

Hyperspectral Remote Sensing

Hyperspectral Remote Sensing

Michael T. Eismann

SPIE PRESS
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Eismann, Michael Theodore, 1964-

Hyperspectral remote sensing / Michael Eismann.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-8194-8787-2

1. Remote sensing. 2. Multispectral photography. 3. Image processing. I. Title.

G70.4.E39 2012

621.36'78--dc23

2011046489

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360.676.3290

Fax: +1 360.647.1445

Email: Books@spie.org

Web: <http://spie.org>

The content of this book is a work of the U.S. Government and is not subject to copyright. The presentation format of this work by the publisher is protected, and may not be reproduced or distributed without written permission of the publisher.

Publication Year: 2012

The content of this book reflects the work and thought of the author. Every effort has been made to publish reliable and accurate information herein, but the publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Printed in the United States of America.

Second printing 2017

For updates to this book, visit <http://spie.org> and type "PM210" in the search field.

SPIE.

Dedicated with love to Michelle, Maria, and Katie

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 Kirchhoff’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 Spectro- graph 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 Spectrom- eter 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

Preface

Hyperspectral imaging is an emerging field of electro-optical and infrared remote sensing. Advancements in sensing and processing technology have reached a level that allows hyperspectral imaging to be more widely applied to remote sensing problems. Because of this, I was asked roughly six years ago to serve as an adjunct faculty member at the Air Force Institute of Technology in Ohio to construct and teach a graduate course on this subject as part of their optical engineering program. As I searched for a suitable textbook from which to teach this course, it became apparent to me that there were none that provided the comprehensive treatment I felt the subject required. Hyperspectral remote sensing is a highly multidisciplinary field, and I believe that a student of this subject matter should appreciate and understand all of its major facets, including material spectroscopy, radiative transfer, imaging spectrometry, and hyperspectral data processing. There are many resources that suitably cover these areas individually, but none that are all inclusive. This book is my attempt to provide an end-to-end treatment of hyperspectral remote sensing technology.

I have been using this textbook in manuscript form to teach a one-quarter class at the graduate level, with Masters and Ph.D. students taking the course as an elective and subsequently performing their research in the hyperspectral remote sensing field. The amount of material is arguably too much to fit within a single quarter and would ideally be spread over a semester or two quarters if possible. The content of the book is oriented toward the physical principles of hyperspectral remote sensing as opposed to applications of hyperspectral technology, with the expectation that students finish the class armed with the required knowledge to become practitioners in the field; be able to understand the immense literature available in this technology area; and apply their knowledge to the understanding of material spectral properties, the design of hyperspectral systems, the analysis of hyperspectral imagery, and the application of the technology to specific problems.

There are many people I would like to thank for helping me complete this book. First, I would like to thank the Air Force Research Laboratory for their support of this endeavor, and my many colleagues in the

hyperspectral remote sensing field from whom I have drawn knowledge and inspiration during the 15 years I have performed research in this area. I would like to thank all of my OENG 647 Hyperspectral Remote Sensing students at the Air Force Institute of Technology who suffered through early versions of this manuscript and provided invaluable feedback to help improve it. In particular, I owe great thanks to Joseph Meola of the Air Force Research Laboratory, who performed a very thorough review of the manuscript, made numerous corrections and suggestions, and contributed material to Chapters 10 and 14, including participating in useful technical discussions concerning nuances of signal processing theory. I am very grateful for thorough, insightful, and constructive reviews of my original manuscript performed by Dr. John Schott of the Rochester Institute of Technology and Dr. Joseph Shaw of Montana State University on behalf of SPIE Press, as well as Tim Lamkins, Dara Burrows, and their staff at SPIE Press for turning my manuscript into an actual book. Additionally, I would like to acknowledge the support of Philip Maciejewski of the Air Force Research Laboratory for performing vegetation spectral measurements, the National Aeronautics and Space Agency (NASA) for the Hyperion data, the Defense Intelligence Agency for the HYDICE data, John Hackwell and the Aerospace Corporation for the SEBASS data, Patrick Brezonik and the University of Minnesota for the lake reflectance spectra, Joseph Shaw of Montana State University for the downwelling FTIR measurements, Bill Smith of NASA Langley Research Center for the GIFTS schematic and example data, and others acknowledged throughout this book for the courtesy of using results published in other books and journals.

Finally, this book would not have been possible were it not for the help and support of my wife Michelle and daughters Maria and Katie, who provided great patience and encouragement during the many hours that their husband and father was preparing, typing, and editing this book instead of giving time to them and attending to other things around our home. Now that this immense undertaking is completed, I hope to make up for some of what was lost.

Michael T. Eismann
Beavercreek, Ohio
March 2012

List of Acronyms

ACE	adaptive coherence/cosine estimator
ADC	analog-to-digital conversion
AHI	Airborne Hyperspectral Imager
AIRIS	Adaptive Infrared Imaging Spectroradiometer
AIS	Airborne Imaging Spectrometer
amu	atomic mass unit
AOTF	acousto-optic tunable filter
AR	antireflection (coating)
ARCHER	Airborne Real-Time Cueing Hyperspectral Enhanced Reconnaissance
ARM	Atmospheric Radiation Measurement (site)
ASD	adaptive subspace detector
ATREM	atmospheric removal program
AUC	area under (the ROC) curve
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BI	bare-soil index
BLIP	background-limited performance
BRDF	bidirectional reflectance distribution function
CBAD	cluster-based anomaly detector
CCD	charge-coupled device
CCSMF	class-conditional spectral matched filter
CDF	cumulative distribution function
CEM	constrained energy minimization (detector)
CFAR	constant false-alarm rate
CMOS	complementary metal-oxide semiconductor
COMPASS	Compact Airborne Spectral Sensor
CSD	complementary subspace detector
CTIS	chromotomographic imaging spectrometer
DDR-SDRAM	double-data-rate synchronous dynamic random access memory
DFT	discrete Fourier transform
DHR	directional hemispherical reflectance
DIRSIG	Digital Image and Remote Sensing Image Generation
DISORT	multiple-scattering discrete-ordinate radiative transfer program for a multilayered plane-parallel medium
DN	data number
DOP	degree of polarization

ED	Euclidian distance (detector)
ELM	empirical line method
EM	expectation maximization (algorithm)
EO/IR	electro-optical and infrared
FAM	false-alarm mitigation
FAR	false-alarm rate
FCBAD	fuzzy cluster-based anomaly detector
FFT	fast Fourier transform
FIRST	Field Portable Imaging Radiometric Spectrometer Technology (spectrometer)
FLAASH	fast line-of-sight atmospheric analysis of spectral hypercubes
FOV	field of view
FPA	focal plane array
fps	frames per second
FTHSI	Fourier Transform Hyperspectral Imager
FTIR	Fourier transform infrared (spectrometer)
FTMF	finite target matched filter
FTS	Fourier transform spectrometer
FWHM	full-width at half-maximum
GIFTS	Geosynchronous Imaging Fourier Transform Spectrometer
GIQE	general image-quality equation
GLRT	generalized likelihood ratio test
GMM	Gaussian mixture model
GMRX	Gaussian mixture Reed–Xiaoli (detector)
GRD	ground-resolved distance
GSD	ground-sample distance
HDR	hemispherical directional reflectance
HICO TM	Hyperspectral Imager for the Coastal Ocean
HITRAN	high-resolution transmission molecular absorption
HYDICE	Hyperspectral Digital Imagery Collection Experiment
ICA	independent component analysis
IFOV	instantaneous field of view
IS	integrating sphere
ISAC	in-scene atmospheric compensation
ISMIC	improved split-and-merge clustering
ISODATA	iterative self-organizing data analysis technique
JPL	Jet Propulsion Lab
JSD	joint subspace detector
kNN	k nearest neighbor
KS	Kolmogorov–Smirnov (test)

LARS	least-angle regression
LBG	Linde–Buzo–Gray (clustering)
LMM	linear mixing model
LOS	line of sight
LRT	likelihood ratio test
LVF	linear variable filter
LWIR	longwave infrared
MBCD	model-based change detector
MD	Mahalanobis distance
ML	maximum likelihood (algorithm)
MLE	maximum-likelihood estimate
MNF	maximum (or minimum) noise fraction
MODTRAN	moderate-resolution atmospheric transmission and radiance code
MSE	mean-squared error
MTF	modulation transfer function
MTMF	mixture-tuned matched filter
MWIR	midwave infrared
NA	numerical aperture
NAPC	noise-adjusted principal component
NCM	normal compositional model
NDVI	Normalized Differential Vegetation Index
NEI	noise-equivalent irradiance
NEL	noise-equivalent radiance
NEP	noise-equivalent power
NESR	noise-equivalent spectral radiance
NIIRS	Normalized Image Interpretability Rating Scale
NIR	near infrared
NIST	National Institute of Standards and Technology
NVIS	night vision imaging spectrometer
OPD	optical path difference
OPRA	oblique projection retrieval of the atmosphere
OSP	orthogonal subspace projection
PALM	pair-wise adaptive linear matched (filter)
PC	principal component
PCA	principal-component analysis
PPI TM	Pixel Purity Index TM
ppm	parts per million
PSF	point spread function
QSF	quadratic spectral filter
QTH	quartz tungsten

QUAC	quick atmospheric compensation
RMS	root mean square
ROC	receiver operating characteristic
ROIC	readout integrated circuit
RX	Reed–Xiaoli (detector)
SAM	spectral angle mapper
SCR	signal-to-clutter ratio
SEBASS	Spectrally Enhanced Broadband Array Spectrograph System
SEM	stochastic expectation maximization
SMF	spectral matched filter
SMIFTS	Spatially Modulated Imaging Fourier Transform Spectrometer
SMM	stochastic mixing model
SNR	signal-to-noise ratio
SRF	spectral response function
SS	subspace (detector)
SS-ACE	subspace adaptive coherence/cosine estimator
SSD	subpixel subspace detector
SSRX	subspace Reed–Xiaoli (detector)
SVD	singular-value decomposition
SVM	support vector machine
SWIR	shortwave infrared
SWIR1	short-wavelength end of the SWIR spectral region
SWIR2	long-wavelength end of the SWIR spectral region
TMA	three-mirror anastigmatic (design)
USGS	United States Geological Survey
VIS	visible
VNIR	visible and near-infrared
ZPD	zero path difference