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Radar for Meteorological and Atmospheric Observations

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Foreword

During the past several decades an appreciable amount of research and development has been focused on the use of remote sensing techniques to better our understanding of weather and the atmosphere. Radar has the obvious advantage of providing observations with temporal and/or spatial continuity which is leading to improved forecasts of weather.

Observations and interpretation of Doppler and polarimetric weather radar data, combined with in situ observations, have led to giant leaps in our understanding of the dynamics and microphysics of weather systems. Complementary to weather radar observations are those obtained with typically longer wavelength radars (i.e., wavelengths from meters to centimeters versus centimeters to millimeters used to observe precipitation and clouds), observing the precipitation-free atmosphere. The echoing mechanism at these longer wavelengths is typically Bragg scatter from refractive index perturbations caused by turbulent mixing, or reflection from sharp gradients in refractive index. These long-wavelength and super-powerful radars, referred to as atmospheric radars, have mapped the vertical structure of reflectivity and radial winds in the clear atmosphere from below a kilometer to well above 100 km, whereas meteorological radars map the reflectivity and radial velocities of precipitation and cloud particles on horizontal surfaces at various heights in the troposphere. Weather and cloud radar research has attracted the attention of meteorologists whereas atmospheric radar research has primarily attracted the attention of atmospheric physicists.

The authors have done a remarkable job of combing the results of research in these two disciplines to provide readers with a comprehensive overview of the outstanding observations that have been made with radar used as a remote sensor of weather and atmospheric phenomena. This book has a generous amount of figures that display many of the remote sensing facilities to give the reader a quick appreciation for the variety of atmospheric and meteorological radar types around the world, many of which are unique and interesting. Furthermore, liberal reference to publications provides readers a vast reservoir for further pursuit of their preferred topics of interest. In addition this book presents the fundamentals of remote sensing so that students and professors, with a minimal background in physics and electromagnetic theory, and engineers in the field can better understand the potential and limitations of radar in observing weather and the atmosphere while learning about the various instruments and techniques used in remote sensing. The authors plan to maintain a Website where comments from readers can be addressed and where supplements to the book can be found; this will help to keep the book current and up-to-date.

Norman, OK Richard J. Doviak

Preface

With the application of radar to observations of the atmosphere, various weather phenomena and winds in the clear atmosphere can be monitored and mapped in real time. Great progress in understanding weather and the dynamics of the atmosphere has been made using radar, which brings new observational discoveries and promotes further understanding of our environment.

Remote sensing with radar has been developed in the interdisciplinary domains of physical science and engineering. In the past, advances in weather and the atmospheric sciences have developed independently because the respective engineering efforts and scientific studies were conducted within relatively separate communities. However, the scientific and technical bases for atmospheric observations with radar can be treated in common. We worked in academia (Fukao) and industry (Hamazu) and have collaborated to develop various types of weather and atmospheric radars. Routine discussion with our colleagues convinced us that understanding of weather and atmospheric radars can be deepened if they are described comprehensively and systematically in one volume using common approaches whenever possible.

This book is written for scientists, engineers, students, and other interested meteorological and atmospheric personnel. In this book, we try to bridge the gap in our understanding of weather and atmospheric radar. The book consists of two parts. The first half, Chaps. 1–7, mainly discusses the theoretical bases of weather and atmospheric radar, and the last half, Chaps. 8–12, describes actual systems and observations with these radars. This interdisciplinary book was first published in Japanese by the Kyoto University Press in 2005. In the English version, all chapters including those dealing with recent developments contain more in-depth coverage than does the original.

Kyoto, Japan — Shoichiro Fukao
Iga, Japan — Kyosuke Hamazu

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Kyoto, Japan Shoichiro Fukao
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Contents

List of Symbols

a	Attenuation rate $[\mathrm{m}^{-1}]$, mean radius of the Earth (6370 km), semi-major axis diameter of spheroid rain drop
a_e	Effective Earth radius
a_T	Temperature lapse rate
A	Attenuation coefficient $[\mathrm{dB\ km}^{-1}]$, physical antenna aperture
$\boldsymbol{A}$	Vector potential
A_e	Effective antenna aperture
b	Semi-minor axis diameter of spheroid rain drop
B	Frequency bandwidth of the receiver
$\boldsymbol{B}$	Magnetic flux density
B_f	Filter bandwidth
B_n	Noise bandwidth
c	Speed of light (in vacuum) $[\mathrm{m\ s}^{-1}]$
c_a	Sound velocity
$\boldsymbol{c}_\mathrm{a}$	Apparent sound velocity
$\boldsymbol{c}_\mathrm{s}$	True sound velocity
C_n^2	Refractive index structure constant $[\mathrm{m}^{-2/3}]$
C_p	Specific heat capacity at constant pressure ($\simeq 1004$) $[\mathrm{J\ K}^{-1}\ \mathrm{kg}^{-1}]$
d	Distance between successive element antennas
D	Detectability of radar signal, diameter of raindrop, wind direction,
$\boldsymbol{D}$	Electric flux density
D_0	Median volume diameter
D_a	Antenna diameter, distance of two separated antennas
D_m	Mass weighted mean drop diameter
D_r	Dynamic range of A/D conversion
D_rmax	Maximum dynamic range
e	Partial pressure of water vapor [hPa]
E	Total energy of a receiver input signal, withstand voltage $[\mathrm{V\ mm}^{-1}]$
$\boldsymbol{E}$	Electric field strength
$\boldsymbol{E}_0$	Incident electric field
E_a	Array factor

$\boldsymbol{E}_\mathrm{s}$	Scattered electric field
f	Radar frequency (transmitted frequency) [Hz]
f_0	Carrier frequency [Hz]
f_c	Frequency of coherent oscillator (COHO)
f_d	Doppler frequency (Doppler shift)
f_dmax	Maximum measurable Doppler frequency
f_i	Inertial frequency
f_N	Nyquist frequency
f_p	Pulse repetition frequency
f_s	Frequency of stabilized local oscillator (STALO), sampling frequency
F	Noise figure
F_r	Froude Number
g	Antenna gain at the direction of the maximum radiation pattern (main lobe) in linear unit, radiation pattern of the element antenna (or element pattern), gravitational acceleration
g_at	Transmission gain of the RASS
g_D	Directivity of antenna
G	Antenna gain in decibel
h	Altitude (height from sea level), beam height, mountain height
$\boldsymbol{H}$	Magnetic field strength
H_1	Scale height (7.3 km)
$\mathbf{i}_i$	Unit vector along the radar beam direction
I	Electric current, in-phase component of the complex signal
I_a	Acoustic intensity $[\mathrm{W\ m^{-2}}]$
j	Imaginary unit $(j^2 = -1)$
$\boldsymbol{J}$	Electric current density
k	Boltzmann constant $(= 1.38 \times 10^{-23}\ \mathrm{J\ K^{-1}})$, radar wave number $(= \omega\sqrt{\varepsilon\mu} = 2\pi/\lambda)$
k_a	Imaginary part of the complex refractive index, wave number of acoustic wave
$\boldsymbol{k}_\mathrm{s}$	Scattering vector wave number
K	Thermodynamic temperature measured in kelvins, vertical eddy diffusivity
K_DP	Specific differential phase $[\mathrm{deg\ km^{-1}}]$
l	Autocorrelation time lag, length of short dipole (differential antenna), loss value in a true number
$\boldsymbol{l}$	Separation of the scatterer from the volume center
l_0	Inner scale of turbulence
l_K	Kolmogoroff microscale
L	Loss value in decibel
L_B	Maximum scale of eddy in the inertial subrange (or buoyancy lengthscale)
Ldr	Linear depolarization ratio in linear unit
LDR	Linear depolarization ratio in decibel
m	Complex refractive index of drop (or particle), modified refractive index, vertical wavenumber
m_n	The *n*th moment of drop size distribution

M	Mean molecular weight of the atmosphere, number of DFT or FFT points, number of signal samples along sample time axis (total number of samples), refractive modulus,
M_B	Total number of points of periodogram (FFT points)
M_{coh}	Number of coherent integration
M_I	Number of independent samples
M_{inc}	Number of incoherent integration
M_n	Refractive index gradient (=dn/dz)
M_s	Total number of actual signal samples
M_v	Total water vapor content [kg mm^{-3}]
n	Refractive index
n_r	Real part of the complex refractive index
N	Bit length, Brunt Väisälä frequency, number of element antenna, number of raindrops, number of range samples, Nyquist number
N_0	Parameter of drop size distribution (intercept parameter)
$N(D)$	Drop size distribution (DSD)
N_e	Density of free electron [m^{-3}]
N_T	Total number of raindrops
p	Atmospheric pressure [hPa]
P	Breakdown power, total electric power
$\boldsymbol{P}$	Dielectric polarization
P_a	Transmitted power from sound wave source
P_{ar}	Received power backscattered from sound wave surface
P_r	Received signal power
P_s	Scattered power
P_t	Transmitted power, peak transmitted power
$\boldsymbol{P}_V$	Dipole moment
q	Humidity mixing ratio [kg kg^{-1}]
q_e	Linear density of meteor trail [m^{-1}]
Q	Quadrature phase component of the complex signal
r	Distance between the radar and the scatterer, range
r_a	Maximum observable range
r_R	Distance between bistatic scatterer and receiver
r_T	Distance between transmitter and bistatic scatterer
R	Gas constant, rainfall rate,
R_d	Transmitter's duty cycle
R_f	Flux Richardson number
R_i	Richardson number
R_R	Radiation resistance of short dipole
R_{sp}	Specific constant of drying air $(= 287\ \mathrm{J\ K^{-1}\ kg^{-1}})$
s_f	Frequency stability
$\boldsymbol{s}$	Backscattering matrix of the linear polarization wave
S	Power density, signal power
$\boldsymbol{S}$	Complex Poynting vector
S_i	Incident power density

S_N	Power spectral density of noise
S_s	Scattered power density
S_S	Power spectral density of signal
S_w	Vertical shear [s^{-1}]
SNR	Signal-to-noise ratio
t	Time
T	Atmospheric temperature [K], noise temperature [K], period of gravity wave, pulse repetition time (PRT) [s], time period
T_0	Room temperature (290 K)
T_c	Correlation time
T_e	Equivalent input noise temperature
T_i	Input noise temperature, independent sample time
T_s	Sample time interval (sampling interval), sky noise temperature
T_sys	System noise temperature
T_v	Temperature of moist atmosphere
T_W	Window width
u	East-west (zonal) wind
$\overline{u}$	Mean zonal wind
u'	Horizontal IGW perturbation from turbulence
U	Horizontal wind speed
v	Phase velocity of electromagnetic wave
v'	Fluctuation component of wind perpendicular to the direction of wave travel
$\boldsymbol{v}$	Wind vector $(v_x,\ v_y,\ v_z)$
v_d	Doppler velocity
$\overline{v}_d$	Mean Doppler velocity
v_h	Horizontal wind velocity
v_N	Nyquist velocity (Nyquist limit)
v_r	Radial velocity
V	Radar resolution volume
V_6	Resolution volume circumscribed by the 6 dB contour of radar parameters
V_D	Volume of raindrop
w	Vertical wind velocity (or vertical component of wind velocity; v_z)
w'	Vertical IGW perturbation from turbulence
w_T	Terminal velocity of precipitation (fall speed)
W	Cloud water content (or water content in unit volume) [$\mathrm{g\ m}^{-3}$]
W_B	Bandwidth of the signal
z	Altitude, height from sea level [km]
Z	Radar reflectivity factor
Z_dr	Differential reflectivity in linear unit
Z_DR	Differential reflectivity in decibel
Z_e	Equivalent radar reflectivity factor
Z_i	Radar reflectivity factor for ice particles
α	Azimuth angle of the baseline formed between two antennas in SDI
β	Bistatic angle

γ	Specific heat ratio of ideal gas ($\simeq 1.4$ for dry air)
Γ	Dry adiabatic lapse rate ($= g/C_\mathrm{p} \simeq 9.80$) [K km^{-1}]
δ	Differential scattering phase, direction of horizontal wind, phase difference between successive element antennas
Δ	Resolution of the A/D converter
ε	Turbulent energy dissipation rate
ε	Permittivity [F m^{-1}]
ε_0	Permittivity in vacuum [F m^{-1}]
ζ	Axis ratio b/a, where a is the semi-major axis diameter and b the semi-minor axis diameter of a flat raindrop
η	Radar reflectivity
η_1	Efficiency of antenna
η_a	Antenna aperture efficiency
η_i	Intrinsic impedance (or wave impedance) ($= \sqrt{\mu/\varepsilon}$)
θ	Zenith angle of radar beam
θ_1	One-way beamwidth between half-power points (or beam width)
θ_e	Elevation angle of radar beam
ϑ_B	One way half-power beamwidth in the E-plane [rad]
Θ	Potential temperature
κ	Wave number for Bragg scattering
$\boldsymbol{\kappa}$	Wave number vector for Bragg scattering
κ_a	Wave number vector for acoustic wave
κ_b	Wave number corresponding to the Bragg scale
κ_B	Wave number corresponding to buoyancy lengthscale ($= 2\pi/L_\mathrm{B}$)
λ	Radar wavelength [m]
Λ	Parameter of drop size distribution (or slope parameter)
Λ_s	Structure wavelength of perturbations within inertial subrange
μ	Permeability [H m^{-1}]
μ_0	Permeability in vacuum [H m^{-1}]
ν	Kinematic viscosity (dynamic viscosity divided by the fluid density)
ρ	Electric charge density [C m^{-1}], radar cross section [m^2]
$\lvert\rho\rvert^2$	Partial reflection coefficient
ρ_a	Atmospheric density [kg m^{-3}]
ρ_hv	Correlation coefficient between horizontally and vertically polarized waves
ρ_v	Water vapor density [g m^{-3}]
ρ_w	Density of precipitation particles [g m^{-3}](= 10^6 for water)
σ	Electric conductivity [S m^{-1}]
σ_a	Absorption cross section
σ_b	Backscattering cross section
σ_f	Doppler frequency spectrum width [Hz]
σ_s	Scattering cross section
σ_t	Extinction (or attenuation) cross section
σ_v	Doppler velocity spectrum width [m s^{-1}]
σ_{vn}	Doppler velocity spectrum width normalized with the Nyquist width
τ	Transmitted pules width [s], time lag

τ_{i}	Independent sample time
τ_{c}	Correlation time
ϕ	Angular distance from the beam axis in the H-plane
ϕ_{h}	Phase delay per unit distance (one way) for horizontally polarized wave [rad]
ϕ_{v}	Phase delay per unit distance (one way) for vertically polarized wave [rad]
Φ_{DP}	Differential phase in two-way $(\Phi_{\mathrm{DP}} = \Phi_{\mathrm{hh}} - \Phi_{\mathrm{hh}})$ [deg]
Φ_{hh}	Phase shift in round trip between radar and scatterer for horizontally polarized wave [deg]
Φ_{vv}	Phase shift in round trip between radar and scatterer for vertically polarized wave [deg]
φ	Phase of received echo signal, zenith angle in the H-plane based on radar beam axis
φ_{B}	One way half-power beamwidth in the H-plane [rad]
χ	Angle between the direction of polarization of the incident electric field and the direction of scattering vector (= $\pi/2$ for backscattering
Ψ	Differential phase of measured signals between horizontally and vertically polarized waves [deg], scalar potential
ω	Angular frequency [rad s^{-1}]
ω_{d}	Doppler angular frequency
ω_{i}	Intrinsic frequency
Ω	Angular velocity of the Earth's rotation $(= 7.292 \times 10^{-5}\ \mathrm{s}^{-1})$

List of Abbreviations

A/D	Analog to digital
AFWS	Air Force Weather Service
AGC	Automatic gain control
AGL	Above ground level
AMeDAS	Automated Meteorological Rata Acquisition System
AMS	American Meteorological Society
ARM	Atmospheric Research Measurement program
ATC	Air traffic control
ATSR	Alternate transmission and simultaneous reception
BL	Boundary layer
BLR	Boundary layer radar
CAP	Cooperative Agency Profiler
CAT	Clear air turbulence
CCIR	International Radio Consultative Committee
CDL	Coherent Doppler lidar
CIRA	Committee on Space Research (COSPA) International Reference Atmosphere
COCO	Coaxial-collinear
COHO	Coherent oscillator
COST	European Cooperation in Science and Technology
CRI	Coherent radar imaging
CST	Central Standard Time
CSU	Colorado State University
DBS	Doppler beam swinging
DFT	Discrete Fourier transform
DIF	Decimation-in-frequency
DIT	Decimation-in-time
DOA	Direction of arrival
DPR	Dual-frequency Precipitation Radar
DRAW	Doppler Radar for Airport Weather
DSD	Drop size distribution

EAR	Equatorial Atmospheric Radar
ECCD	Electromagnetically coupled coaxial dipole
EIK	Extended interaction amplifier
EST	Eastern Standard Time
FAA	Federal Aviation Administration
FCA	Full correlation analysis
FDI	Frequency domain interferometry
FET	Field effect transistor
FFT	First Fourier transform
FII	Frequency domain interferometric imaging
FIR	Finite impulse response
FMCW	Frequency-modulated continuous waves
FRP	Fiber-reinforced plastic
FSA	Full spectral analysis
FWHM	Full width at half maximum
GMAP	Gaussian model adaptive processing
GMS	Geostationary meteorological satellite
GMT	Greenwich mean time
GPM	Global Precipitation Measurement
GPS	Global positioning system
GTS	Global Telecommunication System
HEMT	High electric mobility transistor
HS	Hail signal
HVPS	High-Volume Particle Spectrometer
I	In-phase
IDFT	Inverse discrete Fourier transform
IF	Intermediate frequency
IFFT	Inverse fast Fourier transform
IGW	Inertia-gravity wave
IIR	Infinite impulse response
IR	Infrared radiation
IS	Incoherent scatter
ITU	International Telecommunication Union
JAFNA	Joint Air Force and NASA
JAXA	Japan Aerospace Exploration Agency
JMA	Japan Meteorological Agency
JST	Japan Standard Time
KH	Kelvin–Helmholtz
KIX	Kansai International Airport
LAN	Local area network
LDR	Linear depolarization ratio
LEO	Low Earth orbit
LHC	Left-hand circular
LLJ	Low-level jet
LNA	Low noise amplifier

LO	Local frequency
LT	Local time
LTR	Lower Troposphere Radar
M-P	Marshall–Palmer
MEM	Maximum entropy method
MESFET	Metal-semiconductor FET
ML	Multi-lag
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
MLM	Maximum likelihood method
MMIC	Monolithic microwave integrated circuit
MOPA	Master oscillator and power amplifier
MP	Multi-parameter
MPIfR	Max-Planck-Institut für Radioastronomie
MPM	Millimeter-wavelength propagation model
MRI	Meteorological Research institute
MSM	Mesoscale numerical model
MST	Mesospheric-stratospheric-tropospheric
MU	Middle and Upper atmosphere
MUSIC	Multiple signal classification
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NIED	National Research Institute for Earth Science and Disaster Prevention
NOAA	National Oceanic and Atmospheric Administration
NPN	NOAA Profiler Network
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
ORDA	Open radar data acquisition
OTH	Over the horizon
PA	Power-aperture
PANSY	Program of the Antarctic Syowa MST/IS Radar
PBL	Planetary boundary layer
PBS	Post beam steering
PHS	Personal Handy-phone System
POS	Positioning
PPI	Plan position indicator
PR	Precipitation radar
PRF	Pulse repetition frequency
PRT	Pulse repetition time
PSS	Post static steering
PUP	Principal user processor
Q	Quadrature-phase
RASS	Radio acoustic sounding system
RCS	Radar cross section
RDA	Radar data acquisition

rf	Radio frequency
RHC	Right-hand circular
RHI	Range height indicator
RIM	Range imaging
ROPS	Radar Observation data Processing System
RPG	Radar product generator
RPM	Rotation per minute
RX	Receiver
SA	Spaced antenna
SAD	Spaced antenna drift
SCSI	Small Computer System Interface
SDI	Spatial domain interferometry
SI	Le Système International
SNR	Signal-to-noise ratio
SPBS	Sequential post beam steering
SSPA	Solid state power amplifier
ST	Stratospheric-tropospheric
STALO	Stabilized local oscillator
STC	Sensitivity time control
STSR	Simultaneous transmission and simultaneous reception
SVD	Singular value decomposition
T	Tropospheric
TAI	Temps Atomique International
TC	Tropical cyclone
TDWR	Terminal Doppler Weather Radar
TEP	Turbulent eddy profiler
TOGA-COARE	Tropical Ocean Global Atmosphere–Coupled Ocean Atmosphere Research Experiment
TPPN	Trans-Pacific Profiler Network
TR	Transmitter/receiver
TRMM	Tropical Rainfall Measurement Mission
TWT	Traveling wave tube
TX	Transmitter
UHF	Ultrahigh frequency
UTC	Coordinated Universal Time
VAD	Velocity azimuth display
VCP	Volume coverage pattern
VHF	Very high frequency
VIL	Vertical integrated liquid
VVP	Volume velocity processing
WCB	Warm conveyor belt
WCRP	World Climate Research Program
WINDAS	Wind Profiler Data Acquisition System
WRC	World Telecommunication Conference
WMO	World Meteorological Organization

Chapter 1
Introduction

1.1 Principle of Radar

A variety of weather and atmospheric phenomena occur and change every moment in the Earth's atmosphere. This book presents the techniques and sciences of remote sensing various phenomena with radar. Remote sensing is a technique that indirectly measures target without touching it directly in a distant place. Radar is an abbreviation for "RAdio Detection And Ranging", which is an electronic system that generates electromagnetic waves in the transmitter, radiates them into space via antenna, receives the scattered signal returning from the target, and measures the position, movement of the target, etc. Usually, the same antenna is used for transmission of the electromagnetic wave and reception of the return signal. The target position is obtained according to the direction where the scattered signal returns to the antenna, and to the distance calculated by the lapse of time that the electromagnetic waves make in the round-trip between radar and target.

As for the targets that scatter electromagnetic waves, various types of scatterers are known, e.g., isolated objectives such as aircrafts and ships, minute distributed particles such as precipitation and clouds, and perturbations of radio refractive index due to atmospheric turbulence. In this book, the properties of scatterers such as precipitations, clouds, and fogs associated with weather, and refractive index perturbations caused by atmospheric turbulence are presented. The former is mainly observed with meteorological radar (or weather radar), and the latter with atmospheric radar. The conceptual diagrams of meteorological radar and atmospheric radar are shown in Fig. 1.1a and b, respectively. The atmospheric radars typically make observations overhead (i.e., at high elevation angles), whereas meteorological radars typically scan the atmosphere at relatively low elevation angles. Furthermore meteorological radars typically use parabolic reflector antennas whereas atmospheric radars use phased array antennas. Although the frequencies adopted for meteorological and atmospheric radars are different due to the difference of scattering mechanisms of the targets, many aspects of the basic configuration

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