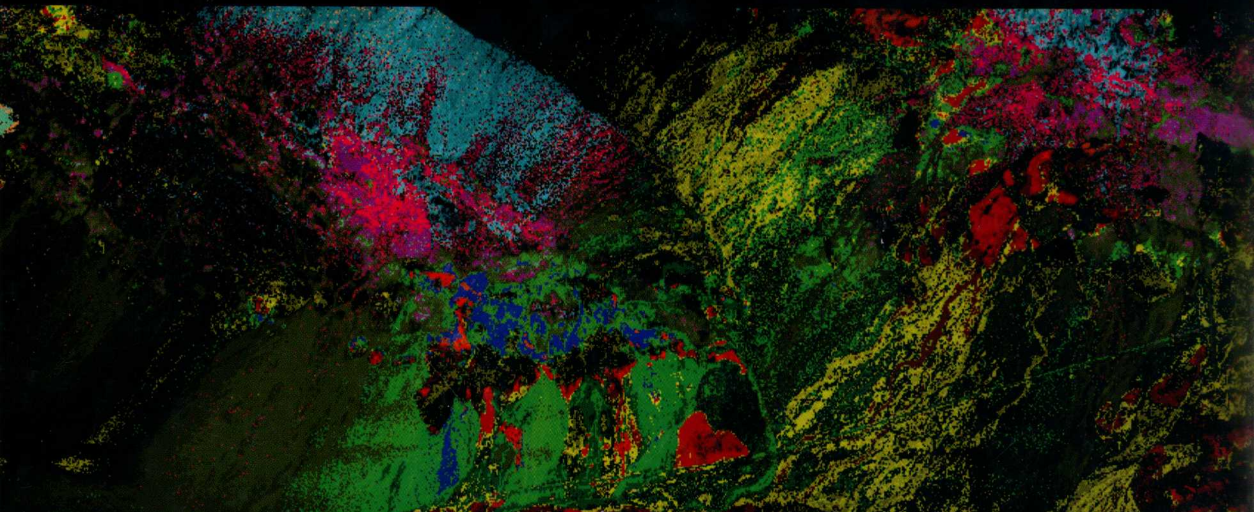
HYPERSPECTRAL DATA PROCESSING

Algorithm Design and Analysis

CHEIN-I CHANG



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This book is dedicated to members of my family, specifically my mother who provided me with her timeless support and encouragement during the course of preparing this book. It is also dedicated to all of my students who have contributed to this book.

Preface

Hyperspectral imaging has witnessed tremendous growth over the past few years. Still its applications to new areas are yet to be explored. Many hyperspectral imaging techniques have been developed and reported in various venues. My first book, *Hyperspectral Imaging: Techniques for Spectral Detection and Classification*, referenced as Chang (2003a), was written in an attempt to summarize the research conducted at that time in my laboratory (remote sensing signal and image processing laboratory, RSSIPL) and to provide readers with a peek of this fascinating and exciting area. With rapid advancement in this area many signal processing techniques have been developed for hyperspectral signal and image processing. This book has been written with four goals in mind. One is to continuously explore new statistical signal processing algorithms in this area for various applications. Many results in this book are new, particularly some in Chapters 2, 4, 5–6, 11, 16, 18–19, 23, 24, 29, 30–31, and 33. A second goal is to supplement Chang (2003a), where many potential research efforts were only briefly mentioned (in Chapter 18 of the book). A third goal is to distinguish this book from Chang (2003a) in many ways. Unlike Chang (2003a) where the main theme was hyperspectral target detection and classification from a viewpoint of subpixel and mixed pixel analysis, this book is focused on more in-depth treatment of hyperspectral signal and image processing from a statistical signal processing point of view. A fourth and last goal is to focus on several unsettled but very important issues that have been avoided and never addressed in the past.

One issue is "how many spectral signatures are required to unmix data?" arising in linear hyperspectral unmixing. This has been a long-standing and unresolved issue in remote sensing image processing, specifically hyperspectral imaging, since the number of signatures to be used for data unmixing has a significant impact on image analysis while its accurate number is never known in real applications. Another is "how many pure spectral signatures, referred to as endmembers, are supposed to be present in the data to be processed?" It is common practice to assume that the number of signatures used for spectral unmixing is the same number of endmembers. Unfortunately, such a claim, which has been widely accepted by the community, is not always true in practical applications (see Chapter 17). The issue of endmembers has not received much interest in multispectral image analysis because of its low spectral and spatial resolutions that generally result in mixed data sample vectors. However, due to recent advances in hyperspectral imaging sensors with hundreds of contiguous spectral bands endmember extraction has become increasingly important since endmembers provide crucial "nonliteral" information in spectral interpretation, characterization, and analysis. Interestingly, this issue has never been seriously addressed until recently when it has been investigated by a series of papers (Chang, 2006ab; Chang and

Plaza, 2006; Chang *et al.*, 2006; Plaza and Chang 2006) by introducing a new concept of virtual dimensionality (VD). Besides, some controversial issues result from misinterpreting VD. Therefore, one of the major chapters in this book is Chapter 5, which revisits VD to explore its utility in various applications. Unlike the intrinsic dimensionality (ID), also known as effective dimensionality (ED), which is somewhat abstract and defined as the minimum number of parameters to represent general high-dimensional multivariate data, VD is more practical and realistic. It is defined as the number of "*spectrally*" distinct signatures particularly developed for hyperspectral data in which the non-literal (spectral) information is more crucial and vital than information provided by other dimensions such as spatial information. In particular, an issue arises in how to define the spectral distinction among signatures in VD estimation. Furthermore, unlike ID that is a one-size-fits-all definition for all data sets, VD should adapt to data sets used for different applications as well as vary with the techniques used to estimate VD. In order to address this issue, Chapter 5 explores two types of VD criteria, data characterization-driven criteria and data representation-driven criteria, to define spectrally distinct signatures, and further decouples the concept of VD from the techniques used to estimate VD. Consequently, when VD is poorly estimated by one technique for a particular data set, it is not the definition of VD to be blamed, but rather the technique used for VD estimation that is not applicable to this particular data set. In addition, an issue related to VD is "characterization of pixel information." For example, an anomaly is not necessarily an endmember and vice versa. So, the issues "what is the distinction between these two?" and "how do we characterize these two?" become interesting issues in hyperspectral data exploitation to be discussed in Chapter 18.

Another interesting topic presented in this book is a new concept of "hyperspectral information compression" introduced in Chapters 19–23. It is different from the commonly used so-called hyperspectral data compression in the sense that hyperspectral information compression is generally performed based on the information required to be retained rather than the size of hyperspectral data to be compressed. Therefore, a more appropriate term to be used is "exploitation-based lossy hyperspectral data compression." Nevertheless, it should be noted that the definitions and terminologies used in these chapters are by no means standard.

Finally, an issue of "multispectral imagery versus hyperspectral imagery" is also investigated. It seems that there is no cut-and-dried definition to distinguish these two terminologies. A general understanding of distinguishing these two is that a hyperspectral image is acquired by hundreds of *contiguous* spectral channels/bands with very high spectral resolution, while a multispectral image is collected by tens of *discrete* spectral channels/bands with low spectral resolution. If this interpretation is used, we run into a dilemma, "how many spectral channels/bands are enough for a remotely sensed image to be called a hyperspectral image?" or "how fine the spectral resolution should be for a remote sensing image to be considered as a hyperspectral image?" For example, if we take a small set of hyperspectral band images with spectral resolution 10 nm, say five spectral band images, to form a five-dimensional image cube, do we still consider this new-formed five-dimensional image cube as a hyperspectral image or simply a multispectral image? If we adopt the former definition based on the number of bands, this five-dimensional image cube should be viewed as a multispectral image. On the other hand, if we adopt the latter definition based on spectral resolution, the five-dimensional image cube should be considered as a hyperspectral image. Thus far, it seems that there is no general consensus on this issue. In Chapter 31, an attempt is made to address this issue from a viewpoint of how two versions of independent component analysis (ICA), over-complete ICA, and under-complete ICA can be used to resolve this long-debated issue in the context of linear spectral mixture analysis (LSMA). After all, some of these issues may never be settled or standardized for years to come. Many researchers can always argue differently at their discretion and provide their own versions of interpretation. I have no intention of disputing any of them, but rather respect their opinions.

Since processing hyperspectral signatures as one-dimensional signals and processing hyperspectral images as three-dimensional image cubes are rather different, this book makes a distinction by treating hyperspectral image processing and hyperspectral signal processing in two separate categories to avoid confusion. To this end, three categories are specifically outlined in this book: Category A: hyperspectral image processing; Category B: hyperspectral signal processing; and Category C: applications.

For better understanding, a set of six chapters is included in PART I as preliminaries that cover fundamentals and provide a basic background required for readers to follow algorithm design and development discussed in this book. Category A is made up of 15 chapters (Chapters 7–23) treated separately in four different parts, Part II to Part V. Category B consists of six chapters (Chapters 24–29) in two separate parts, Part VI and Part VII. Finally, applications make up Category C.

It is worth noting that many materials presented in this book have been only available after Chang (2003a). Theses include endmember extraction (Chapters 7–11), algorithm design using different levels of information (supervised linear hyperspectral mixture analysis in Chapters 12–15), pixel characterization and analysis (unsupervised hyperspectral analysis in Chapters 16–18), exploitation-based hyperspectral information compression (Chapters 19–23), hyperspectral signature coding and characterization (Chapters 24–29), and applications (Chapters 30–32) in Category C.

There are three unique features in this book that cannot be found in Chang (2003a): (1) Part I: preliminaries (Chapters 2–6); (2) extensive studies of synthetic image-based experiments for performance evaluation; and (3) an appendix on algorithm compendium that compiles recently developed signal processing algorithms developed in the RSSIPL, all of which are believed to be useful and beneficial to those who design and develop algorithms for hyperspectral signal/image processing. Because this book also addresses many issues that were not explored in Chang (2003a), it can be used in conjunction with Chang (2003a) without much overlap, where the latter provides necessary basic background in design and development of statistical signal processing algorithms for hyperspectral image analysis, especially for subpixel detection and mixed pixel classification. Therefore, on one end, those who have been involved in hyperspectral imaging and are familiar with hyperspectral imaging techniques will find this book useful as reference material. On the other end, those who are new will find this book a good and valuable guide on the topics that may interest them.

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As a final note, I would like to share that this book was supposed to be delivered by 2008. The most important factor that caused the delay is the urge to include the latest reports on hyperspectral data analysis. It is very difficult and challenging to keep a track of such new developments. Nevertheless, this book has grown three times larger than what I had originally proposed. Those who are interested in my forthcoming 2013 book can have a quick peek of these topics briefly discussed in Chapter 33, which includes a new development of target-characterized virtual dimensionality (VD), real-time and progressive processing of endmember extraction, unsupervised target detection, anomaly detection, as well as their field programmable gate array (FPGA) implementation.

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