Hyperspectral Imaging Remote Sensing

A practical and self-contained guide to the principles, techniques, models, and tools of imaging spectroscopy. Bringing together material from essential physics and digital signal processing, the book covers key topics such as sensor design and calibration, atmospheric inversion and model techniques, and processing and exploitation algorithms. Readers will learn how to apply the main algorithms to practical problems, how to choose the best algorithm for a particular application, and how to process and interpret hyperspectral imaging data. A wealth of additional materials accompany the book online, including example projects and data for students, and problem solutions and viewgraphs for instructors.

This is an essential text for senior undergraduate and graduate students looking to learn the fundamentals of imaging spectroscopy, and an invaluable reference for scientists and engineers working in the field.

Dimitris G. Manolakis is a Senior Member of Technical Staff at MIT Lincoln Laboratory in Lexington, Massachusetts. He is the co-author of Applied Digital Signal Processing (Cambridge University Press, 2011), and has taught at various institutions including Northeastern University, Boston College, and Worcester Polytechnic Institute. He is an IEEE Fellow, and in 2013 he received the IEEE Signal Processing Society Education Award.

Ronald B. Lockwood is a Member of Technical Staff at MIT Lincoln Laboratory. He previously worked at the Air Force Research Laboratory, where he developed imaging spectrometers for both space-based and airborne applications. He has also developed vicarious calibration techniques in collaboration with colleagues at the University of Arizona and the NASA Goddard Space Flight Center.

Thomas W. Cooley is the Air Force Research Laboratory Senior Scientist for Space Situational Awareness, and has made significant contributions to the fields of atmospheric compensation and spectral data analysis. He developed the ARTEMIS sensor program, which was successfully launched in 2009, and he has published over 70 research papers.
“The authors have done a masterful job of integrating and presenting the diverse subjects that form the foundation of the field of hyperspectral imaging and applications. This comprehensive textbook will clearly become one of the standard references for all who wish to learn about both fundamentals and advanced applications in this important field.”

Charles Bachmann, Rochester Institute of Technology

“An extraordinarily comprehensive treatment of hyperspectral remote sensing by three of the field’s noted authorities. An indispensable reference for those new to the field and for the seasoned professional.”

Ronald G. Resmini, George Mason University
Hyperspectral Imaging Remote Sensing

Physics, Sensors, and Algorithms

DIMITRIS G. MANOLAKIS
Massachusetts Institute of Technology
Lincoln Laboratory

RONALD B. LOCKWOOD
Massachusetts Institute of Technology
Lincoln Laboratory

THOMAS W. COOLEY
To Anna
DGM

To Susan
RBL

To Claire, Kate, and Mary
TWC
## Contents

*Preface*

<table>
<thead>
<tr>
<th>1 Introduction</th>
<th>page xi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Infrared Sensing Phenomenology</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Hyperspectral Imaging Sensors</td>
<td>8</td>
</tr>
<tr>
<td>1.4 Data Preprocessing</td>
<td>15</td>
</tr>
<tr>
<td>1.5 Data Exploitation Algorithms</td>
<td>19</td>
</tr>
<tr>
<td>1.6 Applications of Imaging Spectroscopy</td>
<td>25</td>
</tr>
<tr>
<td>1.7 History of Spectral Remote Sensing</td>
<td>28</td>
</tr>
<tr>
<td>1.8 Summary and Further Reading</td>
<td>33</td>
</tr>
<tr>
<td>1.9 Book Organization</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2 The Remote Sensing Environment</th>
<th>36</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Electromagnetic Radiation</td>
<td>36</td>
</tr>
<tr>
<td>2.2 Diffraction and Interference</td>
<td>41</td>
</tr>
<tr>
<td>2.3 Basic Radiometry</td>
<td>50</td>
</tr>
<tr>
<td>2.4 Radiation Sources</td>
<td>55</td>
</tr>
<tr>
<td>2.5 Quantum Mechanical Results</td>
<td>61</td>
</tr>
<tr>
<td>2.6 Spectral Line Shapes</td>
<td>76</td>
</tr>
<tr>
<td>2.7 Atmospheric Scattering Essentials</td>
<td>84</td>
</tr>
<tr>
<td>2.8 Optical Thickness</td>
<td>95</td>
</tr>
<tr>
<td>2.9 Properties of the Atmosphere</td>
<td>102</td>
</tr>
<tr>
<td>2.10 Summary and Further Reading</td>
<td>114</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3 Spectral Properties of Materials</th>
<th>117</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Introduction</td>
<td>117</td>
</tr>
<tr>
<td>3.2 Geometrical Description</td>
<td>118</td>
</tr>
<tr>
<td>3.3 Directional Emissivity</td>
<td>126</td>
</tr>
<tr>
<td>3.4 Volume Scattering of Materials</td>
<td>128</td>
</tr>
<tr>
<td>3.5 Elements of Mineral Spectroscopy</td>
<td>131</td>
</tr>
<tr>
<td>3.6 Organic Spectroscopy</td>
<td>144</td>
</tr>
<tr>
<td>3.7 Man-Made Materials</td>
<td>148</td>
</tr>
</tbody>
</table>
Contents

3.8 Long Wave Infrared Spectra 150
3.9 Summary and Further Reading 151

4 Imaging Spectrometers 154
4.1 Telescopes 155
4.2 Imaging Spectrometer Common Concepts 161
4.3 Dispersive Imaging Spectrometer Fundamentals 171
4.4 Dispersive Imaging Spectrometer Designs 195
4.5 Interference Imaging Spectrometer Fundamentals 209
4.6 Data Acquisition with Imaging Spectrometers 222
4.7 Summary and Further Reading 224

5 Imaging Spectrometer Characterization and Data Calibration 228
5.1 Introduction 228
5.2 Application of the Measurement Equation 229
5.3 Spectral Characterization 231
5.4 Radiometric Characterization 238
5.5 Spatial Characterization 261
5.6 Advanced Calibration Techniques 262
5.7 Error Analysis 263
5.8 Radiometric Performance Modeling 269
5.9 Vicarious Calibration 280
5.10 Summary and Further Reading 292

6 Radiative Transfer and Atmospheric Compensation 295
6.1 Radiative Transfer 295
6.2 General Solution to the Radiative Transfer Equation 303
6.3 Modeling Tools of Radiative Transfer 312
6.4 Reflective Atmospheric Compensation 322
6.5 Estimating Model Parameters from Scene Data 330
6.6 Reflective Compensation Implementation 344
6.7 Atmospheric Compensation in the Thermal Infrared 351
6.8 Summary and Further Reading 358

7 Statistical Models for Spectral Data 360
7.1 Univariate Distributions – Variance 360
7.2 Bivariate Distributions – Covariance 363
7.3 Random Vectors – Covariance Matrix 367
7.4 Multivariate Distributions 371
7.5 Maximum Likelihood Parameter Estimation 383
7.6 Statistical Analysis of Hyperspectral Imaging Data 387
7.7 Gaussian Mixture Models 394
7.8 Summary and Further Reading 403
## Contents

### 8 Linear Spectral Transformations

8.1 Introduction 406  
8.2 Implications of High-Dimensionality 408  
8.3 Principal Components Analysis: Theory 411  
8.4 Principal Components Analysis: Application 421  
8.5 Diagonalizing Two Different Covariance Matrices 424  
8.6 Maximum Noise Fraction (MNF) Transform 428  
8.7 Canonical Correlation Analysis (CCA) 429  
8.8 Linear Discriminant Analysis 432  
8.9 Linear Spectral-Band Estimation 437  
8.10 Summary and Further Reading 441

### 9 Spectral Mixture Analysis

9.1 Spectral Mixing 443  
9.2 The Linear Mixing Model 446  
9.3 Endmember Determination Techniques 451  
9.4 Fill-Fraction Estimation Techniques 453  
9.5 The Method of Least Squares Estimation 454  
9.6 Least Squares Computations 463  
9.7 Statistical Properties of Least Squares Estimators 466  
9.8 Generalized Least Squares Estimation 468  
9.9 Maximum Likelihood Estimation 470  
9.10 Regularized Least Squares Problems 471  
9.11 Consequences of Model Misspecification 475  
9.12 Hypotheses Tests for Model Parameters 477  
9.13 Model Selection Criteria 480  
9.14 Variable Selection in Linear Signal Models 482  
9.15 Linear Spectral Mixture Analysis in Practice 487  
9.16 Summary and Further Reading 492

### 10 Signal Detection Theory

10.1 A Simple Decision-Making Problem 494  
10.2 Elements of Statistical Hypotheses Testing 496  
10.3 The General Gaussian Detection Problem 503  
10.4 Gaussian Detectors in the Presence of Unknowns 511  
10.5 Matched Filter and Maximization of Deflection 517  
10.6 Performance Analysis of Matched Filter Detectors 522  
10.7 Detectors for Signals in Subspace Clutter and Isotropic Noise 533  
10.8 Eigenvector Matched Filters 539  
10.9 Robust Matched Filters 541  
10.10 Adaptive Matched Filter Detectors 547  
10.11 Summary and Further Reading 548
Contents

11 Hyperspectral Data Exploitation 551
11.1 Target Detection in the Reflective Infrared 551
11.2 Target Detection Performance Assessment 570
11.3 False Alarm Mitigation and Target Identification 577
11.4 Spectral Landscape Classification 581
11.5 Change Detection 586
11.6 Unique Aspects of Spectral Exploitation in the Thermal Infrared 591
11.7 Remote Sensing of Chemical Clouds: Physics 595
11.8 Remote Sensing of Chemical Clouds: Algorithms 605
11.9 Summary and Further Reading 620

Appendix Introduction to Gaussian Optics 621
A.1 The Optical Path 621
A.2 Ideal Image Formation 624
A.3 The Paraxial Approximation 628
A.4 The Limiting Aperture 633
A.5 Example: The Cooke Triplet 640
A.6 Afocal Systems 642
A.7 Aberration Theory 644
A.8 Summary and Further Reading 652

Bibliography 654
Index 678

Color plate section between pages 338 and 339.
Preface

The roots of education are bitter but the fruit is sweet.

Isocrates, 436-338 BC
Greek orator and rhetorician

Sir Isaac Newton invented the first monochromator with two slits and a prism in 1666, and is largely credited with founding the field of spectroscopy based on his publication of *Opticks* in 1704. Over a century after Newton’s optics experiments, Joseph von Fraunhofer made the significant advance in the field with the use of a diffraction grating to replace the prism as the dispersion element. His ground-breaking studies of emissions from the sun, in which he cataloged the series of absorption features in the solar spectrum that bear his name, established the discipline of spectral remote sensing. An early demonstration of the power of spectroscopy for identification was when Joseph Foucault showed that two of the Fraunhofer lines corresponded to sodium emission. The precision afforded by the diffraction grating facilitated the field of spectroscopy becoming a mainstay for the fields of chemistry, astronomy and, in recent decades, remote sensing. Imaging spectroscopy is a relatively recent discipline which has been made possible by progress in several technology areas including detectors, optical design, optical components, atmospheric radiative transfer, and computer processing, to name just a few. While spectroscopy and imaging techniques have advanced independently, imaging spectroscopy is the merger of both, using spectroscopic techniques to form a multi-band-imaged scene or “hyper-spectral” image.

The hallmark of imaging spectroscopy is the utilization of spectroscopic techniques in which measurements can be used for unambiguous direct and indirect identification of surface materials and atmospheric trace gases. The measurement of the relative concentrations of materials and the ability to distinguish between subtle absorption features of differing materials for a two-dimensional scene are examples of imaging spectroscopy.

The main objective of this book is to present the fundamentals of remote sensing imaging spectroscopy from the perspective of the user. There is a strong interconnection between foundational phenomenology, sensing technology, atmospheric propagation effects, and exploitation algorithms. Successful application of remote sensing imaging spectroscopy requires a working knowledge and fundamental understanding of all
Preface

these aspects. Providing the reader this foundation is the objective of this book. Imaging spectroscopy is also used by meteorologists and atmospheric scientists to directly characterize the properties of the atmosphere. Our focus is on the use of imaging spectrometer data to identify attributes of the surface.

The book covers material from different disciplines ranging from physics, optics, spectroscopy, linear algebra, statistics, and signal processing. Integrating material from such disparate areas is not easy, but we have tried to provide smooth and coherent coverage. The reader is expected to have a basic background in physics, chemistry, electrical engineering, or a related field. We attempt to proceed by introducing concepts from first principles to provide both foundational ideas and consistent nomenclature throughout the text.

We have tried to provide balanced coverage of topics of general interest. However, the selection and emphasis has been, we hope only slightly, biased by our own experience and backgrounds. We have selected material and references to reflect fundamental work and provide useful and practical techniques, insights, and applications. We apologize for any omissions or oversights of areas which may be sought by the reader, but the foundations found throughout the book can be applied to a variety of applications. We provide seminal bibliographic citations to provide historical context for the evolution of the technology both from our direct experience in the field and through judicious examination of the literature.

Special thanks go to Eric Truslow and Mike Piper for their cautious and thorough review, helping with figures, and preparing the solutions manual. Michael Chrisp, Steve Miller, and Kurt Thome lent their considerable expertise in reviewing several chapters. Their contributions are gratefully acknowledged.

Also, RLB was privileged to study atomic physics under the guidance of Chun C. Lin and in close collaboration with L. Wilmer Anderson and James Lawler at the University of Wisconsin at Madison. The presentation in Chapter 4 is extensively based on the course in applied optics that was part of the curriculum there in the late 1980s, co-developed by Edward Miller and Frederick Roesler. In particular, the instrumental spectroscopy formalism here parallels Roesler’s notes and has been adapted for the modest performance of an imaging spectrometer in comparison to the instruments used in, for example, atomic and molecular physics or astrophysics. Fred Roesler collaborated with Pierre Jacquintot early in his career, and his thinking, and therefore this presentation, was heavily influenced by the French spectroscopy school.

RBL would also like to thank his parents, Robert and Sharon Lockwood. Both are educators and farmers who instilled a keen interest in the natural world in each of their children, leading to careers in science and mathematics. Having raised us on a family farm in West Texas, they also ensured that we all have healthy work ethics! This book is a result of their support and encouragement.

Most importantly, we must thank our families for their patience and enduring support for this project. No undertaking of this magnitude and duration is accomplished without a foundation of support to see it through. Anna, Susan, and Mary know the effort and time invested in this undertaking, and each is a pillar of forbearance for the time we have taken to complete this text. We are grateful for their wisdom, support, and endurance.
This undertaking required significant encouragement from our families, friends, and colleagues who recognized the opportunity to provide this compilation for the broader community of scientists, researchers, and students entering the field. We are grateful for the many voices of encouragement throughout this project. We wish also to thank the team at CUP, including Phil Meyler and Heather Brolly, who have patiently awaited the completed manuscript and provided valuable comments and guidance throughout. We hope you find benefit from our enterprise.

Acknowledgments
We have been fortunate to build upon the work of many other researchers, and to have access and help from many colleagues leading up to and through this project. We would like to thank the many scientists and researchers who have contributed directly and indirectly to this undertaking, and specifically want to thank: Gail Anderson, Peter Armstrong, Gregory Berthiaume, Stuart F. Biggar, William Blumberg, Rebecca N. Breiding, Michael Brueggeman, Thomas G. Chrien, James Dodd, David Driscoll, Richard Dunn, Janet Fender, James Gardner, Mary Ann Glennon, Steven Golowich, Peggy Grigsby, Lynn Hatfield, David Hardy, John Jacobson, Angela Kim, Steven Lipson, Joaquin Mason, Karis W. Miles, Dan Mooney, Richard Nadile, Sidi Niu, Martin Pilati, Ryan M. Pospisal, C. Richard Quade, Frederick L. Roesler, Stephanie Schieffer, John Schummers, Vittala Shettigara, Krista Steenbergen, Stanley Straight, Johnny L. Touchstone, Klaes Wandland, Christopher J. Ward, Andrew Weisner, Benjamin Worker, and Randall Zywicki.