5B.2 THE USE OF SIMULTANEOUS HORIZONTAL AND VERTICAL TRANSMISSIONS FOR DUAL-POLARIZATION RADAR METEOROLOGICAL OBSERVATIONS

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Dual-polarization radar measurements have typically been made using either linear or circular transmitted polarizations, and there has been much discussion as to the relative merits of the two approaches. Most radars transmit and receive horizontal and vertical linear polarizations because H and V directly sense the parameters of liquid drops, which are flattened by aerodynamic forces as they fall, effectively aligning them horizontally. The H and V polarizations are transmitted on alternate pulses and are differentially scattered by the flattened drops, enabling one to measure important quantities such as the differential reflectivity $Z_{\rm DR}$, and differential propagation phase ϕ_{dp}. In addition, one can measure the linear depolarization ratio LDR, which (along with ρ_{HV}) detects the presence of irregularly shaped particles such as hail, and particle canting. The alternate H,V approach has the disadvantage that the measurements are obtained from successive transmitted pulses, which are substantially affected by the interpulse Doppler effects. Algorithms have been developed to compensate for the Doppler effects but the effects still increase in the uncertainty of the polarization parameters.

Circular polarization is utilized because the scattering is independent of particle orientation and is therefore a more sensitive detector of random orientation or irregularly shaped particles. In addition, it can be used to determine particle alignment directions. Circular polarization has had the practical disadvantage that two receiving channels are required for the measurements, as opposed to only one channel (for everything except LDR) in alternating H–V measurements. More importantly, there have not been clear and concise formulations for the interpretation of circular polarization measurements. This resulted in part from the fact that circular polarization returns have usually been received in orthogonal LHC/RHC channels, which have highly unbalanced signal-to-noise ratios.

To address the above issues, experiments have been conducted by the CSU-CHILL radar group in which slant $45°$ linear polarization is transmitted in concert with alternating H and V to determine how well the standard polarization quantities of rain ($Z_{\rm DR}$, ϕ_{dp}, and ρ_{HV}) are determined from simultaneous transmissions (Brunkow et al., 2000). The returns are received in an H–V basis. This has led to the proposal that simultaneous transmissions be used to provide dual-polarization capabilities for the NEXRAD radars (Doviak et al., 2000).

Independently, the authors of the present study have been investigating the question of how the parameters of horizontally oriented particles can be determined from circularly polarization transmissions (Scott, 1999). Using the geometric Poincaré formulations of paper 5B.1, the answer turned out to be simple: Instead of receiving circular polarization returns in LHC and RHC channels, they should be received in H and V channels. The New Mexico Tech dual-polarization radar was modified to operate in this mode during the spring of 1998, and observations of storms were obtained both in 1998 and 1999. The results have been reported by Scott (1999) and Scott et al. (2001).

The transmit-circular, recieve H-V mode constitutes a hybrid approach in which transmissions in one polarization basis (circular) are received in another basis (H,V). Equivalently, H and V polarizations are simultaneously transmitted and received. The latter idea was originally proposed by Seliga and Bringi (1976) but its usefulness was not fully recognized or taken advantage of until recently. It in fact provides an optimal way of making dual-polarization measurements. $Z_{\rm DR}$, ϕ_{dp}, and ρ_{HV} are determined from simultaneous returns and are therefore not contaminated by the Doppler effects of alternating H and V transmissions. Because equal H and V powers are transmitted, the signal-to-noise ratios are approximately the same in the two receiver channels. The measurements are speeded up by a factor of two or more by not having to alternate transmissions, and/or the time saved can be used to make polarization diverse measurements (e.g., LHC and $+45°$ linear) to aid in particle identification. An important practical advantage is that a high-power polarization switch is not needed.

An advantage of the Poincaré approach is that it enables one to visualize the depolarization effects geometrically. It has also led to more general formulations of the radar meteorological problem. In particular, the effect of different classes of particles on the polarization state of a radar signal can be straightforwardly determined for arbitrary incident polarizations. The polarization state is characterized by four quantities. The quantities are determined by measuring the covariances $W_1 = \langle \hat{E}_1 \hat{E}_1^* \rangle$ and $W_2 = \langle \hat{E}_2 \hat{E}_2^* \rangle$ of the backscattered returns in orthogonal polarizations, and the magnitude and phase $W = \langle \hat{E}_1 \hat{E}_2^* \rangle = |W| e^{j\phi}$ of the cross-covariance between the orthogonal returns. For signals received in an H–V basis, $W_1 = W_H$, $W_2 = W_V$, and $\phi = \phi_{HV}$. An alternate way of representing the covariances is in terms of the rationalized quantities W_V (or W_H), W_H/W_V, ρ_{HV}, and ϕ_{HV}, where $\rho_{HV} = |W|/\sqrt{W_H W_V}$.

Horizontally oriented particles such as rain change the rationalized H–V covariances in a simple way. In particular, for a general incident polarization, backscatter from the particles changes the covariances from the values incident upon the scattering volume to

$$\begin{aligned} W_V|^{\mathrm{s}} &= k \cdot Z_V \cdot W_V|^{\mathrm{i}} \\ \left.\frac{W_H}{W_V}\right|^{\mathrm{s}} &= Z_{\mathrm{DR}} \cdot \left.\frac{W_H}{W_V}\right|^{\mathrm{i}} \\ \rho_{HV}|^{\mathrm{s}} &= f \cdot \rho_{HV}|^{\mathrm{i}} \\ \phi_{HV}|^{\mathrm{s}} &= \delta_\ell + \phi_{HV}|^{\mathrm{i}} . \end{aligned}$$

In these expressions, the superscripts i and s denote the incident and backscattered values, k is a constant of proportionality, $\delta_\ell = \angle\langle S_{hh} S_{vv}^*\rangle$ is the differential phase upon backscatter for linear incident polarization, and f is the shape correlation parameter, usually called $\rho_{HV}(0)$,

$$\frac{|\langle S_{hh} S_{vv}^*\rangle|}{\sqrt{\langle |S_{hh}|^2\rangle \langle |S_{vv}|^2\rangle}} \leq 1 , \qquad (1)$$

which describes the effect of shape variability in reducing the correlation coefficient ρ_{HV}.

If the medium through which the radar signal propagates to reach the scattering volume also consists of horizontally oriented particles, the propagation effects can also be accounted for in a multiplicative (or additive) way. In particular, letting the transmitted and received covariance values be denoted by the superscripts t and r,

$$\begin{aligned} W_V|^{\mathrm{r}} &= k' \cdot {A_V}^2 Z_V \cdot W_V|^{\mathrm{t}} \\ \left.\frac{W_H}{W_V}\right|^{\mathrm{r}} &= \frac{Z_{\mathrm{DR}}}{(DA)^2} \cdot \left.\frac{W_H}{W_V}\right|^{\mathrm{t}} \\ \phi_{HV}|^{\mathrm{r}} &= -2\phi_{dp} + \delta_\ell + \phi_{HV}|^{\mathrm{t}} \\ \rho_{HV}|^{\mathrm{r}} &= f_{\mathrm{prop}}^2 \cdot f \cdot \rho_{HV}|^{\mathrm{t}} , \end{aligned}$$

where A_V, DA and ϕ_{dp} are the (one-way) attenuation, differential attenuation, and differential phase values. The quantity f_{prop} accounts for the fact that the medium can introduce an unpolarized component during propagation.

The above results have the same basic form as those for alternating H and V transmissions, except that they apply for a general incident polarization. The scattering by horizontally oriented particles is characterized by four quantities: Z_V (or Z_H), Z_{DR}, δ_ℓ, and f (usually termed $\rho_{HV}(0)$). Each quantity has a corresponding propagation effect, namely A_V, DA, ϕ_{dp}, and f_{prop}. In general, the propagation and backscatter effects cannot be distinguished from each other except possibly on the basis of physical relationships (e.g., Torlaschi and Holt, 1993). The f_{prop} term has not previously been recognized but can be significant (Scott et al., 2001) and can cause ρ_{HV} to be different than f.

The above effects can be described geometrically in the Poincaré representation, as shown in Figure 1. The trajectory shows how the received polarization state changes with range from the radar, and the straight lines show how the return from a given range gate is reached. The Poincaré sphere is viewed from above its north or LHC pole, and it is assumed that LHC polarization is transmitted. As indicated in Figure 2 of paper 5B.1, as the signal propagates from the radar to the scattering volume the polarization state will move upward toward the V polarization point as a result of differential attenuation DA and to the right (clockwise around the sphere) as a result of differential propagation phase, ϕ_{dp}. Upon being backscattered, the polarization state is displaced further to the right due to any backscatter phase δ_ℓ and downward toward the H polarization point due to Z_{DR}. Propagation back to the radar rotates the polarization state further to the right and upward. The returns from other gates experience different amounts of depolarization, giving rise to a continuous trajectory of states, as shown. Examples of actual polarization trajectories are presented by Scott et al. (2001).

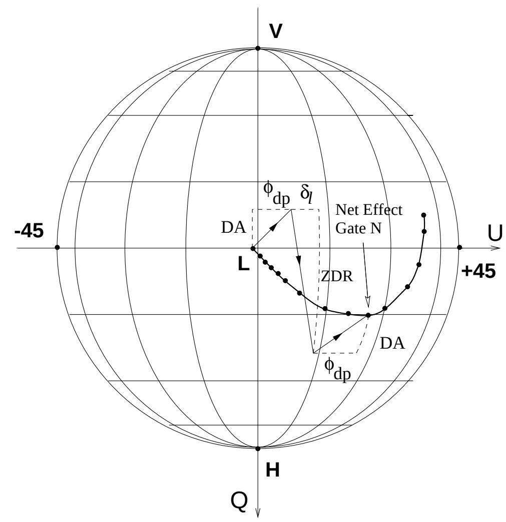

Figure 1. Polarization trajectory for horizontally oriented particles, as viewed from above the Poincaré sphere.

A quantitative description of the above changes is obtained by transforming the the polarization variables from the rationalized covariance quantities to the spherical coordinates (α,ϕ,p) of Figure 2 in 5B.1. In addition to changing α and ϕ, the radius of the Poincaré sphere will in general change as the the degree of polarization p (or equivalently, ρ_{HV}) changes.

The depolarization caused by randomly oriented or irregularly shaped particles such as hail is illustrated qualitatively in Figure 3 of paper 5B.1. The changes are most simply described in terms of the spherical coordinates (δ,τ,p) of the Poincaré sphere. From Scott (1999), the changes are quantitatively expressed by

$$\mathrm{I}|^{\mathrm{s}} = N \cdot S_{\mathrm{avg}} \cdot \mathrm{I}|^{\mathrm{i}}$$

$$\tan(2\tau)|^{s} = \tan(2\tau)|^{i}$$

$$\tan(2\delta)|^{s} = g \cdot \tan(2\delta)|^{i}$$

$$p|^{s} = \frac{p|^{i}}{(2-g)} \sqrt{\cos^2(2\delta|^{\mathrm{i}}) + g^2 \sin^2(2\delta|^{\mathrm{i}})} ,$$

where

$$S_{\rm avg} = \frac{[\langle |S_{xx}|^2\rangle + \langle |S_{yy}|^2\rangle]}{2}$$

is the average backscattering cross-section. The depolarization depends only on g,

$$g = \frac{4{\rm Re}\{\langle S_{xx}S_{yy}^*\rangle\}}{\langle |S_{xx}+S_{yy}|^2\rangle} \ ,$$

a newly-identified parameter of the scatterers that measures the departure of the scatterers from sphericity (Scott, 1999). When $2\delta|^{\rm i} = 0°$ or $90°$, corresponding to linear or circular incident polarization, the polarization state remains unchanged except that some of the polarized power is converted to unpolarized power. The degree of polarization p is decreased by a factor of $g/(2-g)$ for circular incidence and $1/(2-g)$ for linear incidence. For small depolarizations, the decrease in p is a factor of two greater for circular than for linear polarization; for larger depolarizations the difference is greater than a factor of two.

Yet to be formulated are relations describing the effect of randomly oriented particles on the polarization state of the signal. Qualtitatively, the signal will become increasingly unpolarized with range, while at the same time any ellipticity will become more linear. The propagation trajectory will descend along a curved path toward the origin of the Poincaré sphere in a plane of constant orientation angle τ.

The polarization changes produced by particles aligned at an angle τ relative to horizontal are the same as those for horizontally oriented particles, but are rotated by an amount 2τ in the equatorial or Q–U plane of the Poincaré sphere (Figure 4, paper 5B.1). The polarization trajectories through such particles will be similarly rotated in the projection view of Figure 1.

In summary, the generalized results identify two basic classes of scatterers that depolarize the signal: particles which are aligned and those which are randomly oriented. Spherical particles constitute a third class of scatterers, which change the total power but otherwise do not affect the polarization state. It is readily shown that the covariances from a mixture of particle types or classes is the sum of the covariances for each class. Thus,

$$W_H = W_{H(\rm spherical)} + W_{H(\rm aligned)} + W_{H(\rm random)} \ .$$

Similar expressions would hold for W_V and W.

The additive nature of the covariances in principle provides a basis for objectively determining the parameters of a mixture of scatterer types. In the absence of propagation effects, the return from a given range gate is characterized by up to 8 quantities: Z_V, $Z_{\rm DR}$, δ_ℓ, f and the orientation angle τ of any aligned particles, $S_{\rm avg}$ and g of randomly oriented particles, and the total reflectivity Z_S of spherical particles[1]. Transmitting a given polarization provides four measurements, so the eight unknowns could in principle be determined by transmitting two 'independent' polarizations. The problem is substantially complicated by propagation effects, which add additional unknowns that are coupled with the corresponding backscatter parameters and that may change for different transmitted polarizations. The basic question is whether the problem is tractable and amenable to solution (or approximate solution). Although the multiparameter approach is a complicated way of analyzing observations, the considerations in fact govern the extent to which radar observations can be unambiguously and objectively interpreted.

REFERENCES

Brunkow, D., V.N. Bringi, P.C. Kennedy, S.A. Rutledge, V. Chandrasekar, E.A. Mueller, and R.K. Bowie, 2000: A description of the CSU-CHILL National Radar Facility, J. Atmos. Oceanic Tech., 17, 1596-1608.

Doviak, R.J., V. Bringi, A. Ryzhkov, A. Zahrai, and D. Zrnić, 2000: Considerations for polarimetric upgrades to operational WSR-88D radars. J . Atmos. Oceanic Tech., 17, 257-278.

Scott, R., P. Krehbiel, and W. Rison, 2001: The use of simultaneous horizontal and vertical transmissions for dual-polarization radar meteorological observations, J. Atmos. and Oceanic Tech., 18, 629-648.

Scott, R., 1999: Dual-polarization radar meteorology: A geometrical approach. Ph.D. Diss., New Mexico Institute of Mining and Technology, 129 pp. (available at http://lightning.nmt.edu/radar/scott99).

Seliga, T., and V.N. Bringi, 1976: Potential use of radar differential reflectivity measurements at orthogonal polarizations for measuring precipitation, J. Appl. Meteorol., 15, 69-76.

Torlaschi, E., and A.R. Holt, 1993: Separation of propagation and backscattering effects in rain for circular polarization diversity S-band radars, J. Atmos. Oceanic Tech., 10, 465-477.

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[1] An additional variable could be the rms value of canting in the aligned particles.