

Contents

	<i>Preface</i>	page xiii
	<i>Acknowledgments</i>	xvi
1	An overview of the atmosphere	1
	1.1 Introduction	1
	1.2 The origins of radar	2
	1.3 The atmosphere – an overview	6
	1.3.1 The Earth's neutral atmosphere and ionosphere	6
	1.3.2 Causes of the temperature and density structures	13
	1.3.3 Radiative transfer in the troposphere and greenhouse warming	16
	1.3.4 Variability and atmospheric circulation	20
	1.3.5 Atmospheric circulation in the upper stratosphere and mesosphere	29
	1.3.6 Synoptic and mesoscale flows	34
	1.4 Some important thermodynamics and statics	35
	1.4.1 Introduction	35
	1.4.2 Pressure as a function of height	36
	1.4.3 Adiabatic expansion	37
	1.4.4 Adiabatic lapse rate	38
	1.4.5 Brunt–Väisälä frequency	40
	1.4.6 Potential temperature	44
	1.4.7 Atmospheric stability and the Richardson number	45
2	The history of radar in atmospheric investigations	47
	2.1 Introduction	47
	2.2 Meteorological radar	48
	2.3 Doppler methods in radar meteorology	50
	2.4 Ionospheric history pertaining to MST radar	55
	2.5 D-region studies with MF and HF radar	58
	2.6 Meteor physics with radar	70
	2.7 Incoherent scatter radars	73
	2.7.1 Coherent echoes seen with incoherent scatter radars	75

2.8	MST radar techniques at VHF and some atmospheric science highlights	76
2.9	Newer-generation radars	86
2.10	Scattering and partial reflection	88
2.10.1	Specular and Fresnel reflectors	88
2.10.2	Scattering by turbulence	93
2.10.3	Amplitude distributions	94
2.11	VHF-MST radar methods for measuring the horizontal wind velocity	95
2.12	Measuring momentum flux and turbulence	98
2.13	Radar meteorology and networks using MST radars	99
2.14	Strange scatterers in the polar upper atmosphere	100
2.15	Imaging, improving spatial resolution, and application of interferometry	102
2.15.1	Introduction	102
2.15.2	Resolution improvement	103
2.15.3	Interferometry	103
2.15.4	Imaging	105
2.15.5	Frequency domain interferometry	106
2.15.6	Imaging, SDI, FDI, and similar techniques	106
2.15.7	The relation between IDI and FCA-type methods, and the validity of point scatterers	113
2.16	Temperature measurements and RASS	115
2.17	Precipitation measurements with MST radar	117
2.18	Additional applications	118
3	Refractive index of the atmosphere and ionosphere	120
3.1	Introduction	120
3.2	Wave representation	121
3.3	Electromagnetic waves in a dielectric	123
3.3.1	Use of complex numbers	125
3.4	Refractive index of an electron gas	126
3.4.1	Relevance of refractive index in MST studies	129
3.4.2	How can the phase speed be greater than c ?	130
3.5	Radiowave refraction	138
3.5.1	Refraction in the ionosphere	139
3.6	Vertical incidence	141
3.6.1	Evanescence	142
3.6.2	Inclusion of collision rates in the expression for refractive index	143
3.6.3	Inclusion of the magnetic field	146
3.6.4	Inclusion of both the magnetic field and collisional effects	156
3.6.5	More sophisticated equations for refractive index	157
3.7	Electron backscatter cross-section	159
3.7.1	Cross-sections	159
3.7.2	Scattering from a free electron gas	159
3.8	Multiple electrons	165
3.8.1	A regular grid	165

	Contents	vii
3.8.2	Bragg scales	166
3.8.3	Random positions	168
3.8.4	Random electron position	169
3.8.5	Rayleigh distributions	169
3.9	Backscatter cross-sections and reflectivities for a radar	171
3.9.1	Introduction of the spectrum	171
3.9.2	The spectrum of refractive index variations	176
3.10	Impact of electron motions and plasma waves in radiowave scattering	199
3.10.1	Further theory pertaining to scattering	205
3.11	Refractive index and scattering in the neutral atmosphere	205
3.11.1	Expressions for the refractive index in the neutral air	206
3.12	Diffraction, antenna field patterns, and gain	216
4	Fundamental concepts of radar remote sensing	217
4.1	Introduction	217
4.2	The radar targets in MST studies	217
4.3	A simple radar	219
4.4	Radar polar diagrams	222
4.5	Monostatic continuous-wave “radar”	224
4.6	Pulsed radar	230
4.6.1	Backscatter as a convolution	234
4.6.2	Superheterodyne systems	236
4.6.3	Transmit-receive switches	239
4.6.4	Multi-static continuous-wave radar	240
4.7	Combining the pulse equations and the polar diagrams	241
4.8	Optimizing the signal	243
4.8.1	Matched filter	243
4.8.2	Filters and resolution	245
4.8.3	Pulse compression	247
4.9	Doppler radial velocity and coherent integration	253
4.9.1	Radial velocity	253
4.9.2	Coherent integration	257
4.9.3	An alternative to coherent integration	259
4.10	Range and velocity ambiguities: ambiguity function	264
4.10.1	Deliberate range aliasing	266
4.11	Radar calibration	267
5	Configuration of atmospheric radars – antennas, beam patterns, electronics, and calibration	268
5.1	Introduction	268
5.1.1	Monostatic systems: pulsed and FM-CW	268
5.1.2	Multistatic systems	270
5.2	Radar antennas	274
5.2.1	Basic theory	274

5.2.2	Relation between gain, effective area, and beam-width	276
5.2.3	Radiation patterns for simple antennas	285
5.2.4	Reflector antenna	286
5.2.5	Array antenna	288
5.2.6	Element antenna for array	294
5.2.7	Antenna impedance and matching	295
5.2.8	Effect of random errors in an array antenna	298
5.2.9	Digital beam forming (DBF) antennas	299
5.2.10	The feed system	300
5.2.11	Beam steering and phase shifting	301
5.2.12	Adaptive clutter rejection	301
5.3	Transmitter and receiver systems	305
5.3.1	System configuration	305
5.3.2	Transmitter	306
5.3.3	The receiver	308
5.3.4	TR switch	309
5.4	Radar signal acquisition system	312
5.4.1	Digital receiver systems	313
5.4.2	Fully digital systems	314
5.4.3	Pulse-coding, coherent integration, and software issues	314
5.5	Relating backscatter cross-sections and reflectivities to received power	314
5.5.1	An example: naive determination of electron density	315
5.5.2	Determination of turbulence parameters	318
5.6	Calibration	320
5.6.1	Range calibration	321
5.6.2	Calibration of the polar diagram	322
5.6.3	Power calibration	324
6	Examples of specific atmospheric radar systems	337
6.1	Introduction	337
6.2	The SOUSY radar	338
6.2.1	Technical details	341
6.2.2	Summary of the SOUSY radar	350
6.3	The MU radar	350
6.3.1	Introduction	350
6.3.2	Computers	352
6.3.3	The antenna array	353
6.3.4	The transmitter-receiver system	356
6.3.5	Antenna feed mechanism	358
6.3.6	Summary of the MU radar	359
6.4	The CLOVAR radar	359
6.4.1	Introduction	359
6.4.2	The antenna array	360
6.4.3	The controller computer	366

	6.4.4	Beam-pointing	367
	6.4.5	The transmitter, transmit-receive switch, and receiver	370
	6.4.6	System tests and usefulness	370
6.5		More recent radars	372
	6.5.1	The PANSY radar	372
	6.5.2	The MAARSY radar	379
7		Derivation of atmospheric parameters	381
	7.1	Introduction	381
	7.2	Wind vector determination	382
	7.2.1	Doppler measurements	382
	7.2.2	Spaced antenna methods: FCA and interferometer techniques	392
	7.2.3	Brief comments on the various wind-measurement techniques	392
	7.3	Spectral width estimates	393
	7.3.1	Theoretical determinations of the beam-broadened spectral width	398
	7.3.2	“Negative” energy dissipation rates	401
	7.3.3	Extraction of the turbulent kinetic energy dissipation rate	404
	7.4	Power measurements	415
	7.4.1	Modeling the reflection and scattering processes	416
	7.4.2	Converting received powers to backscatter cross-sections	419
	7.4.3	Determination of turbulence intensities from measurements of received power	422
	7.5	Aspect sensitivity of the scatterers	424
	7.5.1	Experimental techniques to determine the nature of the scatterers	427
	7.6	Some interesting tropospheric parameters	436
	7.6.1	VHF radar anisotropy, convection, and precipitation	437
	7.6.2	Tropopause height	437
	7.7	Less easily determined target parameters	438
8		Digital processing of Doppler radar signals	441
	8.1	Analog-to-digital conversion	443
	8.2	Time-domain processing	445
	8.3	Brief review of Fourier analysis	447
	8.3.1	Continuous-time Fourier transform	448
	8.3.2	Discrete-time Fourier transform	452
	8.3.3	Discrete Fourier transform (fast Fourier transform)	455
	8.4	Digital filtering concepts	459
	8.4.1	z -transform and frequency response	459
	8.4.2	Digital filter design	461
	8.5	Review of random processes	465
	8.6	Estimation of the power spectral density	469
	8.6.1	Periodogram and correlogram	470
	8.6.2	Blackman–Tukey method	476

	8.6.3	Averaged periodogram method – Bartlett method	478
	8.6.4	Spectral convolutions and running means	481
	8.6.5	Capon method	482
8.7		The atmospheric Doppler spectrum	491
8.8		Estimation of spectral moments	495
	8.8.1	Time domain estimators (autocovariance method)	497
	8.8.2	Frequency domain estimators	499
9		Multiple-receiver and multiple-frequency radar techniques	504
	9.1	Introduction	504
	9.2	Mathematical framework to describe the radar signal	509
	9.2.1	Scatter from a single scatterer	509
	9.2.2	Scatter from distributed or multiple scatterers	512
	9.2.3	Covariance/correlation functions and the brightness function	513
	9.3	Spaced antenna methods	519
	9.3.1	Fundamental concepts	519
	9.3.2	Full correlation analysis (FCA)	523
	9.4	Interferometry	530
	9.4.1	Radar interferometry (RI)	532
	9.4.2	Frequency domain interferometry (FDI)	535
	9.5	Imaging	537
	9.5.1	Multiple-receiver imaging	538
	9.5.2	Estimation of the weighting vector	541
	9.5.3	Multiple-frequency imaging	543
10		Extended and miscellaneous applications of atmospheric radars	549
	10.1	Introduction	549
	10.2	PMSE and PMWE	550
	10.2.1	Geographical distribution	552
	10.2.2	Reasons for PMSE	554
	10.2.3	Other mesospheric echoes	557
	10.3	Meteor studies	560
	10.3.1	Introduction and radar design	560
	10.3.2	Winds and temperatures	561
	10.3.3	Momentum fluxes	563
	10.3.4	Additional miscellaneous meteor-related studies	565
	10.4	Tropospheric temperature measurements and RASS	566
	10.5	Water in the troposphere and stratosphere	567
	10.5.1	Precipitation measurements with ST radar	567
	10.5.2	Measuring humidity with ST radar	567
	10.6	Other specialized meteorological topics	569
	10.7	Lightning detection with windprofiler radars	570
	10.7.1	The mechanics of lightning	570
	10.7.2	VHF radar and radio observations of lightning	572

10.7.3	Amplitude and phase characteristics of radar returns from lightning	576
10.7.4	VHF radar interferometer observations of lightning	578
10.8	Studies above the mesosphere – plasma and ionospheric processes	581
10.8.1	150 km echoes	583
10.8.2	Other ionospheric research	588
10.9	D-region scatter and the differential absorption experiment	589
10.9.1	DAE (the differential absorption experiment)	589
10.9.2	Passive radar	594
10.10	Astronomical applications	594
10.11	Final comments	595
11	Gravity waves and turbulence	596
11.1	Introduction	596
11.2	Gravity waves	598
11.2.1	The importance of gravity waves	598
11.2.2	A simple description of the generation of gravity waves	599
11.2.3	The fluid dynamical equations of motion	606
11.2.4	The approximations of the equations of motion for gravity wave studies	607
11.2.5	Saturation theory and the “universal spectrum”	611
11.2.6	Measurement techniques for gravity waves	617
11.2.7	Overview of some important gravity wave parameters	619
11.2.8	Seasonal and latitudinal variations	622
11.2.9	Refraction, turning levels, and wave ducting	624
11.2.10	Sources of gravity waves	627
11.2.11	Directions of propagation	629
11.2.12	Breakdown, convective adjustment (shedding), and catastrophic collapse	630
11.2.13	Momentum fluxes, drag forces, and energy fluxes	632
11.2.14	Mean flow interactions	636
11.2.15	Stokes’ drift and wave-induced diffusion	636
11.2.16	Local gravity wave effects	637
11.2.17	Gravity wave parameterization for meteorological models	638
11.3	Turbulence in the upper atmosphere	639
11.3.1	Turbulence structure above the boundary layer	639
11.3.2	The key scales of turbulence	649
11.3.3	The turbopause	652
11.3.4	Turbulence structure functions and spectra	653
11.3.5	Measurement techniques and results for turbulence studies	659
11.3.6	Small-scale structures and anisotropic turbulence	668
11.3.7	Computer modeling of gravity wave breakdown and turbulence production	670

12	Meteorological phenomena in the lower atmosphere	672
12.1	Introduction	672
12.2	Scattering mechanisms	673
12.2.1	Turbulent scatter	674
12.2.2	Specular and quasi-specular reflections	674
12.3	Wind measurements	680
12.3.1	The advantages of wind profilers for meteorological studies	680
12.3.2	Verification of profiler winds	683
12.4	Winds from windprofiler networks	687
12.5	Vertical winds	691
12.6	Tropospheric temperature measurements	695
12.7	Tropopause determinations	695
12.8	Mountain waves	695
12.9	Gravity wave genesis in relation to meteorology	700
12.10	Convection, water, lapse rates, and stability/instability	703
12.10.1	Convection	703
12.10.2	Scale height for a multi-species gas	705
12.10.3	The mixing ratio for water	706
12.10.4	Virtual temperature	709
12.10.5	The dry and moist adiabatic lapse rates	710
12.10.6	The pseudo-adiabatic process	712
12.10.7	The stable and convectively unstable atmosphere	717
12.10.8	KHi studies by MST radar	725
12.10.9	Convection studies with MST radars	725
12.11	Turbulence in meteorology	727
12.12	Precipitation and humidity measurements with ST radars	728
12.13	Boundary layer measurements	728
12.14	Windprofiler contaminants	729
13	Concluding remarks	731
13.1	Introduction	731
13.2	The future	731
	Appendices	734
A	Turbulent spectra and structure functions	734
B	Gain and effective area for a circular aperture	742
	<i>List of symbols used</i>	746
	<i>References</i>	764
	<i>Index</i>	817