国外电子信息精品著作（影印版）

光学遥感信号处理与开发技术

Optical Remote Sensing: Advances in Signal Processing and Exploitation Techniques

Saurabh Prasad
Lori M. Bruce
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内 容 简 介

本书介绍了当前最先进的算法，用来解决在分析光学遥感数据时遇到的问题，如预处理图像、储存和表示高维数据、模式分类、目标识别以及高位图像的可视化等。本书适合相关专业的高年级本科生及研究生阅读。

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By Saurabh Prasad, Lori M. Bruce and Jocelyn Chanussot

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《国外电子信息精品著作》序

20 世纪 90 年代以来，信息科学技术成为世界经济的中坚力量。随着经济全球化的进一步发展，以微电子、计算机、通信和网络技术为代表的信息技术，成为人类社会进步过程中发展最快、渗透性最强、应用面最广的关键技术。信息技术的发展带动了微电子、计算机、通信、网络、超导等产业的发展，促进了生命科学、新材料、能源、航空航天等高新技术产业的成长。信息产业的发展水平不仅是社会物质生产、文化进步的基本要素和必备条件，也是衡量一个国家的综合国力、国际竞争力和发展水平的重要标志。在中国，信息产业在国民经济发展中占有举足轻重的地位，成为国民经济重要支柱产业。然而，中国的信息科学支持技术发展的力度不够，信息技术还处于比较落后的水平，因此，快速发展信息科学技术成为我国迫在眉睫的大事。

要使我国的信息技术更好地发展起来，需要科学工作者和工程技术人员付出艰辛的努力。此外，我们要从客观上为科学工作者和工程技术人员创造更有利于发展的环境，加强对信息技术的支持与投资力度，其中也包括与信息技术相关的图书出版工作。

从出版的角度考虑，除了较好较快地出版具有自主知识产权的成果外，引进国外的优秀出版物是大有裨益的。洋为中用，将国外的优秀著作引进到国内，促进最新的科技成就迅速转化为我们自己的智力成果，无疑是值得高度重视的。科学出版社引进一批国外知名出版社的优秀著作，使我国从事信息技术的广大科学工作者和工程技术人员能以较低的价格购买，对于推动我国信息技术领域的科研与教学是十分有益的事。

此次科学出版社在广泛征求专家意见的基础上，经过反复论证、仔细遴选，共引进了接近 30 本外版书，大体上可以分为两类，第一类是基础理论著作，第二类是工程应用方面的著作。所有的著作都涉及信息领域的最新成果，大多数是 2005 年后出版的，力求" 层次高、内容新、参考性强"。在内容和形式上都体现

了科学出版社一贯奉行的严谨作风。

当然，这批书只能涵盖信息科学技术的一部分，所以这项工作还应该继续下去。对于一些读者面较广、观点新颖、国内缺乏的好书还应该翻译成中文出版，这有利于知识更好更快地传播。同时，我也希望广大读者提出好的建议，以改进和完善丛书的出版工作。

总之，我对科学出版社引进外版书这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

中国科学院院士
中国工程院院士
2006年12月

Preface

The evolution of optical remote sensing over the past few decades has enabled the availability of rich spatial, spectral and temporal information to remote sensing analysts. Although this has opened the doors to immense possibilities for analysis of optical remotely sensed imagery, it has also necessitated advancements in signal processing and exploitation algorithms to keep up with advances in the quality and quantity of available data. As an example, the transition from multispectral to hyperspectral imagery requires conventional statistical pattern classification algorithms to be modified to effectively extract useful information from the high dimensional hyperspectral feature space. Although hyperspectral imagery is expected to provide a much detailed spectral response per pixel, conventional algorithms developed and perfected for multispectral data would often be sub-optimal for hyperspectral data. At best, they would require a significant increase in the ground-truth (training) data employed for analysis—something that is often hard to come by, and is often far too costly. As a result, signal processing and pattern recognition algorithms for analysis of such data are also evolving to cope with such issues and result in practical applications.

The last decade has seen significant advances in algorithms that represent, visualize and analyze optical remotely sensed data. These advances include new algorithms to effectively compress high dimensional imagery data for efficient storage and transmission; new techniques to effectively visualize remotely sensed data; new analysis and classification techniques to analyze and classify remotely sensed imagery; and techniques to fuse remotely sensed imagery acquired simultaneously from different sensing modalities. This book brings together leading experts in these fields with the goal of bringing the cutting edge in signal processing and exploitation research closer to users and developers of remote sensing technology. This book is not intended to be a textbook for introductory remote sensing analysis. There are existing textbooks that provide a tutorial introduction to signal and image processing methods for remote sensing. This book is intended to be a valuable reference to graduate students and researchers in the academia and the industry who are interested in keeping abreast with the current state-of-the-art in signal and image processing techniques for optical remote sensing. This book consists of 15 chapters. Chapter 1 is an introductory chapter that sets the stage for the remainder of this book. In this chapter, we identify three key broad challenges and open problems associated with the analysis of modern optical remotely sensed imagery, and provide a motivation for each of the 14 chapters that follow within the context of these broad challenges. Chapters 2 through 6 present advances in algorithms for effective representation and visualization of high dimensional remotely sensed optical data, including on-board compressive sensing, coded aperture imaging and visualization techniques. Chapters 7 through 12 cover advances in statistical pattern classification and data analysis techniques, including multi-classifier systems and information fusion, morphological profiles, kernel methods, manifold learning and spectral pixel unmixing. Chapters 13 through 15 cover advances in multi-sensor data fusion techniques.

We would like to acknowledge and sincerely thank all contributors who participated in this collection. This book represents the state-of-the-art in signal and image processing research for optical remote sensing and would not have been possible if these contributors, who are leading experts in the field had not come together to work on these chapters. Their feedback and review of all chapters in this book was instrumental in making this a coherent and complete reference.

Mississippi State University, U.S.A., and
Grenoble Institute of Technology, France,
01-July-2010

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Introduction

Saurabh Prasad, Lori M. Bruce and Jocelyn Chanussot

As the name suggests, remote sensing entails the use of sensing instruments for acquiring information remotely about an area of interest on the ground. The term "information" can refer to a wide variety of observable quantities (signals), such as reflected solar radiation across the electromagnetic spectrum and emitted thermal radiation from the earth's surface as measured from handheld [1], airborne [2] or spaceborne imaging sensors [3, 4]; received back-scattered microwave radiation from radio detection and ranging (RADAR), synthetic aperture radar (SAR) [5–8] or light detection and ranging (LIDAR) [9–11] equipment; electrical conductivity as measured from airborne sensors, etc. Availability and effective exploitation of such data has facilitated advances in applied fields such as weather prediction, invasive species management, precision agriculture, urban planning, etc.

This book focuses on advances in signal processing and exploitation techniques for optical remote sensing. Optical remote sensing involves acquisition and analysis of optical data—electromagnetic radiation captured by the sensing modality after reflecting off an area of interest on ground (within the sensor's field of view). Optical remote sensing has come a long way—from gray-scale photogrammetric images to hyperspectral images. The advances in imaging hardware over recent decades have enabled availability of high spatial, spectral and temporal resolution imagery to the remote sensing analyst. These advances have created unique challenges for researchers in the remote sensing community working on algorithms for representation, exploitation and analysis of such data. This book is a collection of chapters representing current state-of-the-art algorithms aimed at overcoming these

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challenges for effective processing and exploitation of remotely sensed optical data. Undergraduate students and newcomers to remote sensing have access to several textbooks on remote sensing that provide a tutorial introduction to the various remote sensing modalities and analysis techniques (e.g., [12–14]). These books are excellent resources for undergraduate and entry-level graduate students. This book is intended for a reader who has some working experience with image processing techniques for remote sensing data and wants to keep abreast with current state-of-the-art algorithms for data processing and exploitation. In particular, we believe that this book will be beneficial to graduate students and researchers who are taking advanced courses in remote sensing, image processing, target recognition and statistical pattern classification. Researchers and professionals in academia and industry working in applied areas such as electrical engineering, civil and environmental engineering, hydrology, geology, etc., who work on developing or employing algorithms for remote sensing data will also find this book useful.

1 Optical Remote Sensing: The Processing Chain

Figure 1 illustrates the processing steps in a typical optical remote sensing analysis chain. In particular, most optical remote sensing systems employ the following flow

1. *Data acquisition and processing*: this involves acquiring data from the sensing modality—handheld sensors (for on-ground data), airborne or satellite imagery (for remotely sensed data). Processing of acquired data is often necessary for mitigating affects of noise and distortion in the acquisition process, such as noise attributed to an over-heated or an improperly calibrated sensor, atmospheric distortion, luminance biases, poor contrast, etc.
2. *Data representation*: this process refers to representing data efficiently for storage, transmission or analysis. Often, optical remote sensing datasets also need to be represented efficiently due to storage and transmission limitations. Further, for effective analysis with such data (for example, for an analysis task based on statistical pattern recognition), it often becomes necessary to represent the data in a "feature" space that is amenable to the analysis task. Such a representation could be based on extracting relevant spatial statistics (e.g., texture information to exploit vicinal-pixel relationships), and spectral responses (to accurately model individual pixels and sub-pixels) from the optical imagery.
3. *Data analysis*: this process involves exploiting the data for answering the underlying remote sensing question (such as "What is the soil moisture distribution of an area", or "What is the land-cover composition of an area", or "Where are strong concentrations of invasive vegetation species for effective control") Depending upon the problem, an appropriate analysis methodology

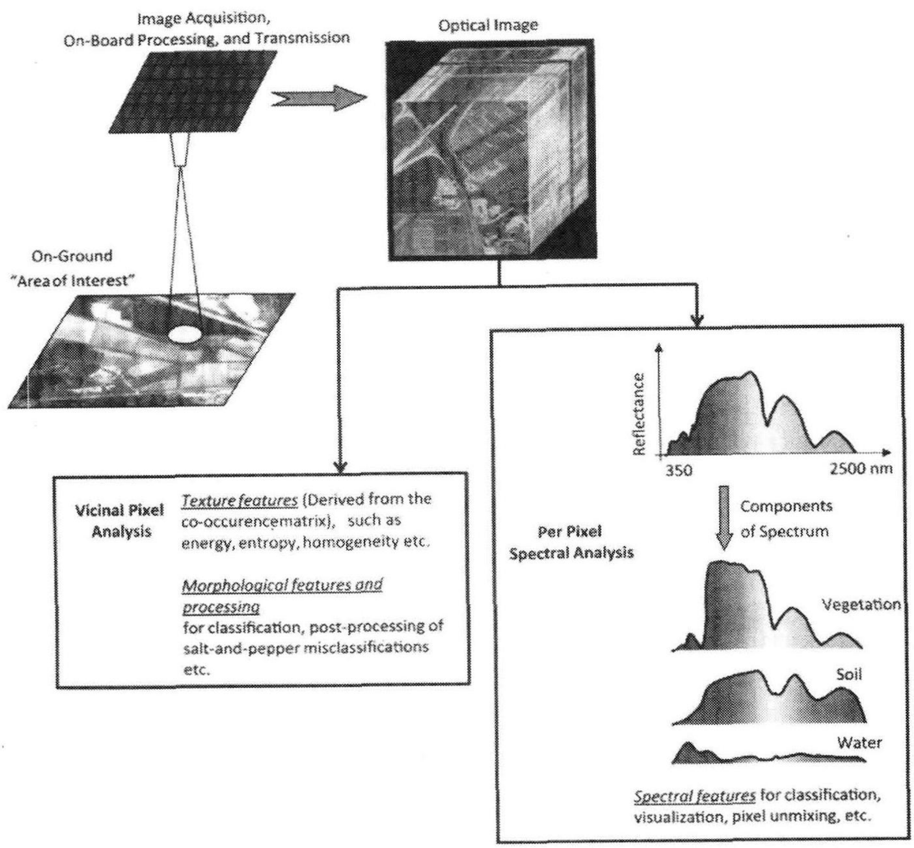

Fig. 1 Typical flow of optical remote sensing systems

(such as statistical pattern recognition, regression analysis, unsupervised clustering, image segmentation) is invoked.

This flow results in answers to the posed remote sensing questions for a particular optical imagery. These are then interpreted for appropriate action by end-users such as scientists, government agencies, policy makers, etc.

There are three key types of optical sensing modalities: (1) handheld, (2) airborne (aerial), and, (3) spaceborne (on board a satellite). In most practical applications, spaceborne or aerial imagery is employed for analysis [2, 4, 15–18]. Trade-offs exist between spaceborne and airborne imagery, and the decision on which modality to employ for a particular application is made based on weighing in the advantages and disadvantages of each. Trade-offs include spatial and spectral resolution, ability to acquire imagery on demand, etc. versus cost, wider coverage area, repeatability, etc. Data acquired from handheld sensors is typically employed for "ground-truthing", that is, for accurately capturing spectral responses and spatial coordinates of various "classes" (objects of interest on ground), for effective training and validation of classification systems.

This book focuses on cutting-edge signal processing and exploitation techniques for addressing challenges in steps 2 and 3 of the flow outlined above. Some good references for a tutorial overview of various sensing modalities, sensor specifications, design principles, benefits and limitations of various sensors include [12–15, 19]. Kerekes et al. [20] provide an advanced overview of cutting-edge optical imaging systems, including the physics of image generation and sensing technologies, sources of noise and distortion and their impact on exploitation algorithms. Richards et al. [14] describe in detail the processing techniques employed for correcting errors due to atmospheric affects, geometric distortion, radiometric distortion, and related techniques that are carried out post-acquisition, such as georeferencing, geocoding, image registration, geometric enhancement, radiometric enhancement, etc. Examples of good tutorial introductions covering basics of image analysis and signal processing techniques for hyperspectral remotely sensed data include Landgrebe [21] and Shaw and Manolakis [22].

2 Optical Remote Sensing: Key Challenges for Signal Processing and Effective Exploitation

Early optical remote sensing systems relied on multispectral sensors, which are characterized by a small number of wide spectral bands [12, 13, 15]. Although multispectral sensors are still employed by analysts, in recent years, the remote sensing community has seen a steady shift to hyperspectral sensors, which are characterized by hundreds of fine resolution co-registered spectral bands, as the dominant technology for various tasks such as land-cover classification, environmental and ecological monitoring, etc. [2, 4, 15–17, 19–26]. Such data has the potential to reveal the underlying phenomenology as described by spectral characteristics accurately. For example, in the case of vegetation, such imagery can reveal foliar biophysical and biochemical properties, including the spectral responses at distinct wavelengths corresponding to leaf pigments, cell structure, water content, etc. [19]. This "extension" from multispectral to hyperspectral imaging does not imply that the signal processing and exploitation techniques (such as data compression, visualization and statistical pattern classification) can be simply scaled up to accommodate the extra dimensions in the data. New techniques are being developed that exploit the rich information provided by modern optical sensing modalities. In light of the above discussion, this book addresses the following key challenges:

1. *Challenges in representation and visualization of high dimensional data*: high dimensional optical data, such as hyperspectral data, is traditionally acquired in full dimensionality before being reduced in dimension prior to any processing or analysis. Hence, dataset sizes are becoming ever more voluminous, with both

spectral as well as spatial resolutions continuing to increase, resulting in extremely large quantities of data acquired in typical geospatial sensing systems, with multi-temporal data exacerbating this issue. Ramifications of this issue include: (a) it can burden transmission and storage systems, and (b) displaying the abundant information contained in this high dimensional space for effective visualization becomes challenging.

Chapters 2 through 6 will present advances in representation and visualization techniques for such datasets, including on-board compressive sensing, coded aperture imaging and visualization techniques. In Chap. 2, Christophe presents an overview of conventional and recently developed methods for compression of hyperspectral data. In Chap. 3, Fowler et al. present a review of compressive random projections for compression of hyperspectral imagery—an approach that facilitates the integration of these random projections directly into signal acquisition without incurring a significant sender side computational cost as compared to explicit dimensionality reduction. In Chap. 4, Muise et al. present an integrated sensing and processing system for hyperspectral imagery. The proposed information sensing system integrates sensing and processing, resulting in direct acquisition of data relevant to the application. In Chap. 5, Gupta et al. review various color science issues that arise in the display and representation of artificially colored remote sensing images, and analyze the current state-of-the-art solutions to these challenges. In Chap. 6, Cai et al. review several layered approaches for effective visualization of hyperspectral data. The authors propose a feature-driven multi-layer visualization technique that automatically chooses data visualization techniques based on the spatial distribution and importance of various endmembers.

2. *Challenges in statistical pattern classification and target recognition*: most image analysis techniques for exploiting optical imagery involve statistical pattern recognition or target recognition based approaches. For such analysis methods, the high dimensionality of hyperspectral data is often a double edge sword—the dense spectral sampling per pixel often provides information that can be potentially useful for target recognition and finely resolved land cover classification. This high dimensional feature space often also results in reduced generalization and statistical ill-conditioning. In many practical situations, limited training datasets for modeling class statistics further exacerbates the ill-conditioning problem.

   Another issue commonly encountered when working with optical imagery is that of "mixed" pixels. Traditionally, spatial resolution is often compromised in high spectral resolution imagers. Further, in many situations, relevant features of interest may exist at sub-pixel levels. In other words, the imagery could have "mixed" pixels, representing a spectral response from a mixture of multiple objects. Hence, each pixel in such an image is typically a mixture of multiple classes/objects. However, the dense spectral sampling of hyperspectral data can help in "unmixing" (identifying the relative abundances of each class per pixel) such mixed pixels. Other issues that make this problem more challenging include affects of variations in atmospheric conditions [27], contrast and luminance variations and general variability in the spectral characteristics of the objects on ground (depending upon their interaction with their environment). Algorithms designed for the analysis of such datasets must address these issues.

Chapters 7 through 12 cover advances in statistical pattern classification and data analysis techniques, including multi-classifier systems and information fusion, morphological profiles, kernel methods, manifold learning and spectral pixel unmixing. In Chap. 7, Prasad et al. present a divide-and-conquer approach for statistical pattern classification of high dimensional hyperspectral data. In the proposed approach, a high dimensional classification task is partitioned into many independent smaller dimensional classification tasks, and a decision fusion technique is employed to merge results from this partition. In Chap. 8, Chanussot et al. study the benefits of morphological profile as a tool for analysis of remote sensing data. The chapter reviews this method based on principles of mathematical morphology and granulometry and addresses the key issues when employing this technique for multispectral and hyperspectral data. In Chap. 9, Bakos et al. present a multiple classifier, decision fusion technique for vegetation mapping and monitoring applications. The authors demonstrate the benefits of a classifier ensemble approach for vegetation mapping when employing spatial and spectral information derived from hyperspectral imagery. In Chap. 10, Camps-Valls et al. present a detailed review of applications and recent theoretical developments of kernel methods for remote sensing data analysis. In Chap. 11, Crawford et al. demonstrate the benefits of nonlinear manifold learning for dimensionality reduction and classification of hyperspectral data. In Chap. 12, Plaza et al. present a review of advances in spectral pixel unmixing and endmember extraction techniques (methods that estimate the relative abundances of various classes/endmemebers for each pixel in a mixed-pixel scenario). The chapter reviews both linear and nonlinear pixel unmixing techniques, as well as benefits of incorporating spatial information for pixel unmixing tasks

3. *Challenges in fusing multi-sensor data:* it is now possible to acquire imagery from different sensing modalities and platforms simultaneously (or nearly simultaneously) over the region of interest on ground. This implies potential availability of multiple types of optical data (e.g., high spatial resolution gray-level or multispectral imagery and high spectral resolution hyperspectral imagery), or multiple types of passive and active remotely sensed data (e.g., optical imagery and SAR or LIDAR imagery). Such multi-source data can potentially play a complimentary role—for example, (1) high spatial resolution optical imagery can provide useful vicinal-pixel and texture information, while high spectral resolution imagery can reveal valuable sub-pixel spectral characteristics, (2) optical imagery can potentially capture and help characterize surface phenomena (such as reflectance characteristics over the electromagnetic

spectrum per pixel, texture characteristics between neighboring pixels, etc.), while a ground-penetrating SAR imagery can reveal sub-surface characteristics, such as soil moisture, etc. There is hence a potential to improve analysis techniques by exploiting the diversity of information available with such multi-sensor data. In this book, we consider the following possible multi-source scenarios—optical imagery acquired from different sensors with different specifications (e.g., different spectral and spatial characteristics), or acquired from the same sensor at different times (e.g., multi-temporal imagery for change detection tasks), or a combination of optical and active remotely sensed imagery (e.g., optical and SAR imagery).

Chapters 13 through 15 cover advances in multi-sensor data fusion techniques. In Chap. 13, Bruzzone et al. study and present techniques to minimize affects of registration noise between images acquired over the same geographic area at different times on the change detection performance. Fusion of hyperspectral imagery with panchromatic or multispectral imagery for enhancing the spatial resolution of hyperspectral imagery is commonly employed by remote sensing analysts. In Chap. 14, Garzelli et al. study the effects of such spatial enhancement of hyperspectral imagery on spectral distributions. In Chap. 15, Dell'Acqua et al. demonstrate the benefits of fusion of optical and SAR data for a practical remote sensing task—seismic vulnerability mapping of buildings.

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