Contents

Preface xiii
Preface to the First Edition xv
List of Symbols xvii

1. Introduction 1
   1.1 Historical Background 1
   1.2 The Plan of the Book 7

2. Electromagnetic Waves and Propagation 10
   2.1 Waves 10
   2.2 Propagation Paths 14
      2.2.1 Refractive Index of Air 14
      2.2.2 Refractivity N 16
      2.2.3 Spherically Stratified Atmospheres 18
   Problems 28

3. Radar and Its Environment 30
   3.1 The Doppler Radar (Transmitting Aspects) 30
      3.1.1 The Electromagnetic Beam 32
      3.1.2 Antenna Gain 34
   3.2 The Scattering Cross Section 35
   3.3 Attenuation 38
      3.3.1 Attenuation in Rain 39
      3.3.2 Attenuation in Clouds 43
      3.3.3 Attenuation in Snow 44
      3.3.4 Attenuation in Gases 44
3.4 The Doppler Radar (Receiving Aspects) 45
3.4.1 The Radar Equation 46
3.4.2 The Incoherent Receiver 48
3.4.3 The Coherent Receiver (In-Phase and Quadrature Components) 50

3.5 Practical Considerations 54
3.5.1 System Noise Temperature 54
3.5.2 Bandwidth 57
3.5.3 Filtered Waveform 58
3.5.4 Signal-to-Noise Ratio, Matched Filters 60

3.6 Ambiguities 60
Problems 62

4. Weather Signals 64
4.1 Weather Signal Samples 64
4.2 The Power Sample 67
4.3 Signal Statistics 69
4.4 The Weather Radar Equation 72
4.4.1 Receiver Calibration 74
4.4.2 The Range-Weighting Function 75
4.4.3 Finite Bandwidth Power Loss 79
4.4.4 The Resolution Volume 80
4.4.5 Reflectivity Factors 82
4.5 Signal-to-Noise Ratio for Distributed Scatterers 83
4.6 Correlation of Samples along Range Time 84
Problems 85

5. Doppler Spectra of Weather Signals 87
5.1 Spectral Analysis of Weather Signals 87
5.1.1 Discrete Fourier Transform 87
5.1.2 Convolution and Correlation 92
5.1.3 Power Spectrum of Random Sequences 95
5.1.4 Bias, Variance, and the Window Effect 98
5.1.5 Expressing Spectral Estimates in Terms of the True Spectrum 100
5.1.6 Variance of the Periodogram 105
5.2 Weather Signal Spectrum and Its Relation to Reflectivity and Radial Velocity Fields 106
<table>
<thead>
<tr>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2.1 Power Spectrum for Uniform Shear and Reflectivity</td>
</tr>
<tr>
<td>5.2.2 Contributions of Independent Meteorological Mechanisms to the Power Spectrum</td>
</tr>
<tr>
<td>5.2.3 Probability Distribution of Turbulent Velocities Related to the Power Spectrum</td>
</tr>
<tr>
<td>5.3 Velocity Spectrum Width</td>
</tr>
<tr>
<td>Problems</td>
</tr>
<tr>
<td><strong>6. Weather Signal Processing</strong></td>
</tr>
<tr>
<td>6.1 Spectral Moments</td>
</tr>
<tr>
<td>6.2 Weather Signals in a Receiver</td>
</tr>
<tr>
<td>6.3 Signal Power Estimation</td>
</tr>
<tr>
<td>6.3.1 Sample Time Averaging</td>
</tr>
<tr>
<td>6.3.2 Range Time Averaging</td>
</tr>
<tr>
<td>6.4 Mean Frequency Estimators</td>
</tr>
<tr>
<td>6.4.1 Autocovariance Processing: The Pulse Pair Processor</td>
</tr>
<tr>
<td>6.4.2 Spectral Processing</td>
</tr>
<tr>
<td>6.5 Estimators of the Spectrum Width</td>
</tr>
<tr>
<td>6.5.1 Autocovariance Processing</td>
</tr>
<tr>
<td>6.5.2 Spectral Processing</td>
</tr>
<tr>
<td>6.6 Minimum Variance Bounds</td>
</tr>
<tr>
<td>6.7 Performance on Data</td>
</tr>
<tr>
<td>6.8 Signal Processing for Coherent Polarimetric Radar</td>
</tr>
<tr>
<td>6.8.1 Reflectivity and Differential Reflectivity</td>
</tr>
<tr>
<td>6.8.2 Mean Radial Velocity and Differential Propagation Phase</td>
</tr>
<tr>
<td>6.8.3 Specific Differential Phase</td>
</tr>
<tr>
<td>6.8.4 Spectrum Width</td>
</tr>
<tr>
<td>6.8.5 Correlation Coefficient</td>
</tr>
<tr>
<td>6.8.6 A Signal Processing Scheme for Echoes with Alternating Polarization</td>
</tr>
<tr>
<td>6.9 Concluding Remarks</td>
</tr>
<tr>
<td>Problems</td>
</tr>
<tr>
<td><strong>7. Considerations in the Observation of Weather</strong></td>
</tr>
<tr>
<td>7.1 Range Ambiguities</td>
</tr>
<tr>
<td>7.2 Velocity Ambiguities</td>
</tr>
<tr>
<td>7.3 Signal Coherency</td>
</tr>
</tbody>
</table>
7.4 Techniques to Mitigate the Effects of Ambiguities 167
7.4.1 Phase Diversity 167
7.4.2 Spaced Pairs with Polarization Coding 170
7.4.3 Staggering the PRT to Increase the Unambiguous Velocity 171
7.4.4 Interlaced Sampling 175
7.4.5 Correcting Aliased Velocities 177
7.5 Methods to Decrease the Acquisition Time 179
7.5.1 Frequency Diversity 180
7.5.2 Random Signal Transmission 181
7.6 Pulse Compression 184
7.7 Artifacts 187
7.7.1 Quantization and Saturation Noises 188
7.7.2 Amplitude and Phase Imbalances 190
7.7.3 Phase Jitter 192
7.8 Effective Pattern of a Scanning Radar 193
7.9 Antenna Sidelobes 197
7.10 Clutter 199
7.10.1 Ground Clutter and Its Suppression 200
7.10.2 Other Clutter 206
Problems 207

8. Precipitation Measurements 209
8.1 Drop Size Distributions 210
8.1.1 Cloud Drop Size Distributions 210
8.1.2 Raindrop Size Distributions 212
8.1.3 Hailstone Size Distributions 215
8.2 Terminal Velocities 216
8.3 Rainfall Rate, Reflectivity, and Liquid Water Content 218
8.3.1 Liquid Water Content 218
8.3.2 Reflectivity Factor Z 219
8.3.3 Rainfall Rate 222
8.4 Single-Parameter Measurement of Precipitation 223
8.4.1 Reflectivity Factor Method 223
8.4.2 Attenuation Method 231
8.4.3 Differential Phase Method 234
8.5 Multiple-Parameter Measurements of Precipitation 235
9. Observations of Winds, Storms, and Related Phenomena 280

9.1 Thunderstorm Structure 281

9.2 Wind Measurement with Two Doppler Radars 288

9.2.1 Wind Field Synthesis 289
9.2.2 Supercell Thunderstorms 293
9.2.3 Ordinary Thunderstorms 301

9.3 Wind Measurement with One Doppler Radar 304

9.3.1 Linear Wind Fields 306
9.3.2 Uniform Wind along a Circular Arc 310
9.3.3 Linear Wind over a Circle (VAD) 311
9.3.4 Prestorm Application 317
9.3.5 Large-Scale Horizontal Wind 323
9.3.6 Large-Scale Vertical Wind 325
9.3.7 Flow Models 328

9.4 Severe Storms 328

9.5 Mesocyclones and Tornadoes 335

9.5.1 Smoothing of a Vortex Signature 338
9.5.2 High-Resolution Images of a Tornado 340
9.5.3 Doppler Spectra of Tornadoes 344

9.6 Downdrafts and Outflows 351

9.6.1 Density Currents 352
9.6.2 Convergence Bands 357
9.6.3 Downbursts and Microbursts 359

9.7 Buoyancy Waves 363

9.7.1 Observation in a VAD 364
9.7.2 Large-Amplitude Buoyancy Waves 365

9.8 Large Weather Systems 371

9.8.1 Mesoscale Convective Systems 371
9.8.2 Hurricanes and Typhoons 376
## Contents

9.8.3  *Cold Fronts and Dry Lines*  378

9.9  Lightning  380

9.9.1  *Physical Characteristics Determined by Radar*  380

9.9.2  *Lightning and Storm Structure*  382

Problems  383

### 10. Measurements of Turbulence  386

10.1  Statistical Theory of Turbulence  386

10.1.1  *Turbulence Spectra and the Correlation Function*  386

10.1.2  *Structure Functions, Locally Homogeneous Fields*  391

10.1.3  *Structure and Spectral Functions, Locally Isotropic Fields*  393

10.1.4  *Chandrasekhar's Theory*  395

10.2  Spatial Spectra of Point and Average Velocities  398

10.2.1  *Filtering by the Weighting Function*  398

10.2.2  *Variance of Point and Average Velocities*  403

10.2.3  *Turbulence Parameters from a Single Radar*  404

10.2.4  *Turbulence Parameters from Two Doppler Radars*  407

10.3  Doppler Spectrum Width and Eddy Dissipation Rate  408

10.4  Doppler Spectrum Width in Severe Thunderstorms  410

Problems  422

### 11. Observations of Fair Weather  424

11.1  Reflection, Refraction, and Scatter: Coherence  424

11.2  Formulation of the Wave Equation for Inhomogeneous and Turbulent Media  426

11.3  Solution for Fields Scattered by Irregularities  430

11.4  Small Volume Scatter  435

11.4.1  *Bragg Scatter*  437

11.4.2  *Radio Acoustic Sounding System (RASS)*  440

11.4.3  *Expected Scattered Power Density*  443

11.5  Common Volume Scatter  452

11.5.1  *Correlation Length Shorter Than the Fresnel Length*  453

11.5.2  *Correlation Length Comparable to or Larger Than the Fresnel Length*  455

11.5.3  *The Spectral Representation*  460

11.5.4  *Scattering from Anisotropic Irregularities, an Example*  463