Contents

Preface ..... **xv**

List of Acronyms ..... **xvii**

Chapter 1 Introduction **1**

1.1 Hyperspectral Remote Sensing 2
1.2 Elements of Hyperspectral Sensing 7
1.2.1 Material spectroscopy 8
1.2.2 Radiative transfer 9
1.2.3 Imaging spectrometry 14
1.2.4 Hyperspectral data processing 20
1.3 Examples of Remote Sensing Applications 21
1.4 Summary 33
References 33

Chapter 2 Optical Radiation and Matter **37**

2.1 Propagation of Electromagnetic Radiation 37
2.1.1 Propagation in free space 38
2.1.2 Propagation in dense media 39
2.1.3 Plane waves in dense media 41
2.2 Complex Index of Refraction 44
2.2.1 Relationship with the complex dielectric constant 44
2.2.2 Lorentz oscillator model 45
2.2.3 Drude theory of strong conductors 52
2.3 Propagation through Homogenous Media 53
2.4 Reflection and Transmission at Dielectric Interfaces 56
2.5 Reflection and Transmission at Conductor Interfaces 61
2.6 Radiometry 69
2.6.1 Point sources 71
2.6.2 Lambertian sources 72
2.6.3 Spherical scatterers 73
2.7 Propagation through Scattering Media 74
2.7.1 Mie scattering theory 76
2.7.2 Rayleigh scattering theory 78

2.8 Summary 80
2.9 Further Reading 81
References 81

Chapter 3 Atomic and Molecular Spectroscopy 83

3.1 Quantum Mechanics 83
3.1.1 Stationary states of a quantum mechanical system 85
3.1.2 Interaction with electromagnetic radiation 86
3.1.3 Born–Oppenheimer approximation 90
3.2 Electromagnetic Absorption and Emission 91
3.2.1 Einstein coefficients 92
3.2.2 Line broadening 93
3.3 Electronic Spectroscopy of Atoms 95
3.3.1 Single-electron atoms 96
3.3.2 Polyelectronic atoms 101
3.4 Rotational Spectroscopy of Molecules 107
3.5 Vibrational Spectroscopy of Molecules 111
3.5.1 Diatomic molecules 111
3.5.2 Polyatomic molecules 120
3.6 Electronic Spectroscopy of Molecules 123
3.7 Summary 130
3.8 Further Reading 130
References 131

Chapter 4 Spectral Properties of Materials 133

4.1 Apparent Spectral Properties 133
4.1.1 Homogenous absorbing layer 134
4.1.2 Opaque scattering layer 138
4.1.3 Transparent scattering layer 141
4.1.4 Multiple absorbing layers 142
4.1.5 Multilayer dielectric thin films 144
4.1.6 Rough-surface reflectance 146
4.1.7 Emissivity and Kirchoff's law 150
4.2 Common Remote Sensing Materials 154
4.2.1 Atmospheric gases 154
4.2.2 Liquid water 158
4.2.3 Vegetation 163
4.2.4 Minerals 172
4.2.5 Soils 179
4.2.6 Road materials 186
4.2.7 Metals 189
4.2.8 Paints and coatings 191

4.3 Summary 193
4.4 Further Reading 195
References 196

Chapter 5 Remotely Sensed Spectral Radiance 199

5.1 Radiative Transfer Modeling 199
5.1.1 Atmospheric modeling 201
5.1.2 Moderate-resolution atmospheric transmission and radiation code 206
5.1.3 Atmospheric path transmission 209
5.1.4 Atmospheric path radiance 217
5.1.5 Downwelling radiance 221
5.2 Remote Sensing Models 227
5.2.1 Facet model for a solid surface 228
5.2.2 Gaseous effluent model 233
5.2.3 Shallow-water model 235
5.3 Summary 241
References 241

Chapter 6 Imaging System Design and Analysis 243

6.1 Remote Imaging Systems 243
6.2 Optical System Design 247
6.2.1 Point spread function 247
6.2.2 Optical aberrations 250
6.2.3 Modulation transfer function 256
6.2.4 Lens design 257
6.3 FPA Materials and Devices 266
6.3.1 Quantum detectors 268
6.3.2 Photoconductors 270
6.3.3 Photodiodes 272
6.3.4 Detector materials 275
6.3.5 Detector noise 281
6.3.6 Detector performance 285
6.4 Radiometric Sensitivity 286
6.4.1 Signal and background radiance 288
6.4.2 Focal plane irradiance 289
6.4.3 Photoelectronic conversion 291
6.4.4 Total system noise 292
6.4.5 Total system performance 294
6.5 Spatial Sampling 296
6.6 Spatial Resolution 300
6.6.1 Ground-resolved distance 301

6.6.2 System modulation transfer function 302
6.7 Image Quality 307
6.8 Summary 310
6.9 Further Reading 310
References 311

Chapter 7 Dispersive Spectrometer Design and Analysis 313

7.1 Prism Spectrometers 314
7.1.1 Prism dispersion 315
7.1.2 Prism spectrometer design 319
7.2 Grating Spectrometers 324
7.2.1 Grating diffraction 325
7.2.2 Grating spectrometer design 331
7.3 Imaging Spectrometer Performance 338
7.3.1 Spatial and spectral mapping 338
7.3.2 Spatial and spectral response functions 340
7.3.3 Radiometric sensitivity 346
7.4 System Examples 348
7.4.1 Airborne Visible/Infrared Imaging Spectrometer 349
7.4.2 Hyperspectral Digital Imagery Collection Experiment 351
7.4.3 Hyperion 353
7.4.4 Compact Airborne Spectral Sensor 354
7.4.5 Spatially Enhanced Broadband Array Spectrograph System 357
7.4.6 Airborne Hyperspectral Imager 357
7.5 Summary 360
References 361

Chapter 8 Fourier Transform Spectrometer Design and Analysis 363

8.1 Fourier Transform Spectrometers 364
8.1.1 Interferograms 366
8.1.2 Spectrum reconstruction 368
8.1.3 Spectral resolution 369
8.1.4 Spectral range 370
8.1.5 Apodization 372
8.1.6 Uncompensated interferograms 373
8.2 Imaging Temporal Fourier Transform Spectrometers 373
8.2.1 Off-axis effects 375
8.2.2 Additional design considerations 376

8.3 Spatial Fourier Transform Spectrometers 377
8.4 Radiometric Sensitivity 380
8.4.1 Signal-to-noise ratio 380
8.4.2 Noise-equivalent spectral radiance 382
8.4.3 Imaging spectrometer sensitivity comparison 384
8.5 System Examples 387
8.5.1 Field-Portable Imaging Radiometric Spectrometer Technology 387
8.5.2 Geosynchronous Imaging Fourier Transform Spectrometer 388
8.5.3 Spatially Modulated Imaging Fourier Transform Spectrometer 390
8.5.4 Fourier Transform Hyperspectral Imager 391
8.6 Summary 393
References 393

Chapter 9 Additional Imaging Spectrometer Designs 395

9.1 Fabry–Pérot Imaging Spectrometer 395
9.2 Acousto-optic Tunable Filter 400
9.3 Wedge Imaging Spectrometer 403
9.4 Chromotomographic Imaging Spectrometer 407
9.4.1 Rotating direct-view prism spectrometer 408
9.4.2 Multi-order diffraction instrument 413
9.5 Summary 415
References 415

Chapter 10 Imaging Spectrometer Calibration 417

10.1 Spectral Calibration 417
10.1.1 Spectral mapping estimation 418
10.1.2 Spectral calibration sources 419
10.1.3 Spectral-response-function estimation 420
10.1.4 Spectral calibration example 421
10.2 Radiometric Calibration 423
10.2.1 Nonuniformity correction of panchromatic imaging systems 424
10.2.2 Radiometric calibration sources 431
10.2.3 Dispersive imaging spectrometer calibration 435
10.2.4 Imaging Fourier transform spectrometer calibration 444
10.3 Scene-Based Calibration 445
10.3.1 Vicarious calibration 446
10.3.2 Statistical averaging 446

10.4 Summary 449
References 449

Chapter 11 Atmospheric Compensation 451

11.1 In-Scene Methods 452
11.1.1 Empirical line method 454
11.1.2 Vegetation normalization 458
11.1.3 Blackbody normalization 467
11.1.4 Temperature–emissivity separation 476
11.2 Model-Based Methods 485
11.2.1 Atmospheric Removal Program 485
11.2.2 Fast line-of-sight atmospheric analysis of spectral hypercubes 490
11.2.3 Coupled-subspace model 492
11.2.4 Oblique projection retrieval of the atmosphere 495
11.3 Summary 498
References 500

Chapter 12 Spectral Data Models 503

12.1 Hyperspectral Data Representation 503
12.1.1 Geometrical representation 504
12.1.2 Statistical representation 507
12.2 Dimensionality Reduction 510
12.2.1 Principal-component analysis 510
12.2.2 Centering and whitening 513
12.2.3 Noise-adjusted principal-components analysis 516
12.2.4 Independent component analysis 520
12.2.5 Subspace model 523
12.2.6 Dimensionality estimation 526
12.3 Linear Mixing Model 529
12.3.1 Endmember determination 531
12.3.2 Abundance estimation 535
12.3.3 Limitations of the linear mixing model 537
12.4 Extensions of the Multivariate Normal Model 539
12.4.1 Local normal model 540
12.4.2 Normal mixture model 544
12.4.3 Generalized elliptically contoured distributions 549
12.5 Stochastic Mixture Model 551
12.5.1 Discrete stochastic mixture model 553
12.5.2 Estimation algorithm 555
12.5.3 Examples of results 558

12.6 Summary 558
12.7 Further Reading 560
References 560

Chapter 13 Hyperspectral Image Classification 563

13.1 Classification Theory 563
13.2 Feature Extraction 569
13.2.1 Statistical separability 570
13.2.2 Spectral derivatives 572
13.3 Linear Classification Algorithms 573
13.3.1 ***k***-means algorithm 580
13.3.2 Iterative self-organizing data analysis technique 584
13.3.3 Improved split-and-merge clustering 586
13.3.4 Linear support vector machine 589
13.4 Quadratic Classification Algorithms 593
13.4.1 Simple quadratic clustering 594
13.4.2 Maximum-likelihood clustering 595
13.4.3 Stochastic expectation maximization 598
13.5 Nonlinear Classification Algorithms 605
13.5.1 Nonparametric classification 606
13.5.2 Kernel support vector machine 612
13.6 Summary 614
13.7 Further Reading 615
References 615

Chapter 14 Hyperspectral Target Detection 617

14.1 Target Detection Theory 617
14.1.1 Likelihood ratio test 618
14.1.2 Multivariate normal model 620
14.1.3 Generalized likelihood ratio test 622
14.2 Anomaly Detection 624
14.2.1 Mahalanobis distance detector 624
14.2.2 Reed–Xiaoli detector 630
14.2.3 Subspace Reed–Xiaoli detector 633
14.2.4 Complementary subspace detector 635
14.2.5 Normal mixture model detectors 638
14.3 Signature-Matched Detection 646
14.3.1 Spectral angle mapper 646
14.3.2 Spectral matched filter 649
14.3.3 Constrained energy minimization 657
14.3.4 Adaptive coherence/cosine estimator 658
14.3.5 Subpixel spectral matched filter 662

14.3.6 Spectral matched filter with normal mixture model 666
14.3.7 Orthogonal subspace projection 669
14.4 False-Alarm Mitigation 674
14.4.1 Quadratic matched filter 674
14.4.2 Subpixel replacement model 676
14.4.3 Mixture-tuned matched filter 678
14.4.4 Finite target matched filter 680
14.4.5 Least-angle regression 682
14.5 Matched Subspace Detection 684
14.5.1 Target subspace models 685
14.5.2 Subspace adaptive coherence/cosine estimator 689
14.5.3 Joint subspace detector 692
14.5.4 Adaptive subspace detector 694
14.6 Change Detection 695
14.6.1 Affine change model 696
14.6.2 Change detection using global prediction 698
14.6.3 Change detection using spectrally segmented prediction 703
14.6.4 Model-based change detection 707
14.7 Summary 712
14.8 Further Reading 714
References 714

Index **717**