption of incompressibility, to the horizontal wind field, identified convergence with the estimates of air vertical velocity gradients, $\partial w/\partial z$. By integrating $\partial w/\partial z$ with suitable boundary conditions, it is possible to estimate, not only one vertical updraft profile, but the complete structure of updrafts inside the whole storm. Details on the structure of updrafts will be controlled by the sharpness of the velocity gradients and the inherent velocity resolution of the radar equipment.

Comparison of the updrafts structure with the three dimensional distribution of the particles' vertical velocity (and its spectrum) which is derived simultaneously from the Doppler data, provides knowledge of the distribution of particles' terminal speed within the storm. This, in turn, provides means for defining, in any region of the observed storm the precipitation particles' terminal velocities and therefore their size distribution. The method has obvious application for the monitoring and study of such important processes as hail formation; its use should provide significant improvement of our knowledge of convective storm processes and provide a firm basis for a more efficient control of their behavior.

The three Doppler radar concept is far more complicated than the usual weather radar systems presently used in meteorological research. It can operate effectively only if efficient digital computer means are used to process the data. The Doppler information must by necessity be stored in a digital format compatible with computer use.

It is impractical and time consuming for the systematic scanning of a storm to restrict the Doppler observations obtained at a given time, to the intersection of the three radar beams in space. Indeed, when the radar beam is aimed in a fixed direction, a large number of ranges can be simultaneously processed therefore adding to the Doppler information with respect to that provided by only one selected region. It is more appropriate that the radial velocity data provided by the three radars be acquired and processed separately, thereby leading to separate estimates of the three radial velocity fields. Since the process of scanning the storm will take an appreciable time, time-space interpolation techniques will be necessary to express the radial motion fields at the same time.

Radar beam scanning systems capable of systematically and automatically acquiring the Doppler data in limited angular regions controlled by the storm position with respect to the radar, are required for efficient use of the method. Digital control of a stepping radar beam must be preferred, as means for providing data easier to manipulate with digital computers.

The proposed method might seem to be difficult to implement because of the three-Doppler radar logistic problems involved. Let me make a few comments.

The velocity resolution of a well designed Doppler radar is sufficient to provide acceptable accuracy for estimating convergence or vorticity. If the radar beams are less than 1^o, their cross section at distances of less than 50 kms ($\leq$ 800 m), will not seriously limit the value of the data and the experiments. Velocity ambiguities can be removed through assumption of continuity of the velocity field therefore providing large nonambiguous maximum ranges. Real-time processing of the data by digital computer in the field will bring serious logistic problems and might be beyond our present capabilities. They can be replaced by the processing, by a large computer, of the data stored on magnetic tape. The use of digital computer is recommended as providing objective methods for filtering, interpolating, and redigitizing the estimated least square field. In order to minimize the problems involved in directing three radar beams at the same time, to the same point in space, it is suggested that the X, Y, Z distribution of three radial velocity fields be separately estimated.

After the three radial velocity fields estimates are digitized in a three dimensional coordinates system common to the three radars, their combination in a set of equations aimed to restore the three components of the motion (and their spectra) will generate the X, Y, Z fields of the three components of particle speed discussed above.

It might be objected that the proposed scheme of three radars is much more sophisticated than the degree of complexity presently used in meteorological radar research. It really is, but it is still far from being as sophisticated as some military radars and certainly can be built at an acceptable cost. The approach to this objective is to design two mobile, low cost, radar prototypes using a wavelength leading to acceptable antenna size (X-band). The testing of these equipments in the field with appropriate Doppler signal recording systems will provide knowledge of the capabilities of the method and open the way for the three radar scheme.

Because of the unusual opportunities of the method and its unique potential for the study of three dimensionally distributed atmospheric phenomenon (such as convective storms), it is hoped that its implementation will represent the most significant contribution of Doppler radar techniques to the field of meteorology.

10. AIRBORNE PULSE DOPPLER RADAR

Ground-based equipment often suffers from lack of mobility e.g., when the observations require that the radar equipment be in close proximity of storms sparsely distributed over large areas. The airborne platform has the required mobility and can be used to analyze convective storm processes by pulse Doppler radar methods.

A vertical pulse Doppler radar beam can be carried by an airplane for the purpose of analyzing the observed vertical motion in a convective storm. The capability of the method is different from that of a ground-based vertically pointing Doppler radar, because the airplane can fly at a speed that is much higher than the storm motion. This capability would permit the vertical velocities of the storm particles to be observed and displayed in vertical cross section as the plane traverses the storm. Furthermore, this scheme could be repeated several times during the life of the storm therefore leading to an estimate of the three dimensional structure of particle vertical velocity. If medium ceiling airplanes are used, the scheme requires that the airplane fly through the storm, which is not applicable to the study of severe storms. However high-ceiling airplanes will have the capability of flying above the storm in regions where flight is not dangerous. The scheme was first proposed by Atlas (1962)*. Logistic and technical problems were involved in the approach, which prevented actual experiments from being conducted. Since then, Doppler radar techniques have improved to the point that it is now feasible to consider that an airborne pulse Doppler radar can be developed at reasonable cost with acceptable chances of success. The magnetic tape recording of the signal aboard the airplane simplifies the scheme, and permits data acquisition techniques which are identical to the ones used by ground-based equipment.

The method can be extended to analyzing the wind field structure inside the storm by means of a side looking radar. Lhermitte and Weickmann (private communication) recommended that two airplanes, flying horizontally along perpendicular paths could look at the same storm, thereby providing the two components of the horizontal particle motion at flight level. This information will allow the estimate of the horizontal motion field, from which estimates of wind convergence can be derived. Slight tilt in the vertical plane of the side-looking radar beams, could provide some altitude scanning. This would allow the observation of the wind at different altitude levels without impairing the data by introducing significant vertical contribution due to the particle's velocities.

The airborne pulse Doppler radar scheme is particularly suited to the study of convective storms. The cost involved in conducting a feasibility study of the method can be held at a reasonable level by utilizing the techniques identical to these proposed for ground-based Doppler radars. Some of the problems related to the stability of the airborne platform can be solved by classical means or even by proper recording of the directional information for the radar antenna. The airplane is flying at a high speed (50 to 200 m per sec) therefore requiring that the beam be accurately perpendicular to the airplane motion. Smearing of the Doppler by the combination of the airplane's motion and the finite size of the beam will always occur. This effect can however be held to acceptable limits if the antenna width in

*Private communication

the direction of the flight of the airplane is less than 1°. In view of the indicated potential it is therefore recommended that such studies be undertaken in the next few years.

11. CONCLUSION

It is hoped that this review of the applications of pulse Doppler radar techniques to the observation and study of atmospheric phenomena, has adequately demonstrated their excellent potential for solving urgent meteorological problems such as the monitoring and study of processes inside convective storms.

The present method of a ground-based single Doppler radar, with limited signal processing capabilities, suffers from two main weaknesses: (1) only the targets' radial velocity is observed; (2) the signal processing and attainable data reduction techniques fall far short of taking full advantage of the information pertaining to three dimensional fields of motion.

The opinion of the writer is that the subject of meteorological Doppler radars should be enlarged by extending the method to more sophisticated concepts, such as the design and application of a three Doppler radar technique assisted by adequate means for digital recording and processing of the Doppler spectrum. If we do so, the method will provide outstanding results in the study of currently undetectable and poorly understood meteorological phenomena such as convective storms and atmospheric turbulence.

Of course we should not forget that single Doppler radar techniques can also be used to improve the capabilities of conventional radar for the detection, monitoring, and tracking of storms.

The monitoring of hurricane evolution for instance, should be strengthened by continuous observations of the particle radial speed with a horizontal radar beam. Tornadoes might be more easily detected if information on particle radial speeds is added to the information on radar reflectivity. In order to retain the scanning capability of the radars, these techniques should preserve the two-dimensional display (PPI, RHI) of the information which is usual in conventional radar design. We therefore would recommend that radial velocity gating systems be used and that velocity contours be presented on PPI and RHI by use of appropriate methods.

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