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Radar Polarimetry for Weather Observations

Springer

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ISSN 2194-5217 ISSN 2194-5225 (electronic)
ISBN 978-3-030-05092-4 ISBN 978-3-030-05093-1 (eBook)
https://doi.org/10.1007/978-3-030-05093-1

Library of Congress Control Number: 2019930082

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Preface

Prior to the advent of dual-polarization radars, direct interpretation of cloud and precipitation bulk characteristics from radar reflectivity was limited to very few unambiguously defined cases, such as the bright band or large hail. Even then, knowledge of the physical conditions, like the height above ground of enhanced reflectivity areas, was needed to properly interpret and quantify the observations. Polarimetry transformed the way meteorologists look at and interpret the bulk properties of clouds and precipitation. It brought a dramatic change to direct interpretation and quantitative assessment of these properties, so much so that the polarimetric weather radar has transitioned from a scientific instrument to operational use. This is exemplified by the network of the US weather surveillance radars (WSR-88D) which have been upgraded to dual-polarization. Several other countries did or are doing similar upgrade of their national weather radar networks. Moreover, some of the weather radar manufacturers do not even offer single-polarization radars for weather surveillance anymore. The additional information dual-polarization radar provides to forecasters is primarily used for quantitative precipitation estimation (QPE), classification of radar returns, discrimination between meteorological and nonmeteorological scatterers, and severe weather warnings. Identification of meteorological scatterers provides an added positive impact on QPE. Potential improvements of QPE were used as principal justifications for the introduction of the Doppler capability (in the 1980s) and dual-polarization upgrade of operational weather radars. Lately, interest is rising within the numerical weather prediction (NWP) community to incorporate polarimetric data into NWP models either via assimilation or through improvement of their microphysical parameterization.

Although there are numerous scientific papers and reports about weather radar polarimetry and its applications, books on the subject are few. We hope that this monograph adds variety and some material not compiled elsewhere. It is meant for practicing radar meteorologists, hydrologists, cloud physicists, and modelers who are interested in the bulk properties of hydrometeors and quantification of these with the goals to improve precipitation measurements, understanding of precipitation processes, or model forecasts. We have made a deliberate attempt to tightly connect the microphysical processes responsible for the development and evolution of the clouds' bulk physical properties to the polarimetric variables. The book contains instructions on how to simulate realistic polarimetric variables. It also demonstrates that the polarimetric variables from all but the precipitation containing large (Mie) scatterers can be adequately related to bulk precipitation physics using simple closed-form solutions. It also addresses the problem of determining the polarimetric variables from the output of NWP models.

To make the book self-contained, we included fundamental topics in polarimetry such as polarimetric variables, polarimetric radar, and scattering. We hope that the practical aspects, references, and instructions contained herein will be beneficial to those entering this fascinating field as well as to those needing quick answers concerning practical applications of weather radar polarimetry. Much of the material in this book came from the research the authors did at the National Severe Storms Laboratory and the Cooperative Institute for Mesoscale Meteorological Studies. Polarimetric work at the National Severe Storms Laboratory started under the directorship of Dr. E. Kessler and continued under Dr. R. Maddox, Dr. J. Kimpel, and Dr. S. Koch. Crucial were two NSSL radars, first Cimarron and then KOUN, to test various design/engineering aspects of dual polarimetry. These radars also provided valuable data for analysis and interpretation.

The able engineering team responsible for implementation of dual-polarization consisted of D. Sirmans, A. Zahrai, J. Carter, M. Schmidt, and R. Wahkinney. To them and other NSSL support staff, we extend sincere thanks. The National Research Council postdoctoral associates at NSSL, Dr. M. Sachidananda and Dr. N. Balakrishnan, made pioneering contributions at the time when these were most needed. Collaboration with Dr. J. Straka from the University of Oklahoma brought rigor to polarimetric classification of echoes and introduced the subject to the community. Significant contributions to Chaps. 7 and 8 are from Dr. M. Kumjian's works. Discussions with Drs. R. Doviak (NSSL), G. Zhang, V. Melnikov (University of Oklahoma), S. Matrosov (University of Colorado in Boulder), and V. Bringi (Colorado State University) were always illuminating.

We express our deep gratitude to our international partners and colleagues, A. Khain, M. Pinsky, C. Simmer, S. Troemel, K.-E. Kim, D.-I. Lee, G. Lee, R. Kaltenboeck, D. Hudak, S. Boodoo, and many others for their fruitful collaboration and exchange of ideas and data. We also acknowledge help from our colleagues at NSSL/CIMMS, D. Forsyth, T. Schuur, J. Krause, P. Zhang, L. Borowska, H. Reeves, K. Ortega, in the pursuit of our research. The partnership with Drs. R. Palmer and T.-Y. Yu from the Advanced Radar Research Center and their generosity in sharing the OU-PRIME polarimetric data are greatly appreciated.

Last but not least, our students J. Conway, B. Gordon, M. Loney, P, Schlatter, M. Askelson, S. Bachmann, S. Giangrande, S. Ganson, H.-S. Park, J.-Y. Gu, J. Picca, J. Snyder, J. Carlin, P. Bukovcic, D. Mirkovic, E. Griffin, and A. Murphy were sounding boards for testing concepts and ideas, as well as for generating new ones.

Funding for dual-polarization work, although sparse, was sufficient to keep us hungry for more; thank you OAR/NOAA. Token support was provided by the FAA, NSF, and NASA. Dr. J. Rasmussen, Head of OAR in the 1990s, funded specifically dual-polarization work. Dr. E. Friday, Director of the National Weather Service, arranged the transfer of the WSR-88D (KOUN) from NWS to NSSL. This was a tremendous help to NSSL's research and facilitated the upgrade of the WSR-88D network to dual-polarization.

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Contents

Abbreviations

α	Canting angle
α	Ratio A/K_{DP}
β	Antenna elevation angle
β	Ratio $A_{\mathrm{DP}}/K_{\mathrm{DP}}$
δ	Backscatter differential phase
ε	Dielectric constant
ε_w	Dielectric constant of water
ε_i	Dielectric constant of solid ice
ε_s	Dielectric constant of snow
η	Reflectivity (cross section per unit volume)
η_o	120π (Ω), free space impedance
θ	Angular distance from the beam axis
θ_e	Elevation angle
θ_1	One-way beamwidth between half-power points
λ	Electromagnetic wavelength
Λ	Slope of the exponential raindrop size distribution
Λ_s	Slope of the exponential size distribution of snow/ice
μ	Shape parameter of the Gamma distribution
ρ_a	Mass density of air
ρ_i	Density of solid ice
ρ_{hv}	Correlation coefficient between horizontally and vertically polarized return signals
$\rho_{xh,xv}$	Correlation coefficients between cross-polar (x) and copolar (h,v) components of the returned signal
ρ_s	Density of snow
ρ_w	Density of water
σ	Width of canting angle distribution
σ_b	Backscattering cross section
σ_e	Extinction or attenuation cross section
σ_v	Doppler spectrum width (m s^{-1})
σ_{vn}	Normalized spectrum width ($4\sigma_{\mathrm{v}}T_{\mathrm{s}}/\lambda$)

σ_θ^2	Second central moment of the two-way antenna radiation pattern
τ	Pulse width
τ_s	Range time delay
ϕ	Azimuth
Φ_{DP}	Differential phase
Ψ	Angle between the axis of rotation of scatterer and the direction of wave propagation
ω	Angular frequency
A_{DP}	Specific differential attenuation (dB km^{-1})
$A_{h,v}$	Specific attenuation at orthogonal polarizations (dB km^{-1})
A_i	Aggregation value for i-th radar echo class
$A_1 - A_5$	Angular moments of particle orientation distributions
c	Speed of light (3×10^8 m s^{-1})
$c_{h,v}$	Speeds of EM waves (polarization H or V) in anisotropic medium
C	Capacitance of particle
CDR	Circular depolarization ratio (dB)
C_{dr}	Circular depolarization ratio (linear units)
D_a	Diameter of the antenna system
D_e	Diameter of an equivalent volume spherical raindrop
D_o	Median volume diameter of particle
D_m	Mean volume (or mass-weighted) diameter of particle
D_v	Diffusivity of water vapor
e	Partial pressure of water vapor
$\mathbf{e}_h$, $\mathbf{e}_v$	Unit vectors in the h and v direction, abbreviated with $\mathbf{e}_{h,v}$
E	Electric field intensity
$\mathrm{E}_{h,v}$	Components of the complex $\vec{\mathbf{E}}$ vector along the $\mathbf{e}_{h,v}$ directions
$E_{h,v}$	Phasor representation of the h and v components
E_w	Saturated vapor pressure with respect to water
E_s	Saturated vapor pressure with respect to ice
$\boldsymbol{E}$	Phasor matrix representation: $\boldsymbol{E} = [E_h, E_v]^T$
$\vec{\mathbf{E}}$	Electric field vector (complex) containing time variation
$\vec{\boldsymbol{E}}$	Phasor vector representation: $\vec{\boldsymbol{E}} = E_h\mathbf{e}_h + E_v\mathbf{e}_v$
f	Frequency
f_d	Doppler frequency shift
f_{rim}	Degree of riming
f_w	Mass water fraction
$f^2(\theta,\phi)$	Normalized one-way power gain of radiation pattern
F	Ventilation coefficient
g	Gravitational constant (9.81 m s^{-2})
g	Antenna gain
$I(\mathbf{r},\mathbf{r}_1)$	Illumination function
$I(t)$	In-phase component of the phasor signal
IWC	Ice water content (g m^{-3})

k	Electromagnetic wave number ($2\pi/\lambda$) in vacuum
K	Thermal conductivity of air
$k_{h,v}$	Complex wave number in atmosphere with scatterers
K_{DP}	Specific differential phase (deg km^{-1})
K_w	$(\varepsilon_w - 1)/(\varepsilon_w + 2)$
K_i	$(\varepsilon_i - 1)/(\varepsilon_i + 2)$
$l_{h,v}$	One-way propagation loss due to scatter and absorption (≥ 1)
ln	Natural logarithm
log	Logarithm to base 10
$\boldsymbol{L}$	Matrix of losses
$L_{a,b}$	Shape factors of spheroidal particle
$l_{h,v}$	Loss factors at orthogonal polarizations (≥ 1)
l_r	Range weighting function loss factor (≥ 1)
L_f	Latent heat of fusion (melting)
L_r	10 log l_{r} (dB)
L_v	Latent heat of vaporization
LDR	Linear depolarization ratio (dB)
L_{dr}	Linear depolarization ratio (linear units)
LWC	Liquid water content (g m^{-3})
m	Mass of particle
M	Number of signal samples (or sample pairs) along sample time axis
M_{I}	Number of independent samples
$n_{h,v}$	Refractive index (complex) of atmosphere with hydrometeors
$\Delta n^{(\mathrm{air})}$	Contribution to refractive index by air
$\Delta n_{h,v}^{(\mathrm{scat})}$	Contribution to refractive index by scatterers (hydrometeors)
$N_{h,v}$	White noise power in the orthogonal receiver channels
$N(D_e)$	Drop size distribution (m^{-3} mm^{-1})
N_{Re}	Reynolds number
N_0	Intercept parameter of the exponential and gamma size distribution of raindrops
N_{0s}	Intercept parameter of the exponential size distribution of ice/snow
N_w	Intercept parameter of the normalized size distribution of raindrops
N_0^*	Intercept parameter of the normalized size distribution of ice/snow
N_t	Total concentration of particles (m^{-3})
P	Atmospheric pressure
P^r	Received signal power
P^t	Peak transmitted power
$P^{(i)}(V_j)$	Membership function of the variable "*j*" and class "*i*"
PIA	Two-way path-integrated attenuation (dB)
PIA	Two-way path-integrated attenuation in linear scale
Q_w	Total water content
$Q(t)$	Quadrature-phase component of the complex signal
r	Range to scatterer
r_a	Unambiguous range

r_6	6-dB range width of resolution volume
$\mathbf{r_o}$	Vector range to the resolution volume V_6 center
r_m	Aspect ratio of melting graupel/hail
r_w	Axis ratio of raindrops
R	Rain rate (mm h^{-1})
RH	Relative humidity of air (%)
$R_{\mathrm{hh,vv}}(T_{\mathrm{s}})$	Autocorrelations of weather signal
R_{hv}	Cross-correlation of weather signals of H and V polarization
R_v	Gas constant for water vapor
$s^{(0)}_{\mathrm{hh,vv}}$	Forward-scattering coefficient of a scatterer
s_{mn}	Backscattering coefficient of a scatterer, incident polarization is *n* (H or V), backscattered is *m* (H or V)
$s_{a,b}$	Backscattering coefficients of a spheroidal scatterer: subscript a is for incident polarization parallel to the rotation axis and subscript b for incident polarization perpendicular to this axis
$\vec{\mathbf{S}}$	Power density of the electromagnetic wave
$\mathbf{S}$	Scattering matrix
S	Snow water equivalent rate (mm h^{-1})
S_w	Vapor saturation ratio with respect to water
S_i	Vapor saturation ratio with respect to ice
SNR	Signal-to-noise ratio (dB)
snr	Signal-to-noise ratio (linear scale)
$\mathbf{T}$	Transmission matrix
T_s	Pulse repetition time
T	Temperature in C^o
v	Doppler velocity (m s^{-1})
V_6	Resolution volume size
$V_{\mathrm{hh,vv}}$	Voltage complex representations (contains $j2\pi f$)
$V_{\mathrm{hh,vv}}$	Voltage phasor representations
V_t	Terminal velocity of hydrometeor (m s^{-1})
$W(r)$	Range weighting function
$Z_{\mathrm{H,V}}$	Reflectivity factors for horizontal and vertical polarizations (dBZ)
$Z_{h,v}$	Reflectivity factors for horizontal and vertical polarizations (mm^6 m^{-3})
Z_{dr}	Differential reflectivity in linear units (Z_h/Z_v)
Z_{DR}	Differential reflectivity (dB)
Z_{DP}	Reflectivity difference ($Z_{\mathrm{h}} - Z_{\mathrm{v}}$) in mm^6 m^{-3}