

## Introduction to Dual Polarization Weather Radar

An interdisciplinary and easy-to-understand introduction to the subject, covering fundamental theory and practical applications supported by numerous operational examples. This balanced text will allow you to begin from how the radar makes observations and move deeper through electromagnetic scattering theory and cloud microphysics to understand and interpret data as they appear on the display. It uses illustrations and images of real radar observations to convey the concepts and theory of atmospheric processes typically observed with weather radar, as well as presenting a working knowledge of the radar system itself. In addition to covering the fundamentals of scattering and atmospheric physics, topics include system hardware, signal processing, and radar networks. This is the perfect tool for scientists and engineers working on weather radars or using their data, as well as senior undergraduate and graduate students studying weather radars for the first time.

**V. Chandrasekar (Chandra)** is a University Distinguished Professor at Colorado State University. He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), the International Union of Radio Science (URSI), and the American Meteorological Society.

**Robert M. Beauchamp** is a systems engineer at the Jet Propulsion Laboratory, California Institute of Technology. His expertise is in radar systems and signal processing.

**Renzo Bechini** is a weather radar expert with 25 years of professional experience in the operation of dual polarization systems. He is currently a weather radar specialist at the regional agency for environmental protection, Arpa Piemonte, in Turin, Italy.

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V. Chandrasekar , Robert M. Beauchamp , Renzo Bechini

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# Introduction to Dual Polarization Weather Radar

Fundamentals, Applications, and Networks

V. CHANDRASEKAR

ROBERT M. BEAUCHAMP

RENZO BECHINI



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## Preface

Historically, new ideas and hypotheses start in specific research areas fostered by a small community through journal papers and monographs. As their appreciation and practicality toward applications grow through the community of researchers, the work is standardized. It is added to the curriculum and textbooks, becoming part of the education at universities. There are numerous examples in history, such as special topics in applied mathematics and statistics being transformed into modern signal processing, or advanced semiconductor physics becoming the electronics and computing boom of the second half of the twentieth century. Weather radars, and more specifically for our purposes, polarimetric weather radars, have undergone the same evolutionary process. Dual polarization radar is part of the standard radar meteorology or remote-sensing curriculum in universities. Through its evolution from a fledgling field of research in the late 1970s to standard weather-observing equipment today, many advanced books have become available in the literature on the topic, starting in 2001 with the first book on polarimetric Doppler weather radar from Cambridge University Press. This book continues this goal: to distill and disseminate fundamental science and practical engineering knowledge about dual polarization weather radar and its applications in an introductory style.

Radar meteorology is a unique subject. The title itself indicates its interdisciplinary nature, combining the fields of radar and meteorology. Radar systems are the workhorse of weather services and atmospheric researchers around the world. They are used to observe the big picture of atmospheric systems as well as the detailed structure of storms. Weather radars are routinely used in multiple lines of business, including national, regional, and private weather services; hydrologic and agricultural industries; and the aviation sector. The adoption of dual polarization for radar systems beyond the research community coincided with a number of other technological revolutions that made it possible. Examples include the leapfrogging of technology in microwave and radio-frequency devices driven by the revolution in communication and digital signal processing, as well as the exponential growth of affordable computing power and data storage. The conversion of weather radar systems all over the world to the use of dual polarization technology began in the 1990s. Today, dual polarization is standard equipment for most operational weather radars.

The application of radars to meteorology has widespread appeal and has become a core topic in the curricula of meteorology, atmospheric science, atmospheric physics, electrical engineering, and geoscience programs. Fundamentally, radar meteorology is an interdisciplinary topic covering the engineering of the radar system, the physics of wave propagation and scattering, the science of atmospheric processes, and the applications of weather observation and prediction. There is a real need for an introductory-level textbook devoted to the interdisciplinary aspects of “radar” and “meteorology” comprising “radar meteorology.” This book aims to serve that goal. With all worthwhile endeavors come challenges, and the task of writing an introductory textbook for dual polarization radar meteorology is no different. We recognize that students in these curricula follow different paths and academic interests, from their core classes through their junior year’s undergraduate curricula. This book takes on the challenge of developing a cogent introductory textbook for an audience from diverse science and engineering backgrounds.

The book consists of 10 chapters, with the early chapters focused on fundamentals. The first chapter introduces dual polarization weather radar and the book in general. At the chapter’s end, a route map through this book’s 10 chapters is presented as a guide for students, teachers, and practitioners as they take a journey through this book. Pure science students can skip a subset of the engineering-oriented chapters, and similarly, pure engineering students can skip a subset of the physical science chapters. For professionals pursuing a goal of “lifelong learning,” or to refresh their knowledge on new techniques and technologies, an accelerated pathway is presented that is focused on applications. The material in this book is intended for students and practitioners who have completed junior-level science, technology, engineering, and mathematics (STEM) coursework. Each chapter has a set of assignments and online supplements.

We had to make another important decision as part of writing this book: whether to present the illustrations in color. After extensive deliberation, we decided to keep the print version of this book in black and white (B&W), for multiple reasons, including (a) B&W books leave a smaller footprint on the environment, (b) many publications are resorting to color rendering in electronic form to make room for future growth in color illustrations, and (c) this book’s focus is on introductory concepts.

After the introduction, Chapter 2 presents a basic introduction to polarization and radar systems for readers of all backgrounds. Chapters 3 and 4 are science-oriented chapters and present the essential precipitation physics and introductory scattering principles for precipitation. Chapters 5 and 6 shift the focus toward engineering, introducing radar signals, followed by weather signal processing. Starting with Chapter 7 on data quality and data science, the book merges the science and engineering branches, focusing on application. This trend continues for radar observations (Chapter 8) and rainfall estimation (Chapter 9) and ends with Chapter 10 on radar networks. The last four chapters are applications directly suited for radar meteorology practitioners.

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V. Chandrasekar, Robert M. Beauchamp, and Renzo Bechini

## Notations and Acronyms

$[F_{rx}]$	receive antenna's dual polarization matrix
$[F_{tx}]$	transmit antenna's dual polarization matrix
$[M]$	transmitter's dual polarization matrix
$[R]$	radar receiver's dual polarization matrix
$[S]$	dual polarization scattering matrix
$[T]$	propagation channel's dual polarization matrix
$[T_{rx}]$	receive channel's dual polarization matrix
$[T_{tx}]$	transmit channel's dual polarization matrix
$\alpha$	Erlang distribution's shape parameter
$\alpha$	Tukey window's taper fraction
$\alpha$	attenuation constant
$\bar{\eta}$	reflectivity
$\bar{b}_h$	mean minimum beam height within the network's cell
$\bar{b}_s$	mean radar beam size within the network cell
$\bar{E}$	average collection efficiency of raindrops
$\bar{r}_i$	ice average radius
$\bar{r}_m$	mass-weighted mean axis ratio
$\bar{r}_z$	reflectivity-weighted axis ratio
$\bar{S}$	averaged power spectrum
$\bar{v}$	mean Doppler velocity
$\bar{v}_p$	precipitation's mean velocity
$\bar{Z}_{\min}$	mean detection sensitivity within the network cell
$\beta$	canting angle
$\beta$	phase constant
$\beta$	slope parameter for linear drop shape model
$\beta_e$	equivalent slope for linear drop shape model
$\Delta\omega$	angular frequency resolution
$\Delta f$	frequency resolution
$\delta k$	weighted difference of specific attenuation
$\Delta r$	range resolution
$\delta r$	Doppler frequency induced range migration
$\Delta t$	elapsed time
$\Delta t_{2\text{way}}$	round-trip time delay
$\Delta v$	Doppler velocity resolution

$\delta$	exponent of snowfall velocity-size relation
$\delta_{\text{co}}$	backscatter differential phase shift
$\dot{\psi}_{\text{ant}}$	antenna angular scan rate
$\epsilon$	electric permittivity
$\epsilon$	measurement error
$\epsilon_0$	electric permittivity of free-space ( $\approx 8.854 \cdot 10^{-12}$ Farad $\text{m}^{-1}$ )
$\epsilon_{\text{eff}}$	effective permittivity
$\epsilon_e$	environment's permittivity
$\epsilon_i$	inclusion's permittivity
$\epsilon_r''$	dielectric constant's imaginary part
$\epsilon_r'$	dielectric constant's real part
$\epsilon_r$	dielectric constant, relative permittivity
$\epsilon_s$	static, low-frequency relative permittivity of water
$\eta$	characteristic impedance
$\Gamma$	gamma function
$\Gamma$	reflection coefficient
$\gamma$	Barnes analysis annealing parameter
$\gamma$	propagation constant, $\gamma = jk$
$\hat{\Psi}_{\text{dp}}$	measured differential phase shift
$\hat{h}$	horizontal polarization's unit vector
$\hat{i}$	incident direction's unit vector
$\hat{k}$	propagation direction's unit vector
$\hat{K}_{\text{dp}}$	estimated specific differential phase shift
$\hat{r}_{xy}$	biased covariance estimate
$\hat{s}$	scattering direction's unit vector
$\hat{v}$	vertical polarization's unit vector
$\kappa$	velocity extension ratio
$\Lambda$	particle size distribution's size (slope) parameter
$\lambda$	smoothing factor for spline fitting
$\lambda$	wavelength
<b>A</b>	multi-Doppler geometry matrix
<b>a</b>	unit vector along the radar's radial direction
<b>C</b>	covariance matrix
<b>E</b>	electric field vector
<b>H</b>	magnetic field vector
<b>h</b>	filter vector
<b>J</b>	current density vector
<b>m</b>	waveform vector
<b>P</b>	polarization current vector
<b>P</b>	polarization sampling vector
<b>S</b>	Poynting vector
<b>S</b>	dual polarization scattering matrix
<b>S</b>	scattering matrix
<b>v</b>	particle velocity vector

<b>X</b>	signal matrix
<b>X<sub>f</sub></b>	waveform's sidelobe matrix
<b>y</b>	convolution output vector
<b>ATAR</b>	alternate transmit, alternate receive
<b>ATSR</b>	alternate transmit, simultaneous receive
<b>CPI</b>	coherent processing interval
<b>DSD</b>	raindrop size distribution
<b>HPBW</b>	half-power beamwidth
<b>ICPR<sub>2</sub></b>	two-way integrated cross-polar ratio
<b>ICPR<sub>2</sub><sup>(ub)</sup></b>	two-way integrated cross-polar ratio's upper bound
<b>ISL</b>	integrated sidelobe level
<b>IWC</b>	ice water content
<b>LDR</b>	linear depolarization ratio
<b>LDR<sub>limit</sub></b>	antenna's minimum LDR
<b>LDR<sub>hv</sub></b>	vertical linear depolarization ratio
<b>LDR<sub>vh</sub></b>	horizontal linear depolarization ratio
<b>MBF</b>	fuzzy logic membership function
<b>NCP</b>	normalized coherent power
<b>NCP<sub>thres</sub></b>	normalized coherent power's threshold for signal detection
<b>NF</b>	noise figure
<b>PDF</b>	probability density function
<b>PIA</b>	path-integrated attenuation
<b>PIA<sub>1way</sub></b>	one-way path-integrated attenuation
<b>PPI</b>	plan position indicator
<b>PRF</b>	pulse repetition frequency
<b>PRT</b>	pulse repetition time
<b>PSD</b>	particle size distribution
<b>PSL</b>	peak sidelobe level
<b>RCA</b>	relative calibration adjustment
<b>RCS</b>	radar cross-section
<b>RHI</b>	range height indicator
<b>RH</b>	relative humidity
<b>SNR</b>	signal-to-noise ratio
<b>SQI</b>	signal quality index
<b>STSR</b>	simultaneous transmit, simultaneous receive
<b>TBP</b>	time-bandwidth product
<b>μ</b>	magnetic permeability
<b>μ</b>	mean
<b>μ</b>	particle size distributions' shape parameter
<b>μ<sup>0</sup></b>	magnetic permeability of free-space ( $4\pi \cdot 10^{-7}$ Henries m <sup>-1</sup> )
<b>μ<sub>m</sub></b>	m <sup>th</sup> spectral moment
<b>ν</b>	kinematic viscosity of air
<b>Ω</b>	solid angle
<b>ω</b>	angular frequency

$\omega_0$	radar carrier's angular frequency
$\omega_s$	pulse repetition angular frequency
$\phi$	azimuth angle
$\dot{\phi}$	rate of change of the drop size
$\phi_1$	antenna's half-power beamwidth in azimuth
$\Phi_{dp}$	propagation differential phase shift
$\Phi_{dp}^{sys}$	system differential phase
$\phi_{pc}$	phase code
$\phi_{sys}$	system's phase shift
$\phi_{vel}$	velocity-induced phase shift
$\psi_{ant}$	angular scanning extent of a CPI
$\Psi_{dp}$	total differential phase shift
$\rho$	correlation coefficient
$\rho$	density
$\rho_{co}$	complex-valued copolar correlation coefficient
$\rho_{snow}$	snowflake density
$\rho_s$	spatial correlation coefficient
$\rho_s$	water vapor density at water saturation
$\rho_v$	water vapor density
$\rho_w$	water density ( $997 \text{ kg m}^{-3} \approx 1 \text{ g cm}^{-3}$ )
$\rho_{cx}$	cross-polarization correlation coefficient
$\rho_{hv}$	copolar correlation coefficient, linear polarization
$\rho_{hv}^{(m)}$	measured copolar correlation with a reflectivity gradient
$\rho_{si}$	water vapor density at ice saturation
$\rho_{vs}$	water vapor density at the drop's surface
$\rho_{xx}$	autocorrelation of $x$
$\rho_{xy}$	cross-correlation of $x$ and $y$
$\sigma$	electrical conductivity
$\sigma$	radar cross-section
$\sigma$	standard deviation
$\sigma^2$	variance
$\sigma_a$	absorption cross-section
$\sigma_b$	backscatter radar cross-section
$\sigma_e$	extinction cross-section
$\sigma_h$	clutter's horizontal polarization scattering amplitude
$\sigma_s$	total scattering cross-section
$\sigma_v$	Doppler spectrum width
$\sigma_v$	clutter's vertical polarization scattering amplitude
$\sigma_w$	surface tension of water ( $0.07275 \text{ J m}^{-2}$ )
$\sigma_w^2$	white-noise signal's variance
$\sigma_{bi}$	bistatic radar cross-section
$\sigma_{vc}$	clutter's spectrum width
$\sigma_{vn}$	normalized Doppler spectrum width

$\sigma_{vp}$	precipitation's spectrum width
$\tan \delta$	loss tangent
$\tau$	time delay
<b>s</b>	far-field scattering amplitude vector
$\theta$	complex-valued angular differential phase shift
$\theta$	elevation angle
$\theta$	incidence angle
$\theta$	wave's incident angle
$\theta_1$	antenna's half-power beamwidth in elevation
$\theta_{\text{err}}$	antenna's pointing error
$\theta_{\text{HPBW}}$	antenna's half-power beamwidth
$\theta_{\text{sep}}$	network's angular separation between radars
$\theta_{ik}$	azimuth difference for Barnes analysis
$\tilde{\mathbf{h}}$	minimum integrated sidelobe level filter's vector
$\tilde{p}$	signal's power estimate
$\tilde{r}_{xy}$	unbiased covariance estimate
$\varphi$	radar signal's phase
$\varphi_{frdp}$	receive antenna's differential phase
$\varphi_{ftdp}$	transmit antenna's differential phase
$\varphi_{rdp}$	receiver's differential phase
$\varphi_{txh}$	horizontal polarization's transmit phase
$\varphi_{txv}$	vertical polarization's transmit phase
$\varphi_{tx}$	relative transmit phase
$\widehat{\text{LHC}}$	left-hand circular polarization's unit vector
$\widehat{\text{RHC}}$	right-hand circular polarization's unit vector
$\widehat{S}$	estimated power spectrum
$\widehat{X}$	estimated signal spectrum
$A$	cross-sectional area
$A$	normalized coherent power threshold's performance constant
$A$	specific attenuation
$a$	$K_{dp}$ -Z scale coefficient
$a$	antenna gain's model coefficient
$a$	beta MBF's spread parameter
$a$	radar signal's amplitude
$a$	radius of Earth
$a$	spheroid's equatorial radius
$a$	transmitter's gain coefficient
$A_{1\text{way}}$	one-way specific attenuation
$A_{2\text{way}}$	two-way specific attenuation
$A_{\text{beam}}^{(\text{weighted})}$	$V_6$ cross-sectional area
$A_{dp}$	specific differential attenuation
$A_a$	antenna collecting area
$A_e$	antenna effective area



$a_e$	effective radius of Earth
$B$	bandwidth
$b$	$K_{dp}$ - $Z$ exponential coefficient
$b$	beta MBF's slope parameter
$b$	observation volume's diameter with a circular antenna
$b$	spheroid's radius along the axis of symmetry
$b_\phi$	observation volume's width in azimuth
$b_\theta$	observation volume's height in elevation
$b_h$	minimum beam height
$b_s$	radar beam size
$C$	$\text{Re}(p_h - p_v)$ vs. $(1 - r)$ slope
$C$	capacitance of the ice crystal
$C$	weather radar constant
$c$	IWC estimator's scale coefficient
$c$	electromagnetic wave's propagation speed, speed of light
$c$	speed of light
$c_0$	speed of light in free space ( $299,792,458 \text{ m s}^{-1} \approx 3 \cdot 10^8 \text{ m s}^{-1}$ )
$C_{\text{gas}}$	two-way atmospheric gas specific attenuation
$C_h$	horizontal polarization's weather radar constant
$C_v$	vertical polarization's weather radar constant
$CN$	complex-valued Gaussian (normal) distribution's PDF
$D$	drop's equivalent spherical diameter
$D$	equivalent spherical diameter of ice particles
$D$	raindrop's equivalent-volume spherical diameter
$d$	Euclidean distance
$D_0$	median equivolume diameter
$D_{ev}$	drop's diameter that completely evaporates after falling $h$ distance
$D_{\text{max}}$	maximum drop diameter of the DSD
$D_{\text{min}}$	minimum drop diameter of the DSD
$d_a$	antenna diameter
$D_e$	volume-equivalent spherical diameter
$D_m$	mass-weighted mean diameter
$D_p$	DSD's $p^{\text{th}}$ moment
$D_s$	maximum snowflake dimension
$D_v$	diffusion coefficient for water vapor in air
$D_w$	melted ice equivalent drop diameter
$D_z$	reflectivity-weighted mean diameter
$df$	frequency offset
$E$	collision-coalescence collection efficiency of raindrops
$e$	electric field component
$e$	prolate shape factor
$e$	water-vapor pressure
$e_a$	antenna aperture's efficiency
$E_h$	horizontal polarization's electric field

$e_h$	horizontal polarization's received signal
$e_s$	saturation vapor pressure with respect to water
$E_v$	vertical polarization's electric field
$e_v$	vertical polarization's received signal
$e_{si}$	saturation vapor pressure with respect to ice
$E_{tx}$	transmitted energy
$f(\mu)$	normalized PDS's shape function
$f(Z_{dr})$	rain/hail partition function
$F$	antenna feed's forward distance
$F$	antenna pattern's complex amplitude
$F$	noise factor
$f$	complex-valued forward-scattering amplitude
$f$	frequency
$f$	normalized antenna pattern's complex amplitude
$f$	oblate shape factor
$f$	observation field
$f$	volume fraction
$f_0$	radar carrier's frequency
$f_1$	pulse repetition frequency for PRT 1
$f_2$	pulse repetition frequency for PRT 2
$f_e$	environment's volume fraction
$F_{ice}$	model for IWC or snowfall rate
$f_{IF}$	intermediate frequency
$f_i$	inclusion's volume fraction
$f_{LO}$	local oscillator's frequency
$F_d$	vapor diffusion term
$f_D$	probability density function
$f_d$	Doppler frequency shift
$F_d^i$	vapor diffusion term for ice
$f_E$	Erlang distribution's probability density function
$F_h$	horizontal force acting on the raindrop
$F_k$	heat-conductivity term
$F_k^i$	heat-conductivity term for ice
$f_s$	pulse repetition frequency
$F_v$	vertical force acting on the raindrop
$f_v$	ventilation factor
$f_\varphi$	phase distribution's probability density function
$f_a$	amplitude distribution's probability density function
$F_{co}$	antenna pattern's copolar complex amplitude
$f_{co}$	normalized antenna copolar pattern's complex amplitude
$F_{cx}$	antenna pattern's cross-polar complex amplitude
$f_{cx}$	normalized antenna pattern's cross-polar complex amplitude
$F_{Em}$	Power estimator's cumulative density function
$f_{Em}$	Power estimator's probability density function

$F_{hh}$	antenna pattern's horizontal copolar complex amplitude
$f_{hh}$	normalized antenna pattern's horizontal copolar complex amplitude
$F_{hv}$	antenna pattern's vertical cross-polar complex amplitude
$f_{hv}$	normalized antenna pattern's vertical cross-polar complex amplitude
$f_N$	Gaussian (normal) distribution's probability density function
$f_p$	power distribution's probability density function
$f_{rcx}$	receive antenna's cross-polar complex-valued gain
$f_{rhh}$	receive antenna's horizontal copolar complex-valued gain
$f_{rvv}$	receive antenna's vertical copolar complex-valued gain
$f_{tcx}$	transmit antenna's cross-polar complex-valued gain
$f_{thh}$	transmit antenna's horizontal copolar complex-valued gain
$f_{tvv}$	transmit antenna's vertical copolar complex-valued gain
$F_{vh}$	antenna pattern's horizontal cross-polar complex amplitude
$f_{vh}$	normalized antenna pattern's horizontal cross-polar complex amplitude
$F_{vv}$	antenna pattern's vertical copolar complex amplitude
$f_{vv}$	normalized antenna pattern's vertical copolar complex amplitude
$G$	Gaussian-shaped spectrum
$G$	antenna gain
$G$	antenna's one-way gain, including radar calibration correction factor
$G$	component gain
$g$	Gaussian-shaped time-domain function
$g$	coefficient for $K_{dp}/Z_h$ relation
$g$	gravitational acceleration constant ( $9.81 \text{ m s}^{-2}$ on Earth)
$G_0$	antenna boresight gain
$G_0$	antenna's one-way gain
$G_n$	antenna pattern's normalized gain model
$G_{h0}$	antenna horizontal polarization's boresight gain
$G_{rx}$	receiver's gain
$G_r$	receiving antenna's gain
$G_t$	transmitting antenna's gain
$G_{v0}$	antenna vertical polarization's boresight gain
$h$	fall distance
$h$	filter's impulse response
$h$	height
$h$	window function
$h_0$	height of the radar's antenna
$H_{dr}$	hail differential reflectivity parameter
$H_h$	horizontal polarization's magnetic field
$h_t$	triangle window function
$H_v$	vertical polarization's magnetic field
$I$	scatterer power
$I_Z$	network cell's sensitivity improvement factor
$j$	imaginary number, $\sqrt{-1}$
$K$	velocity extension factor

$k$	angular wavenumber or phase constant
$k$	frequency sample index
$k$	propagation constant, $k = -j\gamma$
$k_0$	propagation constant of free-space
$K_{dp}$	specific differential phase shift
$k_{eff}$	effective propagation constant for a mixture
$K_{opt}$	window constant for calculating optimal number of samples
$k_\theta$	Barnes analysis azimuth smoothing parameter
$K_a$	thermal conductivity of air
$k_a$	antenna beamwidth factor
$k_B$	Boltzmann constant ( $1.380649 \cdot 10^{-23} \text{ J K}^{-1}$ )
$k_d$	Barnes analysis fall-off range parameter
$k_L$	attenuation coefficient
$k_r$	Barnes analysis radial smoothing parameter
$L$	depolarization factor
$L$	latent heat of vaporization
$l$	attenuation through precipitation
$l_{isl}$	mainlobe's maximum sample lag
$l_{radome}$	one-way radome loss
$l_{rx}$	receiver loss
$l_{tx}$	transmitter loss
$L_D$	filter loss from Doppler frequency shift
$L_f$	filter loss factor
$L_s$	latent heat of sublimation
$L_w$	waveform loss factor
$M$	$K_{dp}$ estimator's sample length
$M$	network's overlap ratio
$M$	number of countered particles
$M$	number of spectrum to average
$M$	range-time signal's length
$m$	raindrop mass
$m$	transmit waveform
$m_{isl}$	mainlobe's sample width
$m_h$	horizontal polarization's transmitted waveform
$m_v$	vertical polarization's transmitted waveform
$N(D)$	particle size distribution
$N(D)$	raindrop-size distribution
$N$	Gaussian (normal) distribution's probability density function
$N$	number of radars in the network
$N$	number of samples in the integration time
$N$	number of samples in the waveform
$n$	an integer index
$n$	index of refraction
$n$	noise power

$N_0$	particle size distribution's concentration (intercept) parameter
$N_{\text{norm}}$	normalized particle-size distribution
$N_{\text{opt}}$	optimal number of samples for maximum spectrum SNR
$N_c$	number of hydrometeor classes
$n_c$	number concentration
$N_I$	number of independent samples
$N_i$	ice particle number concentration
$N_s$	snowflake particle size distribution just above the melting layer
$N_v$	number of classifier input variables
$N_w$	normalized PSD's intercept parameter
$N_w$	raindrop size distribution just below the melting layer
$P$	polar coordinate domain
$p$	polarization factor
$p$	total source power
$P_c$	clutter's power
$P_i$	intrinsic (unattenuated) echo power
$P_m$	measured (with attenuation) echo power
$P_n$	noise's power
$P_p$	precipitation's power
$P_r$	power at the receiver
$P_t$	transmitter's power
$P_s$	scattered wave's power
$P_s$	signal's power
$P_{th}$	horizontal polarization's transmit power
$P_{tv}$	vertical polarization's transmit power
$q$	$K_{dp}$ estimator error function weight
$R$	particle or drop radius
$R$	rain rate
$r$	covariance
$r$	particle or drop radius
$r$	raindrop's axis ratio
$r$	range
$R_{\text{ATSR}}$	ATSR samples' covariance matrix
$r_{\text{cell}}$	network cell range
$r_{\text{max}}$	radar's maximum range
$r_{\text{sep}}$	network's separation range between radars
$R_{\text{STSR}}$	STSR samples' covariance matrix
$r_a$	unambiguous range
$r_m$	radius of influence
$r_r$	range from the scatterer to receiver
$r_s$	calibration sphere's radius
$r_t$	range from the transmitter to scatterer
$R_v$	gas constant for water vapor ( $461.5 \text{ J kg}^{-1} \text{ K}^{-1}$ )

$r_{ff}$	Fraunhofer distance, the antenna far-field's starting range
$r_{ik}$	radial difference for Barnes analysis
$R_{SS}$	scatterer's linear polarization covariance matrix
$r_{xx}$	autocovariance of $x$
$r_{xy}$	cross-covariance of $x$ and $y$
$S$	power density
$S$	power spectrum
$S$	water-equivalent snowfall rate
$s$	echo signal
$s$	ice crystal surface
$s$	path segment
$s$	spline solution
$s$	vertical wind shear
$s_a$	azimuth's arc distance
$S_c$	clutter's Doppler spectrum model
$s_e$	elevation's arc distance
$S_i$	incident power density
$S_i$	water vapor saturation ratio with respect to ice
$S_k$	fuzzy logic class's confidence
$S_n$	noise's Doppler spectrum model
$S_p$	precipitation's Doppler spectrum model
$S_r$	power density at the receiving antenna
$S_s$	scattered power density
$S_w$	water vapor saturation ratio
$S_x$	received signal's Doppler spectrum model
$S_{\Phi_{dp}}$	spectral differential propagation phase
$S_{\rho_{hv}}$	spectral copolar correlation
$s_{hh}$	horizontal polarization's copolar complex scattering amplitude
$s_{vv}$	vertical polarization's copolar complex scattering amplitude
$S_{Z_{dr}}$	spectral differential reflectivity
$T$	temperature
$T$	total observation time
$t$	time
$T_0$	noise factor's reference temperature
$T_D$	decorrelation time
$T_n$	noise temperature
$T_s$	pulse repetition interval
$T_u$	PRT for equivalent unfolded unambiguous velocity
$T_{sys}$	system's noise temperature
$T_{tx}$	transmitted pulse's duration
$U$	horizontal wind velocity
$u$	particle velocity in the $x$ direction
$V$	sphere's volume
$V$	volume

$v$	particle velocity in the $y$ direction
$v$	scatterer's velocity
$v$	wave's propagation speed
$V_6$	radar observation volume at -6 dB extent
$v_a$	unambiguous velocity
$v_r$	radial Doppler velocity
$V_t$	terminal velocity
$v_u$	unfolded unambiguous velocity
$V_{ts}$	terminal velocity of snow and ice precipitation particles
$w'$	modified weighting parameter
$W$	liquid water content
$w$	$K_{dp}$ estimator error function weight
$w$	Doppler spectrum width
$w$	Tukey window function
$w$	fuzzy logic membership weight
$w$	particle velocity in the $z$ direction
$w$	updraft velocity
$w$	white-noise signal
$w^*$	Bergeron process's threshold for vertical velocity
$X$	frequency spectrum of a radar signal
$x$	Cartesian position in the west-to-east direction
$x$	MBF input variable
$x$	radar signal
$x_{2way}$	signal after two-way phase shift
$x_{coded}$	phase-coded signal
$x_{decoded}$	signal demodulated by the phase code
$x_E$	relative position in the west-to-east direction
$x_I$	radar signal's in-phase (real) component
$x_Q$	radar signal's quadrature (imaginary) component
$x_{bb}$	complex-valued signal at base-band frequency
$x_{rf}$	complex-valued signal at the radio frequency
$x_{rf}$	radio frequency signal
$y$	Cartesian position in the south-to-north direction
$y_E$	relative position in the south-to-north direction
$Z$	reflectivity factor
$z$	Cartesian position in the nadir-to-zenith direction
$z$	altitude
$Z^{95}$	clutter's 95th-percentile measured reflectivity
$Z_{dr}$	differential reflectivity
$Z_{dr}^{(bis)}$	bistatic differential reflectivity
$Z_{intrinsic}$	scattering volume's true equivalent reflectivity factor
$Z_{max}$	minimum sensitivity at maximum range
$z_{top}$	initial altitude
$Z_e$	equivalent reflectivity factor

$z_E$	relative position in the nadir-to-zenith direction
$Z_e^{\min}$	minimum detectable reflectivity factor
$Z_h$	horizontal polarization's equivalent reflectivity factor
$Z_n$	noise's equivalent reflectivity factor
$Z_v$	vertical polarization's equivalent reflectivity factor