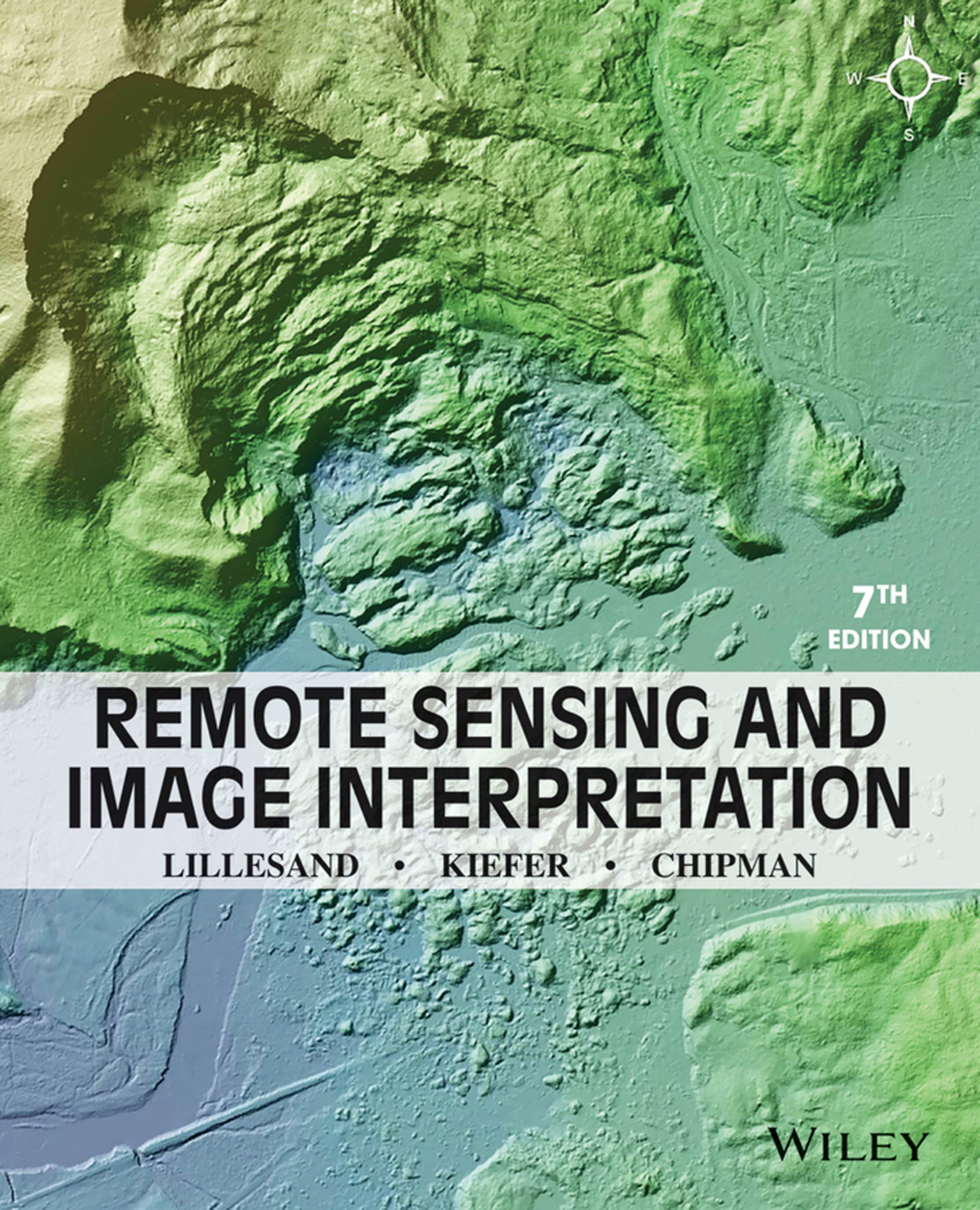

7TH EDITION

REMOTE SENSING AND IMAGE INTERPRETATION

LILLESAND • KIEFER • CHIPMAN

WILEY

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Seventh Edition

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This book was set in 10/12 New Aster by Laserwords and printed and bound by Courier Westford.

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Library of Congress Cataloging-in-Publication Data

Lillesand, Thomas M.
Remote sensing and image interpretation / Thomas M. Lillesand, Ralph W. Kiefer,
Jonathan W. Chipman. — Seventh edition.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-34328-9 (paperback)
1. Remote sensing. I. Kiefer, Ralph W. II. Chipman, Jonathan W. III. Title.
G70.4.L54 2015
621.36'78—dc23
2014046641

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

PREFACE

This book is designed to be primarily used in two ways: as a textbook in introductory courses in remote sensing and image interpretation and as a reference for the burgeoning number of practitioners who use geospatial information and analysis in their work. Rapid advances in computational power and sensor design are allowing remote sensing and its kindred technologies, such as geographic information systems (GIS) and the Global Positioning System (GPS), to play an increasingly important role in science, engineering, resource management, commerce, and other fields of human endeavor. Because of the wide range of academic and professional settings in which this book might be used, we have made this discussion "discipline neutral." That is, rather than writing a book heavily oriented toward a single field such as business, ecology, engineering, forestry, geography, geology, urban and regional planning, or water resource management, we approach the subject in such a manner that students and practitioners in any discipline should gain a clear understanding of remote sensing systems and their virtually unlimited applications. In short, anyone involved in geospatial data acquisition and analysis should find this book to be a valuable text and reference.

The world has changed dramatically since the first edition of this book was published, nearly four decades ago. Students may read this new edition in an ebook format on a tablet or laptop computer whose processing power and user interface are beyond the dreams of the scientists and engineers who pioneered the use of computers in remote sensing and image interpretation in the 1960s and early 1970s. The book's readers have diversified as the field of remote sensing has become a truly international activity, with countries in Asia, Africa, and Latin America contributing at all levels from training new remote sensing analysts, to using geospatial technology in managing their natural resources, to launching and operating new earth observation satellites. At the same time, the proliferation of high-resolution image-based visualization platforms—from Google Earth to Microsoft's Bing Maps—is in a sense turning everyone with access to the Internet into an "armchair remote-sensing aficionado." Acquiring the expertise to produce informed, reliable *interpretations* of all this newly available imagery, however, takes time and effort. To paraphrase the words attributed to Euclid, there is no royal road to image analysis—developing these skills still requires a solid grounding in the principles of electromagnetic radiation, sensor design, digital image processing, and applications.

This edition of the book strongly emphasizes digital image acquisition and analysis, while retaining basic information about earlier analog sensors and methods (from which a vast amount of archival data exist, increasingly valuable as a source for studies of long-term change). We have expanded our coverage of lidar systems and of 3D remote sensing more generally, including digital photogrammetric methods such as structure-from-motion (SFM). In keeping with the changes sweeping the field today, images acquired from uninhabited aerial system (UAS) platforms are now included among the figures and color plates, along with images from many of the new optical and radar satellites that have been launched since the previous edition was published. On the image analysis side, the continuing improvement in computational power has led to an increased emphasis on techniques that take advantage of high-volume data sets, such as those dealing with neural network classification, object-based image analysis, change detection, and image time-series analysis.

While adding in new material (including many new images and color plates) and updating our coverage of topics from previous editions, we have also made some improvements to the organization of the book. Most notably, what was formerly Chapter 4—on visual image interpretation—has been split. The first sections, dealing with methods for visual image interpretation, have been brought into Chapter 1, in recognition of the importance of visual interpretation throughout the book (and the field). The remainder of the former Chapter 4 has been moved to the end of the book and expanded into a new, broader review of applications of remote sensing not limited to visual methods alone. In addition, our coverage of radar and lidar systems has been moved ahead of the chapters on digital image analysis methods and applications of remote sensing.

Despite these changes, we have also endeavored to retain the traditional strengths of this book, which date back to the very first edition. As noted above, the book is deliberately "discipline neutral" and can serve as an introduction to the principles, methods, and applications of remote sensing across many different subject areas. There is enough material in this book for it to be used in many different ways. Some courses may omit certain chapters and use the book in a one-semester or one-quarter course; the book may also be used in a two-course sequence. Others may use this discussion in a series of modular courses, or in a shortcourse/workshop format. Beyond the classroom, the remote sensing practitioner will find this book an enduring reference guide—technology changes constantly, but the fundamental principles of remote sensing remain the same. We have designed the book with these different potential uses in mind.

As always, this edition stands upon the shoulders of those that preceded it. Many individuals contributed to the first six editions of this book, and we thank them again, collectively, for their generosity in sharing their time and expertise. In addition, we would like to acknowledge the efforts of all the expert reviewers who have helped guide changes in this edition and previous editions. We thank the reviewers for their comments and suggestions.

Illustration materials for this edition were provided by: Dr. Sam Batzli, USGS WisconsinView program, University of Wisconsin—Madison Space Science and Engineering Center; Ruediger Wagner, Vice President of Imaging, Geospatial Solutions Division and Jennifer Bumford, Marketing and Communications, Leica Geosystems; Philipp Grimm, Marketing and Sales Manager, ILI GmbH; Jan Schoderer, Sales Director UltraCam Business Unit and Alexander Wiechert, Business Director, Microsoft Photogrammetry; Roz Brown, Media Relations Manager, Ball Aerospace; Rick Holasek, NovaSol; Stephen Lich and Jason Howse, ITRES, Inc.; Qinghua Guo and Jacob Flanagan, UC-Merced; Dr. Thomas Morrison, Wake Forest University; Dr. Andrea Laliberte, Earthmetrics, Inc.; Dr. Christoph Borel-Donohue, Research Associate Professor of Engineering Physics, U.S. Air Force Institute of Technology; Elsevier Limited, the German Aerospace Center (DLR), Airbus Defence & Space, the Canadian Space Agency, Leica Geosystems, and the U.S. Library of Congress. Dr. Douglas Bolger, Dartmouth College, and Dr. Julian Fennessy, Giraffe Conservation Foundation, generously contributed to the discussion of wildlife monitoring in Chapter 8, including the giraffe telemetry data used in Figure 8.24. Our particular thanks go to those who kindly shared imagery and information about the Oso landslide in Washington State, including images that ultimately appeared in a figure, a color plate, and the front and back covers of this book; these sources include Rochelle Higgins and Susan Jackson at Quantum Spatial, Scott Campbell at the Washington State Department of Transportation, and Dr. Ralph Haugerud of the U.S. Geological Survey.

Numerous suggestions relative to the photogrammetric material contained in this edition were provided by Thomas Asbeck, CP, PE, PLS; Dr. Terry Keating, CP, PE, PLS; and Michael Renslow, CP, RPP.

We also thank the many faculty, academic staff, and graduate and undergraduate students at Dartmouth College and the University of Wisconsin—Madison who made valuable contributions to this edition, both directly and indirectly.

Special recognition is due our families for their patient understanding and encouragement while this edition was in preparation.

Finally, we want to encourage you, the reader, to use the knowledge of remote sensing that you might gain from this book to literally make the world a better place. Remote sensing technology has proven to provide numerous scientific, commercial, and social benefits. Among these is not only the efficiency it brings to the day-to-day decision-making process in an ever-increasing range of applications, but also the potential this field holds for improving the stewardship of earth's resources and the global environment. This book is intended to provide a technical foundation for you to aid in making this tremendous potential a reality.

Thomas M. Lillesand
Ralph W. Kiefer
Jonathan W. Chipman

This book is dedicated to the peaceful application of remote sensing in order to maximize the scientific, social, and commercial benefits of this technology for all humankind.

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Appendices—Available online at www.wiley.com/college/lillesand

1

CONCEPTS AND FOUNDATIONS OF REMOTE SENSING

1.1 INTRODUCTION

Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation. As you read these words, you are employing remote sensing. Your eyes are acting as sensors that respond to the light reflected from this page. The "data" your eyes acquire are impulses corresponding to the amount of light reflected from the dark and light areas on the page. These data are analyzed, or interpreted, in your mental computer to enable you to explain the dark areas on the page as a collection of letters forming words. Beyond this, you recognize that the words form sentences, and you interpret the information that the sentences convey.

In many respects, remote sensing can be thought of as a reading process. Using various sensors, we remotely collect *data* that may be analyzed to obtain *information* about the objects, areas, or phenomena being investigated. The remotely collected data can be of many forms, including variations in force distributions, acoustic wave distributions, or electromagnetic energy distributions. For example, a gravity meter acquires data on variations in the distribution of the force of gravity. Sonar, like a bat's navigation system, obtains data on variations in acoustic wave distributions. Our eyes acquire data on variations in electromagnetic energy distributions.

Overview of the Electromagnetic Remote Sensing Process

This book is about *electromagnetic* energy sensors that are operated from airborne and spaceborne platforms to assist in inventorying, mapping, and monitoring earth resources. These sensors acquire data on the way various earth surface features emit and reflect electromagnetic energy, and these data are analyzed to provide information about the resources under investigation.

Figure 1.1 schematically illustrates the generalized processes and elements involved in electromagnetic remote sensing of earth resources. The two basic processes involved are *data acquisition* and *data analysis*. The elements of the data acquisition process are energy sources (*a*), propagation of energy through the atmosphere (*b*), energy interactions with earth surface features (*c*), retransmission of energy through the atmosphere (*d*), airborne and/or spaceborne sensors (*e*), resulting in the generation of sensor data in pictorial and/or digital form (*f*). In short, we use sensors to record variations in the way earth surface features reflect and emit electromagnetic energy. The data analysis process (*g*) involves examining the data using various viewing and interpretation devices to analyze pictorial data and/or a computer to analyze digital sensor data. Reference data about the resources being studied (such as soil maps, crop statistics, or field-check data) are used

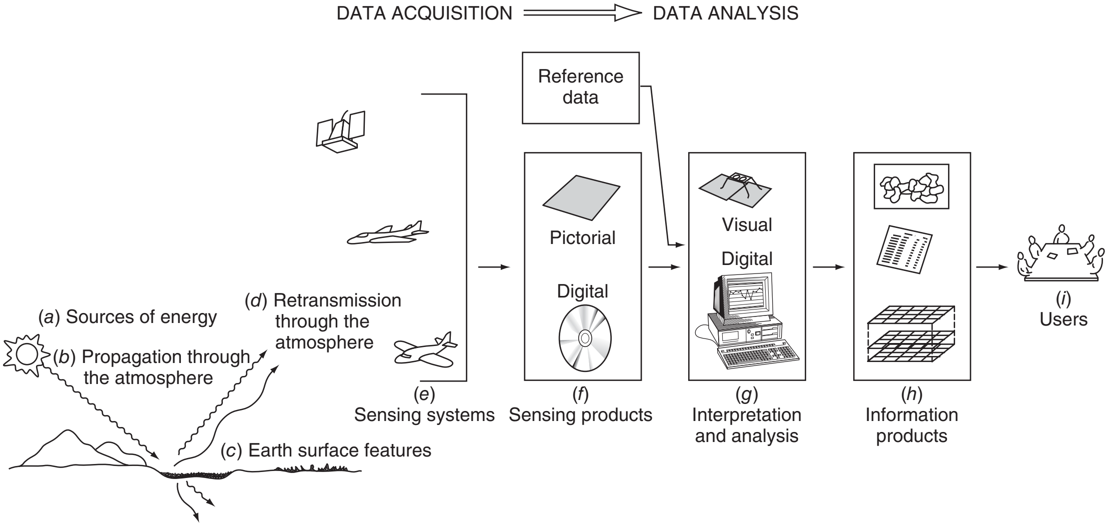

Figure 1.1 Electromagnetic remote sensing of earth resources.

when and where available to assist in the data analysis. With the aid of the reference data, the analyst extracts information about the type, extent, location, and condition of the various resources over which the sensor data were collected. This information is then compiled (*h*), generally in the form of maps, tables, or digital spatial data that can be merged with other "layers" of information in a *geographic information system* (*GIS*). Finally, the information is presented to users (*i*), who apply it to their decision-making process.

Organization of the Book

In the remainder of this chapter, we discuss the basic principles underlying the remote sensing process. We begin with the fundamentals of electromagnetic energy and then consider how the energy interacts with the atmosphere and with earth surface features. Next, we summarize the process of acquiring remotely sensed data and introduce the concepts underlying digital imagery formats. We also discuss the role that reference data play in the data analysis procedure and describe how the spatial location of reference data observed in the field is often determined using *Global Positioning System* (*GPS*) methods. These basics will permit us to conceptualize the strengths and limitations of "real" remote sensing systems and to examine the ways in which they depart from an "ideal" remote sensing system. We then discuss briefly the rudiments of GIS technology and the spatial frameworks (coordinate systems and datums) used to represent the positions of geographic features in space. Because visual examination of imagery will play an important role in every subsequent chapter of this book, this first chapter concludes with an overview of the concepts and processes involved in visual interpretation of remotely sensed images. By the end of this chapter, the reader should have a grasp of the foundations of remote sensing and an appreciation for the close relationship among remote sensing, GPS methods, and GIS operations.

Chapters 2 and 3 deal primarily with photographic remote sensing. Chapter 2 describes the basic tools used in acquiring aerial photographs, including both analog and digital camera systems. Digital videography is also treated in Chapter 2. Chapter 3 describes the photogrammetric procedures by which precise spatial measurements, maps, digital elevation models (DEMs), orthophotos, and other derived products are made from airphotos.

Discussion of nonphotographic systems begins in Chapter 4, which describes the acquisition of airborne multispectral, thermal, and hyperspectral data. In Chapter 5 we discuss the characteristics of spaceborne remote sensing systems and examine the principal satellite systems used to collect imagery from reflected and emitted radiance on a global basis. These satellite systems range from the Landsat and SPOT series of moderate-resolution instruments, to the latest generation of high-resolution commercially operated systems, to various meteorological and global monitoring systems.

Chapter 6 is concerned with the collection and analysis of radar and lidar data. Both airborne and spaceborne systems are discussed. Included in this latter category are such systems as the ALOS, Envisat, ERS, JERS, Radarsat, and ICESat satellite systems.

In essence, from Chapter 2 through Chapter 6, this book progresses from the simplest sensing systems to the more complex. There is also a progression from short to long wavelengths along the electromagnetic spectrum (see Section 1.2). That is, discussion centers on photography in the ultraviolet, visible, and near-infrared regions, multispectral sensing (including thermal sensing using emitted long-wavelength infrared radiation), and radar sensing in the microwave region.

The final two chapters of the book deal with the manipulation, interpretation, and analysis of images. Chapter 7 treats the subject of digital image processing and describes the most commonly employed procedures through which computer-assisted image interpretation is accomplished. Chapter 8 presents a broad range of applications of remote sensing, including both visual interpretation and computer-aided analysis of image data.

Throughout this book, the International System of Units (SI) is used. Tables are included to assist the reader in converting between SI and units of other measurement systems.

Finally, a Works Cited section provides a list of references cited in the text. It is not intended to be a compendium of general sources of additional information. Three appendices provided on the publisher's website (http://www.wiley.com/college/lillesand) offer further information about particular topics at a level of detail beyond what could be included in the text itself. Appendix A summarizes the various concepts, terms, and units commonly used in radiation measurement in remote sensing. Appendix B includes sample coordinate transformation and resampling procedures used in digital image processing. Appendix C discusses some of the concepts, terminology, and units used to describe radar signals.

1.2 ENERGY SOURCES AND RADIATION PRINCIPLES

Visible light is only one of many forms of electromagnetic energy. Radio waves, ultraviolet rays, radiant heat, and X-rays are other familiar forms. All this energy is inherently similar and propagates in accordance with basic wave theory. As shown in Figure 1.2, this theory describes electromagnetic energy as traveling in a harmonic, sinusoidal fashion at the "velocity of light" c. The distance from one wave peak to the next is the *wavelength* λ, and the number of peaks passing a fixed point in space per unit time is the wave *frequency* v.

From basic physics, waves obey the general equation

$$c = v\lambda \tag{1.1}$$

Because c is essentially a constant $\left(3 \times 10^{8}\,\text{m/sec}\right)$, frequency v and wavelength λ for any given wave are related inversely, and either term can be used to

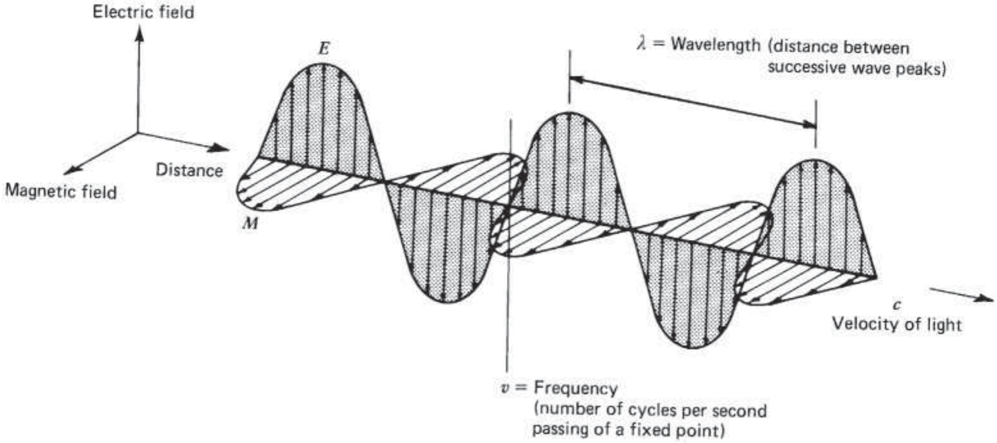

Figure 1.2 Electromagnetic wave. Components include a sinusoidal electric wave (E) and a similar magnetic wave (M) at right angles, both being perpendicular to the direction of propagation.

characterize a wave. In remote sensing, it is most common to categorize electromagnetic waves by their wavelength location within the *electromagnetic spectrum* (Figure 1.3). The most prevalent unit used to measure wavelength along the spectrum is the *micrometer* (μm). A micrometer equals 1×10^{-6} m.

Although names (such as "ultraviolet" and "microwave") are generally assigned to regions of the electromagnetic spectrum for convenience, there is no clear-cut dividing line between one nominal spectral region and the next. Divisions of the spectrum have grown from the various methods for sensing each type of radiation more so than from inherent differences in the energy characteristics of various wavelengths. Also, it should be noted that the portions of the

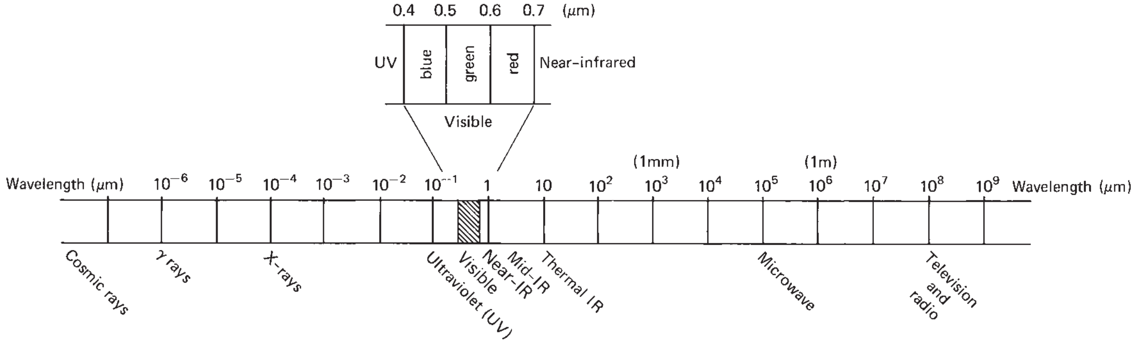

Figure 1.3 Electromagnetic spectrum.

electromagnetic spectrum used in remote sensing lie along a continuum characterized by magnitude changes of many powers of 10. Hence, the use of logarithmic plots to depict the electromagnetic spectrum is quite common. The "visible" portion of such a plot is an extremely small one, because the spectral sensitivity of the human eye extends only from about 0.4 μm to approximately 0.7 μm. The color "blue" is ascribed to the approximate range of 0.4 to 0.5 μm, "green" to 0.5 to 0.6 μm, and "red" to 0.6 to 0.7 μm. *Ultraviolet* (*UV*) energy adjoins the blue end of the visible portion of the spectrum. Beyond the red end of the visible region are three different categories of *infrared* (*IR*) waves: *near IR* (from 0.7 to 1.3 μm), *mid IR* (from 1.3 to 3 μm; also referred to as *shortwave IR* or *SWIR*), and *thermal IR* (beyond 3 to 14 μm, sometimes referred to as *longwave IR*). At much longer wavelengths (1 mm to 1 m) is the *microwave* portion of the spectrum.

Most common sensing systems operate in one or several of the visible, IR, or microwave portions of the spectrum. *Within the IR portion of the spectrum, it should be noted that only thermal-IR energy is directly related to the sensation of heat; near- and mid-IR energy are not*.

Although many characteristics of electromagnetic radiation are most easily described by wave theory, another theory offers useful insights into how electromagnetic energy interacts with matter. This theory—the particle theory—suggests that electromagnetic radiation is composed of many discrete units called *photons* or *quanta*. The energy of a quantum is given as

$$Q = hv \tag{1.2}$$

where

Q = energy of a quantum, joules (J)
h = Planck's constant, 6.626×10^{-34} J sec
v = frequency

We can relate the wave and quantum models of electromagnetic radiation behavior by solving Eq. 1.1 for v and substituting into Eq. 1.2 to obtain

$$Q = \frac{hc}{\lambda} \tag{1.3}$$

Thus, we see that the energy of a quantum is inversely proportional to its wavelength. *The longer the wavelength involved, the lower its energy content*. This has important implications in remote sensing from the standpoint that naturally emitted long wavelength radiation, such as microwave emission from terrain features, is more difficult to sense than radiation of shorter wavelengths, such as emitted thermal IR energy. The low energy content of long wavelength radiation means that, in general, systems operating at long wavelengths must "view" large areas of the earth at any given time in order to obtain a detectable energy signal.

The sun is the most obvious source of electromagnetic radiation for remote sensing. However, *all* matter at temperatures above absolute zero (0 K, or −273°C) continuously emits electromagnetic radiation. Thus, terrestrial objects are also sources of radiation, although it is of considerably different magnitude and spectral composition than that of the sun. How much energy any object radiates is, among other things, a function of the surface temperature of the object. This property is expressed by the *Stefan–Boltzmann law*, which states that

$$M = \sigma T^4 \tag{1.4}$$

where

M = total radiant exitance from the surface of a material, watts (W) m^{-2}
σ = *Stefan–Boltzmann constant*, $5.6697 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
T = absolute temperature (K) of the emitting material

The particular units and the value of the constant are not critical for the student to remember, yet it is important to note that the total energy emitted from an object varies as T^4 and therefore increases very rapidly with increases in temperature. Also, it should be noted that this law is expressed for an energy source that behaves as a *blackbody*. A blackbody is a hypothetical, ideal radiator that totally absorbs and reemits all energy incident upon it. Actual objects only approach this ideal. We further explore the implications of this fact in Chapter 4; suffice it to say for now that the energy emitted from an object is primarily a function of its temperature, as given by Eq. 1.4.

Just as the total energy emitted by an object varies with temperature, the spectral distribution of the emitted energy also varies. Figure 1.4 shows energy distribution curves for blackbodies at temperatures ranging from 200 to 6000 K. The units on the ordinate scale $(\mathrm{W\,m^{-2}}\mu\mathrm{m}^{-1})$ express the radiant power coming from a blackbody per 1-μm spectral interval. Hence, the *area* under these curves equals the total radiant exitance, M, and the curves illustrate graphically what the Stefan–Boltzmann law expresses mathematically: The higher the temperature of the radiator, the greater the total amount of radiation it emits. The curves also show that there is a shift toward shorter wavelengths in the peak of a blackbody radiation distribution as temperature increases. The *dominant wavelength*, or wavelength at which a blackbody radiation curve reaches a maximum, is related to its temperature by *Wien's displacement law*,

$$\lambda_m = \frac{A}{T} \tag{1.5}$$

where

λ_m = wavelength of maximum spectral radiant exitance, μm
A = $2898\ \mu\mathrm{m\,K}$
T = temperature, K

Thus, for a blackbody, the wavelength at which the maximum spectral radiant exitance occurs varies inversely with the blackbody's absolute temperature. We observe this phenomenon when a metal body such as a piece of iron is heated. As the object becomes progressively hotter, it begins to glow and its color

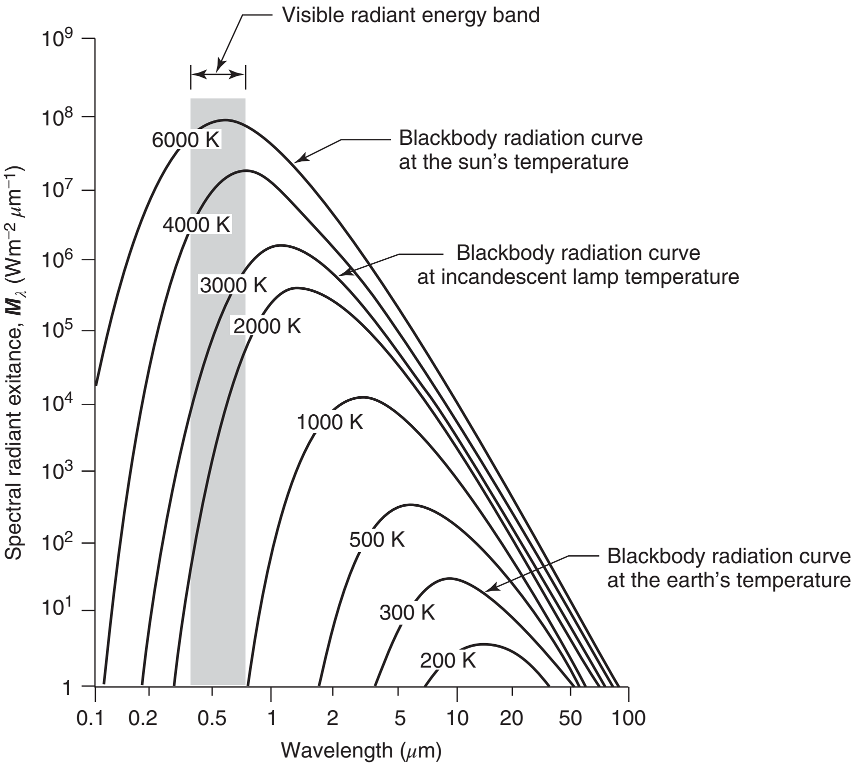

Figure 1.4 Spectral distribution of energy radiated from blackbodies of various temperatures. (Note that spectral radiant exitance M_λ is the energy emitted per unit wavelength interval. Total radiant exitance M is given by the area under the spectral radiant exitance curves.)

changes successively to shorter wavelengths—from dull red to orange to yellow and eventually to white.

The sun emits radiation in the same manner as a blackbody radiator whose temperature is about 6000 K (Figure 1.4). Many incandescent lamps emit radiation typified by a 3000 K blackbody radiation curve. Consequently, incandescent lamps have a relatively low output of blue energy, and they do not have the same spectral constituency as sunlight.

The earth's ambient temperature (i.e., the temperature of surface materials such as soil, water, and vegetation) is about 300 K (27°C). From Wien's displacement law, this means the maximum spectral radiant exitance from earth features occurs at a wavelength of about 9.7 μm. Because this radiation correlates with terrestrial heat, it is termed "thermal infrared" energy. This energy can neither be seen nor photographed, but it can be sensed with such thermal devices as radiometers and scanners (described in Chapter 4). By comparison, the sun has a much higher energy peak that occurs at about 0.5 μm, as indicated in Figure 1.4.

Our eyes—and photographic sensors—are sensitive to energy of this magnitude and wavelength. Thus, when the sun is present, we can observe earth features by virtue of *reflected* solar energy. Once again, the longer wavelength energy *emitted* by ambient earth features can be observed only with a nonphotographic sensing system. The general dividing line between reflected and emitted IR wavelengths is approximately 3 μm. Below this wavelength, reflected energy predominates; above it, emitted energy prevails.

Certain sensors, such as radar systems, supply their own source of energy to illuminate features of interest. These systems are termed "active" systems, in contrast to "passive" systems that sense naturally available energy. A very common example of an active system is a camera utilizing a flash. The same camera used in sunlight becomes a passive sensor.

1.3 ENERGY INTERACTIONS IN THE ATMOSPHERE

Irrespective of its source, all radiation detected by remote sensors passes through some distance, or *path length*, of atmosphere. The path length involved can vary widely. For example, space photography results from sunlight that passes through the full thickness of the earth's atmosphere twice on its journey from source to sensor. On the other hand, an airborne thermal sensor detects energy emitted directly from objects on the earth, so a single, relatively short atmospheric path length is involved. The net effect of the atmosphere varies with these differences in path length and also varies with the magnitude of the energy signal being sensed, the atmospheric conditions present, and the wavelengths involved.

Because of the varied nature of atmospheric effects, we treat this subject on a sensor-by-sensor basis in other chapters. Here, we merely wish to introduce the notion that the atmosphere can have a profound effect on, among other things, the intensity and spectral composition of radiation available to any sensing system. These effects are caused principally through the mechanisms of atmospheric *scattering* and *absorption*.

Scattering

Atmospheric scattering is the unpredictable diffusion of radiation by particles in the atmosphere. *Rayleigh scatter* is common when radiation interacts with atmospheric molecules and other tiny particles that are much smaller in diameter than the wavelength of the interacting radiation. The effect of Rayleigh scatter is inversely proportional to the fourth power of wavelength. Hence, there is a much stronger tendency for short wavelengths to be scattered by this mechanism than long wavelengths.

A "blue" sky is a manifestation of Rayleigh scatter. In the absence of scatter, the sky would appear black. But, as sunlight interacts with the earth's atmosphere,