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Meteorological Doppler Radar

R. Lhermitte

Conventional microwave radars have been widely used for the observation and study of precipitation systems since the early stages of their development. Indeed, microwave radars have become useful meteorological instruments for the observation of the three-dimensional structure of convective storms and for the monitoring of rainfall over large areas for hydrological studies. However, even though it provides continuous monitoring of the three-dimensional structure of storms and some estimate of their intensity from the observation of backscattered signal power, the conventional radar fails to reveal directly the kinematics of a convective storm. Since convective storms in the huge intertropical convergence zone contribute significantly to large-scale circulation and sometimes produce large damaging hail and tornadoes when occurring over land, the observation and study of their dynamics have been a very important goal to which continuous research efforts have been devoted in the past few years.

It was not until a decade ago that the application of Doppler techniques to meteorological radars was proposed. Doppler radars provide information on target movements, thereby allowing observation of particle velocities within storms. Since the horizontal velocity of precipitation particles is generally that of the surrounding air, it was expected that measurement of particulate motions would provide an effective means for observing horizontal winds inside convective storms.

The rate of change of the distance of a target from the radar produces variations of the backscattered signal phase, which can be interpreted as a

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virtual increase (for approaching motion) or decrease (for receding motion) of the signal microwave frequency and therefore can be used as means for sensing the particle's radial velocity. The Doppler frequency shift, f_d, is expressed by

$$f_d = 2f_0 \frac{v}{c} \qquad (1)$$

with f_0 the frequency of the incident radar signal, v the target radial velocity, and c the velocity of propagation of electromagnetic waves. Since the velocity of meteorological targets is limited to a very small fraction (10^{-8} to 10^{-6}) of the velocity of electromagnetic waves, the Doppler frequency shift is very small and must be measured by special techniques in which evaluation of the backscattered signal phase and its time variation is made each time a new radar pulse is sent to the target. This effective sampling of the received signal limits the maximum Doppler frequency shift that can be measured without ambiguity. Increasing the sampling rate to facilitate velocity measurements reduces the maximum unambiguous distance—limited by the available time between successive radar pulses—at which targets can be observed. The choice of a longer radar wavelength decreases the Doppler frequency shift for the same radial velocity and therefore increases the velocity coverage for the same maximum range.

The techniques required to measure the small Doppler frequency shift have been known for years, but their applicability to meteorological observations has been severely limited by the lack of appropriate means for processing the Doppler information coming at an unusually high rate from extensive storms. Precipitation has the form of distributed target, that is, numerous small scatterers distributed over large regions of space. The backscattered signal which is sampled at a given time after the radar-transmitted pulse is due to the contribution of a finite scattering region limited by the radar beam cross section and half of the length of the radar pulse in space. With microwave radars having a pulse length on the order of 1 microsecond, the radial extent of this scattering region is 150 meters. If the radar has a maximum range of 150 kilometers, 1000 of these regions can be selected by means of range gates for any position of the radar beam.

In each scattering region the backscattered signal is composed of a sum of individual scattering amplitudes, each having a Doppler frequency shift associated with the radial velocity of the scatterer contributing to that signal. Therefore, in each scattering region, a spectrum of frequency shifts (Doppler spectrum) which represents the statistics of radial velocities is observed. In the case of complete statistical independence between radial velocity and target size, the Doppler spectrum will represent the true distribution of the scatterers' radial velocities. The first moment of the distribution (mean Doppler velocity) can then be identified with mean airflow if the targets are moving at the surrounding airspeed, which is a reasonable assumption for the precipitation particles' horizontal motion. The spectrum width is related to the space variability of the target's motion in the scattering region. Since the backscatter signal selected at a given range is due to the linear addition of scattering amplitudes resulting from scatterers moving independently, a frequency analysis of the backscattered signal, selected at a given range, provides means for evaluation of the Doppler spectrum at this particular range. This processing can be done by frequency analysis of the selected signal, which must then be performed at a large number of selected distances within the maximum range (range gates) to take advantage of the radar range resolution and coverage. Conventional beam scanning techniques will then allow this operation to be extended to the three-dimensional region covered by the radar.

The development of the techniques required for the mapping and storing of this Doppler information in the form of either the Doppler spectra or the spectral moments is discussed in this short article. It will also be mentioned that the prospects for effective study of the dynamics of convective storms are much better if the observations are made by a dual Doppler radar system from which two radial components of the motion can be observed.

Doppler Signal Processing

The signal processing techniques required to observe and measure the small Doppler frequency shift have been known for years. However, the rate at which these operations must be done in the case of meteorological targets has been well beyond the capabilities of the analog techniques for signal frequency analysis available in the past. Fast Fourier transform operations done by on-line digital computers provide an appropriate and practically unlimited answer to Doppler signal processing requirements. These techniques are based on fast real time digitization of the radar signals, done sequentially for successive range gates. The digitized signals are subsequently processed by an on-line hardware digital computer. Two classes of processing systems have been developed: Fourier transforms of the signal, leading to the expression of the complete spectra and subsequently the spectral moments, and arithmetic processing of spectral moments alone without the Fourier transform operation.

The numerical Fourier transform of N samples C_k acquired as a function of time at each range gate can be represented by

$$C_j = \sum_{k=1}^{N} C_k \exp\left(\frac{-i2\pi kj}{N}\right) \qquad (2)$$

The C_k are the complex signal samples at equal time intervals and the C_j are complex frequency samples. This operation provides a number of spectrum estimates uniformly spaced along the Doppler frequency range which is limited by the radar sampling rate f_r (from $+f_r/2$ approaching, to $-f_r/2$ receding). For a 10-centimeter wavelength radar operating at a repetition rate of 1000 pulses per second, the corresponding velocity coverage is ± 25 meters per second. The conventional Fourier method requires that N^2 complex multiplications be performed for each complete spectrum. Therefore, the evaluation of Fourier transforms is usually done with a rational fast Fourier transform algorithm which makes possible a high computational speed.

Since it is practically observed that 256 time samples provide an adequate representation of a Doppler spectrum, the complete fast Fourier transform operation for each spectrum requires approximately 2000 complex multiplications and additions which can be easily performed in much less than a millisecond with parallel multipliers using standard speed integrated circuits. However, even if such a computational speed is not a challenge for hard-wired digital computers, the availability of a memory of substantial size for the storing of the digitized radar samples is still required to take advantage of that computational speed. If the samples are acquired at each range gate at a rate of 1000 per second (radar pulse

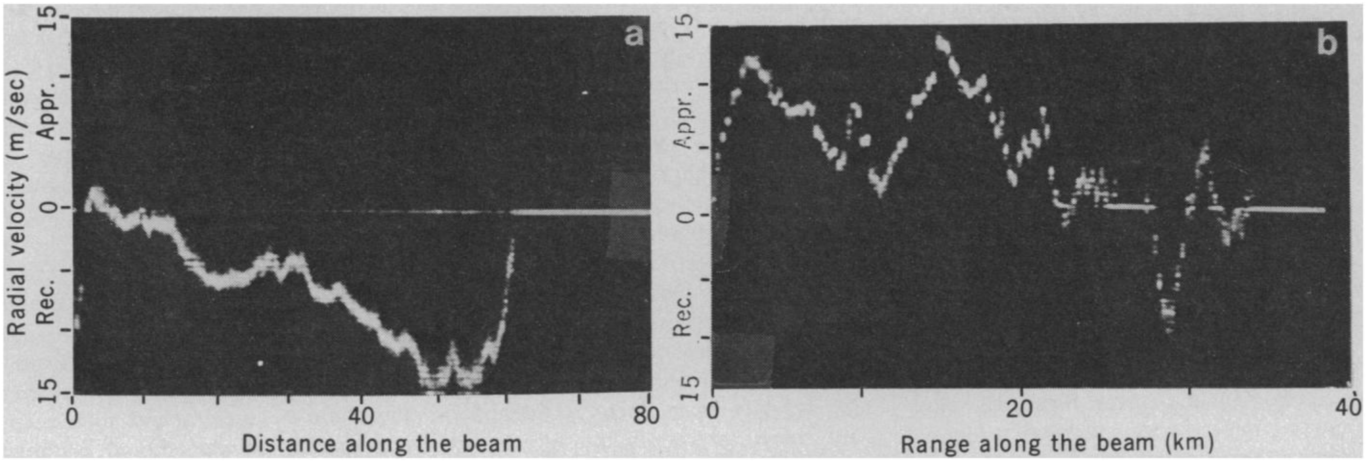

Fig. 1. (a) Radial velocity processed by a mean Doppler estimator at 256 range gates and presented as a function of radar range. The data were obtained in the Miami area (19 July, 9:25 a.m. EDST; at A, 283° and E, 00°) inside a widespread precipitation. Note the continuity of the pattern and the systematic increase of the velocity with distance. (b) Same as (a), but for data acquired inside a convective (19 July, 10:38 EDST; at A, 174° and E, 20°) storm. Approaching motion is above the zero line and receding motion below. Note the steep radial velocity gradients. A and E, respectively, are the azimuths and elevation angles of the radar beam; *Appr.*, approaching; *Rec.*, receding.

repetition rate), the computer can easily process 256 spectra during the time required to store the signal at one range gate. Therefore, digital signals should be stored simultaneously at 256 range gates to match the speed of the Fourier transform computer. This rate still does not duplicate the usual range resolution of radars (typically 1 microsecond between range gates), but even with this limited range resolution, the memory should have the capability of storing more than 65,000 complex samples (16 bits) so that the digital computing system can operate continuously. The recording of the computed spectra in long-range storage memory for further analysis is an even more difficult problem, since the computer provides frequency samples at a rate equal to that for time samples.

A substantial amount of velocity information is contained in the expression of only the first and second moments of the spectra. The selection of these spectral parameters allows mapping of the velocity information in three-dimensional space and therefore provides a useful presentation of the three-dimensional structure of the radial velocity field in the region which has been systematically scanned by the radar beam. If only measurements of the first and second moments of the spectra are desired, they can be obtained from estimates which do not involve the complete Fourier transform operation. Several estimators have been proposed which involve arithmetic processing of the signal and the accumulation of the processed signals in an integrator. A typical example is the evaluation of the complex autocorrelation function of the backscattered signal which is done simultaneously at all range gates. The complex radar signal is sampled and digitized in real time, and the signal complex autocovariance μ_{11} is evaluated at each range gate as given by

$$\mu_{11} = \frac{1}{N}\sum_{k=1}^{N} C_k C^*_{k+1} \qquad (3)$$

where C^*_k denotes the complex conjugate. C_k and C_{k+1} are successive complex time samples selected at the same range gate. The following quantity can be evaluated

$$\rho_{11} = \sum_{1}^{N} C_k C^*_{k+1} \Big/ \sum_{1}^{N} C_k C^*_k \qquad (4)$$

where ρ_{11} is essentially the signal autocorrelation function, $\rho(\tau)$, expressed at a time τ equal to the time between successive signal samples (radar pulse repetition period) acquired at the same range.

It can be shown that

$$\rho(\tau) = \rho_e(\tau)\exp(-i\,\omega_0\tau) \qquad (5)$$

where $\rho_e(\tau)$ is a real quantity defined by

$$\rho_e(\tau) = \int S(\omega - \omega_0)\cos\omega\tau\, d\omega \qquad (6)$$

with the condition that

$$\int S(\omega - \omega_0)\sin\omega\tau\, d\omega = 0 \qquad (7)$$

where $S(\omega - \omega_0)$ is the Doppler spectrum $S(\omega)$ shifted by ω_0.

Since $\rho_e(\tau)$ is real, $\omega_0 = \tan - 1\ B(\tau)/A(\tau)$ where $A(\tau)$ and $B(\tau)$, respectively, are the real and imaginary part of the sampled autocovariance function expressed in Eq. 3. It can be shown that for symmetric or narrow Doppler spectra, ω_0 is in fact the mean angular frequency. So if the method is applied to the processing of Doppler signals, the measured quantity is the mean Doppler frequency. If the spectrum is wide and asymmetric, there is a slight bias of the mean frequency estimate which can be specified if the spectrum shape is known. The expression (Eq. 3) can be easily evaluated at a large number of range gates by digital arithmetic processing followed by a recirculating shift register acting as an integrator. The second central moment (variance) which is related to the spectrum width can be processed in a similar way. The method, which offers a Doppler data processing rate limited only by the speed at which radar signals can be digitized, therefore represents a much awaited practical answer for the treatment of meteorological Doppler radar information. Figure 1, a and b, shows two examples of data obtained with such a method. It must be noted that the method allows the real time presentation of the radial velocity fields in the form of velocity contours.

Multi-Doppler Radar Method

A single Doppler radar equipped with the on-line processing systems mentioned above provides three-dimensional observations and mapping of only the radial velocities of precipitation particles. The method has been used for observing precipitation particles' vertical velocities with the radar beam pointed vertically so that particle size or air vertical velocity can be derived from the observed data. Horizontal wind can be probed by a method involving complete 360° scanning of a tilted radar beam, essentially providing different radial velocity components of the same wind, if the radar is inside a widespread precipitation system where the wind is horizontally homogeneous. These techniques are not applicable to the study of the structure and kinematics of localized convective storms, which basically requires the simultaneous use of several Doppler radars installed at different locations and observing the same storm. In this method the radar beams are cooperatively scanning the same region and thereby provide several radial components of the particle velocities, so that two- or three-dimensional velocity can be observed.

A dual Doppler radar system which provides two-dimensional velocity estimates is the first and most important step in this direction. In this method, two Doppler radar beams scan a common atmospheric region, a tilted plane intersecting the line joining the two radars. The tilt of the plane is controlled by a programmed relation between the azimuth and elevation angles of the radar beams. A set of such planes provides three-dimensional scanning of the region of interest. The planes must intersect the base line joining the two radars but can be on either side of that line, so that complete coverage of the three-dimensional space within radar range can be made.

At any point in a tilted plane, except on the base line joining the two radars, two different radial velocity components can be observed or derived from the radial velocity samples observed by the two radars. These two radial velocity estimates can then be used to compute the two-dimensional velocity vector at that point on the plane. For a small tilt of the plane, the vertical velocity of the precipitation particles does not contribute significantly to the observed Doppler velocity. For larger tilts, the mean terminal velocity of the particles, which is not directly related to any component of air velocity (velocity with respect to the air due to particle mass), must be estimated from simultaneous measurements of precipitation intensity. Removing the contribution due to terminal velocity from the observed radial velocities and assuming again that particles are moving at the airspeed leads to the expression of the components u', v' of the three-dimensional air velocity projected on the tilted plane. Inspection of the vector field will reveal patterns of convergence and vorticity of the observed motion field which can be used for descriptive modeling of kinematic processes. An example of this process is shown in Fig. 2.

Convergence of the motion field in the tilted plane can be evaluated quantitatively so that the velocity component w' normal to the plane can be evaluated from the equation of continuity for a noncompressible fluid:

$$\frac{\partial u'}{\partial x'} + \frac{\partial v'}{\partial y'} + \frac{\partial w'}{\partial z'} = 0 \qquad (8)$$

In this equation, x' and y', respectively, are rectangular coordinates parallel to and perpendicular to the base line. The use of the equation of continuity, which relies on steady-state kinematic condition in convective storms, is very important since it virtually removes the need for a third radar which would cause much more complexity.

The use of the dual Doppler radar method in conjunction with means for fast processing of the mean Doppler estimates such as those discussed above and also digital systems for the reduction of radial velocity fields in terms of the two-dimensional velocity estimates u' and v' is expected to bring a significant contribution to the observation and study of convective storms. On-line systems are now being developed which will automatically plot the velocity vector field and the signal intensity in real time.

A dual Doppler radar system using the above principles has been developed at the University of Miami, under a research grant from the National Science Foundation and additional support from the Office of Naval Research. The system is capable of observing the precipitation particle motion fields anywhere in an area 60 by 60 kilometers, with a resolution of approximately 500 meters. The mean Doppler and radar signal intensity data are stored digitally on magnetic tape and processed in the manner discussed above, so that vector plots of the motion field are obtained

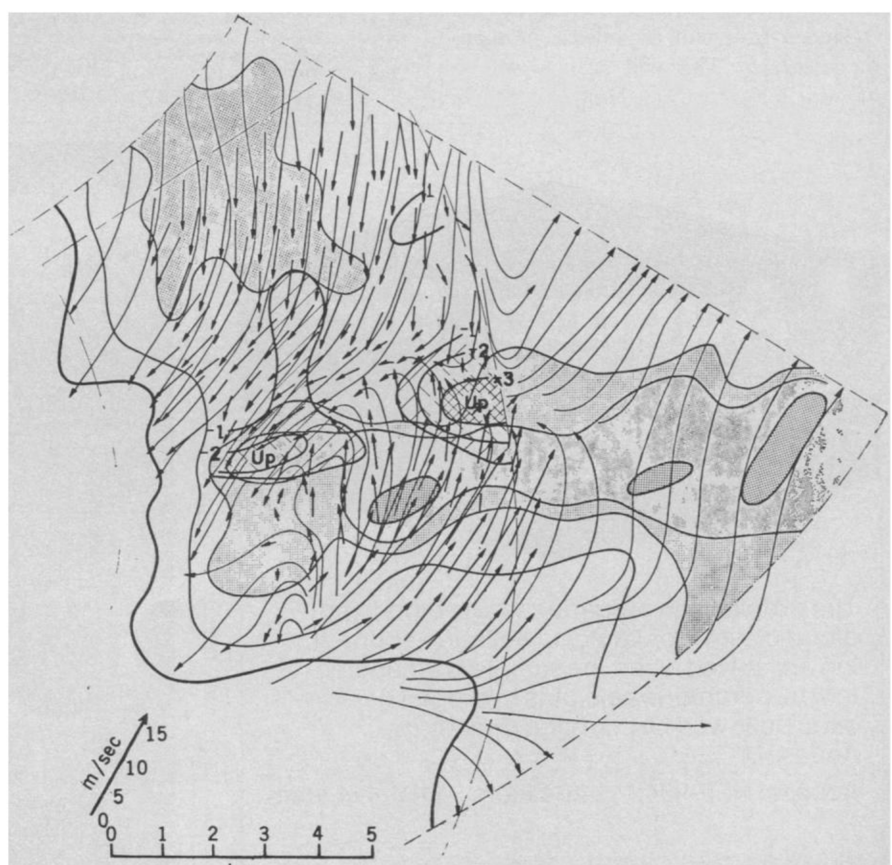

Fig. 2. Two-dimensional wind field observed inside a convective storm at a mean altitude of 400 meters by two Doppler radars located at two different locations. The arrows show the direction and speed of the motion. The solid line indicates the storm boundary and the shaded areas indicate regions of increased precipitation intensity. Note the position of the two updrafts marked *Up* which have been evaluated by applying the equation of continuity to the wind field observed in several planes. The numbers near *Up* are estimates of the magnitude of the updrafts in meters per second.

in the region covered by the radar. Dual Doppler radar systems are also being used and developed by the National Oceanic and Atmospheric Administration, the National Severe Storms Laboratory, and also by the National Center for Atmospheric Research in conjunction with the National Hail Research Experiment sponsored by the National Science Foundation.

The method offers a unique opportunity to observe the wind field in precipitating convective storms at all stages of their development. The probing of convergence/updraft structures inside the precipitation regions in a manner discussed above will allow better description and study of a storm's inflow and outflow. The presence of vorticity and its vertical transport can also be assessed. Suspected interactions between the circulation of adjacent convective storms can be monitored and studied. Mixing processes can be identified from Doppler spectrum width and related to the structure of the organized wind field.

In addition, it should be possible to extend the dual Doppler method to the storm environment by release of manmade targets. This will bring a wealth of new information about convective storms and, therefore, should provide a significant contribution to the study of intense small-scale convective processes.

Note

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