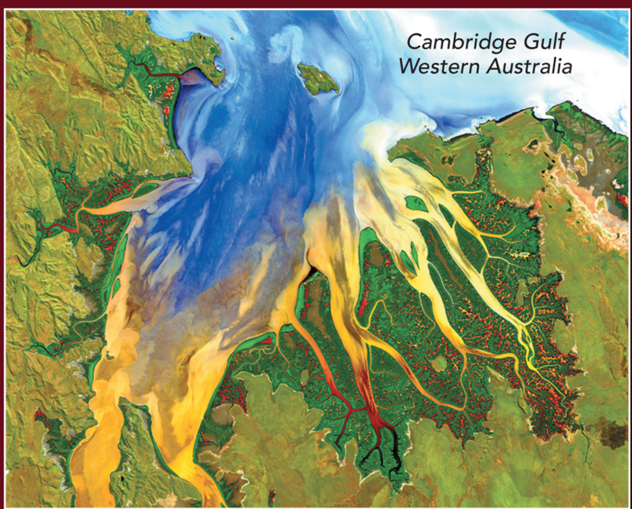
INTRODUCTORY
DIGITAL IMAGE PROCESSING
A Remote Sensing Perspective

4th Edition



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A Remote Sensing Perspective

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A Remote Sensing Perspective

John R. Jensen
University of South Carolina

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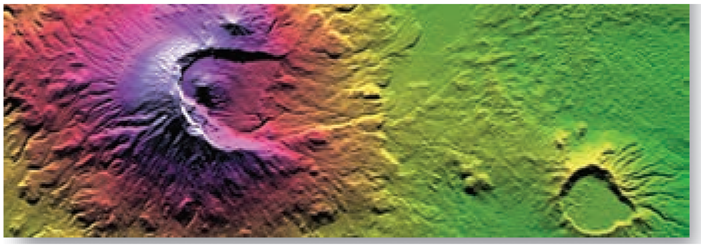

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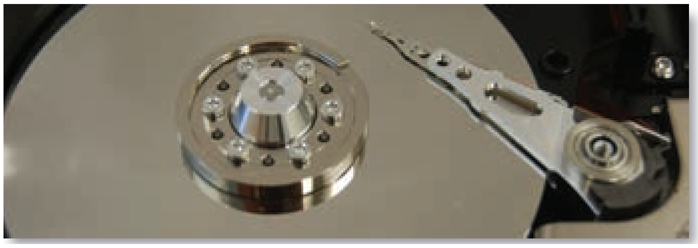

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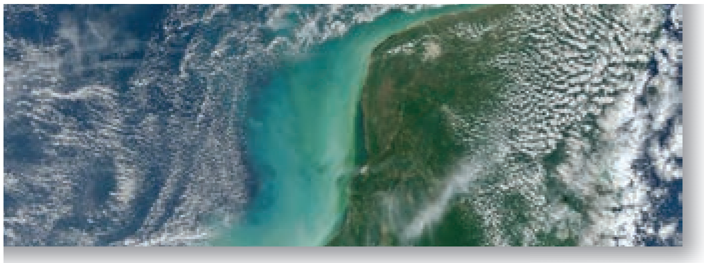

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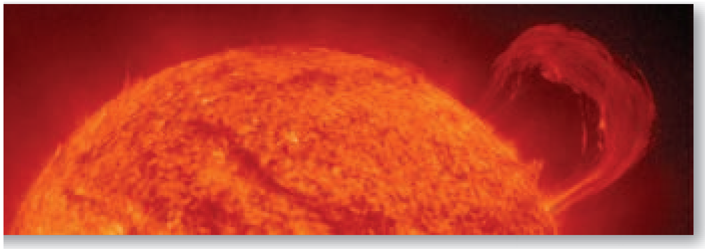

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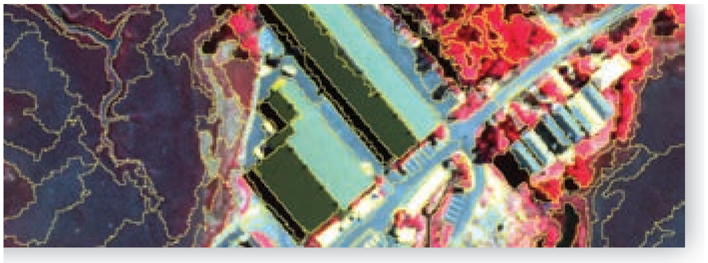

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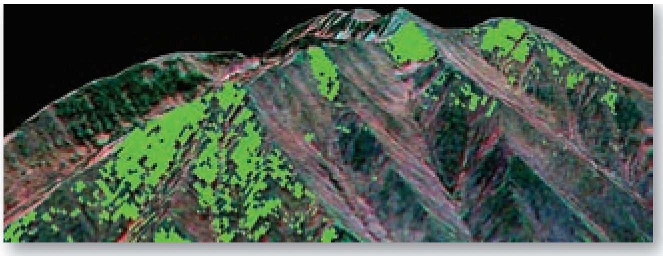

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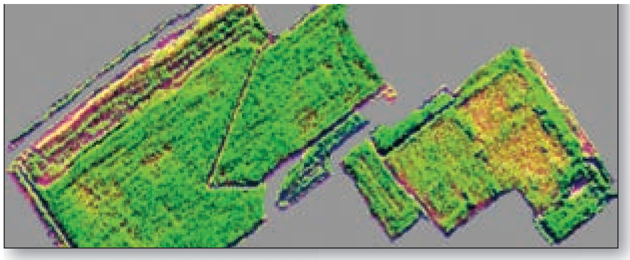

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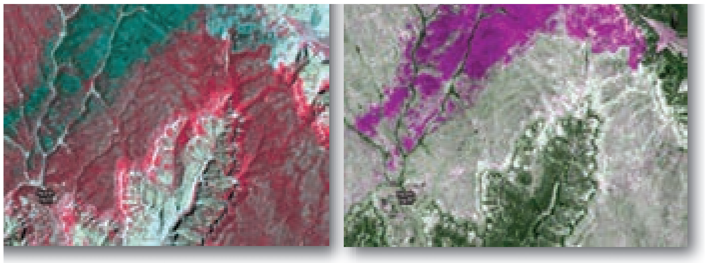

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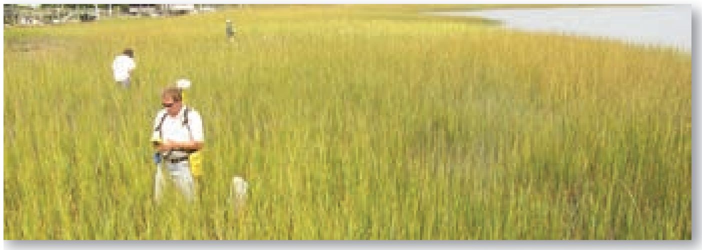

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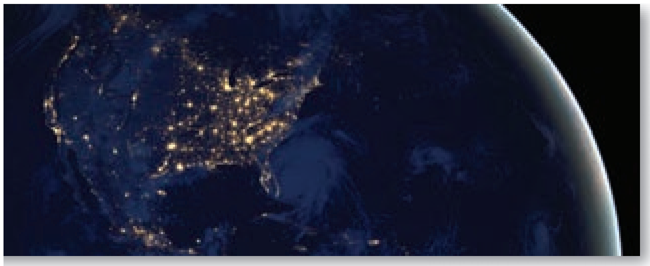

Preface

New to the 4th Edition

The 4th edition of *Introductory Digital Image Processing: A Remote Sensing Perspective* provides up-to-date information on analytical methods used to analyze digital remote sensing data. The book is ideal for introductory through graduate level university instruction in departments that routinely analyze airborne and/or satellite remote sensor data to solve geospatial problems, including: geography, geology, marine science, forestry, anthropology, biology, soil science, agronomy, urban planning, and others.

Introductory Digital Image Processing (4^{th} edition) is now in full-color. This is important because many digital image processing concepts are best described and demonstrated using a) color diagrams and illustrations, b) the original digital remote sensing displayed in color, and c) digital image processing-derived color images and thematic maps. The reader can now examine the color illustrations and images at their appropriate location in the book rather than having to go to a special signature of color plates.

The goal of this book has always been to take relatively sophisticated digital image processing methods and algorithms and make them as easy to understand as possible for students and for remote sensing scientists. Therefore, the reader will notice that each chapter contains a substantial reference list that can be used by students and scientists as a starting place for their digital image processing project or research. A new appendix provides sources of imagery and other geospatial information. Below is a summary of the major content and improvements in the fourth edition.

Chapter 1: Remote Sensing and Digital Image Processing

Greater emphasis is now placed on the importance of ground reference information that can be used to calibrate remote sensor data and assess the accuracy of remote sensing-derived products such as thematic maps. The "Remote Sensing Process" has been updated to reflect recent innovations in digital image processing. Greater emphasis is now placed on the use of remote sensing to solve local, high-spatial resolution problems as well as for use in global climate change research. This chapter now includes detailed information about the increasing demand for people trained in remote sensing digital image processing. Information is provided from a) the NRC (2013) *Future U.S. Workforce for Geospatial Intelligence* study, and b) U.S. Department of Labor Employment and Training Administration (USDOLETA, 2014) data about the 39,900 "Remote Sensing Scientists and Technologists" and "Remote Sensing Technicians" job openings projected from 2012–2022. Many of these geospatial occupations require training in remote sensing digital image processing.

Chapter 2: Remote Sensing Data Collection

This chapter provides information about historical, current, and projected sources of remotely sensed data. Detailed information about new and proposed satellite remote sensing systems (e.g., Astrium's Pleiades and SPOT 6; DigitalGlobe's GeoEye-1, GeoEye-2, WorldView-1, WorldView-2, WorldView-3; India's CartoSat and ResourceSat; Israel's EROS A2; Korea's KOMPSAT; NASA's Landsat 8; NOAA's NPOESS; RapidEye, etc.) and airborne remote sensing systems (e.g., PICTOMETRY, Microsoft's UltraCAM, Leica's Airborne Digital System 80) are included in the fourth edition. Technical details about decommissioned (e.g., SPOT 1, 2; Landsat 5), degraded (e.g., Landsat 7 ETM^+) or failed (e.g., European Space Agency Envisat) sensor systems are provided.

Chapter 3: Digital Image Processing Hardware and Software

As expected, the computer hardware (e.g., CPUs, RAM, mass storage, digitization technology, displays, transfer/storage technology) and software [e.g., multispectral, hyperspectral, per-pixel, object-based image analysis (OBIA)] necessary to perform digital image processing have progressed significantly since the last edition. Improvements in computer hardware often used to perform digital image processing are discussed. The most important functions, characteristics and sources of the major digital image processing software are provided.

Chapter 4: Image Quality Assessment and Statistical Evaluation

Basic digital image processing mathematical notation is reviewed along with the significance of the histogram. The importance of metadata is introduced. Visual methods of assessing image quality are presented including three-dimensional representation. Univariate and multivariate methods of assessing the initial quality of digital remote sensor data are refreshed. A new section on geostatistical analysis, autocorrelation, and kriging interpolation is provided.

Chapter 5: Display Alternatives and Scientific Visualization

New information is provided on: liquid crystal displays (LCD), image compression alternatives, color coordinate systems (RGB, Intensity-Hue-Saturation, and Chromaticity), the use of 8- and 24-bit color look-up tables, and new methods of merging (fusing) different types of imagery (e.g., Gram-Schmidt, regression Kriging). Additional information is provided about measuring distance, perimeter, shape, and polygon area using digital imagery.

Chapter 6: Electromagnetic Radiation Principles and Radiometric Correction

Additional information is provided about electromagnetic radiation principles (e.g., Fraunhofer absorption features) and the spectral reflectance characteristics of selected natural and human-made materials. Updated information about the most important radiometric correction algorithms is provided, including: a) those that perform absolute radiometric correction (e.g., ACORN, FLAASH, QUAC, ATCOR, empirical line calibration) and, b) those that perform relative radiometric correction (e.g., single and multiple-date image normalization).

Chapter 7: Geometric Correction

Traditional as well as improved methods of image-to-map rectification and image-to-image registration are provided. In addition, this edition contains an expanded discussion on developable surfaces and the properties and advantages/disadvantages of several of the most heavily used cylindrical, azimuthal, and conical map projections. MODIS satellite imagery is projected using selected map projections (e.g., Mercator, Lambert Azimuthal Equal-area). The image mosaicking section contains new examples and demonstrates the characteristics of the USGS annual mosaic of Landsat ETM$^+$ data (i.e., the *WELD: Web-enabled Landsat Data* project).

Chapter 8: Image Enhancement

The image magnification and reduction sections are revised. In addition, the following image enhancement techniques are updated: band ratioing, neighborhood raster operations, spatial convolution filtering and edge enhancement, frequency filtering, texture extraction, and Principal Components Analysis (PCA). The vegetation indices (VI) section has been significantly revised to include new information on the dominant factors controlling leaf reflectance and the introduction of numerous new indices with graphic examples. Several new texture transforms are introduced (e.g., Moran's *I* Spatial Autocorrelation) and new information is provided on the extraction of texture from images using Grey-level Co-occurrence Matrices (GLCM). The chapter concludes with a new discussion on landscape ecology metrics that can be extracted from remotely sensed data.

Chapter 9: Thematic Information Extraction: Pattern Recognition

Updated information on the American Planning Association Land-Based Classification Standard (NLCS), the U.S. National Land Cover Database (NLCD) Classification System, NOAA's Coastal Change Analysis Program (C-CAP) Classification Scheme, and the IGBP Land-Cover Classification System is included. New methods of feature (band) selection are introduced (e.g., Correlation Matrix Feature Selection). Additional information is provided on Object-Based Image Analysis (OBIA) classification methods, including new OBIA application examples.

Chapter 10: Information Extraction Using Artificial Intelligence

New information is provided on image classification using machine-learning decision trees, regression trees, Random Forest (trees), and Support Vector Machines (SVM). Detailed information is now provided on a number of machine-learning, data-mining decision tree/regression tree programs that can be used to develop production rules (e.g., CART, S-Plus, R Development Core Team, C4.5, C5.0, Cubist). New information about advances in neural network analysis of remote sensor data is included for Multi-layer Perceptrons, Kohonen's Self-Organizing Map, and fuzzy ARTMAP neural networks. A new discussion about the advantages and disadvantages of artificial neural networks is provided.

Chapter 11: Information Extraction Using Imaging Spectroscopy

Advances in airborne and satellite hyperspectral data collection are discussed. Advances in the methods used to process and analyze hyperspectral imagery are provided, including: end-member selection and analysis, mapping algorithms, Spectral Mixture Analysis (SMA), continuum removal, spectroscopic library matching techniques, machine-learning hyperspectral analysis techniques, new hyperspectral indices, and derivative spectroscopy.

Chapter 12: Change Detection

This book has always contained detailed digital change detection information. New information is provided on the impact of sensor system look angle and amount of tree or building obscuration. Advances in binary "change/no-change" algorithms are provided including new analytical methods used to identify the change thresholds and new commercial change detection products such as ESRI's *Change Matters* and MDA's *National Urban Change Indicator*. Significant advances in thematic "from-to" change detection algorithms are discussed including photogrammetric and LiDAR-grammetric change detection, OBIA post-classification comparison change detection, and Neighborhood Correlation Image (NCI) change detection.

Chapter 13: Remote Sensing-Derived Thematic Map Accuracy Assessment

There is a significant amount of literature and debate about the best method(s) to use to determine the accuracy of remote sensing-derived thematic map produced from a single date of imagery or a thematic map derived from multiple dates of imagery (i.e., change detection). The accuracy assessment alternatives and characteristics of the debate are discussed more thoroughly.

Appendix: Sources of Imagery and Other Geospatial Information

Remote sensing data is analyzed best when used in conjunction with other geospatial information. To this end, a new appendix is provided that contains a list of selected geospatial datasets that can be evaluated and/or downloaded via the Internet, including: digital elevation information, hydrology, land use/land cover and biodiversity/habitat, road network and population demographic data, and several types of publicly- and commercially-available remote sensor-data. Map or image examples of the datasets are presented where appropriate.

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About the Author

John R. Jensen received a BA in geography from California State University at Fullerton, an MS from Brigham Young University (BYU), and a PhD from the University of California at Los Angeles (UCLA). He is a Carolina Distinguished Professor Emeritus in the Department of Geography at the University of South Carolina. He is a certified photogrammetrist and a past president of the American Society for Photogrammetry & Remote Sensing (ASP&RS): The Geospatial Information Society.

Dr. Jensen has conducted more than 50 remote sensing-related research projects sponsored by NASA, DOE, NOAA, U.S. Bureau of the Census, and the Nature Conservancy and published more than 120 refereed journal articles. He has mentored 34 Ph.D. and 62 master's students.

Dr. Jensen received the *SAIC/ASP&RS John E. Estes Memorial Teaching Award* for education, mentoring, and training in remote sensing and GIS. He received the U.S. Geological Survey (USGS)/National Aeronautics & Space Administration (NASA) *William T. Pecora Award* for his remote sensing research contributions. He received the Association of American Geographers (AAG) *Lifetime Achievement Award* for research and education in remote sensing and GIScience. He became an *Honorary Member* of the ASP&RS in 2013.

He has served on numerous editorial boards and was the Editor-in-chief of the journal *GIScience & Remote Sensing* now published by Taylor & Francis. He is co-author of *Introductory Geographic Information Systems* and author of *Remote Sensing of the Environment: An Earth Resource Perspective*, 2nd edition, also published by Pearson.

Dr. Jensen has been associated with eight National Research Council (NRC) remote sensing-related committees and subsequent National Academy Press publications.

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1 Remote Sensing and Digital Image Processing


Source: NASA

Scientists observe nature and man-made phenomena, make measurements, and then attempt to test hypotheses concerning these phenomena. The data collection may take place directly in the field (referred to as *in situ* or in-place data collection), and/or at some remote distance from the subject matter (commonly referred to as **remote sensing** of the environment). Remote sensing technology is now used routinely to obtain accurate, timely information for a significant variety of applications, including: the study of daily weather and long-term climate change; urban-suburban land-use/land cover monitoring; ecosystem modeling of vegetation, water, snow/ice; food security; military reconnaissance; and many others (NRC, 2007ab, 2009, 2013, 2014). The majority of the remotely sensed data are analyzed using digital image processing techniques.

Overview

This chapter introduces basic *in situ* data-collection considerations. Remote sensing is then formally defined along with its advantages and limitations. The remote sensing–process is introduced with particular attention given to: a) the statement of the problem, b) identification of *in situ* and remote sensing data requirements, c) remote sensing data collection using satellite and airborne sensor systems, d) the conversion of remote sensing data into information using analog and/or digital image processing techniques, and e) accuracy assessment and information presentation alternatives. Earth observation economics are considered along with remote sensing and digital image processing careers in the public and private sectors. The organization of the book is reviewed along with its earth resource analysis perspective.

In Situ Data Collection

One form of *in situ* data collection involves the scientist questioning the phenomena of interest. For example, a census enumerator may go door to door, asking people questions about their age, sex, education, income, etc. These data are recorded and used to document the demographic characteristics of the population.

Conversely, a scientist may use a transducer or other *in situ* instrument to make measurements. Transducers are usually placed in direct physical contact with the object of interest. Many different types of transducers are available. For example, a scientist could use a thermometer to measure the temperature of the air, soil, or water; an anemometer to measure wind speed; or a psychrometer to measure air humidity. The data recorded by the transducers may be an analog electrical signal with voltage variations related to the intensity of the property being measured. Often these analog signals are transformed into digital values using analog-to-digital (A-to-D) conversion procedures. *In situ* data collection using transducers relieves the scientist of monotonous data collection often in inclement weather. Also, the scientist can distribute the transducers at geographic locations throughout the study area, allowing the same type of measurement to be obtained at many locations at the same time. Sometimes data from the transducers are telemetered electronically to a central collection point for rapid evaluation and archiving.

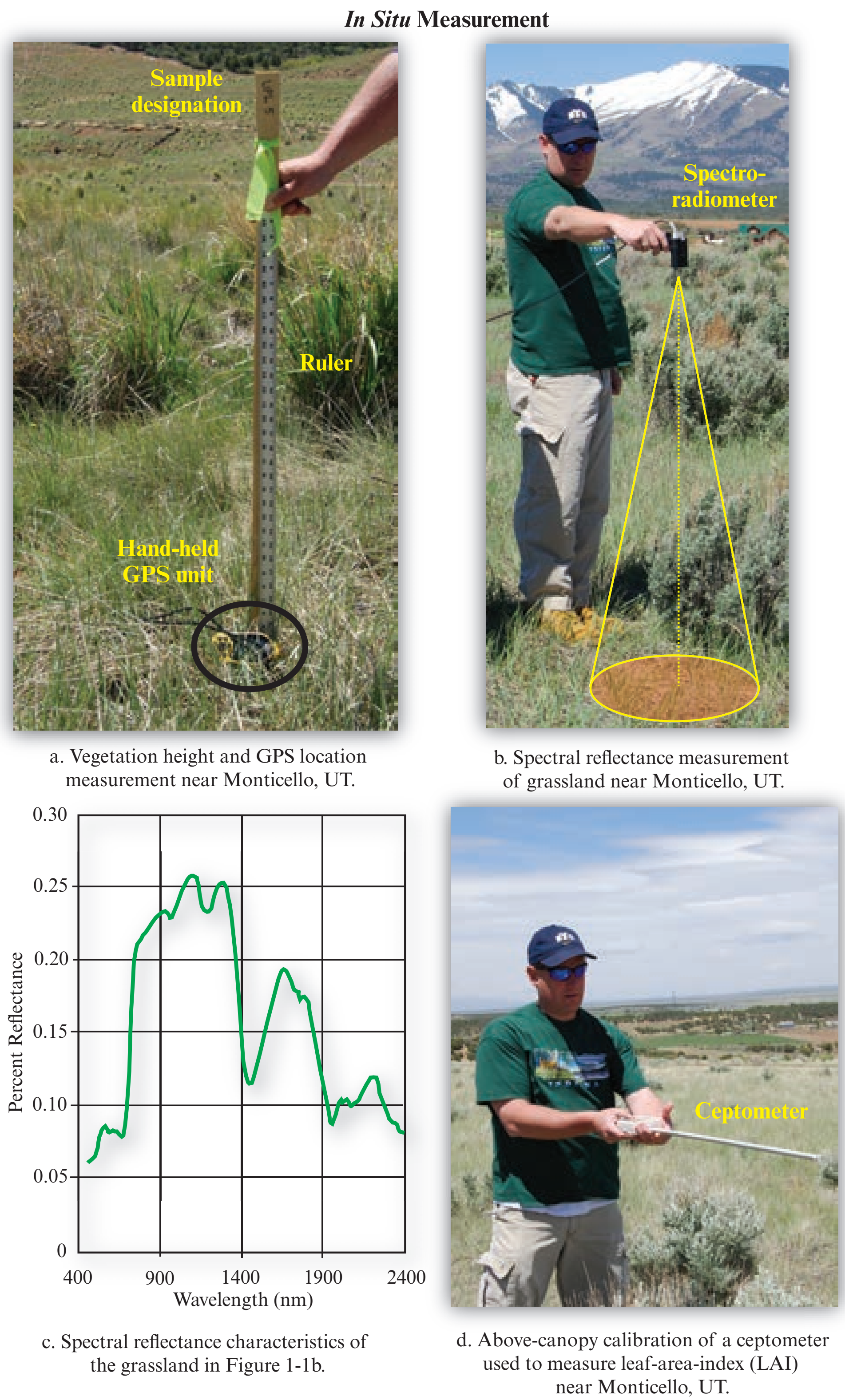


FIGURE 1–1 *In situ* (in-place) data are collected in the field. a) Vegetation height is being measured using a simple metal ruler and geographic location is measured using a hand-held GPS unit. b) Vegetation spectral reflectance information is being collected using a spectroradiometer held approximately 1 m above the canopy. The *in situ* spectral reflectance measurements may be used to calibrate the spectral reflectance measurements obtained from a remote sensing system. c) Spectral reflectance characteristics of the area on the ground in Figure 1-1b. d) The leaf-area-index (LAI) of the grassland can be measured using a ceptometer that records the number of "sunflecks" that pass through the vegetation canopy. Ceptometer measurements are made just above the canopy as shown and on the ground below the canopy. These measurements are then used to compute *in situ* LAI that can be used to calibrate remote sensing–derived LAI estimates.

Several examples of *in situ* data collection on a grassland near Monticello, UT, are demonstrated in Figure 1-1. A stake is used to mark the location of *in situ* sample “UPL 5” in Figure 1-1a. A hand-held Global Positioning System (GPS) unit is placed at the base of the stake to obtain precise *x,y,* and *z* location information about the sample with a horizontal accuracy of approximately ±0.25 m. A dimensionally-stable metal ruler is used to measure the height of the grass at the sample location. A hand-held spectroradiometer is used to measure the spectral reflectance characteristics of the materials within the Instantaneous-Field-Of-View (IFOV) of the radiometer on the ground (Figure 1-1b). The spectral reflectance characteristics of the grassland within the IFOV from 400 – 2,400 nm are shown in Figure 1-1c. A hand-held ceptometer is being used to collect information about incident skylight above the vegetation canopy in Figure 1-1d. The scientist will then place the ceptometer on the ground beneath the vegetation canopy present. Approximately 80 photo-diodes along the linear ceptometer measure the amount of light that makes its way through the vegetation canopy to the ceptometer. The above- and below-canopy ceptometer measurements are used to compute the Leaf-Area-Index (LAI) at the sample location. The greater the amount of vegetation, the greater the LAI. Interestingly, all of these measurement techniques are non-destructive (i.e., vegetation clipping or harvesting is not required).

Data collection by scientists in the field or by instruments placed in the field provides much of the data for physical, biological, and social science research. However, it is important to remember that no matter how careful the scientist is, error may be introduced during the *in situ* data-collection process. First, the scientist in the field can be *intrusive*. This means that unless great care is exercised, the scientist can actually change the characteristics of the phenomenon being measured during the data-collection process. For example, a scientist collecting a vegetation spectral reflectance reading could inadvertently step on the sample site, disturbing the vegetation prior to data collection.

Scientists may also collect data in the field using biased procedures. This introduces *method-produced error*. It could involve the use of a biased sampling design or the systematic, improper use of a piece of equipment. Finally, the *in situ* data-collection measurement device may be calibrated incorrectly. This can result in serious *measurement-device calibration error*.

Intrusive *in situ* data collection, coupled with human method-produced error and measurement-device miscalibration, all contribute to *in situ* data-collection error. Therefore, it is a misnomer to refer to *in situ* data as ground truth data. Instead, we should simply refer to it as *in situ* **ground reference data**, acknowledging that it contains error.

Remote Sensing Data Collection

Fortunately, it is possible to collect information about an object or geographic area from a distant vantage point using **remote sensing** instruments (Figure 1-2). Remote sensing data collection was originally performed using cameras mounted in suborbital aircraft. **Photogrammetry** was defined in the early editions of the *Manual of Photogrammetry* as:

> the art or science of obtaining reliable measurement by means of photography (American Society of Photogrammetry, 1952; 1966).

Photographic interpretation is defined as:

> the act of examining photographic images for the purpose of identifying objects and judging their significance (Colwell, 1960).

Remote sensing was formally defined by the American Society for Photogrammetry and Remote Sensing (ASPRS) as:

> the measurement or acquisition of information of some property of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object or phenomenon under study (Colwell, 1983).

In 1988, ASPRS adopted a **combined definition of photogrammetry and remote sensing**:

> Photogrammetry and remote sensing are the art, science, and technology of obtaining reliable information about physical objects and the environment, through the process of recording, measuring and interpreting imagery and digital representations of energy patterns derived from non-contact sensor systems (Colwell, 1997).

But where did the term *remote sensing* come from? The actual coining of the term goes back to an unpublished paper in the early 1960s by the staff of the Office of Naval Research (ONR) Geography Branch (Pruitt, 1979; Fussell et al., 1986). Evelyn L. Pruitt was the author of the paper. She was assisted by staff member Walter H. Bailey. Aerial photo interpretation had become very important in World War II. The space age was just getting under way with the 1957 launch of *Sputnik* (U.S.S.R.), the 1958 launch of *Explorer 1*

(U.S.), and the collection of photography from the then secret CORONA program initiated in 1960 (Table 1-1, page 11). In addition, the Geography Branch of ONR was expanding its research using instruments other than cameras (e.g., scanners, radiometers) and into regions of the electromagnetic spectrum beyond the visible and near-infrared regions (e.g., thermal infrared, microwave). Thus, in the late 1950s it had become apparent that the prefix "photo" was being stretched too far in view of the fact that the root word, *photography*, literally means "to write with [visible] light" (Colwell, 1997). Evelyn Pruitt (1979) wrote:

> The whole field was in flux and it was difficult for the Geography Program to know which way to move. It was finally decided in 1960 to take the problem to the Advisory Committee. Walter H. Bailey and I pondered a long time on how to present the situation and on what to call the broader field that we felt should be encompassed in a program to replace the aerial photointerpretation project. The term 'photograph' was too limited because it did not cover the regions in the electromagnetic spectrum beyond the 'visible' range, and it was in these nonvisible frequencies that the future of interpretation seemed to lie. 'Aerial' was also too limited in view of the potential for seeing the Earth from space.

The term **remote sensing** was promoted in a series of symposia sponsored by ONR at the Willow Run Laboratories of the University of Michigan in conjunction with the National Research Council throughout the 1960s and early 1970s, and has been in use ever since (Estes and Jensen, 1998).

Remote sensing instruments such as cameras, multispectral and hyperspectral sensors, thermal-infrared detectors, Radio Detection and Ranging (RADAR) sensors, and Light Detection and Ranging (LiDAR) instruments are flown onboard satellites or suborbital aircraft such as airplanes, helicopters, and Unmanned Aerial Vehicles (UAVs) (Figure 1-2). Sound Navigation and Ranging (SONAR) sensors are placed onboard ships and submarines to map the bathymetry of subsurface terrain.

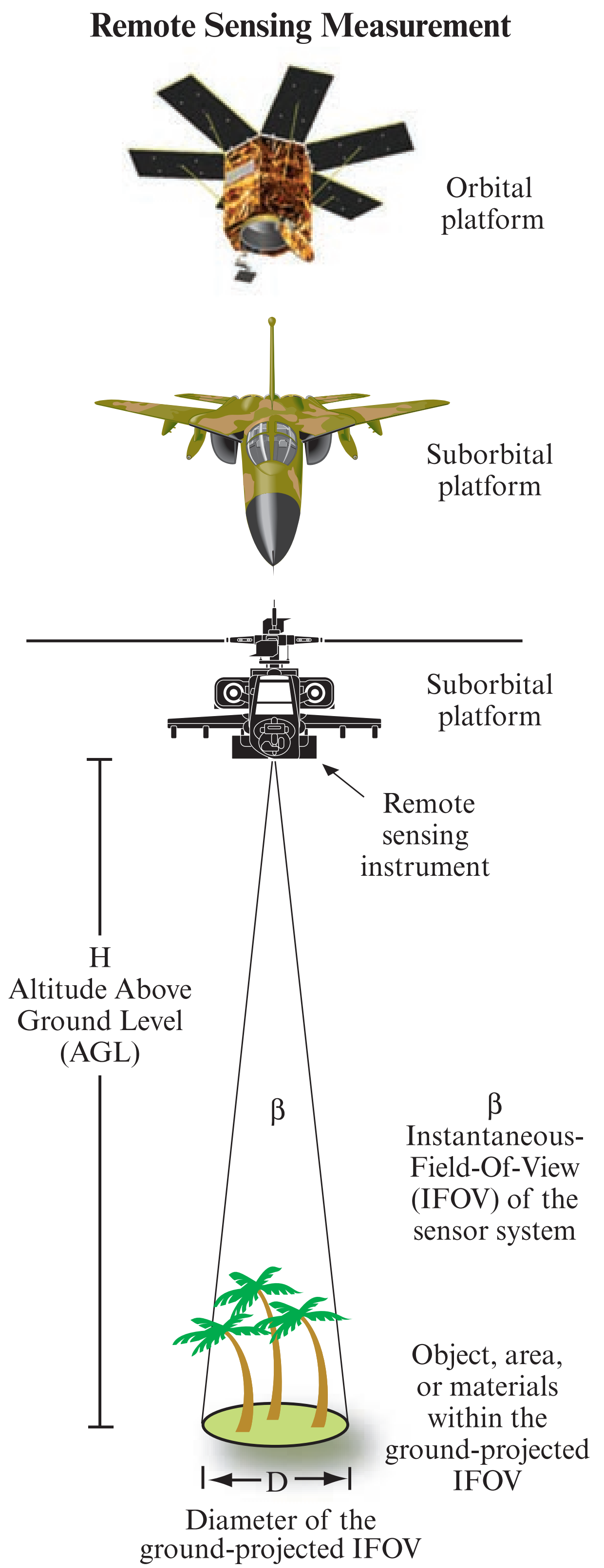


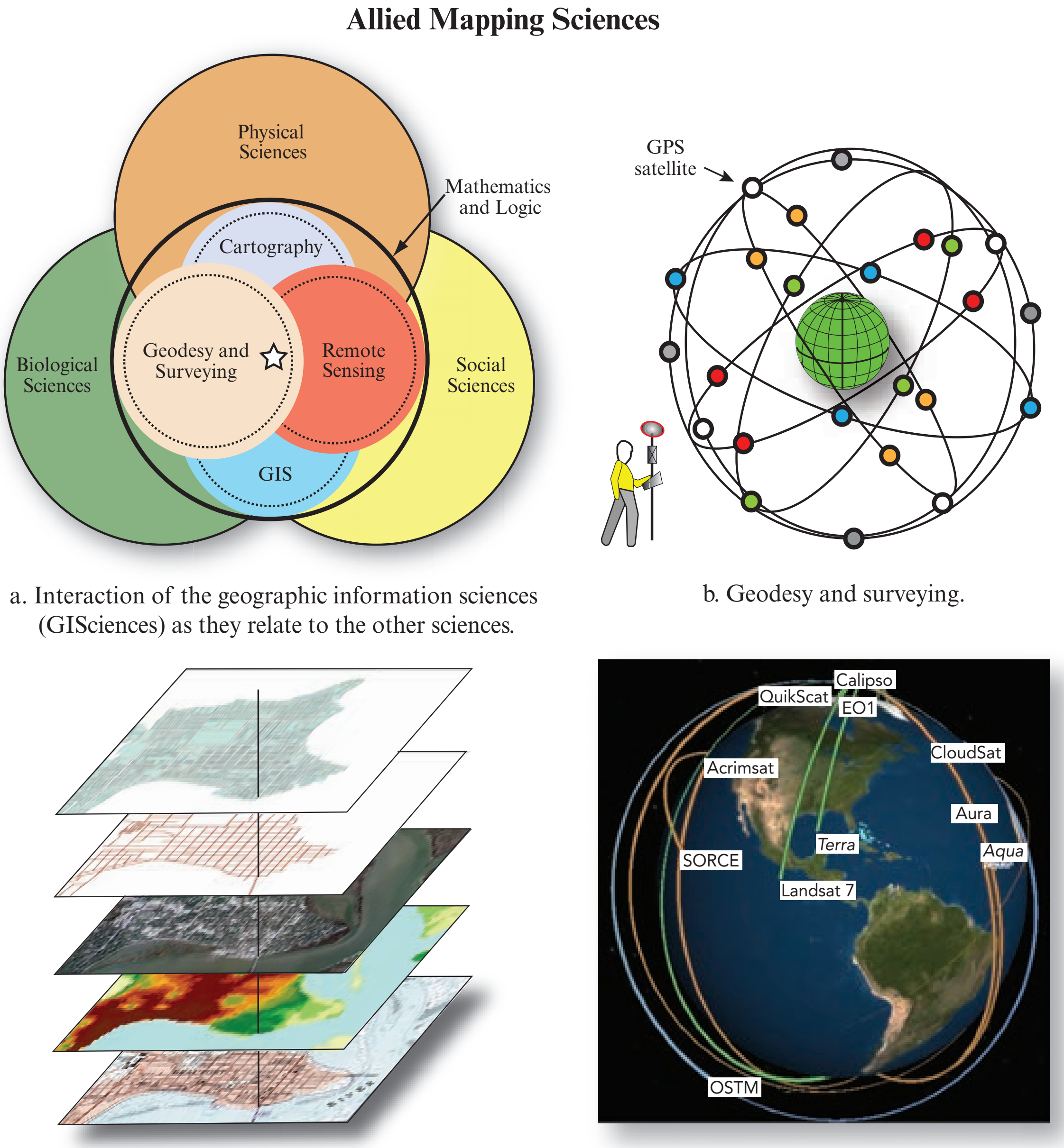
FIGURE 1–2 A remote sensing instrument collects information about an object or phenomenon within the IFOV of the sensor system without being in direct physical contact with it. The remote sensing instrument may be located just a few meters above the ground or onboard an aircraft or satellite platform.

Observations About Remote Sensing

The following brief discussion focuses on various terms found in the formal definitions of remote sensing.

Remote Sensing: Art and/or Science?

Science: A **science** is a broad field of human knowledge concerned with facts held together by principles (rules). Scientists discover and test facts and principles



a. Interaction of the geographic information sciences (GISciences) as they relate to the other sciences.

b. Geodesy and surveying.

c. Cartography and Geographic Information Systems (GIS).

d. Remote sensing.

FIGURE 1–3 a) Interaction model depicting the relationship of the geographic information sciences (geodesy, surveying, cartography, GIS, and remote sensing) as they relate to mathematics and logic and the physical, biological, and social sciences. b) Geodesy and surveying provide geodetic control and detailed local geospatial information. c) Cartographers map geospatial information and Geographic Information Systems are used to model geospatial information. d) Satellite and suborbital remote sensing systems provide much of the useful geospatial information used by cartographers, GIS practitioners, and other scientists.

by the scientific method, an orderly system of solving problems. Scientists generally feel that any subject that humans can study by using the scientific method and other special rules of thinking may be called a science. The sciences include 1) *mathematics and logic*, 2) *physical sciences*, such as physics and chemistry, 3) *biological sciences*, such as botany and zoology, and 4) *social sciences*, such as geography, sociology, and anthropology (Figure 1-3a). Interestingly, some persons do not consider mathematics and logic to be sciences. But the fields of knowledge associated with mathematics and logic are such valuable *tools* for science that we cannot ignore them. The human race's earliest questions were concerned with "how many" and "what belonged together." They struggled to count, to classify, to think systematically, and to describe exactly. In many respects, the state of development of a science is indicated by the use it makes of mathematics. A science seems to begin with simple mathematics to measure, then works toward more complex mathematics to explain.

Remote sensing is a tool or technique similar to mathematics. Using sophisticated sensors to measure the amount of electromagnetic energy exiting an object or geographic area from a distance and then extracting valuable information from the data using mathematically and statistically based algorithms is a scientific activity. Remote sensing functions in harmony with several other geographic information sciences (often referred to as the **GISciences**), including geodesy, surveying, cartography, and Geographic Information Systems (GIS) (Figure 1-3b-d). The model shown in Figure 1-3a suggests there is interaction between the mapping sciences, where no subdiscipline dominates and all are recognized as having unique yet overlapping areas of knowledge and intellectual activity as they are used in physical, biological, and social science research.

Significant advances will continue to be made in all of these technologies. In addition, the technologies will become more integrated with one another. For example, GIS network analysis applications have benefited tremendously from more accurate road network centerline data obtained using GPS units mounted on specially prepared cars or derived from high spatial resolution remote sensor data. Entire industries are now dependent on high spatial resolution satellite and airborne remote sensor data as geographic background imagery for their search engines (e.g., *Google Earth*, *Google Maps*, *Bing Maps*). Remote sensing data collection has benefited from advancements in GPS measurements that are used to improve the geometric accuracy of images and image-derived products that are used so heavily in GIS applications. Terrestrial surveying has been revolutionized by improvements in GPS technology, where measurements as accurate as ± 1 to 3 cm in x, y, and z are now possible.

The theory of science suggests that scientific disciplines go through four classic developmental stages. Wolter (1975) suggested that the growth of a scientific discipline, such as remote sensing, that has its own techniques, methodologies, and intellectual orientation seems to follow the sigmoid or logistic curve illustrated in Figure 1-4. The growth stages of a scientific field are: Stage 1—a preliminary growth period with small increments of literature; Stage 2—a period of exponential growth when the number of publications doubles at regular intervals; Stage 3—a period when the rate of growth begins to decline but annual increments remain constant; and Stage 4—a final period when the rate of growth approaches zero. The characteristics of a scholarly field during each of the stages may be briefly described as follows: Stage 1—little or no social organization; Stage 2—groups of collaborators and existence of invisible colleges, often in the form of ad hoc institutes, research units, etc.; Stage 3—increasing specialization and increasing controversy; and Stage 4—decline in membership in both collaborators and invisible colleges.

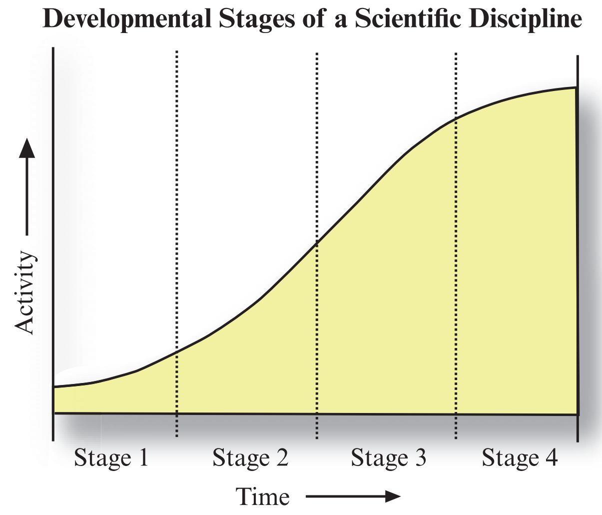


FIGURE 1–4 Developmental stages of a scientific discipline (Source: Wolter, 1975; Jensen and Dahlberg, 1983).

Using this logic, it appears that remote sensing is in Stage 2, experiencing exponential growth since the mid-1960s with the number of publications doubling at regular intervals. Empirical evidence consists of: 1) the organization of many specialized institutes and centers of excellence associated with remote sensing, 2) the organization of numerous professional societies devoted to remote sensing research, 3) the publication of numerous new scholarly remote sensing journals, 4) significant technological advancement such as improved sensor systems and methods of image analysis, and 5) robust self-examination. We may be approaching Stage 3 with increasing specialization and theoretical controversy. However, the rate of growth of remote sensing has not begun to decline. In fact, there has been a tremendous surge in the numbers of persons specializing in remote sensing and commercial firms using remote sensing during the last three decades. Significant improvements in the spatial resolution of satellite remote sensing (e.g., high resolution 1 × 1 m panchromatic data) has brought even more social science GIS practitioners into the fold. Hundreds of new peer-reviewed remote sensing research articles are published every month.

Art: The process of visual photo or image interpretation brings to bear not only scientific knowledge, but all of the background that a person has obtained through his or her lifetime. Such learning cannot be measured, programmed, or completely understood. The synergism of combining scientific knowledge with the real-world analyst experience allows the interpreter to develop heuristic rules of thumb to extract valuable information from the imagery. It is a fact that some image analysts are superior to other image analysts because they: 1) understand the scientific principles better, 2) are more widely traveled and have seen many landscape objects and geographic areas, and/or 3) can synthesize scientific principles and real-world knowledge to reach logical and correct conclusions. Thus, remote sensing image interpretation is both an art and a science.

Information About an Object or Area

Sensors can obtain very specific information about an object (e.g., the diameter of an oak tree crown) or the geographic extent of a phenomenon (e.g., the polygonal boundary of an entire oak forest). The electromagnetic energy emitted or reflected from an object or geographic area is used as a surrogate for the actual property under investigation. The electromagnetic energy measurements are typically turned into information using visual and/or digital image processing techniques.

The Instrument (Sensor)

Remote sensing is performed using an instrument, often referred to as a sensor. The majority of remote sensing instruments record electromagnetic radiation (EMR) that travels at a velocity of 3×10^8 m s^{-1} from the source, directly through the vacuum of space or indirectly by reflection or reradiation to the sensor. The EMR represents a very efficient high-speed communications link between the sensor and the remote phenomenon. In fact, we know of nothing that travels faster than the speed of light. Changes in the amount and properties of the EMR become, upon detection by the sensor, a valuable source of data for interpreting important properties of the phenomenon (e.g., temperature, color). Other types of force fields may be used in place of EMR, such as acoustic (sonar) waves. However, the majority of remotely sensed data collected for Earth resource applications is the result of sensors that record electromagnetic energy.

Distance: How Far Is Remote?

Remote sensing occurs at a distance from the object or area of interest. Interestingly, there is no clear distinction about how great this distance should be. The intervening distance could be 1 cm, 1 m, 100 m, or more than 1 million m from the object or area of interest. Much of astronomy is based on remote sensing. In fact, many of the most innovative remote sensing systems and visual and digital image processing methods were originally developed for remote sensing extraterrestrial landscapes such as the moon, Mars, Saturn, Jupiter, etc. (especially by NASA's Jet Propulsion Laboratory personnel). This text, however, is concerned primarily with remote sensing of the terrestrial Earth, using sensors that are placed on suborbital air-breathing aircraft or orbital satellite platforms placed in the vacuum of space.

Remote sensing and digital image processing techniques can also be used to analyze inner space. For example, an electron microscope can be used to obtain photographs of extremely small objects on the skin, in the eye, etc. An x-ray instrument is a remote sensing system where the skin and muscle are like the atmosphere that must be penetrated, and the interior bone or other matter is the object of interest.

Remote Sensing Advantages and Limitations

Remote sensing has several unique advantages as well as some limitations.

Advantages

Remote sensing is unobtrusive if the sensor is passively recording the electromagnetic energy reflected from or emitted by the phenomenon of interest. This is a very important consideration, as passive remote sensing does not disturb the object or area of interest.

Remote sensing devices are programmed to collect data systematically, such as within a single 9 × 9 in. frame of vertical aerial photography or a matrix (raster) of Landsat 5 Thematic Mapper data. This systematic data collection can remove the sampling bias introduced in some *in situ* investigations.

Remote sensing science is also different from cartography or GIS because these sciences rely on data obtained or synthesized by others. Remote sensing science can provide fundamental, *new* scientific data or information. Under controlled conditions, remote sensing can provide fundamental biophysical information, including: x, y location, z elevation or depth, biomass, temperature, moisture content, etc. In this sense, remote sensing science is much like surveying, providing fundamental information that other sciences can use when conducting scientific investigations. However, unlike much of surveying, the remotely sensed data can be obtained systematically over very large geographic areas rather than just single-point observations. In fact, remote sensing–derived information is now critical to the successful modeling of numerous natural (e.g., water-supply estimation; eutrophication studies; nonpoint source pollution) and cultural (e.g., land-use conversion at the urban fringe; water-demand estimation; population estimation; food security) processes (NRC, 2007a; 2009). A good example is the digital elevation model that is so important in many spatially-distributed GIS models. Digital elevation models are now produced mainly from light detection and ranging

(LiDAR) (e.g., Renslow, 2012), stereoscopic aerial photography, RADAR measurements, or Interferometric Synthetic Aperture Radar (IFSAR) imagery.

Limitations

Remote sensing science has limitations. Perhaps the greatest limitation is that it is often oversold. Remote sensing is not a panacea that will provide all the information needed to conduct physical, biological, or social science research. It simply provides some spatial, spectral, and temporal information of value in a manner that is hopefully efficient and economical.

Human beings select the most appropriate remote sensing system to collect the data, specify the various resolution(s) of the remote sensor data, calibrate the sensor, select the satellite or suborbital platform that will carry the sensor, determine when the data will be collected, and specify how the data are processed. Therefore, human method-produced error may be introduced as the remote sensing instrument and mission parameters are specified.

Powerful active remote sensor systems that emit their own electromagnetic radiation (e.g., LiDAR, RADAR, SONAR) can be intrusive and affect the phenomenon being investigated. Additional research is required to determine how intrusive these active sensors can be.

Remote sensing instruments may become uncalibrated, resulting in uncalibrated remote sensor data. Finally, remote sensor data may be relatively expensive to collect and analyze. Hopefully, the information extracted from the remote sensor data justifies the expense. The greatest expense in a typical remote sensing investigation is for well-trained image analysts, not remote sensor data.

The Remote Sensing Process

Scientists have been developing procedures for collecting and analyzing remotely sensed data for more than 150 years. The first photograph from an aerial platform (a tethered balloon) was obtained in 1858 by the Frenchman Gaspard Felix Tournachon (who called himself Nadar). Significant strides in aerial photography and other remote sensing data collection took place during World Wars I and II, the Korean Conflict, the Cuban Missile Crisis, the Vietnam War, the Gulf War, the war in Bosnia, and the war on terrorism. Basically, military contracts to commercial companies resulted in the development of sophisticated electro-optical multispectral remote sensing systems and thermal infrared and microwave (radar) sensor systems whose characteristics are summarized in Chapter 2. While the majority of the remote sensing systems may have been initially developed for military reconnaissance applications, the systems are now also heavily used for monitoring the Earth's natural resources.

The remote sensing data-collection and analysis procedures used for Earth resource applications are often implemented in a systematic fashion that can be termed the **remote sensing process**. The procedures in the process are summarized here and in Figure 1-5:

- The hypothesis to be tested is defined using a specific type of logic (e.g., inductive, deductive) and an appropriate processing model (e.g., deterministic, stochastic).
- *In situ* and collateral information necessary to calibrate the remote sensor data and/or judge its geometric, radiometric, and thematic characteristics are collected.
- Remote sensor data are collected passively (e.g., digital cameras) or actively (e.g., RADAR, LiDAR) using analog or digital remote sensing instruments, ideally at the same time as the *in situ* data.
- *In situ* and remotely sensed data are processed using a variety of techniques, including: a) analog image processing, b) digital image processing, c) modeling, and d) *n*-dimensional visualization.
- Metadata, processing lineage, and the accuracy of the information are provided and the results communicated using images, graphs, statistical tables, GIS databases, Spatial Decision Support Systems (SDSS), etc.

It is useful to review the characteristics of these remote sensing process procedures.

Statement of the Problem

Sometimes the general public and even children look at aerial photography or other remote sensor data and extract useful information. They do this without a formal hypothesis in mind. Often, however, they interpret the imagery incorrectly because they do not understand the nature of the remote sensing system used to collect the data or appreciate the vertical or oblique perspective of the terrain recorded in the imagery.

Scientists who use remote sensing, on the other hand, are usually trained in the scientific method—a way of thinking about problems and solving them. They use a formal plan that typically has at least five elements: 1) stating the problem, 2) forming the research hypothesis (i.e., a possible explanation), 3) observing and experimenting, 4) interpreting data, and 5) drawing conclusions. It is not necessary to follow this formal plan exactly.

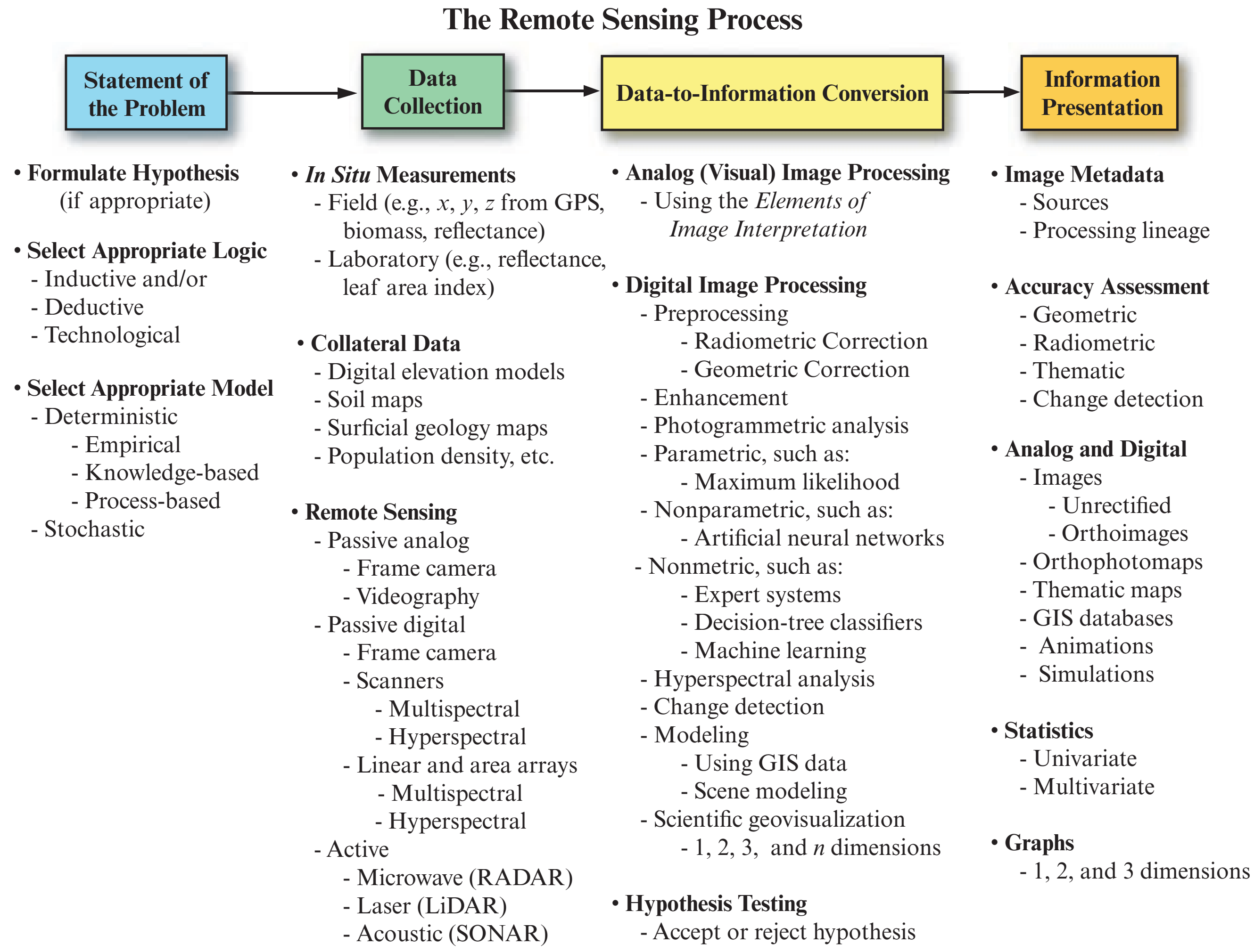


FIGURE 1–5 Scientists generally use the remote sensing process to extract information from remotely-sensed images.

The scientific method is normally used in conjunction with environmental models that are based on two primary types of logic:

- deductive logic, and
- inductive logic.

Models based on deductive and/or inductive logic can be further subdivided according to whether they are processed deterministically or stochastically. Some scientists extract new thematic information directly from remotely sensed imagery without ever explicitly using inductive or deductive logic. They are just interested in extracting information from the imagery using appropriate methods and technology. This technological approach is not as rigorous, but it is common in applied remote sensing. The approach can also generate new knowledge.

Remote sensing is used in both scientific (inductive and deductive) and technological approaches to obtain knowledge. There is discussion as to how the different types of logic used in the remote sensing process yield new scientific knowledge (e.g., Fussell et al., 1986; Curran, 1987; Fisher and Lindenberg, 1989; Dobson, 1993; Skidmore, 2002; Wulder and Coops, 2014).

Identification of *In situ* and Remote Sensing Data Requirements

If a hypothesis is formulated using inductive and/or deductive logic, a list of variables or observations are identified that will be used during the investigation. *In situ* observation and/or remote sensing may be used to collect information on the most important variables.

Scientists using remote sensing technology should be well trained in field and laboratory data-collection procedures. For example, if a scientist wants to map the surface temperature of a lake, it is usually necessary to collect accurate empirical *in situ* lake-temperature measurements at the same time the remote sensor data are collected. The *in situ* data may be used to: 1) calibrate