Correlation Coefficients between Horizontally and Vertically Polarized Returns from Ground Clutter

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ABSTRACT
Characteristics of the magnitude and phase of correlation coefficients between horizontally and vertically polarized returns from ground clutter echoes are quantified by analyzing histograms obtained with an 11-cm wavelength weather surveillance radar in Norman, Oklahoma. The radar receives simultaneously horizontal and vertical (SHV) electric fields and can transmit either horizontal fields or both vertical and horizontal fields. The differences between correlations obtained in this SHV mode and correlations measured in alternate H, V mode are reviewed; a histogram of differential phase obtained in Florida using alternate H, V mode is also presented. Data indicate that the backscatter differential phase of clutter has a broad histogram that completely overlaps the narrow histogram of precipitation echoes. This is important as it implies that a potent discriminator for separating clutter from meteorological echoes is the texture of the differential phase. Values of the copolar cross-correlation coefficient from clutter overlap completely those from precipitation, and effective discrimination is possible only if averages in range are taken. It is demonstrated that the total differential phase (system and backscatter) depends on the polarimetric measurement technique and the type of scatterers. In special circumstances, such as calibrating or monitoring the radar, clutter signal can be beneficial. Specifically, system differential phase can be estimated from histograms of ground clutter, receiver differential phase can be estimated from precipitation returns, and from these two, the differential phase of transmitted waves is easily computed.

1. Introduction
Ground clutter is mostly a nuisance in weather radar applications, and much effort has been (and still is) devoted to finding ways for optimum elimination and/or mitigation of its effects. Current practice on the national network of Doppler radars [Weather Surveillance Radar 1988-Doppler (WSR-88D)] is to filter clutter at locations predetermined with a clutter map or, at the operator’s option, to apply a filter in designated areas. More potent techniques relying on Doppler spectral moments and the texture of reflectivity have also been developed (Kessinger et al. 2003) and will soon become operational.

Polarimetric radar offers much better recognition of clutter than is possible with conventional radar and therefore could enhance the powerful classical frequency domain filters and augment the classification based on spectral moments. One might argue that this advantage is muted if clutter is well filtered through Doppler processing; then there would be little left to recognize in the polarimetric variables. There are at least two situations where this does not hold. One is when the weather signal spectrum overlaps clutter, in which case it might be possible to determine the region of spectral overlap using spectral densities of polarimetric variables. For example, spectral differential reflectivity \(Z_{DR}(\nu)\), \(f\) is Doppler frequency\) computed at discrete Doppler frequencies would have a narrow range of values, about 0–4 dB in rain (Fig. 2 in Straka et al. 2000); \(Z_{DR}\) from clutter has a wide distribution (Balakrishnan et al. 1993) because the equivalent reflecting...
dipoles are randomly oriented with a slight preference for vertical alignment. Hence, it follows that differential reflectivity within the 0–4-dB interval can be due to both rain and clutter. Values outside this interval are likely caused by clutter or other scatterers (such as insects) but not by rain. Similarly, in light precipitation the spectral differential phase $\Phi_{\text{DP}}(f)$ is concentrated at the system phase; values tens of degrees away could be due to clutter. Thus, by analyzing spectral densities of polarimetric variables it might be possible to identify and eliminate contaminated spectral coefficients. The other situation concerns ground clutter received via anomalous propagation for which a clutter map would have to be created instantaneously. Polarimetric variables can be used to identify clutter and immediately activate a filtering procedure. Clearly, quantitative knowledge of polarimetric properties of clutter echo is required to separate it from meteorological signals either at the spectral level or in the fields of spectral moments. Two recent books are devoted entirely to clutter: Billingsley (2001, 212–221) devotes a short section to the polarization dependence of differences in mean clutter strengths and Long (2001) presents a rather extensive theory as well as several examples of cross sections at different polarizations.

Both the magnitude and phase of the complex correlation coefficient (between copolar components of the signal) are suitable for classification of echo type (Straka et al. 2000; Ryzhkov et al. 2005), which is one motivation for this study. The other is to demonstrate that the clutter backscatter differential phase has a peaked distribution centered at zero and therefore can be used for calibration of system differential phase. Herein we report measurements of the copolar cross-correlation coefficient magnitude ($p_{hv}$) and its phase (i.e., the backscatter differential phase $\delta$), and the magnitude of the copolar to cross-co-polar correlation coefficient ($p_{ab}$) and its phase ($\delta_{ab}$) called the cross-polar backscatter differential phase. We present histograms of these variables and suggest that some histograms might be suitable for constructing membership functions in fuzzy logic classification schemes (Zrnić et al. 2001).

The span of the copolar cross-correlation coefficient values from clutter is not well established although it is accepted that it is larger than the span from rain and the mean is smaller (Ryzhkov et al. 1994; Illingworth 2004). Large variations have been reported at incidence angles (i.e., angle subtended between the ray from the radar to the ground and local vertical at the ground) of about 50° (Skriver et al. 1999).

We devote much space to the backscatter differential phase because it turns out that this variable identifies clutter very well and its mean value provides a good estimate of the system's total differential phase. This phase is needed to properly set the phase unwrapping interval (Zahrai and Zrnić 1993) for differential phase measurement. The backscatter differential phase is considered a secondary polarimetric variable of lesser importance for precipitation measurements than is the (forward) specific differential phase or differential reflectivity. This is because the backscatter differential phase is seldom significant. Further, it is hard to sort out the artifacts and separate the propagation differential phase. At 11-cm wavelength the precipitation types that can cause appreciable backscatter differential phase are hail (Balakrishnan and Zrnić 1990) and perhaps large wet aggregates (Zrnić et al. 1993). Insects and birds, however, produce substantial backscatter differential phase; the one from birds is considerably larger (Ryzhkov and Zrnić 1998). Therefore, to separate the two and possibly identify hail, the system differential phase must be known.

The backscatter differential phase of clutter is highly variable and only a few attempts, at large incidence angles [−50° to 70°; Sarabandi (1992); Skriver et al. (1999)], have been made to characterize its distribution. Some authors suggest that distribution of the backscatter differential phase from natural scatterers is centered on zero and that man-made objects often act as corner reflectors causing a 180° shift (van Zyl 1989).

Very little information exists in the literature on the properties of the co-cross-polar correlation coefficient and its phase from ground clutter at high incidence angles typical of weather surveillance radars [Long (2001) has a table and two graphs]. Measurements presented herein fill this gap.

The national WSR-88D network of weather radars will be enhanced with dual-polarization capability in about 2010. For several reasons the chosen polarimetric technique consists of simultaneous transmission and reception of horizontally and vertically (SHV) polarized waves (Doviak et al. 2000). This scheme has been tested at the National Severe Storms Laboratory (NSSL) on the National Ocean and Atmospheric Administration’s research and development WSR-88D [at the Norman, Oklahoma (KOUN), station] radar (Ryzhkov et al. 2005). The radar also has a mode for transmitting horizontal polarization and receiving both the strong copolar component (H) and the weak cross-polar component (V); in short we refer to this mode as the linear depolarization ratio (LDR) mode.

The challenge for the SHV scheme is the proper calibration of differential reflectivity and the determination of the total system differential phase. This challenge is not nearly as daunting in a research environ-
ment as it is in operations where it may not be practical to depend on precipitation for calibrating these variables. Imagine the difficulty if one had to wait for the first precipitation at every one of the 150 plus WSR-88D sites to determine the differential phase of the radar. Our experience with the KOUN radar is that the system differential phase slowly drifts over about a 10° interval. The likely cause is in the active components of the two receivers. We expect larger random variation of the system differential phase from radar to radar. Thus, it is very desirable to have a simple way of estimating the total differential phase such that it can be made on individual radars at the time of retrofit. One attractive way, advocated herein, is from measurements of ground clutter.

To start we review the relevant theory and contrast polarimetric measurements of clutter in the SHV mode with values measured in the alternate H, V mode (Bringi and Chandrasekar 2001). In section 3 we present and analyze several histograms of correlation coefficients and differential phase from ground clutter and contrast these to those from precipitation. Suggestions on how to determine transmitted and received differential phases from such histograms are included.

2. Correlation coefficients

Pertinent relations between backscattering coefficients and estimates of copolar and cross-polar correlation coefficients and their phases are briefly reviewed. Emphasis is placed on the SHV mode of measurement, which is contrasted with the alternate H, V mode of measurements (Doviak et al. 2000).

We start with the backscattering matrix for an ensemble of scatterers,

$$S = \begin{bmatrix}
S_{hh} & S_{hv} \\
S_{hv} & S_{vv}
\end{bmatrix},$$  (1)

and assume the medium between the resolution volume and radar is void of scatterers; thus, there are no propagation effects. Because the scattering is reciprocal, the off-diagonal terms in (1) are equal. The notation in (1) requires further explanation. Specifically, the scattering elements are summations from individual scatterers; that is,

$$S_{hh} = \sum s_{hh}(i) \exp(j\varphi_i),$$

$$S_{hv} = \sum s_{hv}(i) \exp(j\varphi_i),$$

$$S_{vv} = \sum s_{vv}(i) \exp(j\varphi_i),$$  (2)

where $i$ refers to a scatterer at a specific location in the resolution volume and $\varphi_i = -4\pi r_i/\lambda$ is the phase that depends only on the scatterers’ distance from the radar $r_i$ ($\lambda$ is wavelength).

The radar system contributes two distinct phases to the total differential phase: the differential phase in the transmission channel $\Phi_t$ and the differential phase in the receiver channel $\Phi_r$. Thus, the total system differential phase is the sum of the two:

$$\Phi_s = \Phi_t + \Phi_r.$$  (3)

Although (3) applies to either the alternate or simultaneous scheme for polarimetric measurements, its estimates obtained from clutter differ, as demonstrated herein.

a. Copolar cross-correlation coefficient in SHV mode

In the SHV scheme, incident horizontally and vertically polarized electric fields ($E_h$ and $E_v$) at the location of scatterers are related by

$$E_h = E_v e^{-j\Phi_4},$$  (4)

because it is assumed that the propagation is in the air so that the differential attenuation and the cross-coupling along the propagation path are absent, and the transmitted H and V powers are equal (correlation coefficients are not affected by differences in the transmitted powers but the differential reflectivity is). Upon return to the antenna the complex $H_r$ and $V_r$ voltages are measured at the receiver’s output:

$$\begin{bmatrix}
H_r \\
V_r
\end{bmatrix} = \begin{bmatrix}
e^{-j\Phi_6} & 0 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
E_h \\
E_v
\end{bmatrix} + \begin{bmatrix}
n_h \\
n_v
\end{bmatrix},$$  (5)

where, without loss of substance, it is implied that the proportionality constant between the voltages and fields is one and has the correct dimension. Further, the range dependence and radar scaling factors are ignored because they have no effect on the correlation coefficients. The $H_r$ and $V_r$ signals are contaminated with receiver noises, $n_h$ and $n_v$, which may be different.

The intrinsic properties of ground clutter contained in (1) are transformed via (5) into the received $H_r$ and $V_r$ signals. The auto- and cross correlations of these signals are then estimated from which the complex copolar correlation coefficient is computed as (Doviak and Zrnić 1993; Bringi and Chandrasekar 2001)

$$\rho_{hv} \exp(j\Phi_{DP}) = \text{cor}(H_r, V_r),$$  (6)

where the caret (^) indicates that this correlation is obtained in the SHV mode and thus could be biased compared to a value obtained in the alternate H, V mode and cor stands for the complex correlation coeffi-
sufficient. Throughout the paper the symbol $\rho$ refers to the magnitude.

Taking the appropriate expected values of the cross product from (5) [see Doviak et al. 2000, Eq. (A20), which is the same but has no noise terms] results in

$$
\bar{\rho}_{hv} = \frac{(\rho_{hv})^2 + 2\rho_{hv} L_d (Z_{dr})^{1/2} \cos(2\delta_r + \delta) + (L_{dr})^2 Z_{dr}}{(1 + L_{dr} + 1/s_{hr})(1 + L_{dr} Z_{dr} + 1/s_{hr})},
$$

where the intrinsic copolar cross-correlation coefficient is

$$
\rho_{hv} = \langle s_{hh}^* s_{vv}\rangle / \langle |s_{hh}|^2 \rangle \langle |s_{vv}|^2 \rangle^{1/2},
$$

the linear depolarization ratio is

$$
L_{dr} = \langle |s_{hv}|^2 \rangle / \langle |s_{hh}|^2 \rangle,
$$

the intrinsic differential reflectivity is

$$
Z_{dr} = \langle |s_{hh}|^2 \rangle / \langle |s_{vv}|^2 \rangle,
$$

and the backscatter differential phase is

$$
\delta = \arg(s_{hh} s_{vv}^*).
$$

The signal-to-noise ratios (linear units) in the two channels are $s_{hr}$ and $s_{hr}$. Angular brackets indicate the expected value (ensemble average) of the summations over the resolution volume [e.g., $\Sigma s_{hh}^* s_{hh}(i)s_{vv}(i)$ and other terms in (2)], and lowercase subscripts in the linear depolarization ratio $L_{dr}$ and in the differential reflectivity $Z_{dr}$ stand for linear units. To arrive at (7), the complex terms $s_{hh}^* s_{hh}$ and $s_{hv} s_{hv}^*$ were set to zero because the angle between the $s_{hv}$ and $s_{vv}$ or $s_{hh}$ and $s_{hh}$, is expected to be uniformly distributed [this assertion is experimentally confirmed in section 3, and reported by others, e.g., Sarabandi et al. (1991)].

The differential phase is obtained from the arg($H^*_h V_v$) and its mean value is

$$
\Phi_{DP} = \arg(\langle |s_{hv}|^2 \rangle e^{-j\Phi_r} + \langle s_{hh}^* s_{vv}\rangle e^{j\Phi_r}) + \Phi_r.
$$

But, its instantaneous values (from a single pulse) $\Phi_{DP}$ contain the additive terms $\arg(s_{hh} s_{hh})$ and $\arg(s_{hv} s_{hv})$; that is,

$$
\hat{\Phi}_{DP} = \arg(s_{hh} s_{hh} + |s_{hv}|^2 e^{-j\Phi_r} + s_{hh}^* s_{vv} e^{j\Phi_r} + s_{hh}^* s_{sv})
$$

$$
+ \Phi_r + \text{noise terms}.
$$

The noise terms in (9), included for completeness, are cross products between the noise and backscatter coefficients. These are usually much smaller than the ground clutter power.

Clearly in the SHV mode, the coupling of the cross-polar component $s_{hv}$ caused by ground clutter has an effect on $\Phi_{DP}$ (9). In the alternate H, V mode the cross-polar component is always in a separate channel from the strong copolar component; hence, there is no such coupling.

The relative values of various terms in (7a) determine $\bar{\rho}_{hv}$, and similarly the relative magnitude of the terms in (8) and (9) determines what will be added to $\Phi_r$ to produce the measured values of the differential phase. Our measurements indicate that the linear depolarization ratio $\delta_c$ and differential reflectivity $\delta_d$ are quite variable in ground clutter (estimated SD of $L_{DR}$ equals 7.6 dB and for $Z_{DR}$ it is 6.1 dB) and cannot be neglected; therefore, the $\bar{\rho}_{hv}$ can be significantly different from the intrinsic counterpart. Further, the noise powers also affect the results but equally in either the SHV or alternate H, V mode:

$$
\Phi_{DP} = \Phi_s + \Phi_d = \Phi_r + \Phi_r + \delta,
$$

so (8) reduces to

$$
\Phi_{DP} = \Phi_s + \delta = \Phi_r + \Phi_r + \Phi_r + \delta.
$$

Therefore, the distribution of the estimates of the differential phase might have a mean value given by (10) and the spread will be caused by the various terms in (9) and by the noise from the two receivers (which contribute zero bias).

Next we consider rain and light precipitation, and show that $\rho_{hv}$, and $\Phi_{DP}$ have somewhat different distributions. Assume the absence of hydrometeors between the radar and the leading edge of precipitation so that the attenuation or differential phase shift along the path can be ignored. Generally in rain at 10-cm wavelength, the cross coupling due to backscattering is very small [linear depolarization ratio is less than $-25$ dB; Bringi and Chandrasekar (2001, p. 403); Straka et al. (2000)]; therefore, the averages containing $s_{hv}$ terms can be ignored. Moreover, the mean backscatter differential phase is negligible and so is its estimate. Thus, it follows from (7a) that the mean correlation coefficient equals the intrinsic correlation coefficient (if $s_{hv}$ is large) and the mean differential phase (8) is that of the system given by (3), and we expect $\Phi_{DP}$ to have a narrow distribution.

\subsection*{b. Copolar cross-correlation coefficient in sequential mode of transmission}

Consider next what happens if the horizontally and vertically oriented fields are transmitted sequentially. Start with the general backscattering matrix $S$ of individual scatterers in (1). In sequential transmission and with no coupling at the receiver, two states (listed in the next paragraphs) of transmission/reception are pertinent. These are the transmission of horizontally polar-
ized signals with reception of both polarizations and the transmission of vertically polarized signals with reception of both.

Assume that the sequential H and V signals leaving the antenna have equal magnitudes and the phase shift between the two is $\Phi_r$. Then if the H signal is transmitted, the received signal in the channel for horizontal polarization is

$$H_r' = s_{hh}E_r e^{-j(\Phi_r + \Phi_H)} + n_h$$

(11)

and in the channel for vertical polarization the signal is

$$V_r' = s_{vv}E_r e^{-j\Phi_r} + n_v.$$  

(12)

Note that range dependence is ignored (without loss of substance) and the proportionality constant between the left and right term in (11) and (12) is set to one.

If a vertically polarized signal is transmitted, the received $V_r$ signal is

$$V_r = s_{vv}E_v + n_v.$$  

(13)

It is assumed that the Doppler phase shift between (12) and (13) is zero (or that it has been estimated and eliminated). Obviously, the $\rho_{hv}$ can be obtained directly by correlating $H_r$ with $V_r$. The mean phase difference is computed from the argument

$$\Phi_{DP} = \arg(H_r^*V_r) = \Phi_t + \Phi_r + \arg(s_{hh}\ast s_{vv}).$$  

(14)

and the instantaneous value of the phase is

$$\Phi_{DP} = \arg(H_r^*V_r) = \Phi_t + \Phi_r + \arg(s_{hh}\ast s_{vv}) + \text{noise terms.}$$

(15)

The backscatter differential phase (7c) is the last term in (14). Compared to (8), estimate (14) is not biased. More importantly, the estimate (9) has several coupling terms that are not present in (15).

For ground clutter the measured differential phase is

$$\Phi_{DP} = \Phi_t + \Phi_r + \delta.$$  

(16)

Thus, the mean values of the differential phase measured in either the SHV mode or the alternate H, V mode should be equal. We expect that the breadth of the distribution of measurements will be larger for estimates obtained in SHV mode because these contain larger numbers of statistical terms (due to coupling).

Assuming that the elements of the backscattering matrix are jointly Gaussian, one can derive [Middleton 1960, Eq. (9.32); Sarabandi (1992)] the following probability distribution density of $\delta$:

$$p(\delta) = \frac{1 - \rho_{hv}^2}{2\pi(1 - X^2)} \left[ \frac{X}{\sqrt{1 - X^2}} \right] \left( \frac{X}{\sqrt{1 - X^2}} \right),$$

where $X = \rho_{hv}\cos(\delta - \bar{\delta})$.

In precipitation with small particle sizes compared to the wavelength, $\delta$ is very close to zero; hence, $\Phi_{DP} = \Phi_t + \Phi_r$, as is routinely observed.

c. Co-cross-polar correlation coefficient

The correlation coefficient between the copolar and cross-polar components is defined by

$$\rho_{ch} = \frac{\langle s_{hh}\ast s_{vh} \rangle}{\sqrt{\langle |s_{hh}|^2 \rangle \langle |s_{vh}|^2 \rangle}}$$  

(18)

and cannot be measured in the SHV polarimetric mode. It is readily available in the alternate mode as well as in a mode whereby the H polarization exclusively is transmitted and both the H and V signals are received (LDR mode).

The cross-polar to copolar backscatter phase difference is

$$\delta_{ch} = \arg(s_{hv}\ast s_{vh}).$$

(19)

and the argument of the correlation between the copolar and cross-polar signals contains the differential phase of the receiver (i.e., in the absence of the propagation effect):

$$\arg(H_r^*V_r) = \Phi_t + \arg(s_{hv}\ast s_{vh}).$$

(20)

Theoretical considerations, confirmed by measurements at 5-cm (Sarabandi et al. 1991; Sarabandi 1992) and 3-cm wavelength (Long 2001), indicate that $\delta_{ch}$ from ground clutter is uniformly distributed whereas in precipitation it is small (Ryzhkov 2001; Ryzhkov et al. 2002). This offers a possibility to measure the differential phase of the receiver in the LDR mode [via Eq. (20)] from the leading edges of light precipitation (where the differences in phases due to propagation are insignificant).

3. Measurements

Measurements of the correlation coefficients and differential phases from ground clutter are presented in this section. Digital time series data were collected with the KOUN radar, which is a modified WSR-88D so that it can operate in SHV and LDR mode. The digital time series consists of in-phase and quadrature phase components of signals from receivers for horizontal and vertical polarization. Due to recording limitations

$$\frac{\pi}{2} + \tan^{-1}\left(\frac{X}{\sqrt{1 - X^2}}\right).$$
(overcome since the time of collection), time series data could be collected over 100 consecutive range locations spaced by 250 m (a standard gate spacing on the WSR-88D matches the pulsewidth) and starting at arbitrary range delay. Also presented are histograms of differential phase estimates from clutter collected by the National Center for Atmospheric Research’s (NCAR) S-band polarimetric (S-POL) radar in Florida. The S-POL radar operated in alternate H, V mode, which is not available on the KOUN.

Ground scatterers in Oklahoma consist of a mixture of urban terrain, cross-timber wooded area, and rural pastures. Thus, the site is typical of many suburban areas in the Great Plains. There was no noticeable difference in the histograms as a function of season or terrain wetness. In Florida the terrain had fields, palm trees, and marshes; data within 15 km of the radar were analyzed to eliminate returns from sea clutter.

Weather surveillance radars usually obtain data from azimuth sectors that match antenna beamwidth. In the case of WSR-88Ds the beamwidth and the sector are 1° wide. Therefore, for classification purposes estimates obtained over 1° sectors are important. Yet such estimates originate from overlapping patches of ground clutter and hence are not representative of intrinsic clutter properties. We have therefore collected estimates from very small sectors (0.1° and 0.2° by slowly rotating the antenna) and over 1° sectors (by rotating faster). We have also collected some data in range–height indicator (RHI) mode and with stationary antenna. For the differential phase there was no appreciable difference between the histograms from the 0.1° and 1° sectors.

a. Copolar cross-correlation coefficient and differential phase

We start with the histogram of the magnitude of the cross-correlation coefficient \( \hat{\rho}_{hv} \) (Fig. 1) obtained in SHV mode. The time series data were collected between 0.5 and 25 km over the full 360° in the azimuth while the antenna was rotating at 1.5° s\(^{-1}\) (sector of 0.1°, 64 samples per estimate, and pulse repetition frequency of 1013 Hz) and also while the antenna was rotating at 15.8° s\(^{-1}\) (sector of 1°). The dwell time for computing one \( \hat{\rho}_{hv} \) estimate at either rotation rate was 63 ms and the elevation angle was 0.2°. Only data with clutter-to-noise ratios >20 dB are used and there was no noticeable difference between these histograms and the histograms from data with larger clutter-to-noise ratios.

Both histograms (Fig. 1) favor surprisingly high values, considering that no correction for noise (in weak signals) or for the effects of depolarization (7a) was applied. The mean from the data over 0.1° sectors is 0.93 and a large portion of the histogram has values close to one, which is likely due to rigid scatterers. Because there was no noticeable difference between this histogram and histograms collected in stationary mode (same mean and shape) we refer to these values as intrinsic. There is a redistribution of values in histograms from the 1° sector; the occurrence of smaller \( \hat{\rho}_{hv} \) is enhanced at the expense of a reduction in larger values, the mean shifts to 0.778, and a reduced peak close to one persists. The spatial decorrelation of clutter is the likely cause of this difference.

In precipitation, including hail, the \( \hat{\rho}_{hv} \) seldom falls below 0.9 as can be seen in Fig. 2. Hence, the histograms in Fig. 1 completely overlap the one expected from precipitation. Further the two histograms are quite smooth in spite of the large difference in the total number of points; hence, estimates from these histograms should be very close to the true values.

For the intrinsic histogram (Fig. 1), the relative occurrence of values larger than 0.95 is 69% and that of values larger than 0.97 it is 59%. This means that in similar clutter, a significant number of \( \hat{\rho}_{hv} \)'s is indistinguishable from the \( \rho_{hv} \) of rain (Straka et al. 2000). For the histogram from 1° sectors, the relative occurrence of values larger than 0.95 is 24% and for values larger than 0.97 it is 17%.

In spite of the significant overlap with values from precipitation, the fields of \( \hat{\rho}_{hv} \) have been successfully

![Fig. 1. Histogram of the copolar cross-correlation coefficient from ground clutter. Estimates are obtained from 64 consecutive returns (over 63.2-ms interval corresponding to a 0.1° sector, PRF = 1013 Hz in all experiments). Data above SNR = 20 dB (actually clutter-to-noise ratio) compose these histograms and have been collected from a ring encompassing 98 consecutive range locations (0.5–25 km) at an elevation of 0.2°. Date is 5 Feb 2005. Number refers to the total number of points in the histogram for which the antenna rotation was 15.8° s\(^{-1}\) (data were collected from 15 consecutive scans). The number of points at the 1.5° rotation was 7873 (from one scan only).](http://journals.ametsoc.org/jtech/article-pdf/23/3/381/3605832/jtech1856_1.pdf)
used to help identify clutter (Schuur et al. 2003). This is due to averaging in the range of the copolar cross-correlation coefficient. Such averaging concentrates the estimates toward the mean value, that is, transforms the distribution as evidenced in Fig. 1. The dashed curve is a histogram of estimates from the average over 1 km in range (four estimates spaced 250 m apart). Now only about 2.2% of the values exceed 0.95, and 0.7% exceed 0.97; hence, very little overlap with the region from precipitation occurs!

Next we present histograms of the differential phase (Fig. 3). The top curve is the histogram obtained from measurements on single returns (instantaneous), that is, from \( \text{arg}(H^h_i V_i) \), whereas the bottom curve is obtained from estimates of the differential phase. Each estimate is computed as \( \text{arg}(\sum H^h V_i) \) where the sum (over the time index \( i \)) consists of 128 returns during a 0.126-s time interval (sectors of 0.2°). The logarithmic scale on the ordinate is used to make obvious that the two histograms have the same global shape. Further, we have determined that there is no difference in histograms obtained over the 0.2° and 1° sectors. Because instantaneous values are unencumbered by the estimation procedure, they are better suited for comparisons between the SHV and alternate H, V mode. However, we do not have time series data in the alternate H, V mode (to compute instantaneous values) and hence are compelled to use the estimates. Moreover, such estimates are representative of values routinely obtained with scanning radars.

The mean differential phase equals the total system differential phase (3). This becomes apparent if the histograms for clutter and precipitation, as in Fig. 4, are examined. The precipitation was light and the beam swept the same area as was done for Fig. 3. Evident is a narrow peak at \(-141°\) caused by rain on top of a wide distribution caused by clutter. Because the differential backscatter phase shift is negligible, the path is short (less than 25 km), and the reflectivity of the rain is small (\( Z_{\text{dB}} = 30 \text{ dB} \)), the peak of the histogram is a very good estimate of the system differential phase. In Fig. 5 we present a histogram from the precipitation only, obtained 6 days later to contrast its width to that from the clutter.

To explain the differential phase distribution from clutter we have examined short-term histograms (30 s) obtained with a stationary antenna looking over gently rolling terrain. Each estimate of the phase is obtained from 128 samples (dwell time of 0.126 s). The results are of three types. One type of phase measurements has narrow histograms (data within about 30° of the local mean) with little change over time (Fig. 6a); it could be caused by strong specular components of the clutter. The location contained a cemetery with small trees. The second type has wider histograms with mean values gradually shifting over time (Fig. 6b). A road with posts, small houses, and trees taller than houses is lo-
cated in the region were these data were collected. The third type has a wide distribution (about 360°; Fig. 6c), likely caused by the dominant distributed component of objects that are nonhomogeneous and exhibit nonstationary motions; the terrain contained mainly large houses, each on five or more acres, and large trees. The first two types account for some 60%–70% of the cases.

Time variations of the phase from the same locations as in Fig. 6 are presented in Fig. 7. Phases are computed from single returns and are connected with lines. The variation of phase over a 100-ms interval can span 360° as is evidenced in Fig. 7. The bottom graph has small variations; other similar graphs can have any phase but more often than not these values are close to the differential phase of the system (\(\Phi_{\text{DP}}\)). Some exhibit a gradual semimonotonic increase or decrease. Finding an exact expression for the probability density function (pdf) of the ground clutter phase (9) is beyond the scope of this study (a closed-form solution might not be available). Therefore, we resort to an approximation, as follows.

A simple model of the histogram to account for two dominant contributors was fitted to the estimates from Fig. 3 (Fig. 8a). The “model” assumes a dependence given by (17) superposed to a uniform distribution. Strictly, (17) is the distribution of \(\hat{\delta} = \text{arg}(s_{vv}^h s_{hh}^v)\), which has no coupling terms (i.e., those with subscript \(hv\)) like the ones present in (9); nonetheless, we use it here to estimate the effects of coupling. The uniform distribution should account for the effects of noise and possibly approximate some contribution by the coupling terms [i.e., terms other than \(s_{hv}^h s_{vv}^v\) in (9)]. We insert into (17) the estimate \(\hat{p}_{huv} = 0.93\) obtained from data. This correlation estimate is biased (by the coupling terms) compared to the intrinsic correlation, which should be used in (17) but is not available in SHV mode. If anything, this bias increases the breadth of the theoretical pdf but far too little to account for the observed broadening, as we show shortly. Then, we iteratively convolve (17) with a Gaussian pdf by changing its width and level of uniform distribution until the difference between the histogram and the composite distribution is minimized. Inclusion of the Gaussian pdf is required to achieve a fit, and the broadening exemplified by the Gaussian standard deviation (SD) is a good measure of the excess width (Table 1, entry 4) needed to match the histogram. We refer to the convolved distribution (without the uniform part) as quasi Gaussian to distinguish it from the uniform part, and the theoretical part (17).

The uniform distribution component, estimated from the data, accounts for 61% of the integrated theoretical histogram (i.e., the pdf). Note that the SNR of data composing the histogram is larger than 20 dB. Further increasing this threshold reduces both the Gaussian component and the uniform component so that at an SNR above 50 dB the uniform component accounts for 51% of the total. Clearly the differential phase has a strong uniformly distributed part to which the noise is a minor contributor. We suspect that the copolar to cross-polar and cross-polar covariances [i.e., terms other than
\(\langle s_{hh} s_{vv}\rangle\) in Eq. (9)] are contributors to this uniform component. This is corroborated by the fact that the histogram becomes uniform if data with \(\tilde{\rho}_{hv} < 0.7\) are plotted, whereas theoretical pdf (17), even with \(\tilde{\rho}_{hv} = 0.1\), has a well-defined minimum 25% smaller than its peak. Moreover, the differential phase variation with time suggests that the inhomogeneity and nonstationarity of clutter are the other significant contributors.

The departure of the theoretical curve (parameterized as explained) from the data is significant (Fig. 8a). The standard deviation contributed by (17) is 34.3° (Table 1). An additional 41.4° was needed to achieve a good iterative fit (also plotted in Fig. 8a, and listed in Table 1) resulting in the composite standard deviation (rms value) of 53° (Table 1), which excludes the part (∼104°) from the uniform pdf. The total standard deviation composed of the uniform and the composite (quasi Gaussian) is then 87.7° (Table 1, obtained from the weighted average of the variances: uniform and quasi Gaussian).

The histogram of the differential phase obtained in the alternate H, V polarization mode is plotted in Fig. 8b. The differential phase was computed in real time from an alternate sequence of H, V polarized returns. A total of 128 consecutive pulses were used for the

Fig. 6. Histograms of differential phase from strong ground clutter at three range locations: (a) 2.75, (b) 3.75, and (c) 5.25 km. Antenna pointed at 69° in azimuth and 0.2° in elevation. The number of samples per each phase estimate is 128 (dwell time is 0.126 s), the total number of estimates (same as number of records) is 185, and SNR is larger than 55 dB. Time is 1436 UTC 2 Aug 2004.
estimates on NCAR’s SPOL radar in Florida. Data are from RHIs at low elevations so that the effects of scanning are negligible. In this alternate polarization mode the differential phase is unambiguous over a 180° interval; hence, the theoretical model (17) had to be appropriately aliased.

The histogram of $\rho_{hv}$ from Florida clutter (not shown) has essentially the same shape as the one from Oklahoma clutter; the mean value is slightly smaller than the one from Oklahoma’s sectors of 0.1°. This could be within the range of statistical uncertainty but it is consistent with the fact that the Florida location had less urban areas and more trees close to the radar (note that the swaying of tree branches would decrease the $\rho_{hv}$).

Statistical errors in the estimates of the differential phase are comparable for the SHV and alternate mode. Two standard deviations are listed in Table 1 for the model without coupling in the alternate H, V mode. The larger value (44.2°) refers to the SD over a 360° interval (before aliasing) computed from (17). The smaller value (32.9°) is the SD of the aliased pdf [i.e., aliased Eq. (17)], the one that radar measures. Aliasing occurs because Doppler and differential phase measurements are coupled and decoupling amounts to measuring the phase over a 180° interval (Zahrai and Zrnić 1993). Although the SD computed for the SHV mode (34.3°) is considerably smaller than the corresponding SD (44.2°) in the alternate H, V mode, the fit in the SHV mode requires an rms addition of 41.4° (i.e., excess SD). A modest 10° rms addition is required in the alternate H, V mode as the fit is very good. Thus, the following conclusions seem reasonable.

- Variations of differential phase from clutter in both SHV and alternate H, V mode are large.
- The excess SDs estimated in SHV mode are likely due to cross-coupling not captured by the model.
- Contributions by uniform parts of the distributions are comparable for the two modes.
- The uniform part is the major contributor to the variation of the differential phase and it is likely due to nonhomogenous and nonstationary ground clutter.
- Because of aliasing the composite measured SD (in brackets) in the alternate H, V mode is smaller by about a factor of 2 than the SD in the SHV mode.
We admit that additional experiments are desirable to solidify these preliminary conclusions. Nonetheless, the two measurements, with different radars, at different locations, and with different polarimetric modes (SHV in Oklahoma and alternate H, V in Florida) are quite consistent.

The wide distribution of the clutter’s differential phase indicates that its texture (local rms variation) can be a good clutter discriminator. For example, in our classification scheme (Schuur et al. 2003) the membership function for the SD of the differential phase from the ground clutter has compact support from 30° to 60°, which straddles the SDs of the model (34.3°), the Gaussian (41.4°), and the quasi Gaussian (53°) in Table 1. The contribution of the uniform part (87.7%) is out of range of the membership function. This is completely consistent with the posit that the uniform part of the pdf accounts for inhomogenieties whereas the texture is a measure of local variation.

In spite of the very large composite standard deviation, the accuracy of the differential phase measurements might only be limited by an unusually skewed pdf of the ground clutter differential phase. We have no such evidence but expect that the two sites (Oklahoma and Florida) are representative of many WSR-88D locations; hence, the proposed measurement of system phase should be widely applicable. Because the number of points in the histogram is very large, the mean can be estimated with an accuracy much better than 10°, which is quite adequate to set the beginning of the phase unwrapping interval for computing the differential phase in real time.

Radar with SHV mode might have an LDR mode similar to KOUN. Several histograms that follow were obtained in the LDR mode. We start with the co-cross-polar correlation coefficient and co-cross-polar backscatter differential phase.

b. Co-cross-polar correlation coefficient and differential phase

Co-cross-polar correlation coefficient ρ_{xh} has a histogram similar to the co-polar cross-correlation coefficient’s histogram if measurements are made at 0.1° sectors (Fig. 9), although the mean value (about 0.8) is smaller. For values computed over the 1° sector, the histogram has a well-defined peak away from 1 and a mean of about 0.66. In the same figure we present a histogram of the ρ_{xh} obtained from rain. Smaller than about 0.5, values are favored as previously reported (Ryzhkov et al. 2002; Hubbert and Bringi 2003) so that the nonoverlapping region of clutter is at higher values (>~0.6).

The histogram of the copolar to cross-polar backscatter differential phase is flat over the 360° interval for both single-pulse measurements and estimates from 128 pulse pairs (Fig. 10). This is in agreement with “usually uniform distributions” reported at X band by Long (2001, p. 454 and Fig. 7.9). An identical result is obtained from SPOL data obtained with the alternate H, V mode in Florida. Hence, this phase would have no value for the calibration of the radar. Its rough texture might be a good identifier of clutter only if the cross-polar component of the clutter is much stronger than the noise.

In rain the backscatter differential phase between the cross-polar and copolar returns is small (Straka et al. 2000), so the LDR mode can be used to estimate the receiver differential phase Φ_r, from (17b), because only...
the H fields are transmitted. Such a measurement has produced the two histograms in Fig. 10. Again, there was light rain and there were no discernible propagation effects. The histogram from the estimates is much broader (SD/H1100578.1°) than is the histogram of the backscatter differential phase in rain (Fig. 5). Nonetheless, the maximum of the histogram (Fig. 10) is well defined and therefore suitable for determining the differential phase of the receiver (45° here), which can then be combined with the mean from the clutter to obtain the differential phase of the transmitted waves. A very similar conclusion has been made by analyzing the SPOL data (Ryzhkov et al. 2002). We expect the texture of/H9254xh from the ground clutter to be rougher than the texture of/H9254xh because the 104° SD of the former exceeds by 16.3° the SD of the latter (entry 7 in Table 1). The utility of the δxh texture to discriminate clutter remains to be tested.

c. Practical implications

There is no perceptible difference in the histograms of the differential phases from the intrinsic clutter, that is, data over small antenna sectors (0.1°) and histograms from sectors of 1°. Histograms of the correlation coefficients are enhanced at smaller values if the sectors are 1°. In principle some of the presented histograms or modifications thereof could serve as membership (weighting) functions in classifications schemes (Straka et al. 2000; Zrnić et al. 2001; Schuur et al. 2003) so that clutter could be identified and eliminated. It might be advantageous to use nonoverlapping (with weather) parts of the histograms of ground clutter returns to censor data and thus eliminate these from further processing. This applies to histograms of ρhv (values < 0.9) and ρxh (values > 0.6). Better separation can be achieved if ρhv is averaged in range, as is currently done in our classification scheme, and then membership functions are applied (Schuur et al. 2003; Ryzhkov et al. 2005). This, however, does not apply to ρxh, because averaging would increase the overlap of the histograms by reducing the separation between the mean values (Fig. 9).

Averaging concentrates the smoothed value at the mean of the estimates. For example, the mean value of ρhv in most precipitation (except hail) is larger than 0.95, whereas in clutter it is about 0.74 (for data from the 1° sectors). This is sufficient to achieve considerable separation of clutter from precipitation by applying trapezoidal membership functions (Schuur et al. 2003). Somewhat better membership functions might be constructed from the histograms.

Generally, the separation of classes improves if the distributions of the variables corresponding to different classes overlap less. One such variable is the texture (rms fluctuation about a local mean). A glance at a histogram suffices to determine if the texture is rough or smooth. For example, the histogram of the differential phase from the clutter is very broad and from the precipitation it is quite narrow. Therefore, the texture of the differential phase could be as good as or better than ρhv for separating clutter from precipitation.

The other practical implication concerns measurements of the system differential phase and the differential phase of the receiver. The intrinsic differential phase of the ground clutter is centered on zero; hence, the mean measured differential phase from the ground is a good estimate of the system phase. The mean measured differential phase in LDR mode from light precipitation is an estimate of the receiver differential phase. Knowledge of the transmitter and receiver differential phases is needed to compute a proxy of the circular depolarization ratio in the SHV scheme (Matrosov 2004). This parameter, independent of the scatterers’ orientation, might be suitable for separating ice hydrometeors from drops and discriminating types.

4. Conclusions

Statistical properties of the magnitude and phase of the copolar cross-correlation coefficient and the co-

![Fig. 10. Histogram of the total differential phase between copolar and cross-polar signals from precipitation (instantaneous values and estimates) and ground clutter (estimates). The number of samples per phase estimate is 128. The SNR threshold is 20 dB. The antenna was rotating at 1.5° s⁻¹ (same as in Fig. 9), while data from clutter were collected. Precipitation data are the same as used in Fig. 9. (The bottom two histogram are inflated tenfold.)](http://journals.ametsoc.org/doi/abs/10.1175/JTECH1856.1?journalCode=jtech)
cross-polar correlation coefficient from ground clutter have been investigated by histogram analysis. The data were obtained with the National Oceanographic and Atmospheric Administration’s (NOAA) polarimetric radar in Norman, Oklahoma, and with the SPOL radar in Florida; the wavelengths of both radars are 11 cm.

The histogram of the copolar cross-correlation coefficient has a wide distribution and an exponential increase in concentration with increasing $p_{hv}$. This increase is less pronounced for data collected over a sector of 1° as opposed to stationary antenna. In either case the histogram completely overlaps with expected values from precipitation. Only low values of the correlation are outside of expected range for precipitation and therefore could indicate clutter or other nonmeteorological scatterers. Overall, the field of correlation from clutter is very speckled. Nonetheless, averaging of the correlation coefficient over 1 km in range achieves significant separation between clutter and precipitation because most of the average values (97.8%) are outside of the range expected from rain or snow.

The histogram of the co-cross-polar correlation coefficient is very similar to the histogram of the copolar cross-correlation coefficient if an antenna sweeps small sectors (0.1°) during dwell time. For typical sectors of about 1° the histogram has a well-defined peak at about 0.85. The co-cross-polar correlation coefficient from rain is small (<0.5) and is well separated from the histogram of clutter; therefore, averaging in range would be detrimental to discrimination.

The histogram of the total differential phase has two components: a wide uniform distribution on which a quasi Gaussian distribution is superposed. The mean of the histogram is a very good estimate of the system differential phase. This mean is needed to set the beginning of the phase unwrapping interval for computing the differential phase along propagation paths. For that purpose few degrees of accuracy of the mean is sufficient and easily achieved. We submit that the uniform part of the distribution is primarily due to inhomogeneities and the nonstationarity of ground clutter. This we have deduced by examining local histograms, time variations of the differential phase, and a simple theoretical model. Because the width of the histogram (i.e., SD) is large, the spatial fluctuations of the differential phase are large; therefore, its texture (local SD) is a good indicator of clutter returns. It appears that cross-coupling slightly increases the width of the distribution measured in SHV mode compared to the one measured in the alternate H, V mode. The substantial decrease of the width measured in the alternate H, V mode is caused by aliasing of the differential phase into the 180° interval, which is inherent to this mode.

The backscatter differential phase between the co- and cross-polar returns in clutter is uniformly distributed; hence, it adds no information to what is already provided by the copolar differential phase. But, in the presence of light precipitation the histogram is centered on the differential phase of the receiver.

We expect that the distributions of the backscatter differential phase at 5- and 3-cm wavelengths will also have peaks at zero phase and would be wider; this is because the ground roughness to wavelength ratio is larger at shorter wavelengths; hence, resonance effects are more pronounced. For the same reason we expect that the magnitudes of the correlation coefficients’ histograms at values close to one would still have a peak but that it would be smaller.

We have made no attempt, apart from general statements, to tie our measurements to the physical properties of ground objects and their interaction with the electromagnetic fields. For example, we state that the histogram of the backscatter differential phase from clutter has a peak at zero because on average there are more scatterers with equal backscatter (at H and V polarization) phases than with different phases. As to why that should be so, and what types of scatterers these are, we have no clue. This detective work is left to motivated and ambitious graduate students whose age is one-seventh of the cumulative age (172 yr) of the authors.

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