NOAA Technical Memorandum ERL WPL-146

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

A WAVEFORM FOR SHORT-DWELL-TIME METEOROLOGICAL DOPPLER RADARS

R. G. Strauch

Wave Propagation Laboratory
Boulder, Colorado
June 1987

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

NOAA Technical Memorandum ERL WPL-146

A WAVEFORM FOR SHORT-DWELL-TIME METEOROLOGICAL DOPPLER RADARS

R. G. Strauch

Wave Propagation Laboratory
Boulder, Colorado
June 1987

UNITED STATES
DEPARTMENT OF COMMERCE

Malcolm Baldrige,
Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

Anthony J. Calio,
Administrator

Environmental Research
Laboratories

Vernon E. Derr,
Director

NOTICE

Mention of a commercial company or product does not constitute an endorsement by NOAA Environmental Research Laboratories. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the tests of such products is not authorized.

For sale by the National Technical Information Service, 5285 Port Royal Road
Springfield, VA 22161

CONTENTS

A WAVEFORM FOR SHORT-DWELL-TIME METEOROLOGICAL DOPPLER RADARS

R. G. Strauch

ABSTRACT. A modulation waveform for meteorological Doppler radars that obtain estimates of radar reflectivity, mean velocity, and Doppler width with very short dwell time is described. The transmitted signal is a sequence of three identical chirp pulses; signal parameters can be estimated from the radar echoes of a single sequence with standard deviation similar to that of conventional meteorological radars that use dwell time more than an order of magnitude longer.

1. INTRODUCTION

Most meteorological Doppler radars transmit uniformly spaced pulses of a single radio-frequency (RF) carrier. The theoretical bases and the experimental methods for generating, transmitting, receiving, processing, and extracting Doppler parameters with this waveform are well known and widely used. This basic pulse Doppler radar waveform is reasonably suited for 10-cm-wavelength meteorological radars that use mechanically scanned antennas with large apertures. The maximum scan rate allows a dwell time that yields a sufficient number of independent samples for obtaining Doppler parameter estimates with the accuracy needed for most meteorological observations. For example, a 10-cm-wavelength radar with an 8-m-diameter antenna scanned at 20 deg s^{-1} can use a dwell time of about 50 ms and obtain 3-10 independent samples. All meteorological Doppler radars that use this basic modulation face range-velocity aliasing problems in large-scale precipitation systems. The product of unambiguous range (R_a) and unambiguous radial velocity ($\pm V_a$) is $\pm c\lambda/8$ for uniformly spaced pulses, where λ is the radar wavelength and c is the velocity of propagation. Because of the size of precipitation systems and the sensitivity of the radar, an unambiguous range of at least 150 km is desired, and this limits the unambiguous radial velocity to a value smaller than that of scatterers found in some precipitation systems such as convective storms.

The limitations of the basic pulse Doppler radar waveform become more troublesome as the radar wavelength decreases because these radars (typically 3 and 5 cm wavelength) can also detect precipitation at long range, so the range-velocity domain of precipitation scatterers is about the same as for 10-cm-wavelength radars while the product $R_a V_a$ is less. Methods used to alleviate (but not solve) the range-velocity ambiguity problem on research radars involve the use of nonuniformly spaced pulses. At the National Severe Storms Laboratory (NSSL), "interlaced sampling" (Doviak and Zrnic, 1984) is used to measure reflectivity with a large unambiguous range and to assign the velocity estimates, measured with high unambiguous velocity, to the correct range locations (Fig. 1).

Another technique, used by the Wave Propagation Laboratory (WPL) with its 3-cm- and 8-mm-wavelength Doppler radars, is "double pulse" or spaced-pair transmission (Campbell and Strauch, 1976) illustrated in Fig. 2. This waveform was proposed by Rummler (1968) in his development of the autocovariance or "pulse-pair" method of Doppler estimation. Estimation algorithms use the autocovariance at lags 0 and T_1. The double-pulse waveform allows some flexibility in matching the ambiguity properties of the waveform to the meteorology by spacing the time between pulses and the time between pairs of pulses (under computer control) according to the range extent of the meteorological echo or the antenna elevation angle. For example, as the antenna elevation angle increases from 20 to 90 deg, the spacing between the pulses of a pair can be

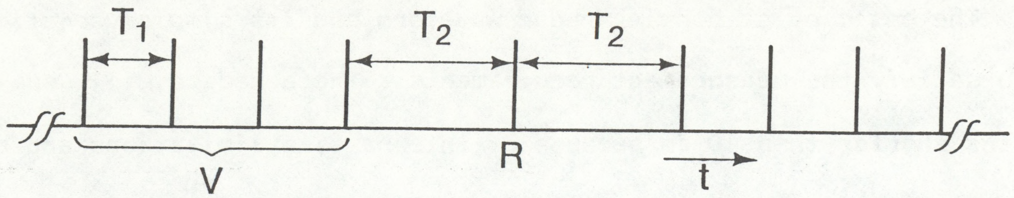

Figure 1. Interlaced transmission for separation of range and velocity measurements (used by NSSL). Velocity measurements are made with pulses separated by T_1; reflectivity is measured with pulse R.

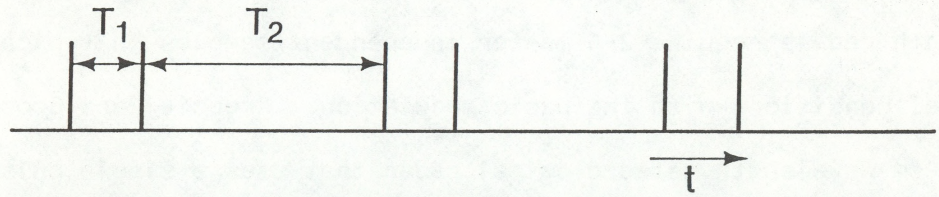

Figure 2. Spaced-pair transmission (used by WPL). Data obtained with consecutive pairs of pulses are independent.

reduced from 300 to 100 μs for precipitation systems with a maximum altitude of 15 km. This increases the unambiguous velocity from ±25 to ±75 m s^{-1} without range aliasing for a 3-cm-wavelength radar. The average duty cycle remains fixed if the spacing between pairs is unchanged. Note that if the range of interest is less than $cT_1/2$ and T_2 is large enough so that no echoes are detectable for $R > cT_2/2$, then the only range aliasing that occurs will cause signals from the first pulse to overlie signals from the second pulse. As discussed later, this degrades the Doppler estimates but does not bias them. If the range of interest is greater than $cT_1/2$, then signals from either pulse can overlie the signals from the other pulse but with a two-pulse sequence the overlaid echoes are always uncorrelated so the Doppler estimates are unbiased.

When the demands placed on the radar are increased, for example by increasing the scan rate of a ground-based or airborne system, an additional complication arises because the dwell time available for signal estimation is reduced. The basic pulse Doppler radar waveform and its simple variations are unable to satisfy the measurement requirements. These radars will usually have wavelengths shorter than 10 cm because of antenna size limitations and/or the need to control the antenna at very high rotation rates. The ambiguity problem must be faced and in addition, the reduced dwell time leads to very few independent samples with the basic pulse Doppler radar waveform. For example, 3-cm-wavelength radars require 2-6 ms for independent samples in typical meteorological conditions with the basic modulation. Krehbiel and Brook (1979) describe a 3-cm-wavelength meteorological radar that uses a single pulse of wideband noise to measure the reflectivity of meteorological targets; the bandwidth of the wideband noise that is transmitted determines the available range resolution and therefore the number of independent samples that may be averaged for a specified range resolution of the output data. This waveform is a type of pulse compression where the available range resolution is not used but rather data from adjacent range resolution cells are averaged to obtain a single estimate with coarser range resolution but with improved precision; the samples that are averaged from resolved range cells are independent so the precision is improved. This waveform enables the radar to map the reflectivity of the scatterers in the hemisphere around the radar in just 30 s, with a measurement uncertainty of 1 dB.

Two new meteorological radar systems that have been under study for the past several years are the airborne Doppler radar (Hildebrand et al., 1983) and the rapid-scan Doppler radar (Carbone and Carpenter, 1983; Keeler and Frush, 1983a). Both would require a waveform that can address the range-velocity aliasing problems and the problems posed by limited dwell time. The Doppler radar waveform described here is suited for both rapid-scan and airborne radar.

2. A WAVEFORM FOR VERY SHORT DWELL TIMES

A waveform that can be used with meteorological Doppler radars that must operate with very short dwell times, such as rapid-scan or airborne systems, is a sequence of three chirp pulses (Fig. 3) with variable time between pulses to match the measurement properties of the waveform to the meteorology. The three pulses have identical linear frequency modulation with sweep width B >> $1/\tau$, where τ is the pulse duration. This waveform combines the wideband pulse concepts of Krehbiel and Brook with the adjustable double pulse used with the WPL radars, and the separation of range and velocity measurements by interlaced transmission used with the NSSL radars. The dwell time is the time of transmission and reception of the three-pulse sequence T, or multiples of T if longer dwell times can be used. For a ground-based system the allowable dwell time depends on the antenna rotation rate and the antenna beamwidth; for an airborne system the motion of the platform must also be considered. For typical ground-based meteorological radar scanning, the antenna rotation rate is

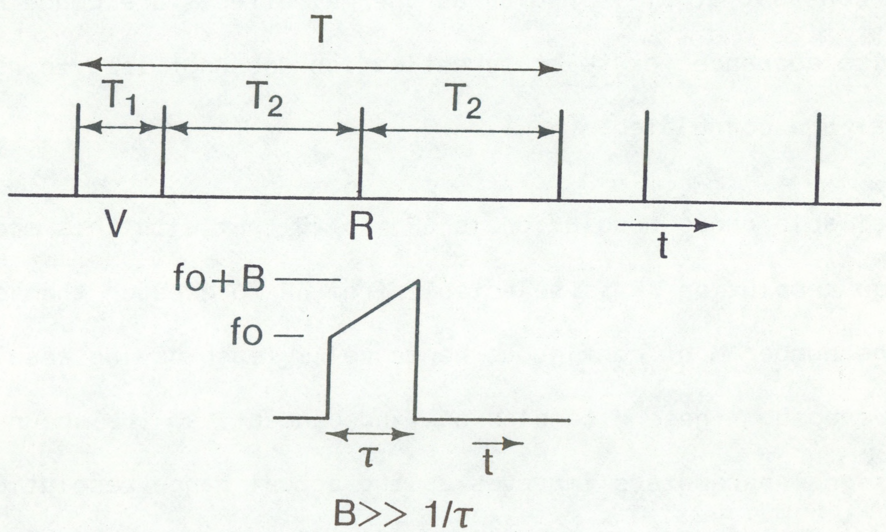

Figure 3. Chirp pulse sequence for rapid scan or airborne Doppler radar (top) and frequency modulation of each pulse (bottom). $T_3 = T_2$ for the basic three-pulse waveform.

about θ_2/T, where θ_2 is the two-way full beamwidth at half power. If a dwell time longer than T can be used, data obtained from the pulses transmitted during multiple intervals of T can be averaged to improve the estimation of signal parameters. This waveform allows a meteorological Doppler radar to scan a hemisphere in less than 1 min.

The first two pulses in the sequence are used to measure velocity; the third pulse is used to measure reflectivity. The spacing between pulses 1 and 2 (T_1) determines the unambiguous velocity $V_a = \pm\lambda/4T_1$. T_1 is selectable depending on the antenna elevation angle, radar wavelength, and the range and range extent of the meteorological system being observed. The interval T_2 following the second pulse allows time for distant echoes to clear the receiver, and the interval T_3 following the third pulse is the time used to measure reflectivity. The third pulse is centered between the second pulse and the start of the next sequence ($T_2 = T_3$) to maximize the unambiguous range interval for reflectivity $R_a = cT_2/2$. The transmitter duty cycle varies during the sequence but can be considered constant at $3\tau/T$ insofar as thermal effects are concerned. Again, the two-pulse sequence for velocity estimation does not lead to range-aliased signals that are correlated.

The available range resolution is $\Delta R = c/2B$, but with this modulation the actual range resolution $\overline{\Delta R}$ is selectable from ΔR to greater than $c\tau/2$ by choosing the number M of contiguous range cells (each having resolution c/2B) that are averaged. These M samples are independent, so the accuracy of the estimated signal parameters improves as the actual range resolution degrades. Reflectivity and velocity data can be treated independently in this tradeoff between range resolution and number of independent samples used for signal estimation. The number of independent estimates that are needed depends on the desired accuracy; the relationships between the number of independent samples and the variance of the measurements of signal power, mean radial velocity, and width of the Doppler spectrum are summarized by Doviak and Zrnic (1984). It is apparent that different tradeoffs can be made if the dwell time can be increased from T to multiples of T, because each three-pulse sequence yields M independent samples. Longer dwell time can be used to improve the accuracy of the estimates or to improve range resolution.

The M independent samples used to estimate signal parameters for $\overline{\Delta R}$ with reduced dwell time are obtained at a signal-to-noise ratio (SNR) that is reduced by M compared with a conventional pulse Doppler radar with resolution $\overline{\Delta R}$ and the same average transmitted power (Keeler and Frush, 1983b). However, if the SNR is greater than 15-20 dB, the variance of the estimate of Doppler spectral parameters is independent of SNR (Doviak and Zrnic, 1984). Therefore, at high SNR the three-pulse sequence of chirp pulses can yield estimates of Doppler parameters with lower standard deviation than a conventional Doppler radar with much longer dwell time. At low SNR the standard deviation of the estimates varies as $[(SNR)(M^{1/2})]^{-1}$; in this case the standard deviation of the estimates obtained with three chirp pulses increases by $M^{1/2}$ compared with a conventional radar that uses M independent samples obtained with longer dwell time because SNR is proportional to 1/M. Keeler and Frush (1983b) show examples of the tradeoffs between SNR and the number of independent samples.

As an example of a radar that requires short dwell time, consider an airborne X-band Doppler radar. Such a radar has been proposed for development by the National Center for Atmospheric Research (NCAR); a preliminary design (Hildebrand et al., 1986) was the subject of a September 1985 workshop. The waveform discussed here was suggested as an alternative to the waveform proposed in the preliminary design. The radar wavelength chosen for this airborne radar is 3 cm. A klystron transmitter tube with 0.006 duty cycle is available. The antenna will rotate much faster than is usual for meteorological Doppler radars, as fast as 60 rpm. The antenna has a diameter of 1.2 m and a half-power beamwidth of about 2 deg. The dwell time may be less than 5 ms, so the three-pulse sequence is chosen as follows:

T = 3 ms, to allow as many as 333 angular resolution cells to be scanned each second.

τ = 6 μs, to utilize the available average power of the transmitter.

T_1 is selected (under computer control) from 100 to 400 μs, resulting in an unambiguous velocity of ±75 to ±18.75 m s^{-1}.

T_2 therefore varies between 1.45 and 1.3 ms so the unambiguous range for reflectivity varies from 217.5 to 195 km.

Suppose the range resolution required in the output data is 300 m; the pulse length is 900 m, and a transmitted bandwidth is chosen to alow 20 independent range samples to be averaged. For M = 20, the sub-resolution range cell is 15 m and B = 10 MHz. The time-bandwidth product is 60. The dwell time is 3 ms or multiples of 3 ms. The highest antenna rotation rate is determined by the two-way beamwidth (about 1.5 deg) and is about 500 deg s^{-1} with a 3 ms dwell time. This waveform allows mechanically scanned antennas to rotate at angular rates that are limited by the spectral broadening that is caused by a moving antenna. This broadening is given by $\alpha\lambda/10.7\ \theta_2$ (Nathanson, 1969) where α is the scan rate. In this example, the broadening is nearly 1 m s^{-1} for a 500 deg s^{-1} rotation. A 1 m s^{-1} broadening by antenna rotation is about the maximum value permitted without significant degradation of mean velocity and spectral width estimates. The chirp pulse waveform allows meteorological Doppler radars to take advantage of rapid scanning offered by electronically scanned antennas; in this example the hemisphere could be covered in 30 s with electronic scanning without spectral broadening caused by a moving antenna.

A special mode is also available for $T_1 = T_2 = T_3 = 1$ ms. This mode allows measurements of the Doppler velocity spectrum with an unambiguous velocity interval of ±7.5 m s^{-1} by the periodogram or by autocovariance analysis with appropriate changes in data processing. It would be used for vertical pointing. Another special mode is possible by reducing the interval T_2 following the second pulse (and increasing the time T_3 between the third pulse and the start of the next sequence), so the signal remains well-correlated between pulses 2 and 3 as well as between pulses 1 and 2. This would be the equivalent of a dual pulse repetition frequency (PRF) mode for velocity measurements. The dual PRF mode can increase the unambiguous velocity (Sirmans et al., 1976). In the basic three-pulse sequence ($T_3 = T_2$) the time between pulses 2 and 3 is typically equal to or greater than the correlation time of the echoes, so this sequence could not be used for dual PRF observations. One operating strategy would be to alternate between a sequence that measures velocity and reflectivity (spacing = T_1, T_2, T_2) and a dual PRF sequence (spacing = T_1, T_2, T_3) for increasing the unambiguous velocity. Yet another modification of the basic waveform would be to select the number of sub-resolution cells that are averaged to match the range resolution to the cross-beam resolution, i.e., $(\Delta R)(M) = R\theta_2$. However, for M less than about 4 the limited number of independent samples would result in "noisy" estimates of velocity and reflectivity. The following discussions of measurement properties of the three-pulse chirp waveform are limited to the basic three-pulse sequence ($T_3 = T_2$).

3. REFLECTIVITY MEASUREMENTS

Reflectivity data obtained with a single chirp pulse (the third pulse of a three-pulse sequence) will be similar to data obtained with a wideband noise pulse (Krehbiel and Brook, 1979). There are $B\tau$ range resolution cells of length c/2B for each pulse duration; the number of range cells that are averaged can be selected from 1 to more than $B\tau$. Krehbiel and Brook averaged the power for the range cells corresponding to a pulse duration ($B\tau$ range cells). The number M of contiguous range cells that are averaged is selectable, and with the chirp waveform proposed here M could be more or less than $B\tau$.

The root-mean-square (rms) fluctuations of signal power in each range resolution cell are equal to the mean signal power (Doviak and Zrnic, 1984), and these fluctuations are reduced by the square root of the number of independent estimates that are averaged. The rms measurement uncertainty for reflectivity is therefore $\overline{P}/M^{1/2}$ where $\overline{P}$ is the mean signal power from a resolution cell. Reflectivity is assumed uniform throughout the range interval $\overline{\Delta R}$. (As noted by Krehbiel and Brook, this result holds for discrete independent samples in range as assumed here.) If the power estimates are from a logarithmic response reciever, the standard deviation of reflectivity estimates will be about $5.6/M^{1/2}$ dB (Doviak and Zrnic, 1984). About 20 independent estimates would result in reflectivity estimates with 1 dB standard deviation if signal power is averaged.

The unambiguous range for reflectivity data is $cT_2/2$. Although in principle T_2 can be made as large as needed to avoid range aliasing (without changing velocity aliasing), the total time of the three-pulse sequence ($T_1 + 2\,T_2$) determines the maximum antenna scan rate, so T_2 must be restricted. If the dwell time can be increased, then T_2 can be increased to increase the unambiguous range for reflectivity data, or data from consecutive three-pulse sequences can be averaged. The radar controller can be programmed to select T_2 according to the scan rate and antenna elevation angle.

4. VELOCITY MEASUREMENTS

The mean velocity and the width of the Doppler spectrum can be estimated from the 0th and 1st lags of the autocovariance of the signal obtained with just two pulses. As with reflectivity measurements, signals from adjacent range resolution cells are averaged to reduce the standard deviation of the estimates. The range resolution for velocity data need not be the same as for reflectivity data. The complex autocovariance at delay 0 and T_1, $R(0)$ and $R(T_1)$, is estimated for each range resolution cell with a single pair of pulses, and these autocovariance estimates are averaged for M range resolution cells before the mean velocity and spectrum width are estimated. M independent pairs of pulses are therefore used in the estimation of mean velocity and spectrum width.

The estimated mean velocity is $\hat{V} = \frac{\lambda}{4\pi T_1} \arg\,[\hat{R}(T_1)]$. The standard deviation of the estimate of mean velocity for M independent pairs of pulses is

$$\text{std. dev. } (\hat{V}) = \frac{\lambda}{4\pi T_1 \rho(T_1)} \left[\frac{(1 + N/S)^2 - \rho^2(T_1)}{2M} \right]^{1/2} \tag{1}$$

(Zrnic, 1977) where N/S is the noise-to-signal ratio for range resolution cells of c/2B, and $\rho(T_1)$ is the magnitude of $R(T_1)$. For a Gaussian Doppler spectrum,

$\rho(T_1) = \exp(-8\pi^2\sigma_v{}^2T_1{}^2/\lambda^2)$ where σ_v is the standard deviation of the Gaussian Doppler spectrum. The expression for the standard deviation of mean velocity estimates is valid for M large enough to satisfy

$$M \gg \frac{\lambda}{4\pi T_1 \sigma_v} \tag{2}$$

and

$$M \gg \frac{(N/S + 1)^2}{\rho^2(T_1)} \quad \text{(Doviak and Zrnic, 1984).} \tag{3}$$

For large S/N and narrow Gaussian spectra ($\sigma_v \ll \lambda/2T_1$), the standard deviation becomes approximately $\sigma_v/(2M)^{1/2}$ or about $\sigma_v/6$ for 20 independent pulse pairs. The general result [Eq. (1)] is shown in Fig. 4. For a 3-cm-wavelength radar with M = 20 and T_1 = 335 μs (V_a = ±22.35 m s^{-1}) the normalized errors (Fig. 4) are converted to std. dev. ($\hat{V}$) in m s^{-1} by multiplying by 10.

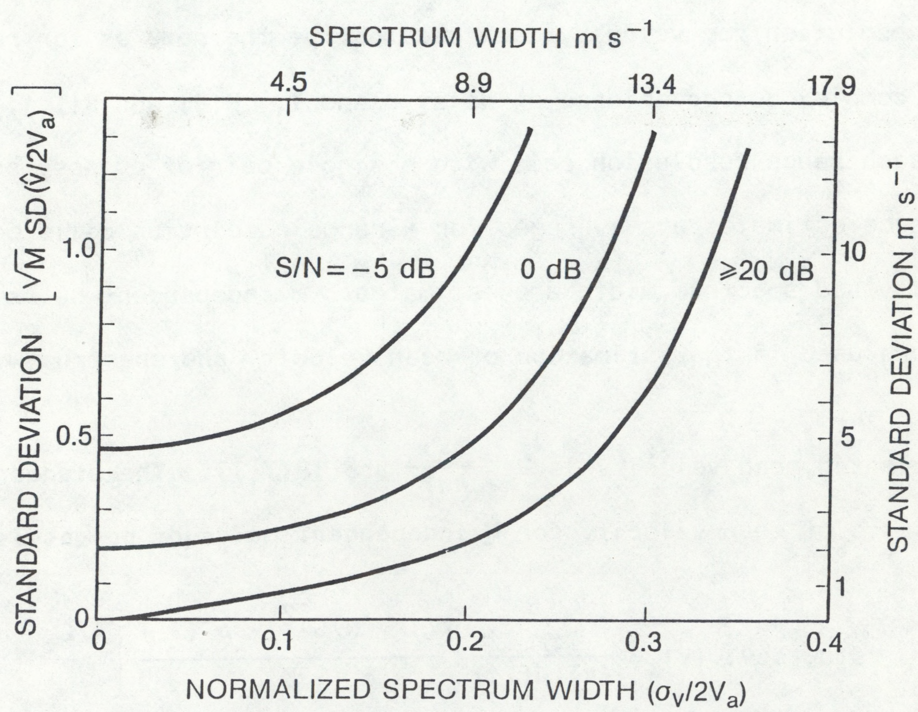

Figure 4. Standard deviation of mean velocity estimates obtained with M independent pairs of pulses. Left and bottom scales are normalized; top and right scales pertain to a 3-cm wavelength radar with T_1 = 335 μs and M = 20.

Figure 4 applies to both the chirp pulse sequence (where only two pulses are used to measure mean velocity and spectrum width) and conventional Doppler radars that use M independent pulse pairs. For the chirp pulses the SNR pertains to range cells with resolution c/2B, and M is the number of contiguous range cells that are averaged. As noted earlier, Fig. 4 shows that if the SNR of range cells with resolution c/2B is $\geq$ 20 dB, then the standard deviation of mean velocity estimates of M averaged range cells with two chirp pulses is the same as the estimates with a conventional Doppler radar that uses M independent pulse pairs with a much longer observation time. If the SNR for the chirp pulses is less than about 15 dB, then the longer observation time with a conventional radar yields lower standard deviation. However, the standard deviation of mean velocity estimates for two chirp pulses with M = 20, SNR = 0 dB and normalized spectrum width of 0.1 will be lower than the standard deviation of a conventional radar with the same observation time and SNR $\geq$ 20 dB. The standard deviation of the two chirp pulses used in the example of an airborne Doppler radar will be less than 1 m s^{-1} at high SNR in most precipitation (width $\leq$ 4.5 m s^{-1}).

The width of the Doppler spectrum can be estimated from

$$\hat{\sigma}_v = \frac{\lambda}{2\pi\sqrt{2}\, T_1}\left[1 - \frac{|\hat{R}(T_1)|}{\hat{S}}\right]^{1/2} \qquad (4)$$

(Zrnic, 1977) where $\hat{S}$ is the estimate of signal power, found from $\hat{S} = \hat{R}(0) - \bar{N}$. Different estimators can be derived for particular spectral shapes; the estimate given in Eq. (4) is an approximation that does not assume a Doppler spectral shape. The standard deviation of the estimate of spectrum width using M independent pulse pairs is given by

$$\text{std dev. } \hat{\sigma}_v = \frac{\lambda}{2\sqrt{2}\,\pi^2 T_1\, \sigma_N\, \rho(T_1)} \cdot \left[\frac{[1-\rho^2(T_1)]^2 + 2[1-\rho^2(T_1)]N/S + [1+\rho^2(T_1)]N^2/S^2}{M}\right]^{1/2} \quad (5)$$

(Doviak and Zrnic, 1984). σ_N is the normalized width of the spectrum $2T_1\sigma_v/\lambda$. Figure 5 shows the standard deviation for the estimate of spectrum width. Figure 5 also applies to both chirp pulses and conventional radars. The normalized errors can be converted to m s^{-1} for a 3-cm-wavelength radar with T_1 = 335 μs and M = 20 as shown in the figure. Again, the results expected with a single three-pulse sequence at high SNR are similar to those obtained with conventional Doppler radars that use longer dwell time.

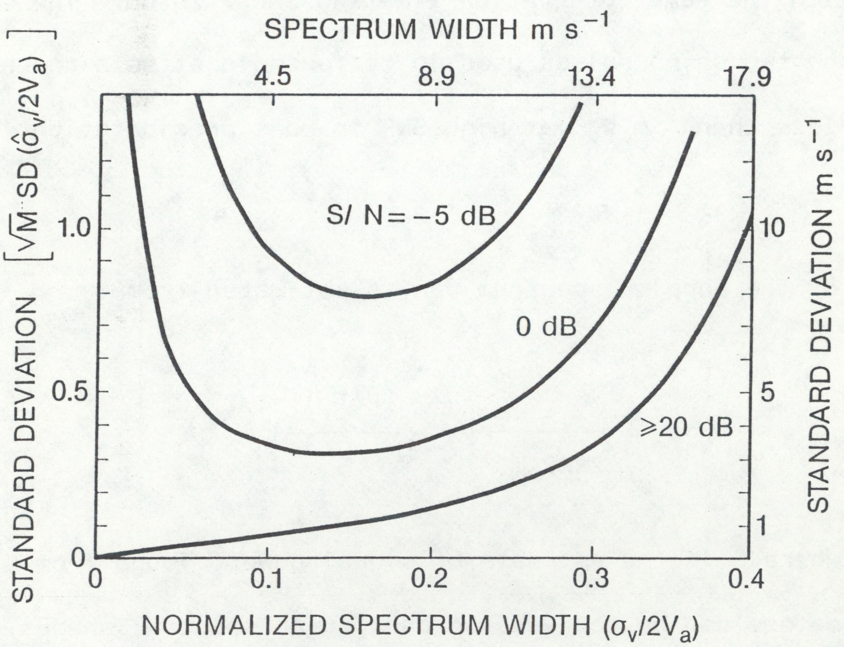

Figure 5. Standard deviation of spectrum width estimates obtained with M independent pairs of pulses. Left and bottom scales are normalized; top and right scales pertain to a 3-cm wavelength radar with T_1 = 335 μs and M = 20.

5. AMBIGUITIES FOR VELOCITY DATA

Range and velocity aliasing of velocity data can be understood qualitatively by examining the effect of aliased signals on R(0) and R(T_1) obtained with two pulses. The maximum range of meteorological echoes is assumed to be $cT_2/2$, and the range to echoes of interest for velocity data is assumed less than $cT_1/2$. Although the latter assumption would not always be valid, rapid scan and airborne Doppler radars are primarily short-range radars. Their angular resolution will be larger than conventional meteorological Doppler radars because they have small-aperture antennas that can be rotated at high rates. Therefore, starting at relatively short range (<60 km), cross-beam linear dimensions of the radar resolution cells will be much larger than the desired data resolution. Rapid scan capability is needed for Doppler radars at short ranges because the meteorological phenomena encompass a large solid angle. The airborne system is also a short-range system because it is able to operate in the proximity of the meteorological event.

As noted earlier, if T_1 is varied with antenna elevation angle, velocity aliasing is eliminated for a significant fraction of the solid angle around the radar. Furthermore, the unambiguous velocity can be extended by the dual pulse repetition rate method. However, for the basic three-pulse sequence, speeds greater than $\lambda/4T_1$ are likely. In this case, the ambiguous velocities have the same measured velocity as they would have when observed with a Doppler radar with uniform pulse spacing; that is, the measured velocity would be $V - (n\lambda/4T_1)$ where n is an integer that places the measured velocity between $\pm(\lambda/4T_1)$. Velocity ambiguities must be resolved by spatial and temporal continuity starting from known boundaries where data are not aliased; for the three-pulse sequence, continuity could be applied starting from high elevation angles where radial velocity would not be aliased.

Range aliasing occurs for echoes whose range is beween $cT_1/2$ and cT_1. If the range to the echo is between cT_1 and $cT_2/2$, there is no range aliasing problem because these echoes would not be observed in the assumed range of interest for velocity measurements ($R \leqslant cT_1/2$). Thus, the range-aliased echoes that cause problems in measuring velocity are those echoes from the first pulse that are received during the sampling for the second pulse; samples for the first pulse will not be contaminated with aliased echoes. The presence of range-aliased echoes can therefore be detected by comparing R(0) measured with the first pulse (for the M range cells that are averaged) and R(0) measured with the second pulse. If there is range aliasing with enough power in the overlaid echo to be detected, R(0) will increase for the second pulse. If range aliasing is detected, R(0) is found from the echo of the first pulse; if no range aliasing is detected, R(0) can be found from both pulses. The variance will be reduced at low SNR if both pulses are used to find R(0). Thus, the presence of aliased echoes may lead to an increase in the uncertainty of R(0) but not a bias.

Range-aliased echoes will also not bias $R(T_1)$ or mean velocity estimates because the range-aliased echoes found in the samples from the second pulse are uncorrelated with the samples from the first pulse. These uncorrelated echoes increase the standard deviation of the velocity estimates because they are effectively an increase in noise for the samples from the second pulse. Range-aliased echoes bias velocity estimates made with Doppler radars that transmit uniformly spaced pulses unless the aliased echoes are made incoherent by some technique such as changing the phase of the transmitter from pulse to pulse, as occurs with magnetron transmitters. If the aliased echoes are incoherent, they effectively increase the noise in all samples. Therefore, with conventional radars, if the aliased echo power is the same as the desired echo power, the signal-to-noise ratio is at most 0 dB and the standard deviation of the estimates of mean velocity and width is increased to about the limit of acceptability. In the three-pulse sequence, the aliased echo power can be somewhat greater before the estimates are degraded since the aliased echo power appears as noise in only one of the samples.

6. AMBIGUITY FUNCTION

The range and velocity aliasing characteristics of the two pulse sequences used to measure velocity can also be studied by the radar ambiguity function (Woodward, 1953). The radar ambiguity function $\chi(\Delta,\phi)$ shows the response of the radar to echoes whose time delay Δ and frequency shift ϕ differ from those of the echo of interest ($\Delta = \phi = 0$). For a two-pulse sequence,

$$\chi(\Delta,\phi) = e^{jn\pi\phi T_1}\, \chi_1(\Delta - nT_1, \phi)\, \frac{\sin(2 - |n|\; \pi\phi T_1)}{2\sin \pi\phi T_1}$$

for $n = 0, \pm 1$ and $|\Delta - nT_1| \leqslant \tau$.

$\chi_1(\Delta,\phi)$ is the ambiguity function for a single pulse, and for the chirp pulse is given by

$$\chi_1(\Delta,\phi) = e^{i\pi\phi\Delta}\, \frac{\tau - |\Delta|}{\tau}\, \frac{\sin[\pi(\frac{B}{\tau}\Delta + \phi)(\tau - |\Delta|)]}{\pi(\frac{B}{\tau}\Delta + \phi)(\tau - |\Delta|)}\, \text{rect}\, \frac{\Delta}{2\tau}$$

where

$$\text{rect } x = 1 \text{ if } |x| < 1/2$$
$$= 0 \text{ if } |x| > 1/2 \quad . \qquad \text{(Deley, 1970)}$$

$|\chi_1(\Delta,\phi)|^2$ is illustrated in Fig. 6. Figure 7 illustrates $|\chi(\Delta,\phi)|^2$ for the two-pulse sequence. Velocity ambiguities for echoes at the same range are located in the n = 0 strip in the (Δ,ϕ) plane. For n = 0 the ambiguity function is

$$\chi(\Delta,\phi) = \chi_1(\Delta,\phi)\, \frac{\sin 2\pi\phi T_1}{2\sin \pi\phi T_1} \text{ for } |\Delta| < \tau \; .$$

The velocity resolution is poor because the signal duration is only T_1; the ambiguity function describes the response for each range cell with range resolution c/2B. Averaging data from M independent pairs of pulses from contiguous range cells effectively increases the signal duration to MT_1, just as when data from independent pairs of pulses obtained from the same range cell with uniformly spaced pulses are averaged. Thus the averaged velocity data with range

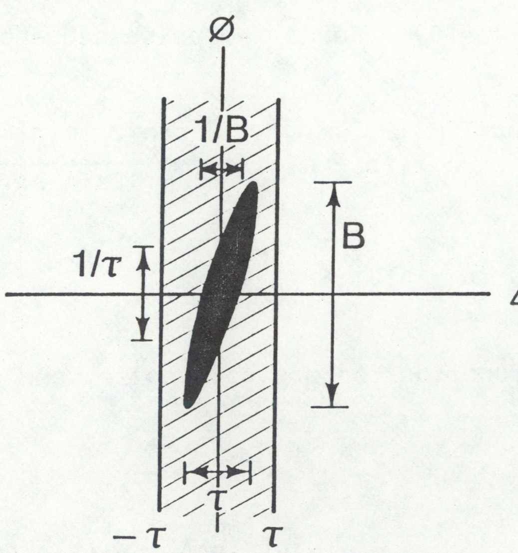

Figure 6. Ambiguity diagram for a single chirp pulse. Dark area represents region where targets are not resolved. Shaded area represents region where unresolved targets have lower response. Clear area represents regions where targets are not observed.

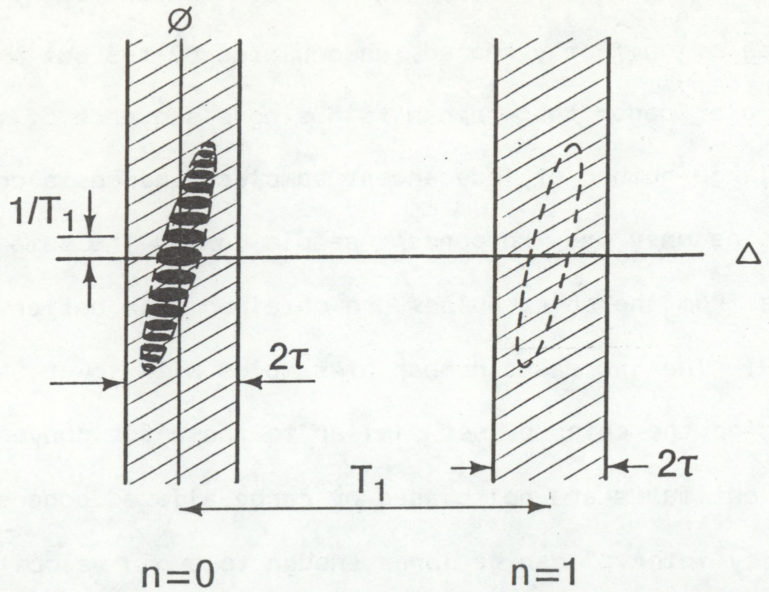

Figure 7. Ambiguity diagrams for a pair of chirp pulses when the maximum range of interest is $cT_1/2$. n = 0 represents region where targets are at the same range but velocity may be ambiguous. n = 1 represents range-ambiguous region. Range ambiguities corresponding to n = -1 are not observed if the maximum range of interest is cT_1.

resolution $\overline{\Delta R}$ have velocity resolution $\sim\lambda/2MT_1$. Range ambiguities correspond to n = ±1. However, if we restrict the maximum range of interest to $cT_1/2$, only the ambiguity for n = +1 will be observed. For n = +1, the ambiguity function is

$$\chi(\Delta,\phi) = \frac{\chi_1(\Delta - T_1,\phi)}{2} \text{ for } |\Delta - T_1| \leqslant \tau .$$

7. CONCLUSIONS

A sequence of three chirp pulses is a waveform that can be used for meteorological Doppler radars that require very short dwell time. At high SNR the measurement uncertainties of signal power, mean velocity, and Doppler spectrum width are shown to be equivalent to those of present ground-based Doppler radars that use a sequence of uniformly spaced, unmodulated pulses but a much longer dwell time. A Doppler radar that transmits a single sequence of three chirp pulses obtains a large number of independent samples, whereas a conventional radar usually obtains only one independent sample during the same observation time. The samples from the chirp pulses are obtained with better range resolution but lower SNR. The increased number of samples with lower SNR tend to make Doppler estimates for the chirp pulses similar to those for conventional Doppler radars. Velocity estimates are not biased by range-aliased echoes, and the unambiguous velocity interval can be large enough to avoid velocity aliasing at high elevation angles. The unambiguous velocity interval can be extended by an effective dual PRF mode that uses only three pulses. The chirp pulse sequence is versatile because pulse spacings and the number of contiguous range resolution cells that are averaged can be changed with antenna elevation angle or the meteorological situation. The price paid for the ability to obtain Doppler estimates at a very high rate is in the cost for the complexity and speed of data processing and, when the SNR is low, a small additional degradation of the accuracy of the estimates. The radar and data processing hardware needed to implement the chirp pulse sequence are available and are described in the literature (Purdy, 1977; Perry and Martinson, 1977).

Acknowledgments. The author gratefully acknowledges the careful review of this manuscript by Jeff Keeler of the National Center for Atmospheric Research and the many helpful discussions with him.

8. REFERENCES

Campbell, W.C., and R.G. Strauch, 1976: Meteorological Doppler radar with double pulse transmission. Preprints, 17th Conf. Radar Meteorol., American Meteorological Society, Boston, 42-44.

Carbone, R.E., and M.J. Carpenter, 1983: Rapid scan Doppler radar development considerations, Part I: Sampling requirements in convective storms. Preprints, 21st Conf. Radar Meteorol., American Meteorological Society, Boston, 278-283.

Deley, G.W., 1970: Waveform design. In Radar Handbook (M.I. Skolnik, Ed.), McGraw-Hill, New York, 3-1 - 3-47.

Doviak, R.J., and D.S. Zrnic, 1984: Doppler Radar and Weather Observations. Academic Press, Orlando, Florida, 458 pp.

Hildebrand, P.H., C. Walther, C.L. Frush, and C.K. Mueller, 1983: Airborne Doppler weather radar: Evaluation and discussion of applications. Preprints, 21st Conf. Radar Meteorol., American Meteorological Society, Boston, 270-277.

Hildebrand, P.H., C. Walther, C.L. Frush, and M.N. Zrubek, 1986: Electra Doppler Radar Design Plan. National Center for Atmospheric Research, Boulder, CO (in press).

Keeler, R.J., and C.L. Frush, 1983a: Rapid scan Doppler radar development considerations, Part II: Technology assessment. Preprints, 21st Conf. Radar Meteorol., American Meteorological Society, Boston, 284-290.

Keeler, R.J., and C.L. Frush, 1983b: Coherent wideband processing of distributed targets. Proc. Int. Geosci. and Remote Sensing Symp., (IGARSS-83) San Francisco.

Krehbiel, P.R., and M. Brook, 1979: A broad-band noise technique for fast-scanning radar observations of clouds and clutter targets. IEEE Trans. Geosci. Electron., Special Issue on Radio Meteorology, GE-17(4), 196-204.

Nathanson, F.E., 1969: Radar Design Principles. McGraw Hill, New York, 616 pp.

Perry, R.P., and L.W. Martinson, 1977: Radar matched filtering. In Radar Technology (E. Brookner), Artech House, Dedham, Mass. 163-169.

Purdy, R.J., 1977: Signal processing linear frequency modulated signals. In Radar Technology (E. Brookner), Artech House, Dedham, Mass. 155-162.

Rummler, W.D., 1968: Introduction of a new estimator for velocity spectral parameters. Tech. Memo, mm-68-4121-5, Bell Telephone Labs., Whippany, New Jersey, 24 pp.

Sirmans, D., D.S. Zrnic, and W. Bumgarner, 1976: Estimation of maximum unambiguous Doppler velocity by use of two sampling rates. Preprints, 17th Conf. Radar Meteorol., American Meteorological Society, Boston, 23-28.

Woodward, P.M., 1953: Probability and Information Theory, with Applications to Radar. Pergamon Press, New York, 128 pp.

Zrnic, D.S., 1977: Spectral moment estimates from correlated pulse pairs. IEEE Trans. Aerosp. Electron. Syst., AES-13, 344-354.