Radar Meteorology

Radar is a key instrument used in meteorology for monitoring wind and precipitation, and has become the primary tool used for short-term weather forecasting. This practical textbook introduces the fundamental concepts behind radar measurements and their meteorological interpretation.

The first part of the book provides the essential background theory behind radar measurements to guide students and practitioners in the proper interpretation of radar reflectivity, Doppler velocity, and dual-polarization imagery. Operational applications are then explored, such as how radar imagery can be used to analyze and forecast convective and widespread weather systems. The book concludes with an overview of current research topics, including the study of clouds and precipitation using ground-based and spaceborne radars, signal processing, and data assimilation.

Numerous full-color illustrations are included, as well as case studies, and a variety of supplementary electronic material, including problem sets and animated time sequences of images to help convey complex concepts. This book is a valuable resource for advanced undergraduate and graduate students in radar meteorology and other related courses, such as precipitation microphysics and dynamics. It will also make a useful reference for researchers, professional meteorologists, and hydrologists.

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Frédéric Fabry
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Principles and Practice

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Preface

"Radar meteorology" is an odd specialty in atmospheric science. As opposed to synoptic meteorology or cloud physics, its focus has been on the instrument from the start. Radar enabled us to observe and understand many previously unknown phenomena. What we could do with this wonderful tool drew together a vibrant community of researchers whose main point in common was the use or the development of radars for meteorology. The instrument became the center of this community. As a result, when radar meteorologists meet, many often talk about instrument characteristics such as frequency, beam width, and transmit power before they talk of science. Early influential textbooks reflected that state of affairs, and many current introductory ones follow the same mold: they tend to be very radar focused, even those that do not describe in great detail the radar and its workings, and they are not very application oriented, despite the fact that the very reason we use radars is for what it allows us to see and do, from meteorological studies to short-term forecasting. Introductions to satellite meteorology, another technically oriented specialty, have managed to free themselves from their heritage: textbooks on how to use satellite imagery can be found, as well as more traditional books focused on radiative transfer. But somehow, introductions to radar meteorology have failed to do so.

Yet, the average weather radar user has changed. Radar is an operational instrument in many countries. It offers the forecasters what is generally the best opportunity to detect rapidly developing storms, and the last one to evaluate whether the weather evolves as expected or not. Also, the twenty-first-century researcher has a different focus: while efforts to improve and better understand radar data remain the principal objective of a necessary core of specialists, the emphasis has shifted toward meteorology and how to make the best use of the rich information provided by radar. Traditional books introducing radar meteorology, and the courses that rely on them, have gradually become disconnected from this changing reality. Furthermore, the historical focus of radar meteorology on the instrument and the physics of its measurements has made the subject difficult to teach and very dry to nonspecialists. This is regrettable given how wonderfully radar can be used to illustrate and understand weather phenomena, and to reinforce the learning of meteorological concepts seen in other courses, especially in precipitation microphysics and dynamics. As a result, a proper introduction on the use of radar for meteorology is often lacking in many university or professional programs, an illogical outcome given the current use of radar in operations and research. The frustration I experienced in the way radar meteorology was (not) taught, including to those who would not take up a career based on radar research, pushed me to write this introductory book.

To be fair, there is one good reason why many textbooks emphasize the more technical side of the basic principles of radar measurements: a proper interpretation of the imagery observed and how it may be corrupted can only be achieved after a thorough understanding of exactly what quantities a radar measures and how it does so. The day when radar imagery will be uncorrupted, free of all unwanted elements, and unambiguous has yet to arrive. Hence, one must still understand how the measurements are taken, what can corrupt them, and how to recognize what is correct from what is suspect. The book must still begin with a sufficient description of the basic principles of radar detection capability for the reader to be able to understand the nature and peculiarities of the data and how they can be contaminated. Subsequent chapters can then concentrate on the uses of radar data, starting with operational uses and gradually shifting to research applications.

An appendix introducing key mathematical and statistical concepts used in radar data analysis and processing completes the book. There are a few ways to use it depending on the level of the course and its emphasis. The appendix can be read as a block after Chapter 3 in the context of a thorough graduate-level course, or by subsections on a need basis, as these subsections are being referred to in the main text. It could also be skipped if the focus of the course is on the operational uses of radar.

The book chapters can be read in a different order depending on one’s interest and focus. The cover-to-cover approach works well as an introduction for future researchers with a meteorology focus. A reader interested in how to use radar data operationally should focus on Chapters 1–8, continuing up to Chapter 12 if the first chapters stimulated your curiosity. A more traditional order of topics of radar meteorology starting with instrument and theory first would be Chapters 1–3, Appendix A, Chapter 13, and then 4–12, possibly skipping over Chapters 7 and 8.

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Notation

List of symbols

a	generic coefficient of a power-law relationship
a	real part of a generic complex number, Appendix A.5
$a_{1,2,\,j}$	real parts of the complex numbers z_1, z_2, z_j
a_e	radius of the Earth
A	amplitude of the radar signal
A_HH	signal amplitude obtained when transmitting and receiving at horizontal polarization, also known as the *copolar* amplitude at horizontal polarization
A_HV	signal amplitude obtained when transmitting at horizontal polarization and receiving at vertical polarization
A_VH	signal amplitude obtained when transmitting at vertical polarization and receiving at horizontal polarization, also known as the *cross-polar* amplitude of the signal
A_VV	signal amplitude obtained when transmitting and receiving at vertical polarization, also known as the *copolar* amplitude at vertical polarization
b	generic exponent of a power-law relationship
b	imaginary part of a generic complex number, Appendix A.5
$b_{1,2,\,j}$	imaginary parts of the complex numbers z_1, z_2, z_j
B	bandwidth of the receiver
c	speed of light
c_j	complex weights to bases functions of a Fourier series, Eq. (A.37)
c_p	specific heat capacity of air at constant pressure
c_s	speed of sound, Eq. (5.3)
c_v	specific heat capacity of air at constant volume
$\mathrm{cov}_{X,Y}$	covariance between the samples X and Y, Eq. (A.13)
$\mathrm{cov}_{X,Y}[l]$	covariance between the samples X and Y at lag l, Eqs. (A.15) and (A.24)
$C_n^{\,2}$	refractive index structure parameter, Eq. (2.9)
dBZ	reflectivity factors in units of decibels, Eq. (3.5)
D	diameter of hydrometeor or target
D_a	diameter of a parabolic reflector
e	partial pressure of water vapor
$E(\lambda)$	Flux of energy at wavelength λ
E_ω	Power spectrum value at wavenumber ω, Eq. (A.41)

f	transmit frequency of the radar
$f()$	function
f_{IF}	intermediate frequency, or frequency of the radar return signal after mixing
f_j	value of a generic discrete function at sample j, Eq. (A.40)
f_{LO}	frequency of the internal local oscillator
f_{lobes}	fraction of the integral of the gain belonging to the sidelobes
f_{r}	pulse repetition frequency, Eq. (2.14) and Fig. 2.14
$F(\omega)$	component of a Fourier transform at wavenumber ω, Eq. (A.39)
$\mathcal{F}()$	Fourier transform operation, Eq. (A.39)
F_ω	component of a discrete Fourier transform at wavenumber ω, Eq. (A.40)
g	acceleration of Earth's gravity
G	gain (or directivity) of the antenna, Eqs. (13.1) and (13.2)
H_{o}	scale height
H_j	sample j of the received signal time series at horizontal polarization
i	$\sqrt{-1}$
$\mathbf{i}$	unit vector in the x (east–west) direction, pointing east
I	component of the received signal in phase with the reference signal, Eq. (A.22)
I_j	component of the sample j of the received signal time series in phase with the reference signal
I_{S_j}	component of the sample j of the received signal time series originating from targets in phase with the reference signal
j, j_1, j_2	indices of series of values
$\mathbf{j}$	unit vector in the y (north–south) direction, pointing north
k	Boltzmann constant, Eq. (13.3) only
k	index to drop or target number
$\mathbf{k}$	unit vector in the z (up–down) direction, pointing up
k_{e}	multiplier to Earth radius for the k_{e} Earth radius approximation, Eq. (2.13)
$\|\|K^2\|\|$	dielectric constant of the scatterers, Eq. (3.3), Table 3.1
K_{dp}	specific differential propagation phase delay
$\|K_w^2\|$	dielectric constant of liquid water
l_{p}	longitude of the radar pulse, Eq. (A.1b)
l	lag, or offset in sample number
l_{rad}	longitude of radar
L	generic horizontal distance
L	interval over which a function f is assumed periodic, Appendix A.5
LDR	linear depolarization ratio, Section 6.2.2
L_{p}	latitude of the radar pulse, Eq. (A.1a)
L_{rad}	latitude of radar
M	number of measurements in a sample
M_{s}	number of measurements or subsamples in a sample
M_λ	number of wavelengths over which a measurement of I and Q is made
n	refractive index of air, Eq. (2.8)
$n(\lambda)$	complex refractive index of a target

n_1, n_2	refractive index of medium 1 and 2, Fig. 2.9
n_p	number of transmit pulses
N	refractivity of air, Section 2.3.1
N	Fraction of the received signal originating from noise, Appendix A.5
$N(D)$	number of scatterers of diameter D per unit volume
$N_f(D)$	number of scatterers of diameter D per unit volume after the growth process, Eq. (9.2)
$N_\mathrm{i}(D)$	initial number of scatterers of diameter D per unit volume before the growth process
N_o	number of scatterers of diameter 0 per unit volume in the context of an exponential drop size distribution
$p()$	probability function
P	air pressure
P_d	power from the direct echo in the context of the mirror image technique, Fig. 12.6
P_g	power from the ground or sea surface in the context of the mirror image technique, Fig. 12.6
P_{HH}	signal power received at horizontal polarization given a transmission at horizontal polarization
P_m	power from the mirror image in the context of the mirror image technique, Fig. 12.6
P_N	noise power, Eq. (13.3)
P_r	returned or received power, Eq. (3.2)
$\overline{P_\mathrm{r}}$	average returned or received power
P_t	power of the transmit pulse
P_{VV}	signal power received at vertical polarization given a transmission at vertical polarization
q	exponent of the power spectrum of atmospheric patterns, Section A.4.4
Q	component of the received signal in quadrature with the reference signal, Eq. (A.24)
Q_j	component of the sample j of the received signal time series in quadrature with the reference signal
Q_{S_j}	component of the sample j of the received signal time series originating from targets in quadrature with the reference signal
r	radar range
r_d	radar range when used within an integral as the variable of integration
$r_{1,2,3,4}$	radar range of targets 1, 2, 3, and 4, Eq. (2.14) and Fig. 2.14
$r_{\max}$	maximum unambiguous range, Eq. (2.15)
r_v	mixing ratio of water vapor
R	rainfall rate, Eq. (3.7)
R'	gas constant of air
s	unit length
$\mathbf{s}$	unit vector perpendicular to the radar phase fronts
S	fraction of the received signal originating from targets (“signal”)

SDR	simultaneous transmit and receive (STAR) differential ratio, Section 6.2.5
S_j	signal fraction of the sample j of the received signal time series
t	time
t_0	time when the transmit pulse was fired, Eq. (2.14) and Fig. 2.14
$t_{1,2,3,4}$	time when the echo from targets 1, 2, 3, and 4 is received, Eq. (2.14) and Fig. 2.14
t_{travel}	time required for the radar pulse to reach the target and come back
T	temperature
T_A	noise temperature of the antenna, Eq. (13.3)
T_co	noise temperature of the cosmic microwave background
T_d	dew point temperature
T_v	virtual temperature, Eq. (5.3)
u	east–west horizontal wind component
u_s	east–west wind components at the surface
v	north–south horizontal wind component
v_DOP	Doppler velocity of the target, Eqs. (5.2) and (A.8)
v_max	Nyquist velocity, Eq. (5.8)
v_s	north–south wind components at the surface
v_sr	speed of propagation of the source region
$\mathbf{v}$	three-dimensional wind
$\mathbf{v}_\textbf{S-R}$	storm-relative wind
$\mathbf{v}_\mathbf{t}$	three-dimensional velocity of targets
V	integer value representing how a field value at one point is encoded in radar archive files
V_j	sample j of the received signal time series at vertical polarization
w	vertical wind component, or updraft velocity
w_f	reflectivity-weighted average terminal fall speed of hydrometeors with respect to still air
$w_\text{r}(D)$	terminal fall speed of a raindrop of diameter D with respect to still air
w_s	vertical air velocity at the surface, Eq. (11.2)
W_a	weighting function with respect to the beam axis describing the angular beam pattern of the radar measurement, Eq. (A.5)
W_r	weighting functions for each cell in range
W_t	weighting functions for each cell in time, Eq. (13.6)
x	east–west distance
X	generic variable or sample
y	north–south distance
Y	generic variable or sample
z	height (everywhere but in Section A.5)
z	generic complex number (Section A.5 only)
$z_{1,2,j}$	generic complex numbers indexed 1, 2, and j
z_rad	altitude of radar
z_s	mean sea-level altitude of the surface terrain
Z	radar reflectivity factor, Eq. (3.1)

Z_{dr}	differential reflectivity
Z_{e}	equivalent radar reflectivity factor, Eq. (3.4)
Z_{H}	radar reflectivity factor at horizontal polarization
Z_{V}	radar reflectivity factor at vertical polarization
$\alpha(s)$	absorptivity of a medium at location s along a path, Fig. 2.12
α_1	angle of incidence from the normal to the interface between the two mediums, Fig. 2.9
α_2	angle of exit from the same normal to the interface between the two mediums, Fig. 2.9
β	volume scattering coefficient, Eq. (2.2)
β_{D}	slope of an exponential drop size distribution
γ	size parameter, Eq. (2.3)
δ_{co}	differential backscattering phase delay, Eq. (6.1)
$\delta\theta$	elevation angle deviation with respect to the beam axis
$\delta\phi$	azimuth angle deviation with respect to the beam axis
$\Delta\varphi$	change in the phase of a target between successive transmit pulses, Eq. (5.7)
$\Delta\phi$	azimuth interval over which pulses are averaged to make a radial
Δr	range interval over which echoes are averaged to make a final range gate
ε	ratio of the gas constants of air and water vapor
ζ	vertical vorticity, everywhere but in Section A.5
ζ	generic complex number, Section A.5 only
$\zeta_{1,2,j}$	generic complex numbers indexed 1, 2, and j
η	radar reflectivity
θ	elevation angle, or angle pointed by the radar with respect to the horizon
θ'	angle with respect to the horizon of the beam as it propagates, Eq. (A.4b)
$\overline{\theta}$	average or center elevation angle
θ_{d}	elevation angle when used within an integral as the integration variable
θ_j	elevation pointed by the antenna when each transmit pulse j was fired
θ_{beam}	half-power beamwidth of the radar, Eq. (2.11)
θ_{lobes}	half-power width of the sidelobe envelope in elevation
λ	wavelength, Eq. (2.17)
μ	mean of a generic population
ξ_{s}	scattering efficiency factor, Eq. (2.4)
ρ	air density
$\rho_{X,Y}$	linear correlation coefficient between two time series X and Y, Eqs. (A.14) and (A.27)
$\rho_{X,Y}[l]$	linear correlation coefficient between two time series X and Y at lag l
ρ_{co}, ρ_{HV}	copolar correlation coefficient
ρ_{i}	density of ice
ρ_{s}	density of snow (air–ice mixture)
σ	standard deviation of a generic population
σ_{b}	backscattering cross-section, Eqs. (2.6) and (2.7)
σ_{s}	standard deviation of a sample, e.g., Eqs. (A.10) and (A.28)
σ_{v}	spectrum width of the Doppler velocity distribution, Eq. (A.32)

τ	transmit pulse duration
τ_{indep}	time to independence of successive radar measurements, Section 2.4.2
T	transmittance of the atmosphere along the path, Eq. (13.4)
φ	phase of a target, Eq. (5.1)
$\varphi_{1,2,3,4}$	phase of targets 1, 2, 3, and 4, Eq. (2.16) and Fig. 2.14
φ_{HH}	copolar phase of echoes or signal at horizontal polarization
φ_{HV}	cross-polar phase of echoes or signal when the radar transmits at horizontal polarization but receives at vertical polarization
φ_{S_j}	phase of the fraction of the signal originating from targets for sample j
φ_{VH}	cross-polar phase of echoes or signal when the radar transmits at vertical polarization but receives at horizontal polarization
φ_{VV}	copolar phase of echoes or signal at vertical polarization
φ_z	argument of a complex number
ω	wavenumber
ϕ	azimuth angle, or clockwise angle with respect to the north direction pointed by the radar
ϕ'	angle with respect to the local north of the beam as it propagates, Eq. (A.2)
$\overline{\phi}$	average or center azimuth
ϕ_{d}	azimuth angle when used within an integral as the integration variable
ϕ_j	azimuth pointed by the antenna when each transmit pulse j was fired
ϕ_{lobes}	half-power widths of the sidelobe envelope in azimuth
Φ_{dp}	two-way differential propagation phase
Ψ_0	phase difference at range zero
Ψ_{dp}	differential phase shift between horizontally and vertically polarized returns, Eq. (6.1)

List of acronyms

AMS	American Meteorological Society
AP	anomalous propagation
ARM	Atmospheric Radiation Measurement (facility)
BWER	bounded weak echo region
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (satellite)
CAPE	convective available potential energy
CAPPI	constant altitude plan position indicator (radar product)
CEDRIC	Custom Editing and Display of Reduced Information in Cartesian space (software)
CIN	convective inhibition (energy)
DAAC	Distributed Active Archive Center
DART	Data Assimilation Research Testbed

DSD	drop size distribution
EarthCARE	Earth Clouds, Aerosols and Radiation Explorer
EL	equilibrium level
EM	electromagnetic (waves)
EOSDIS	NASA Earth Observing System Data and Information System
GHRC	Global Hydrology Resource Center
GNSS	Global Navigation Satellite System
GPM	Global Precipitation Measurement (satellite mission)
HTI	height-time indicator (radar product)
IET	The Institution of Engineering and Technology
JAXA	Japanese Aerospace Exploration Agency
KFTG	identifier code for the Colorado Front Range radar
KGWX	identifier code for the Columbus Air Force Base radar, Mississippi
KICT	identifier code for the Wichita radar, Kansas
KSRX	identifier code for the Fort Smith radar, Arkansas
LCL	liquid condensation level
LFC	level of free convection
MAPLE	McGill algorithm for prediction by Lagrangian extrapolation
MST	mesosphere–stratosphere–troposphere (radars)
NASA	National Aeronautic and Space Administration (USA)
NCAR	National Center for Atmospheric Research (Boulder, CO, USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NWS	National Weather Service (USA)
PANT	positive away, negative toward (sign convention for Doppler velocity)
PPI	plan position indicator (radar product)
PRF	pulse repetition frequency
Radar	radio detection and ranging
RASS	radio acoustic sounding system
RHI	range-height indicator
SPC	Storm Prediction Center
TDWR	Terminal Doppler Weather Radar
TRMM	Tropical Rainfall Measuring Mission
TVS	tornado vortex signature
UCAR	University Corporation for Atmospheric Research (Boulder, CO, USA)
UHF	ultra-high frequencies
US	United States
UTC	universal time coordinate
VAD	velocity–azimuth display (radar product)
VIL	vertically integrated liquid (radar product)
WDTB	Weather Decision Training Branch of NOAA
WER	weak echo region
WSR-88D	Model number of the current operational weather surveillance radar used in the United States
Z–R	reflectivity to rainfall (relationship or equation)