Hyperspectral Remote Sensing
Hyperspectral Remote Sensing

Michael T. Eismann
Dedicated with love to Michelle, Maria, and Katie
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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

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACE</td>
<td>adaptive coherence/cosine estimator</td>
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<tr>
<td>ADC</td>
<td>analog-to-digital conversion</td>
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<tr>
<td>AHI</td>
<td>Airborne Hyperspectral Imager</td>
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<tr>
<td>AIRIS</td>
<td>Adaptive Infrared Imaging Spectroradiometer</td>
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<tr>
<td>AIS</td>
<td>Airborne Imaging Spectrometer</td>
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<tr>
<td>amu</td>
<td>atomic mass unit</td>
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<tr>
<td>AOTF</td>
<td>acousto-optic tunable filter</td>
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<tr>
<td>AR</td>
<td>antireflection (coating)</td>
</tr>
<tr>
<td>ARCHER</td>
<td>Airborne Real-Time Cueing Hyperspectral Enhanced Reconnaissance</td>
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<tr>
<td>ARM</td>
<td>Atmospheric Radiation Measurement (site)</td>
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<tr>
<td>ASD</td>
<td>adaptive subspace detector</td>
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<tr>
<td>ATREM</td>
<td>atmospheric removal program</td>
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<tr>
<td>AUC</td>
<td>area under (the ROC) curve</td>
</tr>
<tr>
<td>AVIRIS</td>
<td>Airborne Visible/Infrared Imaging Spectrometer</td>
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<tr>
<td>BI</td>
<td>bare-soil index</td>
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<tr>
<td>BLIP</td>
<td>background-limited performance</td>
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<tr>
<td>BRDF</td>
<td>bidirectional reflectance distribution function</td>
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<tr>
<td>CBAD</td>
<td>cluster-based anomaly detector</td>
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<tr>
<td>CCD</td>
<td>charge-coupled device</td>
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<td>CCSMF</td>
<td>class-conditional spectral matched filter</td>
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<tr>
<td>CDF</td>
<td>cumulative distribution function</td>
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<td>CEM</td>
<td>constrained energy minimization (detector)</td>
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<tr>
<td>CFAR</td>
<td>constant false-alarm rate</td>
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<td>CMOS</td>
<td>complementary metal-oxide semiconductor</td>
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<td>COMPASS</td>
<td>Compact Airborne Spectral Sensor</td>
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<tr>
<td>CSD</td>
<td>complementary subspace detector</td>
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<td>CTIS</td>
<td>chromotomographic imaging spectrometer</td>
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<tr>
<td>DDR-SDRAM</td>
<td>double-data-rate synchronous dynamic random access memory</td>
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<tr>
<td>DFT</td>
<td>discrete Fourier transform</td>
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<tr>
<td>DHR</td>
<td>directional hemispherical reflectance</td>
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<td>DIRSIG</td>
<td>Digital Image and Remote Sensing Image Generation</td>
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<tr>
<td>DISORT</td>
<td>multiple-scattering discrete-ordinate radiative transfer program for a multilayered plane-parallel medium</td>
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<tr>
<td>DN</td>
<td>data number</td>
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<tr>
<td>DOP</td>
<td>degree of polarization</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>ED</td>
<td>Euclidian distance (detector)</td>
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<td>ELM</td>
<td>empirical line method</td>
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<td>EM</td>
<td>expectation maximization (algorithm)</td>
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<tr>
<td>EO/IR</td>
<td>electro-optical and infrared</td>
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<td>FAM</td>
<td>false-alarm mitigation</td>
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<td>FAR</td>
<td>false-alarm rate</td>
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<td>FCBAD</td>
<td>fuzzy cluster-based anomaly detector</td>
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<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
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<td>FIRST</td>
<td>Field Portable Imaging Radiometric Spectrometer Technology (spectrometer)</td>
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<tr>
<td>FLAASH</td>
<td>fast line-of-sight atmospheric analysis of spectral hypercubes</td>
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<tr>
<td>FOV</td>
<td>field of view</td>
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<td>FPA</td>
<td>focal plane array</td>
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<td>fps</td>
<td>frames per second</td>
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<td>FTHSI</td>
<td>Fourier Transform Hyperspectral Imager</td>
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<tr>
<td>FTIR</td>
<td>Fourier transform infrared (spectrometer)</td>
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<td>FTMF</td>
<td>finite target matched filter</td>
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<td>FTS</td>
<td>Fourier transform spectrometer</td>
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<td>FWHM</td>
<td>full-width at half-maximum</td>
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<tr>
<td>GIFTS</td>
<td>Geosynchronous Imaging Fourier Transform Spectrometer</td>
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<tr>
<td>GIQE</td>
<td>general image-quality equation</td>
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<td>GLRT</td>
<td>generalized likelihood ratio test</td>
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<td>GMM</td>
<td>Gaussian mixture model</td>
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<td>GMRX</td>
<td>Gaussian mixture Reed–Xiaoli (detector)</td>
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<td>GRD</td>
<td>ground-resolved distance</td>
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<td>GSD</td>
<td>ground-sample distance</td>
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<tr>
<td>HDR</td>
<td>hemispherical directional reflectance</td>
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<td>HICO™</td>
<td>Hyperspectral Imager for the Coastal Ocean</td>
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<tr>
<td>HITRAN</td>
<td>high-resolution transmission molecular absorption</td>
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<td>HYDICE</td>
<td>Hyperspectral Digital Imagery Collection Experiment</td>
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<tr>
<td>ICA</td>
<td>independent component analysis</td>
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<tr>
<td>IFOV</td>
<td>instantaneous field of view</td>
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<tr>
<td>IS</td>
<td>integrating sphere</td>
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<td>ISAC</td>
<td>in-scene atmospheric compensation</td>
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<td>ISMC</td>
<td>improved split-and-merge clustering</td>
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<td>ISODATA</td>
<td>iterative self-organizing data analysis technique</td>
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<td>JPL</td>
<td>Jet Propulsion Lab</td>
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<tr>
<td>JSD</td>
<td>joint subspace detector</td>
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<tr>
<td>kNN</td>
<td>$k$ nearest neighbor</td>
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<tr>
<td>KS</td>
<td>Kolmogorov–Smirnov (test)</td>
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<td>Acronym</td>
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<tr>
<td>LARS</td>
<td>least-angle regression</td>
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<td>Linde–Buzo–Gray (clustering)</td>
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<td>LMM</td>
<td>linear mixing model</td>
</tr>
<tr>
<td>LOS</td>
<td>line of sight</td>
</tr>
<tr>
<td>LRT</td>
<td>likelihood ratio test</td>
</tr>
<tr>
<td>LVF</td>
<td>linear variable filter</td>
</tr>
<tr>
<td>LWIR</td>
<td>longwave infrared</td>
</tr>
<tr>
<td>MBCD</td>
<td>model-based change detector</td>
</tr>
<tr>
<td>MD</td>
<td>Mahalanobis distance</td>
</tr>
<tr>
<td>ML</td>
<td>maximum likelihood (algorithm)</td>
</tr>
<tr>
<td>MLE</td>
<td>maximum-likelihood estimate</td>
</tr>
<tr>
<td>MNF</td>
<td>maximum (or minimum) noise fraction</td>
</tr>
<tr>
<td>MODTRAN</td>
<td>moderate-resolution atmospheric transmission and radiance code</td>
</tr>
<tr>
<td>MSE</td>
<td>mean-squared error</td>
</tr>
<tr>
<td>MTF</td>
<td>modulation transfer function</td>
</tr>
<tr>
<td>MTMF</td>
<td>mixture-tuned matched filter</td>
</tr>
<tr>
<td>MWIR</td>
<td>midwave infrared</td>
</tr>
<tr>
<td>NA</td>
<td>numerical aperture</td>
</tr>
<tr>
<td>NAPC</td>
<td>noise-adjusted principal component</td>
</tr>
<tr>
<td>NCM</td>
<td>normal compositional model</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalized Differential Vegetation Index</td>
</tr>
<tr>
<td>NEI</td>
<td>noise-equivalent irradiance</td>
</tr>
<tr>
<td>NEL</td>
<td>noise-equivalent radiance</td>
</tr>
<tr>
<td>NEP</td>
<td>noise-equivalent power</td>
</tr>
<tr>
<td>NESR</td>
<td>noise-equivalent spectral radiance</td>
</tr>
<tr>
<td>NIIRS</td>
<td>Normalized Image Interpretability Rating Scale</td>
</tr>
<tr>
<td>NIR</td>
<td>near infrared</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>NVIS</td>
<td>night vision imaging spectrometer</td>
</tr>
<tr>
<td>OPD</td>
<td>optical path difference</td>
</tr>
<tr>
<td>OPRA</td>
<td>oblique projection retrieval of the atmosphere</td>
</tr>
<tr>
<td>OSP</td>
<td>orthogonal subspace projection</td>
</tr>
<tr>
<td>PALM</td>
<td>pair-wise adaptive linear matched (filter)</td>
</tr>
<tr>
<td>PC</td>
<td>principal component</td>
</tr>
<tr>
<td>PCA</td>
<td>principal-component analysis</td>
</tr>
<tr>
<td>PPI™</td>
<td>Pixel Purity Index™</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>PSF</td>
<td>point spread function</td>
</tr>
<tr>
<td>QSF</td>
<td>quadratic spectral filter</td>
</tr>
<tr>
<td>QTH</td>
<td>quartz tungsten</td>
</tr>
</tbody>
</table>
List of Acronyms

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