structure, drainage density and pattern of the Earth using remote sensor data. The chapter concludes with examples of how remote sensor data may be used to identify geomorphic features on the surface of the Earth.

Acknowledgments

The author wishes to thank the following people for their support and assistance in the preparation of this book. My wife, Marsha, provided patient encouragement during the years of manuscript preparation. Judith Berglund proof-read the manuscript and assisted in the preparation of the Appendix. Tim Ivey, a close friend, offered moral support. Dr. Susan Cutter provided resources and an environment within the Geography Department at the University of South Carolina that facilitated the creation of this book.

The author is indebted to the following scientists who reviewed selected chapters: Dr. John E. Estes, Dr. Glen Gustafson, Dr. Floyd Henderson, Dr. Chor Pang Lo, Dr. Jeff Luvall, Dr. Sunil Narumalani, Dr. Kevin Price, Dr. Dale Quattrochi, Dr. Don Rundquist, Judith Berglund, Jennifer Meisburger, and Steve Schill. Personnel at Prentice-Hall, Inc. were especially helpful including Dan Kaveney (Editor), Amanda Griffith (Assistant editor), and Ed Thomas (Production).

The American Society for Photogrammetry and Remote Sensing, the Association of American Geographers, Geocarto International Centre, Inc., American Elsevier Publishing Co., and Taylor & Francis, Inc. granted permission for the author to extract copyrighted material from his papers and other authors' works published in *Photogrammetric Engineering & Remote Sensing,* the *Manual of Remote Sensing, Manual of Color Aerial Photography, Annals* of the Association of American Geographers, *Geocarto International—A Multidisciplinary Journal of Remote Sensing & GIS, Professional Geographer, Remote Sensing of Environment, International Journal of Remote Sensing,* and *International Journal of Geographical Information Systems.*

John Pike of the Federation of American Scientists made available several useful remote sensing images. Large-scale kite aerial photography was provided by Dr. Cris Benton of the University of California Berkeley. Dr. Stefan Sandmeier of NASA Goddard provided much of the BRDF material.

Several historical photographs were made available by the Harry Ransom Humanities Research Center, University of Texas, Austin, TX, and the Deutsches Museum, Munich, Germany.

A number of federal agencies were helpful, including: personnel of the Smithsonian National Air and Space Museum, the Library of Congress, National Aeronautics and Space Administration (NASA) Observatorium, NASA Goddard Tropical Rainfall Measurement Mission Office (Alan Nelson), NASA Goddard Solar and Heliospheric Observatory (Joseph Gurman), NASA John C. Stennis Space Center Commercial Remote Sensing Program (Dr. Bruce A. Davis), NASA Johnson Space Center (Dr. Kamlesh Lulla), NASA Marshall Space Flight Center (Dr. Dale Quattrochi), NASA Jet Propulsion Laboratory (JPL), U.S. Geological Survey (Don Lauer), USGS Desert Processes Working Group, USGS National Aerial Photography Program (NAPP), USGS Imaging Spectroscopy Lab (Roger Clark), National Oceanic and Atmospheric Administration (NOAA) and the Geological Survey of Canada.

Commercial remote sensing data providers made available examples of their remote sensing instruments and image products. A special thanks to: Space Imaging, Inc. (Linda Lidov), SPOT Image, Inc. (Clark Nelson), Lockheed Martin, Inc. (Jeannie Duisenberg and Eric Schulzinger), Litton Emerge Spatial, Inc. (Don Light), Positive Systems, Inc. (Kim Hickman), ORBIMAGE, Inc. (Sue Hale), EarthWatch, Inc., Intermap, Inc. (Ron Birk), Sovinformsputnik and Aerial Images, Inc. (Michele Hane), Aeromap USA, Inc., Environmental Research Institute of Michigan (Eric Kasischke), RADARSAT, Inc., Eastman Kodak Company (Robert Lundquist and Mary Skerrett), and Hughes Santa Barbara Research Center, Inc. Photogrammetric engineering firms provided information and images of their instruments, including: L-H Systems, Inc. (Dr. A. Stewart Walker), Marconi Integrated Systems, Inc. (Bob Hayes), E. Coyote Enterprises and Z/I Imaging, Inc. (Marilyn O'Cuilinn), Vexcel, Inc., Carl Zeiss, Inc. (Anke B. Shimko), and Optem, Inc. Digital image processing was performed using ERDAS and ENVI software. GIS analysis was performed using ESRI Arc-Info software.

John R. Jensen
University of South Carolina

Remote Sensing of the Environment

1

Scientists are concerned with observing nature, making careful observations and measurements, and then attempting to accept or reject hypotheses concerning these phenomena. The data collection may take place directly in the field (referred to as *in situ* or *in-place* data collection), or at some remote distance from the subject matter.

In Situ Data Collection

One form of *in situ* data collection involves the scientist going out in the field and questioning the phenomena of interest. For example, an enumerator for the decennial (10-year) census goes from door to door, asking people questions about their age, sex, education, income, etc. These data are recorded and used to document quantitatively the demographic characteristics of the population.

Conversely, a scientist may elect to use a *transducer* or other *in situ* measurement device at the study site 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 the speed of the wind; or a psychrometer to measure the humidity of the air. 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 important geographic locations throughout the study area, allowing the same type of measurement to be obtained at many locations at the same instant in time. Sometimes data from the transducers are telemetered electronically to a central collection point for rapid evaluation and archiving.

Two examples of *in situ* data collection are demonstrated in Figure 1-1. Leaf-area-index (LAI) measurements are being collected by a scientist at the study site using a handheld ceptometer in Figure 1-1a. Spectral reflectance measurements of the vegetation canopy are being obtained at the study site using a spectroradiometer in Figure 1-1b. LAI and spectral reflectance measurements obtained in the field may be used to calibrate LAI and spectral reflectance measurements collected by a remote sensing system located on an aircraft or satellite.

Figure 1-1 *In situ* (in-place) data are collected in the field at the study site. a) A scientist is collecting leaf-area-index (LAI) measurements of soybeans (*Glycine max L. Merrill*) using a ceptometer that measures the number of "sunflecks" that pass through the vegetation canopy. The measurements are typically made above the canopy and on the ground below the canopy. The *in situ* LAI measurements may be used to calibrate LAI estimates derived from remote sensor data. b) Spectral reflectance measurements from the vegetation canopy are being collected using a spectroradiometer located 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 onboard an aircraft or satellite.

Data collection by scientists in the field or by instruments placed in the field provide 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 could lean out of a boat to obtain a surface-water sample from a lake. Unfortunately, the movement of the boat into the area may have stirred up the water column in the vicinity of the water sample, resulting in an unrepresentative, or *biased,* sample. Similarly, a scientist collecting a ceptometer LAI reading could inadvertently step on the sample site, compacting the vegetation canopy 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 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

It is also possible to collect information about an object or geographic area from a distant vantage point (Figure 1-2) using specialized instruments (sensors). This remote data collection was originally performed using aerial cameras. *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, 1944; 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).

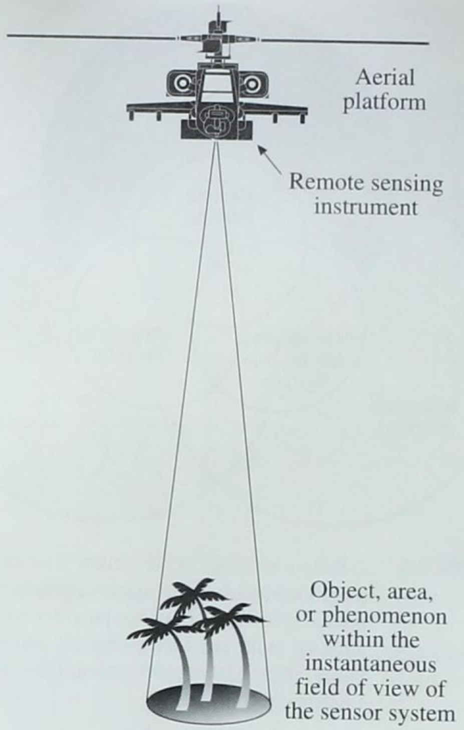


Figure 1-2 A remote sensing instrument collects information about an object or phenomenon within the instantaneous field of view of the sensor system without being in direct physical contact.

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

> *ASPRS Definition:* "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:

> *ASPRS Combined Definition:* "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 noncontact 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 underway 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). 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).

Maximal/Minimal Definitions

Numerous other definitions of remote sensing have been proposed. In fact, Colwell (1984) suggests that "one measure of the newness of a science, or of the rapidity with which it is developing is to be found in the preoccupation of its participating scientists with matters of terminology." Some have proposed an all-encompassing *maximal definition* where:

> *Maximal Definition:* "remote sensing is the acquiring of data about an object without touching it."

Such a definition is short, simple, general, and memorable. Unfortunately, it excludes little from the province of remote sensing (Fussell et al., 1986). It encompasses virtually all remote-sensing devices, including cameras, optical-mechanical scanners, linear and area arrays, lasers, radio-frequency receivers, radar systems, sonar, seismographs, gravimeters, magnetometers, and scintillation counters.

Others have suggested a more sharply focused, *minimalist definition* of remote sensing that adds qualifier after qualifier in an attempt to make certain that only legitimate functions are included in the term's definition. For example,

> *Minimal Definition:* "remote sensing is the noncontact recording of information from the ultraviolet, visible, infrared, and microwave regions of the electromagnetic spectrum by means of instruments such as cameras, scanners, lasers, linear arrays, and/or area arrays located on platforms such as aircraft or spacecraft, and the analysis of acquired information by means of visual and digital image processing."

Robert Green at NASA's Jet Propulsion Lab recently suggested we use the term *remote measurement* because data obtained using the new hyperspectral remote sensing systems are so accurate (Robbins, 1999). Each of the definitions are correct in an appropriate context. It is useful to briefly discuss components of these remote sensing definitions.

Remote Sensing: Art and/or Science?

Science: A *science* is defined as the broad field of human knowledge concerned with facts held together by *principles* (rules). Scientists discover and test these facts and principles by the scientific method, an orderly system of solving problems. Scientists generally feel that any subject that man 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) the *physical sciences*, such as physics and chemistry, 3) the *biological sciences*, such as botany and zoology, and the 4) *social sciences*, such as geography, sociology, and anthropology (Figure 1-3). Interestingly, some persons do not consider mathematics and logic as sciences. But the fields of knowledge associated with mathematics and logic are such valuable *tools* for science that we cannot ignore them. Man's earliest questions were concerned with "how many" and "what belonged together." He 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.

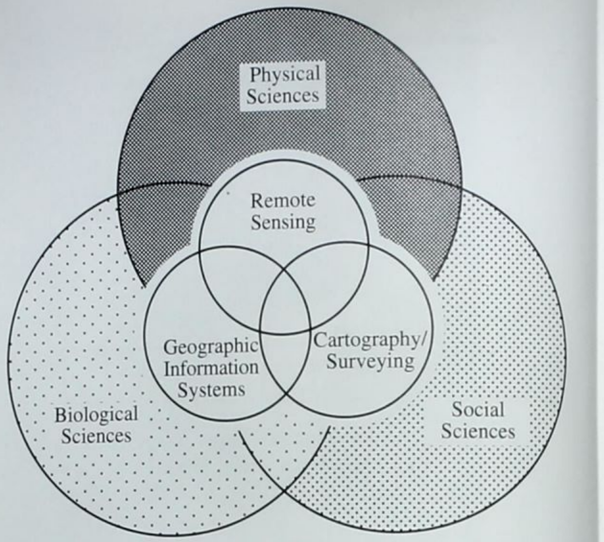


Figure 1-3 A three-way model of interaction between the mapping sciences of remote sensing, geographic information systems, and cartography/surveying as they are used in the physical, biological, and social sciences (after Dahlberg and Jensen, 1986; Fisher and Lindenberg, 1989).

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 (Fussell et al., 1986). It functions in harmony with other *spatial* data-collection techniques or tools of the *mapping sciences*, including cartography and geographic information systems (GIS) (Fussell et al., 1986; Curran, 1987). In fact, Dahlberg and Jensen (1986) and Fisher and Lindenberg (1989) suggest a model where there is three-way interaction between remote sensing, cartography, and GIS, 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 (Figure 1-3).

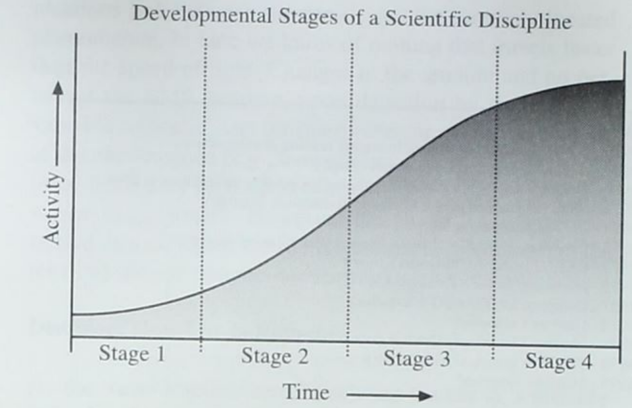


Figure 1-4 The developmental stages of a scientific discipline (adapted from Wolter, 1975; Jensen and Dahlberg, 1983).

The theory of science suggests that scientific disciplines go through four classic developmental stages. Wolter (1975) suggested that the growth of a discrete 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 absolute 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 (Wolter, 1975): 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.

Using this logic, it may be suggested that remote sensing is in Stage 2 of a scientific field, experiencing exponential growth since the mid-1960s with the number of publications doubling at regular intervals (Colwell, 1983; Cracknell and Hayes, 1993). Empirical evidence is presented in Table 1-1, including: 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) intense self-examination. We are 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 recently been a tremendous surge in the numbers of persons specializing in remote sensing and commercial firms using remote sensing during the 1990s (Davis, 1999). Significant improvements in the spatial resolution of satellite remote sensing (e.g., more useful 1 x 1 m panchromatic data) is expected to bring even more social science GIS practictioners 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 a lifetime. Such learning cannot be measured, programmed, or completely understood. The synergism of combining scientific knowledge with 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 much 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 first-hand, and 3) they can synthesize scientific principles and real-world knowledge to reach logical and correct conclusions. Thus, remote sensing 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 must be 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 described in this book 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 an extremely efficient high-speed commu-

Table 1-1. Major Milestones in Remote Sensing

1600 and 1700s
1687 - Sir Isaac Newton's *Principia* summarizes basic laws of mechanics

1800s
1826 - Joseph Nicephore Niepce takes first photographic image
1839 - Louis M. Daguerre invents positive print daguerrotype photography
1839 - William Henry Fox Talbot invents Calotype negative/positive process
1855 - James Clerk Maxwell postulates additive color theory
1858 - Gaspard Felix Tournachon takes first aerial photograph from a balloon
1860s- James Clerk Maxwell develops electromagnetic wave theory
1867 - The term *photogrammetry* is used in a published work
1873 - Herman Vogel extends sensitivity of emulsion dyes to longer wavelengths, paving the way for near-infrared photography

1900
1903 - Airplane invented by Wright Brothers (Dec 17)
1903 - Alfred Maul patents a camera used to obtain photographs from a rocket.

1910s
1910 - International Society for Photogrammetry (ISP) founded in Austria
1913 - First International Congress of ISP in Vienna
1914 - 1918 World War I photo-reconnaissance

1920s
1920 - 1930 Increase in civilian use of photointerpretation and photogrammetry
1926 - Robert Goddard launches liquid-powered rocket (Mar 16)

1930s
1934 - American Society for Photogrammetry (ASP) founded
1934 - *Photogrammetric Engineering* (ASP)
1938 - *Photogrammetria* (ISP)
1939 - 1945 World War II photo-reconnaissance advances

1940s
1940s - Radar invented
1940s - Jet aircraft invented by Germany
1942 - Kodak patents first false-color infrared film
1942 - Launch of German V-2 rocket by Wernher VonBraun (Oct 3)

1950s
1950s - Thermal infrared remote sensing invented by military
1950 - 1953 Korean War aerial reconnaissance
1953 - *Photogrammetric Record* (Photogrammetric Society, U.K.)
1954 - Westinghouse, Inc. develops side-looking airborne radar system
1955 - 1956 U.S. Genetrix balloon reconnaissance program
1956 - 1960 Central Intelligence Agency U-2 aerial reconnaissance program
1957 - Soviet Union launched *Sputnik* satellite (Oct 4)
1958 - United States launched *Explorer 1* satellite (Jan 31)

1960s
1960s - Emphasis primarily on visual image processing
1960s - Michigan Willow Run Laboratory active — evolved into ERIM
1960s- *Intl. Symp. on Remote Sensing of Environment* (ERIM)
1960s - Purdue Lab for Agricultural Remote Sensing (LARS) active
1960s - Forestry Remote Sensing Lab at U.C. Berkeley (Robert Colwell)
1960s - ITC– Delft, initiates photogrammetric education for students worldwide
1960s - Digital image processing initiated at LARS, Berkeley, Kansas, ERIM
1960s - Declassification of radar and thermal infrared sensor systems
1960 - 1972 United States Corona spy satellite program
1960 - *Manual of Photointerpretation* (ASP)
1960 - *Remote sensing* term introduced by Office of Naval Research personnel
1961 - Yuri Gagarin becomes first human to travel in space
1961 - 1963 Mercury space program
1962 - Cuban Missile Crisis — U-2 photo-reconnaissance shown to the public
1964 - SR-71 discussed in President Lyndon Johnson press briefing
1965 - 1966 Gemini space program
1965 - *ISPRS Journal of Photogrammetry & Remote Sensing*
1969 - *Remote Sensing of Environment*, Elsevier

1970s
1970s, 80s - Possible to specialize in remote sensing at universities
1970s -Digital image processing comes of age
1970s -Remote sensing integrated with digital geographic information systems
1972 - ERTS-1 launched (Earth Resource Technology Satellite)
1973 - 1979 Skylab program
1973 - *Canadian Journal of Remote Sensing* (Canadian RS Society)
1975 - ERTS-2 launched (renamed Landsat 2)
1975 - *Manual of Remote Sensing* (ASP)
1977 - European METEOSAT-1 launched
1978 - Landsat 3 launched
1978 - Nimbus 7 launched - Coastal Zone Color Scanner
1978 - TIROS-N launched with AVHRR sensor
1978 - SEASAT launched

1980s
1980s - AAG Remote Sensing Specialty Group > 500 members
1980s - Commercialization attempted – EOSAT, Inc.
1980 - ISP becomes Intl. Soc. for Photogrammetry & Remote Sensing
1980 - *Intl. Journal of Remote Sensing* (Remote Sensing Society)
1980 - European Space Agency (ESA) created (Oct 30)
1980 - *IEEE Trans. Geoscience and Remote Sensing* (GRSS Society)
1981 - First *Intl. Geoscience and Remote Sensing Symposium*
1981 - NASA Space Shuttle program initiated (STS-1)
1981 - NASA Space Shuttle Imaging Radar (SIR - A) launched
1982 - Landsat 4 - Thematic Mapper and MSS launched
1983 - *Manual of Remote Sensing*, 2nd Ed. (ASP)
1983 - *Remote Sensing Reviews*
1984 - Landsat 5 - Thematic Mapper launched
1984 - NASA Space Shuttle Imaging Radar (SIR-B) launched
1986 - SPOT Image, Inc., launched SPOT 1
1986 - *Geocarto International* (Geocarto International Center)
1989 - *The Earth Observer* (NASA Goddard Space Flight Center)

1990s
1990s - Digital soft-copy photogrammetry comes of age
1990s - University degree programs in remote sensing available
1990s - NASA assists commercial use of remote sensing (Stennis Space Center)
1990s - Increased use of hyperspectral and LIDAR sensors
1990 - *Backscatter* (Alliance for Marine Remote Sensing Association)
1990 - SPOT Image, Inc., launched SPOT 2
1991 - NASA initiates "Mission to Planet Earth" (Goddard Space Flight Center)
1991 - European ERS-1 launched
1992 - U.S. Land Remote Sensing Policy Act becomes law
1993 - EOSAT Inc., Landsat 6 did not achieve orbit
1993 - SPOT Image, Inc., launched SPOT 3
1993 - NASA Space Shuttle Imaging Radar (SIR-C) launched
1995 - Canadian RADARSAT-1 launched
1995 - ERS-2 launched
1995 - Indian IRS-1C launched (5 x 5 m)
1995 - Corona imagery declassified, transferred to National Archives
1995 - *The Earth Observer* (EOS-Goddard)
1996 - *Manual of Photographic Interpretation*, 2nd Ed. (ASPRS)
1997 - *Addendum to Manual of Photogrammetry* (ASPRS)
1997 - EarthWatch, Inc., lost contact with Earlybird satellite
1998 - NASA MTPE redefined as "Earth Science Enterprise"
1998 - *Manual of Remote Sensing - Radar* (ASPRS)
1998 - SPOT Image, Inc., launched SPOT 4
1999 - *Manual of Remote Sensing - Geosciences* (ASPRS)
1999 - NASA Landsat 7 Enhanced Thematic Mapper Plus launched (April 15)
1999 - Space Imaging, Inc., IKONOS did not achieve orbit (Apr 27)
1999 - Space Imaging, Inc., launched a second IKONOS (Sept 24)
1999 - NASA *Terra* Earth observing system launched

2000 – 2001
2000 - NASA to initiate New Millennium Program
2000 - OrbView 3,4 to be launched by ORBIMAGE, Inc.
2000 - Quickbird to be launched by EarthWatch, Inc.
2001 - European Space Agency to launch Envisat

nications link between the sensor and the remotely located 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, including sound waves (e.g., sonar). However, the majority of remotely sensed data collected for Earth resource applications are the result of sensors that record electromagnetic energy.

Distance: How Far Is Remote?

As the name implies, 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 distance could be 1 meter, 100 meters, or > 1 million meters from the object or area of interest. In fact, virtually all astronomy is based on remote sensing. 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, Io, Saturn, Jupiter, etc. Remote sensing science conducted by the Jet Propulsion Laboratory at the California Institute of Technology is particularly noteworthy. 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 techniques may also be used to analyze inner space. For example, an electron microscope and associated hardware may be used to obtain photographs of extremely small objects on the skin, in the eye, etc. Similarly, an X-ray device is a remote sensing instrument where the skin and muscle are equivalent to the atmosphere that must be penetrated, and the interior bone or other matter is often 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 often programmed to collect data systematically, such as within a single 9 x 9 in. frame of vertical aerial photography or a matrix (raster) of Landsat image data. This systematic data collection can remove the sampling bias introduced in some *in situ* investigations.

Under carefully controlled conditions, remote sensing can provide fundamental biophysical data, including: x,y location, z elevation or depth, biomass, temperature, moisture content, etc. In this sense it is much like surveying, providing fundamental data that other sciences can use when conducting scientific investigations. However, unlike much of surveying, the remotely sensed data may be obtained systematically over very large geographic areas rather than just single point observations.

Remote sensing is also different from the other mapping sciences such as cartography or GIS because they rely on data produced elsewhere. Remote sensing science yields fundamental scientific information. For example, a properly calibrated thermal infrared remote sensing system can provide a geometrically correct map of land- or sea-surface temperature without any other intervening science. 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 processes (e.g., land-use conversion at the urban fringe; water-demand estimation; population estimation) (Walsh et al., 1999). A good example is the digital elevation model that is so important in many spatially distributed GIS models. Digital elevation models are now produced almost exclusively through the analysis of remotely sensed data.

Limitations

Remote sensing science has limitations. Perhaps the greatest limitation is that its utility is often oversold. *It is not a panacea* that will provide all the information needed for conducting physical, biological, or social science. It simply provides some spatial, spectral, and temporal information of value.

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

Powerful *active* remote sensor systems, such as lasers or radars that emit their own electromagnetic radiation, can be intrusive and affect the phenomenon being investigated.

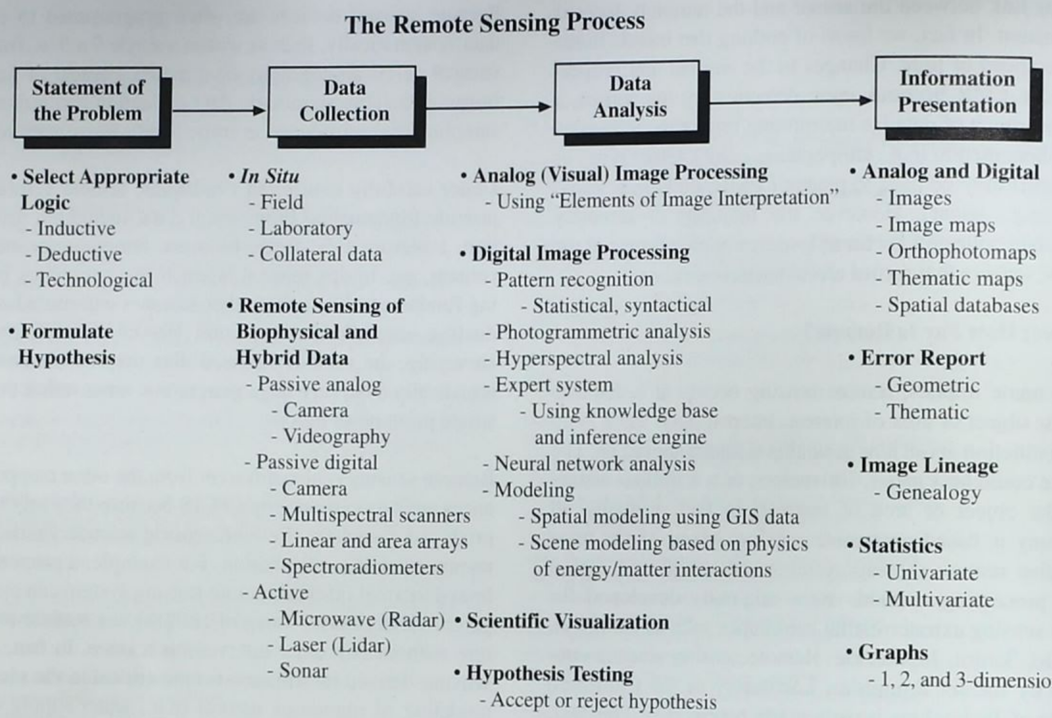


Figure 1-5 Scientists generally follow the remote sensing process when attempting to extract information from remotely sensed data.

Additional research is required to determine how intrusive these active sensors are.

Remote sensing instruments like *in situ* instruments often become uncalibrated, resulting in uncalibrated remote sensor data. Finally, remote sensor data may be expensive to collect and interpret or analyze. Hopefully, the information derived from the remote sensor data is of such value that the expense is warranted.

The Remote Sensing Process

Scientists have been developing procedures for collecting and analyzing remotely sensed data for more than 140 years. The first known 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 War I and II, the Korean conflict, the Cuban Missile Crisis, the Vietnam War, the Gulf War, and the war in Bosnia. Many of the accomplishments are summarized in Table 1-1 and in Chapter 3 (History of Aerial Photography and Aerial Platforms). 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 Chapters 7, 8, and 9, respectively. While the majority of the remote sensing systems may have been initially developed for military reconnaissance applications, the systems are 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 remote sensing process are summarized in Figure 1-5:

- statement of the problem,
- data collection,
- data analysis, and

- presentation of the information so that informed decisions can be made.

It is useful to review the characteristics of these procedures.

Statement of the Problem

The average man or woman and some children can look at aerial photography or other remote sensor data and extract some useful information from it. Generally, they do not interpret the images with any particular plan or hypothesis to test. Unfortunately, it is likely that they may make serious interpretation errors because they do not understand the nature of the remote sensing system used to acquire the data or appreciate the vertical or oblique perspective of the terrain recorded in the imagery.

Scientists who use remote sensing, however, are usually trained in the *scientific method* — a way of thinking about problems and solving them. The formal plan has at least five elements, including: 1) stating the problem, 2) forming the 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.

Three methodologies or types of logic may be used to structure the problem, such as (Curran, 1987):

- inductive logic,
- deductive logic, and/or
- technological logic.

Inductive logic involves observation, classification, generalization, and theory formulation. Inductive logic is used to build an objective description of observed facts or phenomena, which are then shaped and ordered to derive theory and thereby knowledge. Using inductive logic, the procedure starts with a large number of observations (*n*) that are true and hopefully unbiased. For example, we may observe on thousands of aerial images that:

> All healthy green mangrove forests appear red (magenta) on properly exposed color-infrared film.

Before such a theory can be considered legitimate, three conditions must be satisfied: 1) the number of observations must be large, 2) the observation must be repeated under a wide range of conditions, and 3) no accepted observation should *ever* conflict with the derived theory. The most serious limitation of inductive logic is that no number of apparently confirming observations can ever show that a theory is completely true.

The pursuit of knowledge using *deductive* logic has an emphasis not on observation but on the formulation of theory and the testing of hypotheses (Curran, 1987). Typically, the scientist states the problem and puts forth a speculative theory to solve that problem. He or she then puts forth a hypothesis (possible explanation). Observations are then made, often involving remote sensing imagery and *in situ* measurements made at unbiased locations. The null hypothesis is then tested at specific statistical confidence levels (e.g., 0.05 or 0.001). If the observations are such that the null hypothesis can be rejected, then the theory can be considered acceptable in the guarded sense that there is not an empirical basis for doubting its validity. If the observations do not support rejection (falsification) of the null hypothesis, then we must go back to our problem and evaluate other possible explanations that might lead to a falsifiable hypothesis.

For example, suppose we visited 100 mangrove forest sites in Florida and obtained color-infrared aerial photographs at each of the sites. We might develop the following null hypothesis:

> There is no significant relationship between healthy green mangrove forest and a red (magenta) appearance on properly exposed color-infrared film.

If the healthy green mangrove forest at 99 of the 100 sites did indeed have a red (magenta) appearance in the corresponding color-infrared film, then it would be possible for us statistically to reject (falsify) the null hypothesis. We could then state that there appears to be a statistically significant relationship between healthy green vegetation and the red (magenta) appearance on properly exposed color-infrared film. Unfortunately, there is a tendency to suggest that whenever a null hypothesis is not rejected, that either the sensor was not working properly or the ground reference data were in error, i.e., the observations are in doubt, not the theory. Fortunately, scientists wait until a theory is tested numerous times before it is accepted or rejected (Curran, 1987).

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 what some call *applied remote sensing*. The approach can also generate new knowledge.

Remote sensing is used in both scientific (inductive and deductive) and technological approaches to gain knowledge. There is debate as to how the different types of logic used in the remote sensing process and in GIS yield new scientific knowledge (e.g., Fussell et al., 1986; Curran, 1987; Fisher and Lindenberg, 1989; Ryerson, 1989; Duggin and Robinove, 1990; Dobson, 1993; Wright et al., 1997).

Identification of In Situ and Remote Sensing Data Requirements

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

In Situ Data Requirements

Scientists using remote sensing technology should be well trained in field and laboratory data-collection procedures. For example, if a scientist wants to measure the surface temperature of a lake, it is usually essential that some accurate *in situ* lake-temperature measurements be obtained at the same time the remote sensor data are collected. These *in situ* observations may be used to 1) calibrate the remote sensor data, and 2) perform an unbiased accuracy assessment of the final results (Congalton and Green, 1998). Remote sensing textbooks provide some information on field and laboratory sampling techniques. The *in situ* sampling procedures, however, are learned best through formal courses in the sciences (e.g., chemistry, biology, forestry, soils, hydrology, meteorology). In addition, methods of collecting socioeconomic and demographic information in urban environments is often essential (e.g., cultural geography, sociology).

Most *in situ* data are now collected in conjunction with accurate x, y, z global positioning system (GPS) data (Jensen and Cowen, 1999). Scientists should know how to collect the fundamental GPS data and then perform differential correction to obtain the most accurate x, y, z coordinate information. Sometimes *collateral* data (often called *ancillary* data), such as soil maps, political boundary files, and block population statistics, collected by other scientists are of value in the remote sensing process. Ideally, these spatial collateral data reside in a digital GIS.

Usually it is necessary to collect both *in situ* and remotely sensed data because each type of data may be used to calibrate the other. For example, some *in situ* studies sample the environment and obtain county or statewide data such as population density. Remote sensing data can be used to disaggregate this sampled data. The spatial distribution of single- and multiple-family dwellings can be easily identified in high-resolution aerial photography. Such information may be used to disaggregate the population density within a county rather than assuming that the population is spread uniformly throughout the entire county. Similarly, a digital elevation model may be used to identify north-facing slopes and specific ranges of elevation (e.g., 1000 – 2000 m above sea level). Such information is very valuable when conducting a remote sensing vegetation study of mountainous terrain, where certain vegetation types only grow on north-facing slopes at an elevation of 1000 – 2000 m above sea level.

Remote Sensing Data Requirements

Once we have a list of variables, it is useful to determine those that can be remotely sensed. Remote sensing can provide information on two different classes of variables: *biophysical* and *hybrid*. Biophysical variables may be measured directly by the remote sensing system. This means that the remotely sensed data can provide fundamental biological and/or physical (*biophysical*) information directly, without having to use other surrogate or ancillary data. For example, a thermal infrared sensor can record the apparent temperature of a rock outcrop by measuring the radiant flux emitted from its surface. Similarly, it is possible to conduct remote sensing in a very specific region of the spectrum and identify the amount of water vapor in the atmosphere. It is also possible to measure soil moisture content directly using microwave remote sensing techniques (Engman and Chauhan, 1995). All three of these are true biophysical measurements. Such data are useful in physical science models.

Another example is the determination of the precise x, y location and height (z) of an object. Such information can be extracted directly from stereoscopic aerial photography, overlapping satellite imagery (e.g., SPOT) or interferometric radar imagery. A list of selected biophysical variables that can be remotely sensed and useful sensors to acquire such data are found in Table 1-2. The characteristics of most of these sensor systems are discussed in Chapters 7, 8, and 9. Great strides have been made in remotely sensing many of these biophysical variables (Eidenshink, 1992; ESA, 1992). They are important to the national and international effort under way to model the global environment (Lousma, 1993; Asrar and Dozier, 1994; Jones et al.,1997).

Table 1-2. Biophysical and Hybrid Variables and Potentially Useful Remote Sensing Systems (proposed sensor systems are in italics)

Biophysical Variables	Potential Remote Sensing System
x, y Geographic location	Aerial photography, Landsat TM, SPOT HRV, Russian KVR-1000, IRS-1CD, ATLAS, Radarsat, ERS-1,2 microwave, Landsat 7 ETM$^+$, Space Imaging IKONOS, Terra *MODIS, ASTER, EarthWatch Quickbird, ORBIMAGE OrbView 3,4*
z Topographic/bathymetric	Aerial photography, TM, SPOT, IRS-1CD, Radarsat, LIDAR systems, ETM, IKONOS, *ASTER, Quickbird, OrbView 3,4*
Vegetation	
chlorophyll concentration	Air photos, TM, SPOT, IRS-1CD, ETM, IKONOS, *ASTER, MODIS, OrbView 3,4*
biomass (green & dead)	Air photos, AVHRR, TM, SPOT, IRS-1CD, ETM, IKONOS, *MODIS, OrbView 3,4*
foliar water content	Radarsat, ERS-1,2; TM Mid-IR, ETM, IKONOS, *MODIS, ASTER, OrbView 3,4*
Absorbed photosynthetically active radiation	ETM, IKONOS, *MODIS, OrbView 3,4*
phytoplankton	SeaWiFS, TM, AVHRR, ETM, IKONOS, *MODIS, OrbView 3,4*
Surface temperature	GOES, SeaWiFS, AVHRR, TM, Daedalus, ATLAS, ETM, *ASTER, MODIS*
Soil moisture	ALMAZ, TM, ERS-1,2; Radarsat, Intermap Star 3i, IKONOS, *ASTER, OrbView 3,4*
Surface roughness	Air photos, ALMAZ, ERS-1,2; Radarsat, Star 3i, IKONOS, *ASTER, OrbView 3,4*
Evapotranspiration	AVHRR, TM, SPOT, CASI, ETM, *MODIS, ASTER*
Atmosphere tropospheric chemistry, temperature, water vapor, wind speed/direction, energy inputs, precipitation, cloud and aerosol properties	GOES, UARS, ATREM, *MODIS, MISR, CERES, MOPITT*
BRDF (bidirectional reflectance distribution function)	*MODIS, MISR, CERES*
Ocean color, phytoplankton, biochemistry, sea height	TOPEX/POSEIDON, SeaWiFS, ETM, IKONOS, *MODIS, MISR, ASTER, CERES, OrbView 3,4*
Snow and sea ice extent and characteristics	Aerial photography, AVHRR, TM, SPOT, Radarsat, SeaWiFS, IKONOS, ETM, *MODIS, ASTER, OrbView 3,4; Quickbird*
Volcanic effects temperature, gases	ATLAS, *MODIS, MISR, ASTER*
Selected Hybrid Variables	**Potential Remote Sensing System**
Land use urban infrastructure and land use	Aerial photography, AVHRR, TM, SPOT, Russian KVR-1000, IRS-1CD, Radarsat, Star 3i, ETM, IKONOS, *MODIS, ASTER, OrbView 3,4; Quickbird*
Vegetation stress	Aerial photography, Daedalus, ATLAS, AVHRR, TM, SPOT, IRS-1CD, IKONOS, SeaWiFS, ETM, *MODIS, ASTER, OrbView 3,4; Quickbird*

The second general group of variables that may be remotely sensed include *hybrid* variables, created by systematically analyzing more than one biophysical variable. For example, by remotely sensing a plant's chlorophyll absorption characteristics, temperature, and moisture content, it may be possible to model these data to detect vegetation stress, a hybrid variable. The variety of hybrid variables is large; consequently, no attempt is made to identify them. It is important to point out, however, that nominal-scale land-cover mapping is a hybrid variable. The land cover of a particular area on an image is usually derived by evaluating several of the fundamental biophysical variables at one time [e.g., object tone or color, location (x, y), height (z), and perhaps temperature]. So much attention has been placed on remotely sensing this hybrid *nominal*-scale variable that the *interval*- or *ratio*-scaled biophysical variables have been neglected until the last decade. Nominal-scale land-use mapping is an important capability of remote sensing technology and should not be minimized. In fact, many social and physical scientists routinely use such data in their research. However, we now see a dramatic increase in the extraction of interval- and ratio-scaled biophysical data that are so valuable when incorporated into quantitative models that can accept spatially distributed information (e.g., Asrar and Dozier, 1994; Moran et al., 1997; NASA, 1998).

Remote Sensing Data Collection

Remotely sensed data are collected using either passive or active remote sensing systems. *Passive* sensors record naturally occurring electromagnetic radiation that is reflected or emitted from the terrain. For example, cameras and video recorders may be used to record visible and near-infrared energy reflected from the terrain, and a multispectral scanner may be used to record the amount of thermal radiant flux emitted from the terrain. *Active* sensors such as microwave (radar) or sonar bathe the terrain in man-made electromagnetic energy and then record the amount of radiant flux scattered back toward the sensor system.

Remote sensing systems collect analog (e.g., hard-copy aerial photography or video data) and/or digital data [e.g., a matrix (raster) of brightness values obtained using a scanner, linear array, or area array]. A selected list of some of the most important current and proposed remote sensing systems is presented in Table 1-3.

Sensor Resolution

Each remote sensing system has four major resolutions associated with it. These resolutions should be understood by the scientist in order to extract meaningful biophysical or hybrid information from the remotely sensed imagery. *Resolution* (or resolving power) is defined as a measure of the ability of an optical system to distinguish between signals that are spatially near or spectrally similar.

Spectral Resolution: This refers to the number and dimension of specific wavelength intervals in the electromagnetic spectrum to which a remote sensing instrument is sensitive. The Landsat Multispectral Scanner (MSS) provided a tremendous amount of remotely sensed data of much of the Earth which is still of significant value for historical studies. The bandwidths of the four MSS bands are displayed in Figure 1-6a (band 1 = 0.5 – 0.6 µm; band 2 = 0.6 – 0.7 µm; band 3 = 0.7 – 0.8 µm; and band 4 = 0.8 – 1.1 µm). The nominal size of a band may be large (i.e., coarse), as with the Landsat MSS near-infrared band 4 (0.8 – 1.1 µm) or relatively smaller (i.e., finer), as with the Landsat MSS band 3 (0.7 – 0.8 µm). Thus, Landsat MSS band 4 detectors record a relatively large range of reflected near-infrared radiant flux (300 nm) while the MSS band 3 detectors record a much reduced range of near-infrared radiant flux (100 nm).

The four spectral bandwidths associated with the Positive Systems, Inc. ADAR 5500 digital frame camera are shown for comparative purposes (Figure 1-6a). The frame camera's bands are refined to record information in more specific regions of the electromagnetic spectrum (band 1 = 450 – 515 nm; band 2 = 525 – 605 nm; band 3 = 640 – 690 nm; and band 4 = 750 – 900 nm). In fact, there are gaps in the spectral sensitivity of the detectors. Note that this digital camera system is also sensitive to reflected blue wavelength energy.

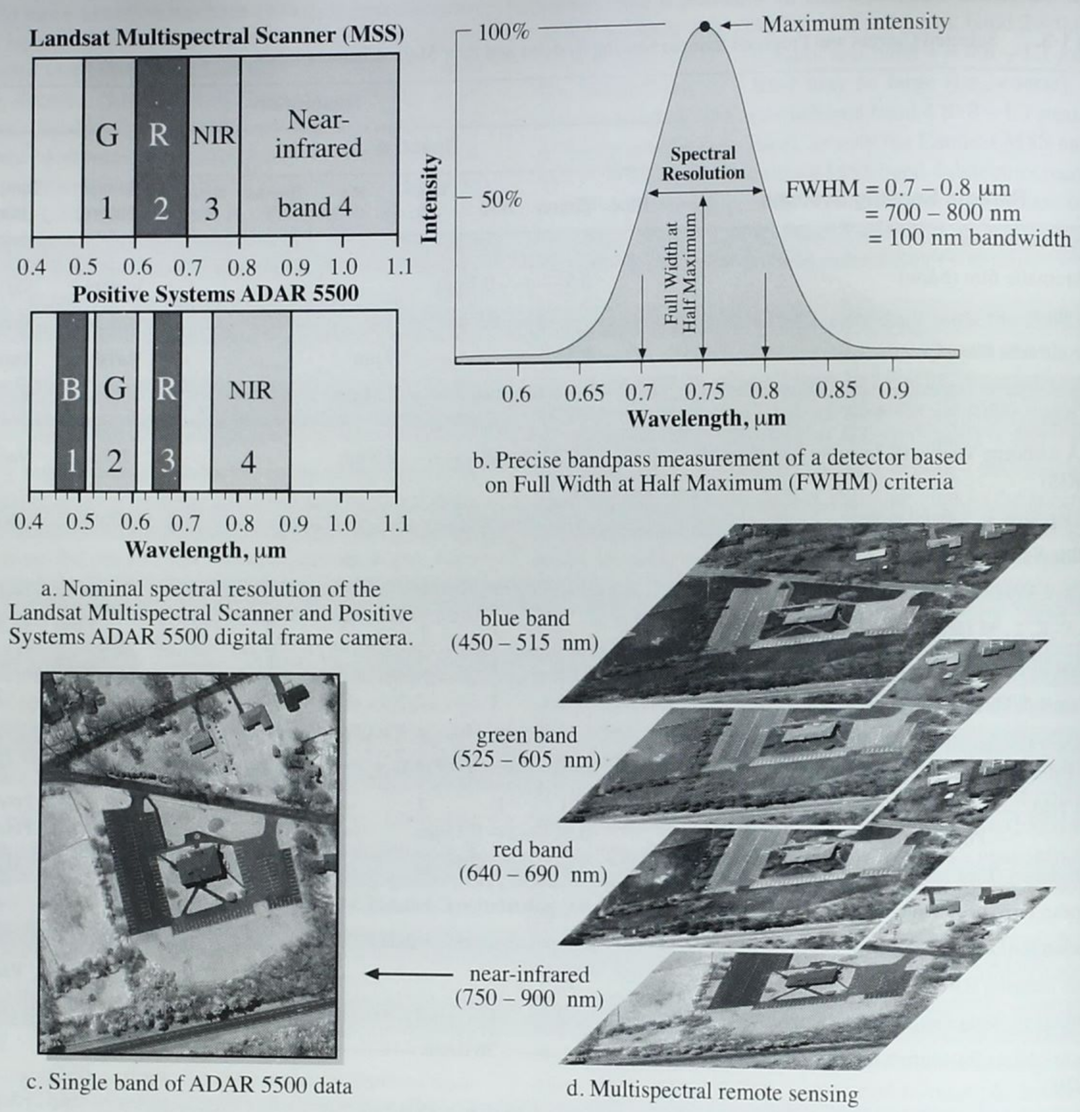
The aforementioned terminology is typically used to describe a sensor's *nominal spectral resolution*. Unfortunately, it is difficult to create a detector that has extremely sharp bandpass boundaries such as those shown in Figure 1-6a. Rather, the more precise method of stating bandwidth is to look at the typical Gaussian-shape of the detector sensitivity, such as the example shown in Figure 1-6b. The analyst then determines the Full Width at Half Maximum (FWHM). In this hypothetical example, the Landsat MSS near-infrared band 3 under investigation is sensitive to energy between 0.7 and 0.8 µm (700 – 800 nm).

Remote sensing systems may be configured to collect data in just a single band or region of the electromagnetic spectrum. For example, an ADAR 5500 band 4 near-infrared image is displayed in Figure 1-6c. *Multispectral* remote sensing takes place when radiant energy is recorded in multiple bands of the electromagnetic spectrum. The ADAR 5500 usually acquires four multispectral bands of imagery during a mission (Figure 1-6d). A *hyperspectral* remote sensing instrument acquires data in hundreds of spectral bands. For example, the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) has 224 bands in the region from 0.4 – 2.5 µm spaced just 10 nm apart based on the FWHM criteria (Clark, 1999). An AVIRIS hyperspectral datacube of Sullivan's Island, SC, is shown in Figure 1-7.

Certain regions or bands of the electromagnetic spectrum are optimum for obtaining information on biophysical parameters. The bands are normally selected to maximize the con-

Table 1-3. Selected Current and Proposed Remote Sensing Systems and their Major Characteristics

	Resolution								
	Spectral								
Remote Sensing Systems	**Blue**	**Green**	**Red**	**Near-IR**	**Mid-IR**	**Thermal IR**	**Micro-wave**	**Spatial (meters)**	**Temporal (days)**
Suborbital Sensors									
Panchromatic film (b&w)		0.5 —— 0.7 µm						Variable	Variable
Color film	0.4 —— 0.7 µm							Variable	Variable
Color-infrared film		0.5 —— 0.9 µm						Variable	Variable
NASA Airborne Terrestrial Applications Sensor (ATLAS)	0.45 —— 8 bands —— 2.35 µm					6	—	2.5 to 25	Variable
NASA Airborne Visible IR Imaging Spectrometer (AVIRIS)	0.41 —— 224 bands —— 2.5 µm							2.5 or 20	Variable
Intermap Star-3i X-band radar							1	Variable	Variable
Satellite Sensors									
NOAA-9 AVHRR LAC	—	—	1	1	—	3	—	1100	14.5/day
NOAA- K, L, M (proposed)	—	—	1	1	2	2	—	1100	14.5/day
Landsat Multispectral Scanner (MSS)	—	1	1	2	—	—	—	79	16–18
Landsat 4-5 Thematic Mapper (TM)	1	1	1	1	2	1	—	30 and 120	16
Landsat 7 Enhanced TM (ETM$^+$) — Multispectral	1	1	1	1	2	1	—	30 and 60	16
— Panchromatic	—	0.52 —— 0.9 µm			—	—	—	15	16
SPOT HRV — Multispectral	—	1	1	1	—	—	—	20	Pointable
— Panchromatic		0.51 —— 0.73 µm			—	—	—	10	Pointable
GOES Series (East and West)	—	0.52 —— 0.72 µm			—	4	—	700	0.5/hr
European Remote Sensing Satellite (ERS-1,2)		VV polarization C-band (5.3 GHz)					1	26 – 28	—
Canadian RADARSAT (several modes)		HH polarization C-band (5.3 GHz)					1	9 to 100	1–6 days
Shuttle Imaging Radar (SIR-C)	—	—	—	—	—	—	3	30	Variable
Sea-Viewing Wide Field-of-View Sensor (SeaWiFS)	3	2	1	2	—	—	—	1130	1
Terra Moderate Resolution Imaging Spectrometer (*MODIS*)	0.405 —— 36 bands —— 14.385 µm						—	250, 500, 1000	1-2
Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (*ASTER*)		0.52 — 3 bands — 0.86 µm						15	5
				1.6 – 6 bands – 2.43 µm				30	16
				8.12 – 5 bands – 11.6 µm				90	16
Terra Multiangle Imaging SpectroRadiometer (*MISR*)	Nine CCD cameras in four bands (440, 550, 670, 860 nm)							275 and 1100	
NASA Topex/Poseidon — TOPEX radar altimeter				(18, 21, 37 GHz)				315 km	10
— POSEIDON single-frequency radiometer				(13.65 GHz)					
NASA Upper Atmosphere Research Satellite (UARS): includes 9 sensors.									
Space Imaging IKONOS — Multispectral	1	1	1	1			—	4	Pointable
— Panchromatic	0.45 —— 0.9 µm					—	—	1	
ORBIMAGE Orbview 3 — Multispectral	1	1	1	1			—	4	Pointable
— Panchromatic	0.45 —— 0.9 µm				—	—	—	1	



a. Nominal spectral resolution of the Landsat Multispectral Scanner and Positive Systems ADAR 5500 digital frame camera.

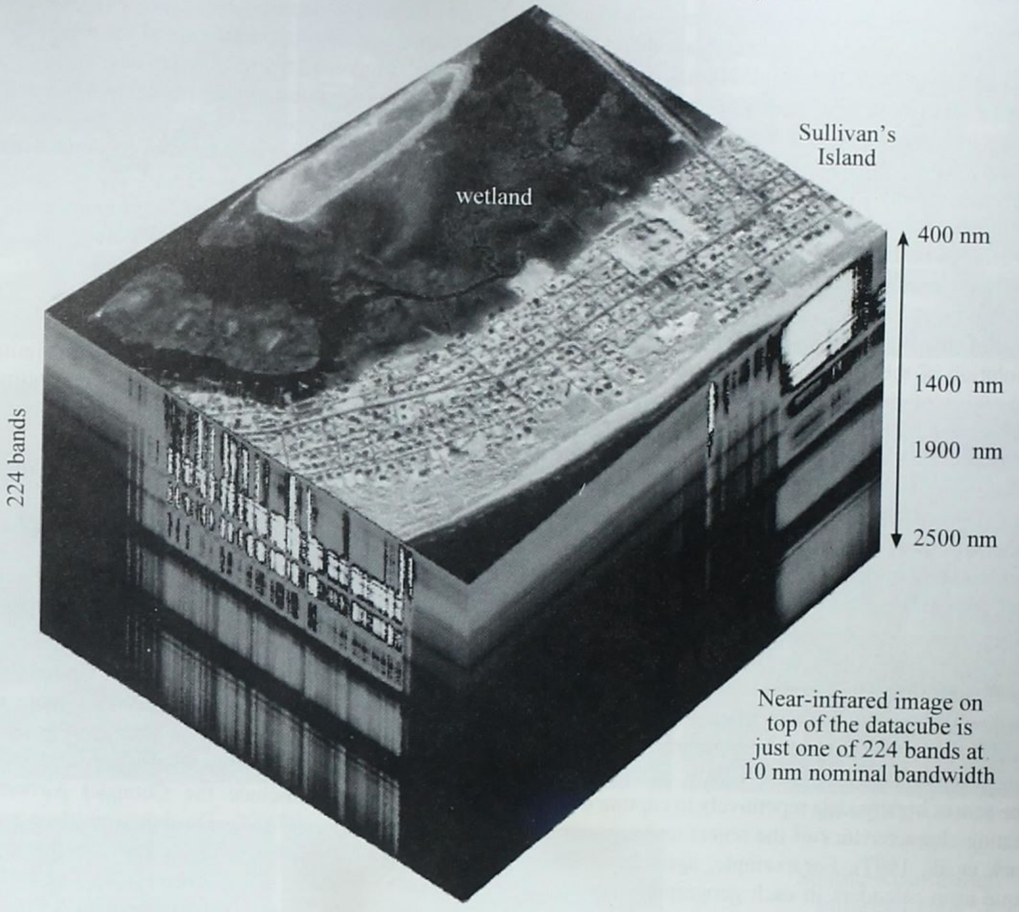
b. Precise bandpass measurement of a detector based on Full Width at Half Maximum (FWHM) criteria

c. Single band of ADAR 5500 data

d. Multispectral remote sensing

Figure 1-6 a) The spectral bandwidths of the four Landsat Multispectral Scanner (MSS) bands (green, red, and two near-infrared) compared with the bandwidths of the Positive Systems ADAR 5500 digital frame camera. b) The true spectral bandwidth is the width of the Gaussian-shaped spectral profile at Full Width at Half Maximum (FWHM) intensity (after Clark, 1999). This example has a spectral bandwidth of 0.1 μm (100 nm) between 700 and 800 nm. c) If desired, it is possible to collect reflected energy in a single band of the electromagnetic spectrum (e.g., 750 – 900 nm). d) Multispectral remote sensing instruments such as the ADAR 5500 collect data in multiple bands of the electromagnetic spectrum (images courtesy of Positive Systems, Inc.).

Airborne Visible Infrared Imaging Spectrometer (AVIRIS) Datacube of Sullivan's Island, SC, Obtained on October 26, 1998



Near-infrared image on top of the datacube is just one of 224 bands at 10 nm nominal bandwidth

Figure 1-7 Hyperspectral remote sensing of Sullivan's Island, SC, on October 26, 1998, using NASA's Airborne Visible Infrared Imaging Spectrometer (AVIRIS). The spatial resolution is 2.5 x 2.5 m. The atmosphere absorbs most of the electromagnetic energy near 1.4 and 1.9 μm (Meisburger and Jensen, 1999; datacube courtesy of NASA Jet Propulsion Laboratory).

trast between the object of interest and its background (i.e., object-to-background contrast). Careful selection of the spectral bands may improve the probability that a feature will be detected and identified and biophysical information extracted.

Spatial Resolution: There is a relationship between the size of a feature to be identified and the spatial resolution of the remote sensing system. *Spatial resolution* is a measure of the smallest angular or linear separation between two objects that can be resolved by the sensor. The spatial resolution of aerial photography may be measured by 1) placing carefully calibrated, parallel black-and-white lines on tarps that are placed in the field, 2) obtaining aerial photography of the study area, and 3) analyzing the photography and computing the number of resolvable *line pairs per millimeter* in the photography. It is also possible to determine the spatial resolution of imagery by computing its modulation transfer function, which is beyond the scope of this text.

Many satellite remote sensing systems operate in fixed orbits with fixed optical systems that have a constant instantaneous-field-of-view (IFOV). For practical purposes, therefore, we define a sensor system's nominal spatial resolution as simply the dimension in meters (or feet) of the ground-projected IFOV. For example, the SPOT panchromatic band has a nominal spatial resolution of 10 x 10 m, the Landsat Thematic Mapper has a nominal spatial resolution of 30 × 30 m for six of its bands, and the Landsat MSS has a nominal spatial resolution of 79 x 79 m. Generally, the smaller the spatial resolution, the greater the resolving power of the sensor system. Figure 1-8 depicts digital camera imagery of an area in Mechanicsville, N.Y. at resolutions ranging from 0.5 x 0.5 m to 80 x 80 m. Note that there is not a significant difference in the interpretability of 0.5 x 0.5 m data, 1 x 1 m data, and even 2 x 2 m data. However, the urban information content decreases rapidly when using 5 x 5 m imagery and is practically useless for urban analysis at spatial resolutions larger than 10 x 10 m. Landsat MSS data is particularly useless (79 x 79 m) for most urban applications.

Another useful rule is that in order to detect a feature, the spatial resolution of the sensor system should be less than one-half the size of the feature measured in its smallest dimension. For example, if we want to identify the location of all oak trees within a city park, the minimum acceptable spatial resolution would be approximately one-half the diameter of the smallest oak tree crown. Even this spatial resolution, however, will not guarantee success if there is no difference between the spectral response of the oak tree (the object) and the soil or grass surrounding it (i.e., its background).

Temporal Resolution: The *temporal resolution* of a remote sensing system refers to how often it records imagery of a particular area. For example, the temporal resolution of the sensor system shown in Figure 1-9a is every 16 days. Ideally, the sensor obtains data repetitively to capture unique discriminating characteristics of the object under investigation (Haack et al., 1997). For example, agricultural crops have unique crop calendars in each geographic region. To measure specific agricultural variables, it is necessary to acquire remotely sensed data at critical dates in the phenological cycle. Analysis of multiple-date imagery provides information on how the variables are changing through time. Change information provides insight into processes influencing the development of the crop (Steven, 1993). Fortunately, several satellite sensor systems such as SPOT are pointable, meaning that they can acquire imagery off-nadir (*nadir* is the point directly beneath the spacecraft) if necessary. This dramatically increases the probability that imagery might be obtained during a growing season or during an emergency. However, the off-nadir oblique viewing also introduces bidirectional reflectance distribution function (BRDF) issues that are addressed in Chapter 10 (Remote Sensing of Vegetation).

Radiometric Resolution: This is defined as the sensitivity of a remote sensing detector to differences in signal strength as it records the radiant flux reflected or emitted from the terrain. It defines the number of just discriminable signal levels; consequently, it can have a significant impact on our ability to measure the properties of scene objects. For example, the original multispectral scanner (MSS) onboard Landsat 1 recorded the reflected radiant energy with a precision of 6-bits (values ranging from 0 to 63). Landsat 4 and 5 Thematic Mapper recorded data in 8-bits (values from 0 to 255). Thus, the Landsat TM sensor had improved radiometric resolution when compared with the original MSS. Several new sensor systems have 12-bit radiometric resolution (values ranging from 0 to 4095) (Figure 1-9b).

Improvements in resolution generally increase the probability that phenomena may be remotely sensed more accurately. The trade-off is that any improvement in resolution will usually require additional data-processing capability for either human or computer-assisted analysis.

Suborbital (Airborne) Remote Sensing Systems

High-quality metric cameras mounted onboard aircraft continue to provide aerial photography for many Earth resource applications. For example, the U.S. Geological Survey's National Aerial Photography Program (NAPP) systematically collects 1:40,000-scale black-and-white or color-infrared aerial photography of much of the United States every 5 to 10 years. In addition, sophisticated remote sensing systems are routinely mounted on aircraft to provide high spatial and spectral resolution multispectral remotely sensed data. Examples include the Compact Airborne Spectrographic Imager (CASI), Daedalus multispectral scanners, and NASA's Airborne Terrestrial Applications Sensor (ATLAS) (Table 1-3). These sensors can collect data on demand when disaster strikes (e.g., oil spills or floods) if cloud-cover conditions permit. There are also numerous radars, such as Intermap's Star-3i radar, that can be flown on aircraft day and night and in inclement weather. Unfortunately, suborbital remote sensor data are usually expensive to acquire per km^2. Also, atmospheric turbulence can cause the data to have severe geometric distortions that can be quite difficult to correct.

Current and Proposed Satellite Remote Sensing Systems

Remote sensing systems onboard satellites provide high-quality, relatively inexpensive data per km^2. For example, the European Remote Sensing Satellite (ERS-1,2) collects 26 × 28 m spatial resolution C-band active microwave (radar) imagery of much of Earth, even through clouds. Similarly, the Canadian Space Agency RADARSAT obtains C-band active microwave imagery. The United States has pro-

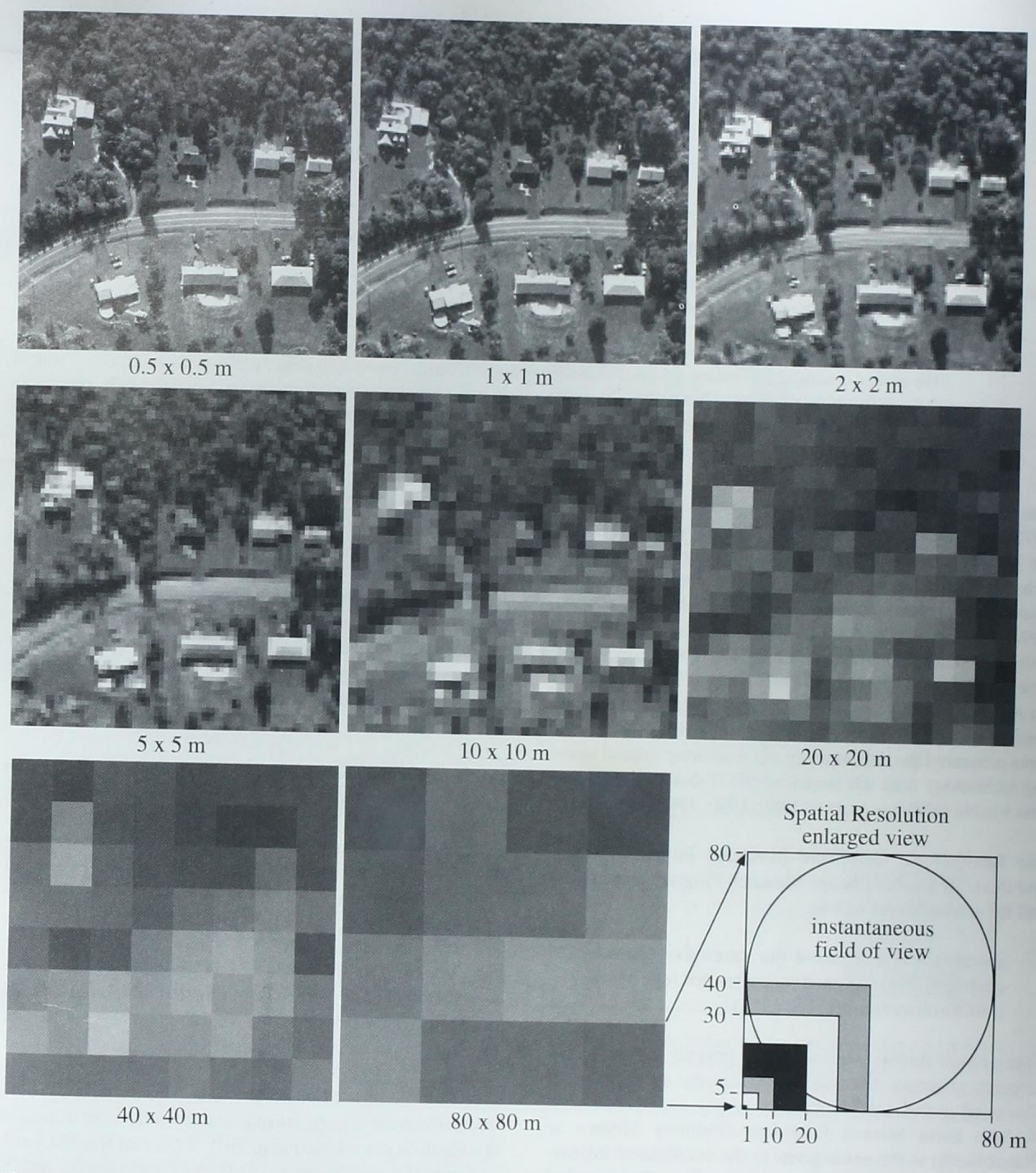

0.5 x 0.5 m
1 x 1 m
2 x 2 m
5 x 5 m
10 x 10 m
20 x 20 m
40 x 40 m
80 x 80 m

Figure 1-8 Imagery of residential housing near Mechanicsville, NY. The data were obtained on June 1, 1998, at a nominal spatial resolution of 0.3 x 0.3 m (approximately 1 x 1 ft) using a digital camera (courtesy of Litton Emerge, Inc.). The original data were resampled to derive the imagery with the simulated spatial resolutions shown.

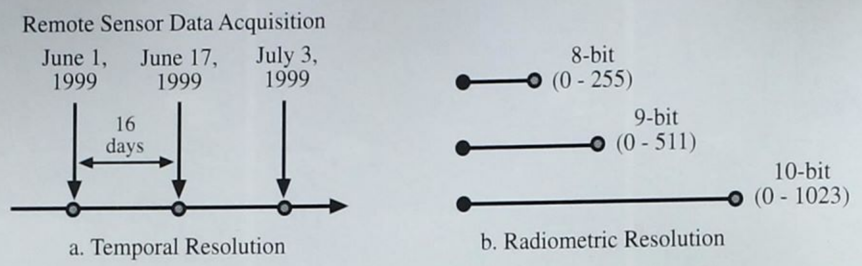


Figure 1-9 a) The temporal resolution of a remote sensing system refers to how often it records imagery of a particular area. This example depicts the systematic collection of data every 16 days, presumably at approximately the same time of day. Landsat Thematic Mapper 4 and 5 had 16-day revisit cycles. b) The radiometric resolution of a remote sensing system is defined as the sensitivity of remote sensing detectors to differences in signal strength as it records the radiant flux reflected or emitted from the terrain. The energy is normally quantized during the analog-to-digital (A-to-D) conversion process to 8, 9, 10, or 12-bits. Think of radiometric resolution as being like a ruler. If you had to measure something very precisely, would you rather have a ruler with just 256 subdivisions (8-bit) or one with 1024 subdivisions (10-bit)? Several new sensor systems record data in 12-bits (0-4095).

gressed from multispectral scanning systems (Landsat MSS, 1972 to present) to more advanced scanning systems (Landsat Thematic Mapper, 1982 to present). The Land Remote Sensing Policy Act of 1992 specified the future of satellite land remote sensing programs in the United States (Asker, 1992; Jensen, 1992). Unfortunately, Landsat 6, with its Enhanced Thematic Mapper (ETM), did not achieve orbit when launched on October 5, 1993. Landsat 7 was launched on April 15, 1999, to relieve the United States' land remote sensing data gap (Henderson, 1994). Meanwhile, the French have pioneered the development of linear array remote sensing technology with the launch of SPOT 1-4 High Resolution Visible (HRV) sensors in 1986, 1990, 1993, and 1998.

The International Geosphere–Biosphere Program (IGBP) and the U. S. Global Change Research Program (USGCRP) call for scientific research to:

> describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system (CEES, 1991).

Space-based remote sensing is an integral part of these research programs because it provides the only means of observing global ecosystems consistently and synoptically. NASA's Earth Science Enterprise (formerly Mission to Planet Earth) is the name given to the coordinated international plan to provide the necessary satellite platforms and instruments, an Earth Observing System Data and Information System (EOSDIS), and related scientific research for IGBP. In particular, new satellite remote sensing instruments will include 1) a series of near-term Earth probes to address discipline-specific measurement needs, 2) a series of multipurpose polar orbiting platforms, initiated in 1988, to acquire 15 years of continuous Earth observations, called the Earth Observing System (EOS), and 3) a series of geostationary platforms carrying advanced multidisciplinary instruments to fly sometime after the year 2000, called the Geostationary Earth Observing System (Price et al., 1994; NASA, 1998). Not everyone is convinced that NASA's Earth Science Enterprise is the most economic way of obtaining the required environmental information (e.g., Hudgins, 1997).

The first of the National Aeronautics and Space Administration Mission to Planet Earth sensors placed in orbit was the Upper Atmosphere Research Satellite (UARS) launched in 1991 (Luther, 1992). The UARS sensors collected information on upper atmospheric chemistry, temperature, wind speed, direction, and energy inputs. The TOPEX/POSEIDON satellite launched in 1992 uses radar altimetry to measure sea-surface height over 90 percent of the world's ice-free oceans. The system acquires global maps of ocean topography (barely perceptible hills and valleys of the sea surface), which scientists use to calculate the speed and direction of ocean currents (Jones, 1992).

The EOS Science Plan: Asrar and Dozier (1994) conceptualized the remote sensing science conducted as part of the Earth Science Enterprise. They suggested that the Earth consists of two subsystems, 1) the physical climate, and 2) biogeochemical cycles, linked by the global hydrologic cycle, as shown in Figure 1-10.

The *physical climate* subsystem is sensitive to fluctuations in the Earth's radiation balance. Human activities have caused changes to the planet's radiative heating mechanism that rival or exceed natural change. For example, increases in greenhouse gases between 1765 and 1990 have caused a radiative forcing of 2.5 W m^{-2}. If this rate is sustained, it could result in global mean temperatures increasing about 0.2 to 0.5°C per decade during the next century. Volcanic eruptions and the ocean's ability to absorb heat may impact the projections. Nevertheless, the following important questions are being addressed using remote sensing (Asrar and Dozier, 1994):

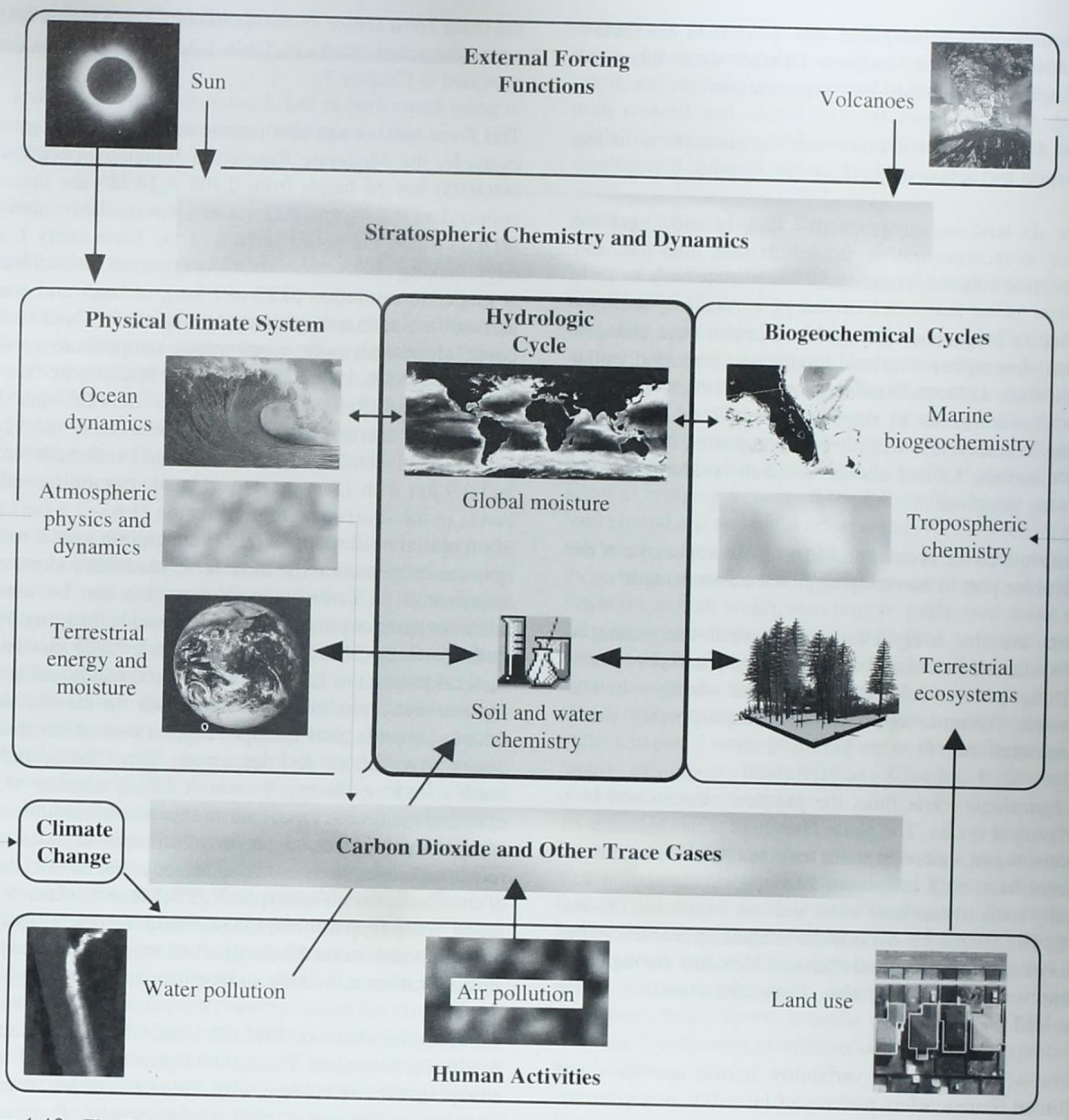


Figure 1-10 The Earth system may be subdivided into two subsystems — the physical climate system and biogeochemical cycles — that are linked by the global hydrologic cycle. Significant changes in the external forcing functions and human activities can have a dramatic impact on the physical climate system, biogeochemical cycles, and the global hydrologic cycle. Examination of these subsystems and their linkages defines the critical questions that the NASA Earth Observing System (EOS) is attempting to answer (after Asrar and Dozier, 1994).

- How do clouds, water vapor, and aerosols in the Earth's radiation and heat budgets change with increased atmospheric greenhouse-gas concentrations?
- How do the oceans interact with the atmosphere in the transport and uptake of heat?
- How do land-surface properties such as snow and ice cover, evapotranspiration, urban/suburban land use, and vegetation influence circulation?

The Earth's *biogeochemical cycles* have also been changed by man. Atmospheric carbon dioxide has increased by 30 percent since 1859, methane by more than 100 percent, and ozone concentrations in the stratosphere have decreased, causing increased levels of ultraviolet radiation to reach the Earth's surface. Global change research is addressing the following questions:

- What role do the oceanic and terrestrial components of the biosphere play in the changing global carbon budget?
- What are the likely effects on natural and managed ecosystems of increased carbon dioxide, acid deposition, shifting patterns of precipitation, and changes in soil erosion, river chemistry, and atmospheric ozone concentrations?

The *hydrologic cycle* links the physical climate and biogeochemical cycles. The phase change of water between its gaseous, liquid, and solid states involves storage and release of latent heat, so it influences atmospheric circulation and globally redistributes both water and heat (Asrar and Dozier, 1994). The hydrologic cycle is the integrating process for the fluxes of water, energy, and chemical elements among components of the Earth System. Important questions to be addressed include:

- How will atmospheric variability, human activities, and climate change affect patterns of humidity, precipitation, evapotranspiration, and soil moisture?
- How does soil moisture vary in time and space?
- Can we predict changes in the global hydrologic cycle using present and future observation systems and models?

EOS AM-1 (now referred to as the *Terra* satellite) houses five remote sensing instruments designed to address many of the previously mentioned research topics (NASA, 1998). The spatial, spectral, and temporal characteristics of three of the main *Terra* sensor systems (*MODIS*, *ASTER*, and *MISR*) are summarized briefly in Table 1-3, with additional detail provided in Chapter 7.

The *Terra* sensors use new remote sensing technology. For example, the Moderate Resolution Imaging Spectrometer (*MODIS*) has 36 bands from 0.405 – 14.385 μm that will collect data at 250- and 500-m and 1-km spatial resolutions. *MODIS* views the entire surface of the Earth every 1 to 2 days, making observations in 36 coregistered spectral bands, at moderate resolution (0.25 to 1 km), of land- and ocean-surface temperature, primary productivity, land-surface cover, clouds, aerosols, water vapor, temperature profiles, and fires (NASA, 1998). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (*ASTER*) has five bands in the thermal infrared region between 8 and 12 μm with 90-m pixels. It also has three broad bands between 0.5 and 0.9 μm with 15-m pixels and stereo capability, and six bands in the shortwave infrared region (1.6 – 2.5 μm) with 30-m spatial resolution. *ASTER* is the highest spatial resolution sensor system on the EOS *Terra* platform and provides information on surface temperature that can be used to model evapotranspiration. The Multi-angle Imaging SpectroRadiometer (*MISR*) has nine separate CCD pushbroom cameras to observe Earth in four spectral bands and at nine separate view angles. It provides data on clouds, atmospheric aerosols, and multiple-angle views of the Earth's deserts, vegetation, and ice cover. The Clouds and the Earth's Radiant Energy System (*CERES*) consists of two scanning radiometers that measure the Earth's radiation balance and provide cloud property estimates to assess their role in radiative fluxes from the surface of the earth to the top of the atmosphere. Finally, *MOPITT* (Measurements of Pollution in the Troposphere) is a scanning radiometer that provides information on the distribution, transport, sources, and sinks of carbon monoxide and methane in the troposphere.

Commercial Vendors: EOSAT, Inc., launched Landsat 6 with its Enhanced Thematic Mapper in 1993. Unfortunately, it failed to achieve orbit. EarthWatch, Inc. launched Earlybird in December, 1997. Unfortunately, all communication with the satellite was lost. Space Imaging, Inc. launched IKONOS on April 27, 1999 and it failed to achieve orbit. A second IKONOS satellite was launched on September 24, 1999. The IKONOS sensor system has a 1 x 1 m panchromatic band as well as four 4 x 4 m multispectral bands (Table 1-3). Similar sensor systems are scheduled to be launched by EarthWatch, Inc. (*Quickbird*) and ORBIMAGE, Inc. (*Orbview 3*) in 2000. ORBIMAGE also plans to launch a hyperspectral satellite remote sensing system in 2000 (*Orbview 4*).

Remote Sensing Data Analysis

The analysis of remotely sensed data is performed using a variety of image processing techniques (Figure 1-11), including:

- analog (visual) image processing of image data and
- digital image processing of digital data.

Both analog and digital image processing should allow the analyst to perform *scientific visualization,* defined as "visually exploring data and information in such a way as to gain understanding and insight into the data" (Pickover, 1991). First, however, it is instructive to ask two questions: Why process the remotely sensed data digitally at all? Isn't visual image analysis sufficient?

Human beings are exceptionally adept at visually interpreting images produced by certain types of remote sensing devices, especially cameras. We could ask, Why try to mimic or improve on this capability? First, there are certain thresholds beyond which the human interpreter cannot detect "just noticeable differences" in the imagery. For example, it is commonly known that an analyst can discriminate only about nine shades of gray when interpreting continuous-tone black-and-white aerial photography. If the data were originally recorded with 256 shades of gray, there may be more subtle information present in the image than the interpreter can extract visually. Furthermore, the interpreter brings to the task all the pressures of the day, making the interpretation generally unrepeatable. Conversely, the results obtained by computer are repeatable (even when wrong!). Also, when it comes to keeping track of a great amount of detailed quantitative information, such as the spectral characteristics of a vegetated field throughout a growing season for crop identification purposes, the computer is very adept at storing and manipulating such tedious information and possibly making a more definitive conclusion as to what crop is being grown. This is not to say that digital image processing is superior to visual image analysis. This is certainly not the case. Rather, there may be times when a digital approach is better suited to the problem at hand.

But what about the actual processes of analog (visual) versus digital image processing? Are there similarities between the goals and methods of both procedures? Estes et al. (1983) suggest that there exist several image-analysis tasks and basic elements of image interpretation that the visual and digital image processing approaches share (Figure 1-11). First, both manual and digital analysis of remotely sensed data seek to detect and identify important phenomena in the scene. Once identified, the phenomena are usually measured, and the information is used in problem solving. Thus, both manual and digital analysis have the same general goals. However, the attainment of these goals may follow significantly different paths.

Analog (Visual) Image Processing

Most of the fundamental elements of image interpretation identified in Figure 1-11 are used in visual image analysis, including size, shape, shadow, color (tone), parallax, pattern, texture, site, and association. The human mind is amazingly adept at recognizing these complex elements in an image or photograph because we constantly process profile views of Earth features every day and continually process images in books and magazines and on television. Furthermore, we are adept at bringing to bear all the knowledge in our personal background and collateral information. We then converge all this evidence to identify phenomena in images and/or to judge their significance. Precise measurement of objects (location, height, width, etc.) may be performed using optical photogrammetric techniques applied to either monoscopic (single-photo) or stereoscopic (overlapping) images. Numerous books have been written on how to perform visual image interpretation and photogrammetric measurement. Chapter 5 summarizes the use of the fundamental elements of image interpretation. Chapter 6 introduces photogrammetry principles.

Interestingly, there is a resurgence in the art and science of visual photointerpretation as the digital remote sensor systems provide higher spatial resolution imagery. For example, Indian IRS-1C panchromatic data (5.8 × 5.8 m) is often photointerpreted and used as a base map in GIS projects. The new 1 x 1 m panchromatic data provided by commercial companies (e.g., Space Imaging IKONOS, ORBIMAGE Orbview 3) will cause even more visual image interpretation to take place.

Digital Image Processing

Scientists have made significant advances in digital image processing of remotely sensed data for scientific visualization and hypothesis testing. The methods are summarized in the companion book by Jensen (1996) and others (e.g., Wolff and Yaeger, 1993; Nadler and Smith, 1993; Schott, 1997). The major types of digital image processing include statistical and syntactical pattern recognition, photogrammetric image processing of stereoscopic imagery, hyperspectral data analysis, and expert system and neural network image analysis.

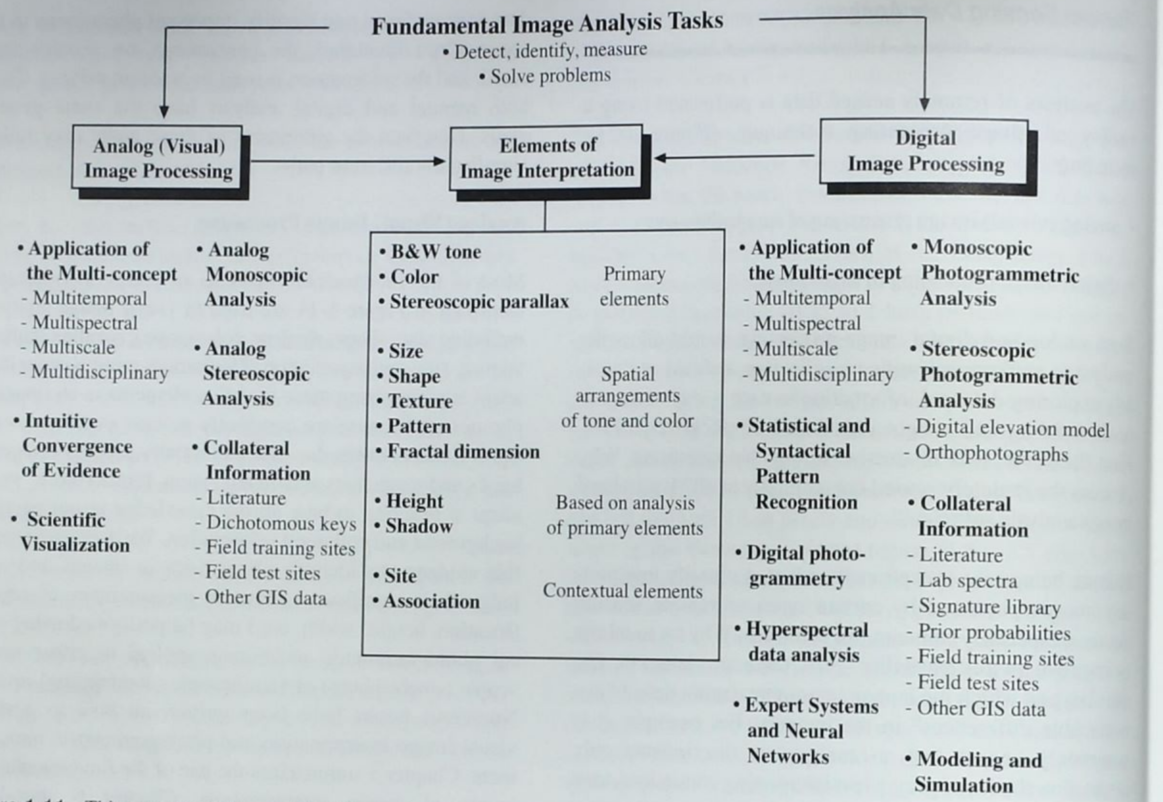


Figure 1-11 This conceptual diagram identifies analog (visual) and computer-assisted digital image processing of remotely sensed data that rely on the analysis of the fundamental elements of image interpretation. Visual analysis at the present time incorporates many more of the complex elements in the analysis of remote sensing images.

Pattern Recognition: Fundamental statistical methods of rectifying remotely sensed data to a map projection, enhancing the data, classifying the data into land use and land cover, and identifying change between dates of imagery are now performed routinely with reasonable precision. Interestingly, most of the computer-assisted image processing to date has involved the use of only a few of the basic elements of image interpretation. In fact, the overwhelming majority of all digital image analysis appears to be dependent primarily on just the *tone* or *color* of individual pixels in the scene using fundamental statistical pattern recognition techniques (Figure 1-11).

Various techniques have been used to incorporate additional elements of image interpretation into the image analysis process. For example, numerous studies have synthesized *texture* information from the spectral data in the imagery. Some have computed the fractal dimension of images and found it to be a valuable element of image interpretation (Emerson et al., 1999). *Contextual* classification has been performed, which makes use of neighboring pixel values, thus incorporating some level of *association* information (Gong and Howarth, 1992). Some image processing now takes into account *fuzzy set logic*, which attempts to model the imprecision in the real world (Ji and Jensen, 1996).

Photogrammetry: Significant advances have been made in the analysis of stereoscopic remote sensor data using computer workstations and digital image processing photogrammetric algorithms (Li, 1998). Soft-copy photogrammetric workstations can be used to extract accurate digital elevation models (DEMs) and differentially corrected orthophotography from the triangulated aerial photography or imagery (Ackerman, 1994; Jensen, 1995). The technology is revolutionizing the way DEMs are collected, especially for developing countries and how orthophotos are produced for rural and urban-suburban applications.

Hyperspectral: Analysts should be aware that special software is required to process the hyperspectral data from spectroradiometer remote sensor systems (e.g., AVIRIS, *MODIS*). Kruse et al. (1992), Landgrebe (1999) and ENVI (1999) have pioneered the development of hyperspectral image analysis software. The software reduces the dimensionality of the data (number of bands) to a manageable degree, while still retaining the essence of the data. Under certain conditions the software can be used to compare the remotely sensed spectral reflectance curves with a library of spectral reflectance curves. Analysts are also able to identify the type and proportion of different materials within an individual picture element (referred to as end-member analysis). This is an exciting area of digital image processing.

Expert Systems and Neural Networks: Humans are very successful at visually interpreting aerial photographs because they focus their real-world knowledge about the study area and their years of visual processing experience on the task. It is difficult to make a computer understand and use the heuristic rules of thumb and knowledge that a human expert uses when interpreting an image (Moller-Jensen, 1990). Nevertheless, there has been considerable success in the use of artificial intelligence (AI) to try to make computers do things that, at the moment, people do better. One area of AI that has great potential in remote sensing image analysis is the use of expert systems. Expert systems can be used to 1) interpret an image, and/or 2) place all the information contained within an image in its proper context with other ancillary data and extract more valuable information (Bolstad and Lillesand, 1992). In the first case, collateral data and rules specified by an expert might be used by novices to more accurately interpret a remotely sensed image (Huang and Jensen, 1998). In the second case, an expert system might be used to produce geological engineering maps from input datasets (bedrock geology, agricultural soils, topography), some of which were derived using remote sensing (Usery et al., 1988). Scientists with good training in an Earth science discipline, an understanding of remote sensing, and expert system skills (e.g., how to create a knowledge base and query it with an inference engine) will make significant contributions in this area.

Neural networks have also been used to analyze remotely sensed data (Hepner et al., 1990; Jensen and Qiu, 1999). Neural networks do not require the input data to be normally distributed. Furthermore, they can be programmed to learn.

Modeling Remote Sensing Data Using A GIS Approach

Remotely sensed data should not be analyzed in a vacuum without the benefit of other collateral information, such as soils, hydrology, and topography (Price et al., 1994; Ramsey et al., 1995). Unfortunately, many scientists promoting the integration of remote sensing and GIS assume that the flow of data should be unidirectional — that is, from the remote sensing system to the GIS. Actually, the backward flow of ancillary data from the GIS to the remote sensing system is very valuable (Stow, 1993). For example, land-cover mapping using remotely sensed data has been significantly improved by incorporating topographic information from digital terrain models and other GIS data (Franklin and Wilson, 1992). Basically, the interface between GIS and remote sensing systems is functional but weak (Lunetta et al., 1991). Each technology suffers from a lack of critical support that could be provided by the other. GIS needs timely, accurate updating of the spatially distributed variables in the database that remote sensing can provide. Remote sensing can benefit from access to accurate ancillary information to improve classification accuracy and other types of modeling (Jensen et al., 1994). Such synergy is critical if successful expert system and neural network analyses are to be performed.

Scene Modeling

Strahler et al. (1986) describe a framework for modeling in remote sensing. Basically, a remote sensing model has three components: 1) a scene model, which specifies the form and nature of the energy and matter within the scene and their spatial and temporal order; 2) an atmospheric model, which describes the interaction between the atmosphere and the energy entering and being emitted from the scene; and 3) a sensor model, which describes the behavior of the sensor in responding to the energy fluxes incident on it and in producing the measurements that constitute the image. They suggest that "the problem of scene inference, then, becomes a problem of model inversion in which the order in the scene is reconstructed from the image and the remote sensing model." For example, Li and Strahler (1985) modeled the optical-geometric properties of a coniferous forest canopy that has been tested extensively (Franklin and Turner, 1992; Woodcock et al., 1997).

Basically, successful remote sensing modeling predicts how much radiant flux in certain wavelengths should exit a particular object (e.g., a conifer canopy) even without actually sensing the object. When the model's prediction is the same as the sensor's measurement, the relationship has been modeled correctly. The scientist then has a greater appreciation for energy-matter interactions in the scene and may be able to extend the logic to other regions or applications with confidence. The remote sensor data can then be used more effectively in physical deterministic models (e.g., watershed runoff, net primary productivity, and evapotranspiration models), which are so important for large ecosystem modeling. Recent work allows one to model the utility of sensors with different spatial resolutions for particular applications such as urban analysis (Collins and Woodcock, 1999).

Information Presentation

Information derived from remote sensor data are usually summarized as an enhanced image, image map, orthophotomap, thematic map, spatial database file, statistic, or graph (Figure 1-5). Thus, the final output products often require knowledge of remote sensing, cartography, GIS, and spatial statistics as well as the systematic science being investigated (e.g., soils, agriculture, forestry, wetland, urban studies). Scientists who understand the rules and synergistic relationship between the technologies can produce output products that communicate effectively. Conversely, those who violate fundamental rules (e.g., cartographic theory or database topology design) often produce poor output products that do not communicate effectively.

Image maps offer scientists an alternative to line maps for many cartographic applications. Thousands of satellite image maps have been produced from Landsat MSS (1:250,000 and 1:500,000 scale), TM (1:100,000 scale) and AVHRR data (Vickers, 1993). Image maps at scales of >1:24,000 are possible with the improved resolution of 1 x 1 m data (Li, 1998). Because image map products can be produced for a fraction of the cost of conventional line maps, they provide the basis for a national map series oriented toward the exploration and economic development of the less developed areas of the world, most of which have not been mapped at scales of 1:100,000 or larger.

Remote sensor data that has been geometrically rectified to a standard map projection is becoming indispensable in most sophisticated GIS databases. This is especially true of orthophotomaps that have the metric qualities of a line map and the information content of an aerial photograph or other type of image (Jensen, 1995).

Unfortunately, *error* is introduced at various stages in the remote sensing process and must be identified and reported. Innovations in error reduction include: 1) recording the genealogy or lineage of the various operations applied to the original remote sensor data (Lanter and Veregin, 1992), 2) documenting the geometric (spatial) error and thematic (attribute) error of the individual source materials, 3) improving legend design, especially for change detection map products derived from remote sensing, and 4) precise error evaluation statistic reporting (Khorram et al., 1999). Many of these concerns have not been adequately addressed. The remote sensing and GIS community should incorporate technologies that carefully track all types of error entering final map and image products (Goodchild and Gopal, 1992). This will result in more accurate information being used in the decision-making process.

Earth Resource Analysis Perspective

Remote sensing may be used for numerous applications, including weapon guidance systems (e.g., the cruise missile), medical image analysis (e.g., X-raying a broken arm), nondestructive evaluation of machinery and products (e.g., on an assembly line), and analysis of Earth's resources. Earth resource information is defined as any information concerning terrestrial vegetation, soils, minerals, rocks, water, and urban infrastructure as well as certain atmospheric characteristics. *This book focuses on the art and science of applying remote sensing for the extraction of useful Earth resource information.* Such information may be useful for modeling the global carbon cycle, the biology and biochemistry of ecosystems, aspects of the global water and energy cycle, climate variability and prediction, atmospheric chemistry, characteristics of the solid Earth, and natural hazards (Paylor et al., 1999).

Book Organization

This chapter defined important terms and provided a perspective on how remote sensing science can be useful for Earth resource investigations. Chapter 2 introduces the fundamental principles of electromagnetic radiation and how this radiation is used to perform remote sensing of the environment. Chapter 3 reviews the history of photography, and aerial and satellite platforms. Chapter 4 introduces the fundamental characteristics of aerial photography, filtration, and film. Chapter 5 presents the fundamental elements of visual image interpretation. Chapter 6 reviews principles of photogrammetry used to extract quantitative information from aerial photography. Chapter 7 presents the characteristics of optical-mechanical remote sensing systems. Chapter 8 introduces thermal infrared remote sensing. Chapter 9 presents active microwave remote sensing. Chapter 10 reviews how remote sensing may be used to extract fundamental biophysical characteristics of terrestrial and aquatic vegetation. Chapter 11 provides insight into remote sensing of terrestrial water, ice, and snow as well as atmospheric water vapor and temperature. Chapter 12 demonstrates how remote sensing can provide unique urban/suburban infrastructure information using a variety of remote sensing systems. Chapter 13 describes how selected soil and mineral characteristics may be remotely sensed and how major geomorphic features on the surface of the Earth may be identified.

References

Ackerman, F., 1994, "Digital Elevation Models: Techniques and Application, Quality Standards, Development," *Proceedings*, Symposium on Mapping and Geographic Information Systems, Athens, GA: International Society for Photogrammetry & Remote Sensing, 30(4):421–432.

American Society of Photogrammetry, 1944, 1952, 1966, *Manual of Photogrammetry*, Falls Church: ASP, multiple editions.

Asker, J. R., 1992, "Congress Considers Landsat 'Decommercialization' Move," *Aviation Week and Space Technology*, May 11, 18–19.

Asrar, G. and J. Dozier, 1994, *EOS: Science Strategy for the Earth Observing System*, Woodbury: American Institute of Physics.

Bolstad, P. V. and T. M. Lillesand, 1992, "Rule-based Classification Models: Flexible Integration of Satellite Imagery and Thematic Spatial Data," *Photogrammetric Engineering & Remote Sensing*, 58(7):965–971.

Budge, A. and S. A. Morain, 1995, "Access Remote Sensing Data for GIS," *GIS World*, 8(2):45–49.

Canadian Space Agency, 1999, *RADARSAT*, Saint-Hubert: RADARSAT Program.

CEES, 1991, *Our Changing Planet: The FY 1992 U.S. Global Change Research Program*, Committee on Earth and Environmental Sciences, Office of Science & Technology, Washington, DC, 21 pp.

Clark, R. N., 1999, *Spectroscopy of Rocks and Minerals, and Principles of Spectroscopy*, Denver: U.S. Geological Survey, http://speclab.cr.usgs.gov, 58 pp.

Collins, J. B. and C. E. Woodcock, 1999, "Geostatistical Estimation of Resolution-Dependent Variance in Remotely Sensed Images," *Photogrammetric Engineering and Remote Sensing*, 65(1):41–50.

Colwell, R. N. (Ed.), 1960, *Manual of Photographic Interpretation*, Falls Church, VA: American Society for Photogrammetry & Remote Sensing.

Colwell, R. N. (Ed.), 1983, *Manual of Remote Sensing*, 2nd. Ed., Falls Church, VA: American Society of Photogrammetry.

Colwell, R. N., 1984, "From Photographic Interpretation to Remote Sensing," *Photogrammetric Engineering and Remote Sensing*, 50(9):1305.

Colwell, R. N., 1997, "History and Place of Photographic Interpretation," *Manual of Photographic Interpretation*, W. R. Philipson (Ed.), 2nd Ed., Bethesda: American Society for Photogrammetry & Remote Sensing, 33–48.

Congalton, R. G. and K. Green, 1998, *Assessing the Accuracy of Remotely Sensed Data*, Boca Raton: Lewis, 137 pp.

Cracknell, A. P. and L. W. B. Hayes, 1993, *Introduction to Remote Sensing*, London: Taylor & Francis, 293 pp.

Curran, P. J., 1987, "Remote Sensing Methodologies and Geography," *International Journal of Remote Sensing*, 8:1255–1275.

Dahlberg, R. W. and J. R. Jensen, 1986, "Education for Cartography and Remote Sensing in the Service of an Information Society: The United States Case," *The American Cartographer*, 13(1):51–71.

Davis, B. A., 1999, "An Overview of NASA's Commercial Remote Sensing Program," *Earth Observation Magazine*, 8(3):58–60.

Dobson, J. E., 1993, "Commentary: A Conceptual Framework for Integrating Remote Sensing, Geographic Information Systems, and Geography," *Photogrammetric Engineering & Remote Sensing*, 59(10):1491–1496.

Duggin, M. J. and C. J. Robinove, 1990, "Assumptions Implicit in Remote Sensing Data Acquisition and Analysis," *International Journal of Remote Sensing*, 11(10):1669–1694.

Eidenshink, J. C., 1992, "1990 Conterminous United States AVHRR Data Set," *Photogrammetric Engineering & Remote Sensing*, 58(6):809–813.

Emerson, C. W., N. Lam, and D. A. Quattrochi, 1999, "Multi-scale Fractal Analysis of Image Texture and Pattern," *Photogrammetric Engineering & Remote Sensing*, 65(1):51–61.

Engman, E. T. and N. Chauhan, 1995, "Status of Microwave Soil Moisture Measurements with Remote Sensing," *Remote Sensing of Environment*, 51:189–198.

ENVI, 1999, *ENVI User's Guide: Environment for Visualizing Images*, Boulder: Research Systems, Inc., 500 pp.