Introduction to Environmental Remote Sensing

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Introduction to Environmental Remote Sensing

David P. Lusch, Ph.D.
Senior Research Specialist
Center for Remote Sensing and GIS
Michigan State University

With a contribution from
William D. Hudson, Ph.D.
Center for Remote Sensing and GIS
Michigan State University

Graphics and Layout
George F. Weisenborn, IV
Paul Rindfleisch
Michael D. Hyslop

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1.1 Objectives

- Define remote sensing
- Explain the relationship of airphoto interpretation to remote sensing
- Review the increasing pace of technological development in remote sensing since the launch of Landsat 1
- List at least five current satellite-based remote sensing systems
- Define the "multi-" concept of remote sensing and describe at least four examples

1.2 Introduction

Remote Sensing is a multi-disciplinary technique of electronic and analog image acquisition and exploitation which includes aerial photography and airphoto interpretation.

It has as its goal: “...the measurement or acquisition of information about some property of an object or phenomenon by a recording device which is not in physical or intimate contact with the object or phenomenon under study...” (Manual of Remote Sensing, 1983)

remote: separated by great intervals
sensing: to detect or characterize

[Remote sensing = detect/characterize at a distance]

Inherent aspects of the above definition:

- data collection
- data analysis

The basic concept of remote sensing is the ability to measure spatial, spectral, and temporal variations.

Spatial — variations in scale/size
Spectral — variations in reflected or emitted radiation
Temporal — variations over time (diurnal, seasonal, annual, etc.)
1.3 Historical Perspective

1839 — Louis J. M. Daguerre of Paris developed a process for making a photograph

1858 — aerial photographs, taken from balloons, used for mapping and military reconnaissance

45 years

1903 — Wright brothers’ first flight

WW I and WW II — major developments for military aerial reconnaissance

1930’s — USDA begins extensive photography programs for civilian uses

1950’s — photogrammetry and photointerpretation firmly institutionalized into a variety of disciplines

1960’s — remote sensing is born from the “space age”

1.4 Development of Photography

1038  In his book on optics, Alhazen describes the camera obscura

1568  Daniello Barbaro of Venice used a lens in the camera obscura

1727  During his experiments concerning the production of phosphorous, Johann Schulze discovers that white chalk moistened with a silver nitrate solution in nitric acid darkened in sunlight

1802  Thomas Wedgwood and Sir Humphrey Davy described a method of producing images (temporarily) on paper coated with nitrate or silver chloride

1822  Joseph Niepce makes the first permanent photographic images on paper coated with silver chloride

1831  Louis Daguerre discovers that silver iodide is photosensitive and that a latent image can be made visible by subjecting the metal photographic plate to mercury vapors
1834  The English scientist William Talbot invented the negative-positive photographic process

1839  Daguerre perfects and publishes his daguerreotype process which utilized sodium thiosulphate as a fixer. The English chemist and astronomer Sir John Herschel had discovered sodium thiosulphate in 1819

1847  Claude De St. Victor succeeds in producing a negative on glass

1851  Frederick Archer invented the wet collodian process. The light-sensitive material had to be prepared just before the intended exposure and had to processed immediately afterwards

1871  Richard Maddox, an English physician, produced the first practical silver-bromide gelatin negatives on glass thereby freeing photographers from having to make their own wet plates

1883  George Eastman invented paper roll films, replacing glass plates

1891  Gabriel Lippmann published his method of interference-color photography

1936  Eastman Kodak Company and Agfa introduced commercially available color film

1.5 Development of Aerial Photography

1783  June  Joseph and Etienne Montgolfier demonstrated the flight of an unmanned, hot-air balloon which attained an altitude of 6,000 feet

August  J.A.C. Charles, a noted French physicist, launched the first hydrogen-filled balloon in an unmanned ascent over the Champ de Mar in Paris

December  Charles and a passenger ascended from the Tuileries Gardens in a hydrogen-filled balloon remaining aloft for nearly two hours and travelling 27 miles

1785  Jean Blanchard, a Frenchman, and John Jeffries, an American, made the first aerial crossing of the English Channel from
Dover to Calais in a balloon

1858 Gaspard Tournachon (Nadar) made the first aerial photograph of Paris from a balloon tethered at an altitude of 80 meters

1860 James Black and Samuel King ascended to an altitude of 630 meters and successfully photographed parts of the city of Boston

1882 The English meteorologist E.D. Archibald made the first successful aerial photographs from a kite

1885 Some of the earliest vertical air photos from balloons were made by Gaston Tissandier and Jacques Ducom

1898 During the Spanish-American War, American troops tried unsuccessfully to utilize balloon photography for tactical reconnaissance

1903 Orville and Wilbur Wright fly the first heavier-than-air aircraft at Kill Devil Hill, North Carolina

Julius Neubronner patented a breast-mounted aerial camera for carrier pigeons

1906 George Lawrence obtained a 1.35 x 2.4 meter picture of San Francisco during the earthquake. His 1,000 pound camera was suspended at an altitude of 610 meters from a battery of 17 kites

1909 April 24 The first aerial photograph from an airplane was taken over Centocelii, Italy. Wilbur Wright was the pilot

1914-1918 Aerial photography played a decisive role as a tactical reconnaissance tool during World War I

1920 Sherman Fairchild designed and built the K-3 aerial camera which incorporated an interlens shutter, motor drive and intervalometer

1925 November 20 Lt. George W. Goddard acquired the first night-time airphoto over Rochester, New York using a flash bomb and photocell-actuated shutter

1934 The American Society of Photogrammetry was formed

1937 USDA-FSA began photographing selected counties in the
1.6 Development of Remote Sensing

- U.S. on a repetitive basis

1939-1945 Aerial reconnaissance during World War II provided over 90% of all the intelligence information to the Allies

1942 Eastman Kodak Company introduced Kodacolor Aero Reversal Film.
   Under the auspices of the Camouflage Section, National Defense Research Committee, the Eastman Kodak Research Laboratories developed a false-color, camouflage-detection film by modifying the blue, green, red sensitivities of Kodacolor Aero film to green, red and infrared [color infrared (CIR) film]

1950's Photogrammetry and photointerpretation become firmly institutionalized in a variety of disciplines

1960's As the techniques to record electromagnetic radiation beyond the range of human vision became available, the new term “remote sensing” was coined by Evelyn Pruitt at the Office of Naval Research to encompass the total observational process from remote platforms

1962 October High-Altitude aerial photographs from U-2 aircraft documented the emplacement of Soviet medium-range ballistic missiles in Cuba

1965 Multispectral camera systems (multiband photography) become commercially available

1969 March SO 65 Multispectral Photographic Experiment was flown onboard Apollo 9
   June NASA’s Manned Spacecraft Center begins high-altitude aerial photography missions as part of the Earth Resources Program

1972 July 23 The Earth Resources Technology Satellite (ERTS-1) was launched. Later renamed Landsat 1

1973 May 14 Skylab was launched and between May 25, 1973 and February 8, 1974 was occupied for a total of 171 days by 3 different three-person crews. Using the Earth Resources Experiment Package (EREP), these astronauts were able to synoptically survey selected areas of the globe. Skylab reentered the earth’s atmosphere on July 11, 1979 and broke-up over the Indian Ocean
1975 January 22 Landsat 2 was launched and nine day repetitive coverage becomes possible

1978 January 6 Landsat 1 was retired after acquiring more than 270,000 scenes of data

March 5 Landsat 3 was launched

June 26 Seasat 1 was launched, but suffered a complete system failure on October 10, 1978

October 13 TIROS-N was launched

1979 June 27 NOAA-6 was launched

1981 June 23 NOAA-7 was launched

November 12-14 SIR-A experiment conducted from Space Shuttle Columbia. 10 million km² of SAR image coverage collected

1982 Landsat 4 is launched. Onboard is a new sensor - Thematic Mapper (TM) which provides 7 spectral channels and 30 meter resolution (120 IFOV on the thermal band)

1984 March 1 Landsat 5 was launched ahead of schedule due to equipment problems with Landsat 4

October 4-13 SIR-B experiment conducted from Space Shuttle Challenger

December 12 NOAA-9 was launched

1985 The American Society of Photogrammetry (ASP) is renamed the American Society of Photogrammetry and Remote Sensing (ASPRS)

1986 February 21 SPOT-1 was launched from Kourou, French Guiana. Onboard were new sensors which pioneered "pushbroom" scanning using arrays of CCD detectors. One panchromatic band (10 m spatial resolution) and 3 multispectral bands (20 m spatial resolution) were provided. Operational stereo imagery from space became possible.

September 17 NOAA-10 was launched.
1987 February 19 MOS-1 (Marine Observation Satellite), Japan’s first earth-resources remote sensing spacecraft, was launched

1988 September 24 NOAA-11 was launched

1990 January 22 SPOT-2 was launched

February 7 MOS-1b was launched

December 31 SPOT-1 retired from active service

1991 May 14 NOAA-12 was launched

July 17 ERS-1 was launched from Kourou, French Guiana. Operational space-borne SAR imagery begins

August 29 IRS-1B, featuring blue, green, red, and NIR sensors and two different ground resolutions (36m and 72m), was launched

1992 February 11 JERS-1 featuring an 18m by 18m resolution synthetic aperture radar (SAR) sensor and a 7 band, 17m by 24m optical sensor, was launched.

August 20 Topex/Posieden, with the mission of detecting minute (~5cm) sea level changes using French and American made altimeters, was launched.

1993 September 26 SPOT-3 was launched.

1994 October 15 IRS-P2 was launched.

November 4 RESURS 01-3, a Russian satellite with the mission of gathering mapping scale data, and large scale measurement and monitoring of agriculture, forestry, coastal zones, ice and snow, was launched.

1995 April 21 ERS-2 was launched.

November 4 RADARSAT, a Canadian satellite featuring a SAR system with variable look angles, resolutions, and swath widths, was launched.

December 28 IRS-1C with a 5m resolution panchromatic band and wide angle viewing capabilities was launched.
1996 March 21 IRS-P3 was launched

August 17 ADEOS - 1, a Japanese made satellite with instrumentation including a five band visible/NIR radiometer (AVNIR) with stereo and pointable capability, a scatterometer to measure wind speed and direction over the world’s oceans (NSCAT), an ozone detector (TOMS), and ocean color and temperature detector (OCTS) was launched.

1997 June 30 Communications with ADEOS - 1 were lost.

August 1 Seastar satellite with the SeaWifs multispectral sensor for taking ocean color measurements was launched.

August 22 LEWIS commercial (TRW Space and Electronics Group) satellite with a 30m resolution, 364 channel hyperspectral imager, and 300m resolution, 256-spectral-channel Linear Etalon Imaging Spectral Array, was launched.

August 28 LEWIS satellite began a slow spin which ultimately lead to complete power loss and a decaying orbit.

September 29 IRS-1D featuring a 5 day repeat cycle on its wide angle and panchromatic instruments, and the LISS 3 instrument were launched.

December 24 Early Bird satellite, a commercial (Earth Watch Inc.) satellite with 0.82m resolution in panchromatic and 3.82m resolution in color wavelengths, and high revisit frequency was launched.

December 28 Communication with Early Bird satellite was lost.

1998 March 24 SPOT-4 carrying dual HRVIR instruments which include a SWIR band and the VEGETATION instrument was launched.

May 13 NOAA-15 was launched.

July INSAT is scheduled to be launched.

November QUIKSCAT, a satellite with a sensor similar to the NSCAT instrument lost on with ADEOS -1 is scheduled to be launched.
1999 April 15 LANDSAT 7 is launched, carrying the ETM+ instrument which features a 15m panchromatic band and a 60m TIR band in addition to its six 30m bands (VIS, NIR & SWIR).

April 22 Ikonos-1, a commercial 1m imaging system, was launched, but failed to achieve orbit.

May Oceansat / IRS-P4 was launched.

September DMSP is scheduled for launch.

September The Shuttle Radar Topography Mission (SRTM) which will use a space borne microwave system and single pass radio interferometry to study Earth surface change and construct three dimensional model of the Earth’s surface is scheduled to be launched.

October Terra (EOS AM-1) is scheduled for launch. It includes ASTER, a 4-band multispectral (visible, shortwave IR, and TIR) sensor; CERES, an instrument used to look at clouds and the radiant energy of the Earth; MISR, a 4-band (3 visible, 1 NIR) radiometer capable of obtaining data from multiple angles; MODIS, a 36-band radiometer with coarse spatial resolution but a 1 to 2 day revisit capacity; and MOPITT, an instrument designed to measure atmospheric carbon monoxide and methane concentrations.

November OrbView-3, a commercial 1m system, is scheduled for launch.

December EO-1 is scheduled to be launched. It will carry the Advanced Land Imager, the “new millennium” replacement of ETM+, providing six Landsat bands plus three new ones: 433-453, 845-890 and 1200-1300 nm. Hyperion, a hyperspectral imager providing 220 bands (from 400-2500 nm at 30 resolution) will also be flown on EO-1.

December NOAA-L is scheduled to be launched.

2000 The following systems are scheduled to be launched:
ADEOS-2
IRS-P6
ENVISAT-1
EOS PM-1
JASON-1
Meteosat 8
OrbView 4
Radarsat 2
1.7 The "multi" Concept

The ability to acquire a multitude of data and to process these data with multiple analysis techniques has led to the more generalized concept of "multi". A combination of factors are considered collectively, compared to using a single product or technique approach.

- Multistation (vs one station)
- Multiband and Multispectral (vs one wave-length band)
- Multidate (vs one date)
- Multipolarization (vs one polarization)
- Multistage (vs one stage or flight altitude)
- Multidirectional (vertical plus oblique directions)
- Multienhancement (vs one enhancement)
- Multidisciplinary Analysis (vs experts from only one discipline)
- Multithematic (a series of maps, each dedicated to the protraying of one particular theme, rather than through only one map)

(source: U.S. Forest Service: *High Altitude Photography Training Manual*)
## Chapter 2  The BioPhysical Basis of Remote Sensing

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- BioPhysical Controls of Vegetation Reflectance
- BioPhysical Controls of Soil Reflectance
- BioPhysical Controls of Water Reflectance
2.1 Objectives

- Label the components of the energy flow diagram for passive remote sensing
- Explain the difference between passive and active remote sensing
- Label the major spectral regions on a diagram of the electromagnetic spectrum and define "optical remote sensing"
- Describe the effects of scattering and absorption in the atmosphere
- Define the term "atmospheric window" and list those which are important to optical remote sensing
- Draw the generalized spectral reflectance curve from 0.4 - 2.5 µm for vegetation, soil, and water
- Given a set of spectral reflectance curves, identify the basic earth feature each represents
- Explain how multispectral reflectance measurements could be exploited to discriminate between vegetation, soil, and water features

2.2 Introduction

The physical basis of remote sensing provides the fundamental theories and principles which underlie all subsequent discussions of remote sensing and its many applications. Electromagnetic energy; its source, properties and interactions in the atmosphere, are briefly discussed. The physical controls of the reflectance, absorptance, and transmittance of solar radiation with respect to earth targets is introduced prior to a detailed, target-specific discussion of the relationship between spectral reflectance and certain biophysical attributes. An understanding of the relationships between certain fundamental biophysical attributes and spectral reflectance is a basic prerequisite to comprehending any remotely-sensed scene acquired in the 400-2500 nm wavelength region.
## 2.3 Radiation Terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiant energy</strong></td>
<td>Q</td>
<td>units: Joules J&lt;br&gt;Energy traveling in the form of electromagnetic waves.</td>
</tr>
<tr>
<td><strong>Radiant flux</strong></td>
<td>$\Phi$</td>
<td>units: Watts W (joules/second)&lt;br&gt;The rate at which radiant energy is transferred from a point or a surface to another surface, a measure of radiant power.</td>
</tr>
<tr>
<td></td>
<td>$\Phi = \frac{dQ}{dt}$</td>
<td></td>
</tr>
<tr>
<td><strong>Radiant flux density</strong></td>
<td>$E$ or $M$</td>
<td>units: Watts per square meter, Wm$^{-2}$&lt;br&gt;The radiant flux at a surface divided by the area of the surface. When referring to the radiant flux <em>incident on</em> a surface, we call it:</td>
</tr>
<tr>
<td></td>
<td>$E = \frac{d\Phi}{dA}$ [Wm$^{-2}$]</td>
<td>When referring to the radiant flux <em>emitted from</em> a surface, we call it:</td>
</tr>
<tr>
<td></td>
<td>$M = \frac{d\Phi}{dA}$ [Wm$^{-2}$]</td>
<td></td>
</tr>
<tr>
<td><strong>Radiant intensity</strong></td>
<td>$I$</td>
<td>units: Watts per steradian, Wsr$^{-1}$&lt;br&gt;Radio flux proceeding from a source per unit solid angle (d$\Omega$)</td>
</tr>
<tr>
<td></td>
<td>$I = \frac{d\Phi}{d\Omega}$</td>
<td></td>
</tr>
<tr>
<td><strong>Radiance</strong></td>
<td>$L$</td>
<td>units: Watts per square meter and steradian, Wm$^{-2}$ sr$^{-1}$&lt;br&gt;Radiant flux propagated in a given direction, per unit solid angle about that direction and per unit area projected normal to the direction (dA cos$\Theta$). The angle $\Theta$ is measured between the direction and a perpendicular to the unit area. Radiance is a geometric radiation quantity that describes the spatial distribution of radiant flux density.</td>
</tr>
<tr>
<td></td>
<td>$L = \frac{d^2\Phi}{d\Omega dA \cos \Theta}$</td>
<td></td>
</tr>
</tbody>
</table>
Bidirectional Reflectance Distribution Factor (BRDF)

The BRDF is the ratio of radiant flux reflected by a target under specified conditions of irradiation and viewing to that reflected by a near-completely reflecting, almost perfectly diffuse reference surface which is identically irradiated and viewed. A “perfectly diffuse” surface reflects equally in all directions (also called a Lambertian reflector). The radiance of a uniformly illuminated Lambertian surface of infinite extent is constant for any viewing angle. If the uniformly illuminated Lambertian surface is small enough so as not to fill the field of view of an observing sensor, the radiance measured by the sensor will be proportional to the cosine of the viewing angle. A “completely reflecting” surface reflects all of the radiant flux falling on it.

The ideal “completely reflecting, perfectly diffuse” surface does not exist, but several useful reference compounds have been developed. Properly prepared barium sulfate (BaSO₄) or magnesium oxide (MgO) reference surfaces closely approximate perfect diffusers for view angles < 45°. Pressed BaSO₄ powder (useful in lab environments only) departs from being “completely reflecting” by less than one percent in the wavelength range 375-1100 nm. Barium sulfate paint (useful in field environments) is almost as good; it departs from the completely reflecting assumption by no more than two percent in the 375-1100 nm wavelength range and is more than 99% reflective from 460-800 nm.

Recently, another compound has been developed as a reference standard which is particularly well-adopted to field conditions. Commonly referred to by the trade name Halon, this fluorocarbon resin is polytetrafluoroethylene (PTFE). PTFE closely approximates a perfect diffuser for view angles < 45°. Pressed PTFE powder (useful in lab environments only) departs from the “completely reflecting” assumption by less than one percent in the wavelength range 350-1800 nm; it is more than 98% reflective in the wavelength range 280-2000 nm.

Schutt et. al. (1981) reviewed BaSO₄ as reflectance standard and noted, “... the IR reflectance of a BaSO₄ standard reflectance diffuser is sensitive to changes in humidity, and its reflectance cannot be recovered once it has been soiled. Clearly, applications of BaSO₄ are limited under certain environmental conditions outside the laboratory.” They tested Halon (PTFE) prepared for spray application and found its reflective properties to be comparable with those of BaSO₄ paint. Furthermore, because PTFE is hydrophobic, it is...
both washable and insensitive to humidity changes. Hence, Schutt et. al. (1981) recommend Halon (PTFE) in place of BaSO₄ paint as a field reflectance standard.

References:


2.4 Electromagnetic Energy

Typical energy flow - passive systems (Figure 2.1)

- energy source
- path length
- atmospheric interactions
- target interactions
- energy sensor
- active vs passive remote sensing

Electromagnetic energy

Electromagnetic radiation (EMR) is a dynamic form of energy made manifest only by its interaction with matter. EMR radiates according to the basic wave theory (Figure 2.2) which describes electromagnetic energy as traveling in a harmonic, sinusoidal fashion at the “velocity of light,” \( c = 3 \times 10^8 \text{ m/s} \). Wavelength (\( \lambda \)) is the linear distance between successive peaks, frequency (\( \nu \)) is the number of peaks passing a fixed point in space per unit time.

\[
c = \nu \lambda
\]
Typical Energy Flow

Wave Theory

\[ c = \nu \cdot \lambda \]
\[ c = 3 \times 10^8 \text{ m/s} \]

\( \lambda = \text{Wavelength} \)
\( \text{(Distance between successive wave peaks)} \)

\( \nu = \text{Frequency} \)
\( \text{(Number of cycles per second passing a fixed point)} \)

Energy received by sensor
Forescattering in the atmosphere
Additional scattering in the atmosphere
Scattering in the atmosphere
Small energy loss in space
Clouds reflect some energy
Not all energy is reflected

Sun

Energy received by sensor
Forescattering in the atmosphere
Additional scattering in the atmosphere
Scattering in the atmosphere
Small energy loss in space
Clouds reflect some energy
Not all energy is reflected

Typical Energy Flow

Wave Theory
The particle theory describes EMR as being composed of many discrete units called photons or quanta. The energy of a quantum is given as

\[ E = h\nu \]

\( E = \) energy of a quantum, Joules (J)
\( h = \) Planck’s constant, \( 6.626 \times 10^{-34} \) J sec.

The wave and quantum models of EMR are related by

\[ E = \frac{hc}{\lambda} \]

The energy of a quantum is inversely proportional to its wavelength. The longer the wavelength, the lower its energy content. This principle has important implications in remote sensing, particularly with regard to naturally emitted microwave radiation — hence the dominance of active microwave sensors.

The sun is the most obvious source of EMR for remote sensing, but ALL matter at temperatures above absolute zero (0 K or -273°C) continuously emit EMR. The amount of energy emitted is a function of the objects surface temperature as set forth in the Stefan-Boltzmann Law.

\[ W = \sigma T^4 \]

\( W = \) total radiant emittance, W / m²
\( \sigma = \) Stefan-Boltzmann constant,
\[ 5.6697 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \]
\( T = \) absolute temperature (K)

Total emitted energy varies with the fourth power of T and therefore increases very rapidly with increases in temperature.

The spectral distribution of emitted energy also varies with temperature according to Wien’s Displacement Law.

\[ \lambda_m = \frac{A}{T} \]

\( \lambda_m = \) wavelength of maximum spectral emittance
\( A = 2898 \mu\text{m} \)
\( T = \) temperature, K

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Together, the Stefan-Boltzmann Law and Wein’s Law stipulate that:

- the higher the temperature of a radiator, the greater the amount of radiation it emits (area under the curve)
- as temperature increases, the peak of the spectral radiation distribution shifts toward shorter wavelengths

The sun emits EMR in a manner similar to a blackbody radiator at 6,000 K and has its peak spectral energy at about 0.5µm. This corresponds to the peak spectral sensitivity of human eyes.

**Electromagnetic Spectrum (Figure 2.3)**

- Ultraviolet \( \lambda < 0.4 \mu m \)
- Visible light \( \lambda = 0.4 \) to \( 0.7 \mu m \)
- Near IR \( \lambda = 0.7 \) to \( 1.35 \mu m \)
  - Photographic IR \( \lambda = 0.7 \) to \( 0.98 \mu m \)
- Middle IR (SWIR)* \( \lambda = 1.35 \) to \( 3.0 \mu m \)
- Thermal IR \( \lambda = 3.0 \) to \( 14.0 \mu m \)
- Microwave \( \lambda = 1\text{ mm} \) to \( 1\text{ m} \)

* Short-Wavelength IR (SWIR)

2.5 **Energy Interactions in the Atmosphere**

The earth’s atmosphere has a profound effect on the intensity and spectral composition of EMR passing through it, principally through the mechanisms of scattering and absorption.

Scattering is unpredictable diffusion of radiation by particles in the atmosphere (Figure 2.4).

**Rayleigh scatter** - diffusion of radiation as it interacts with atmospheric constituents the diameters of which are much smaller than the wavelength of the interacting radiation. The effect of Rayleigh scatter is inversely proportional to the fourth power of wavelength. Short wavelengths are scattered more than long wavelengths, hence the blue sky. **Haze** is a primary effect of Rayleigh scatter.
Electromagnetic Spectrum

2.3

Wavelength (micrometers, μm)

Wavelength (nanometers, nm)

Ultraviolet | Visible | Near IR | Middle IR | Thermal IR | Microwave (radar)

0.1 0.2 0.4 0.7 1.0 5.0 10.0 50.0 100 1,000 10,000 (1 mm) 10,000 (10 mm)

Infrared (IR)
**Mie scatter** - diffusion of radiation by atmospheric particulates having diameters about equal to the wavelength of the interacting radiation. Water vapor and dust are the major causes.

**Nonselective scatter** - radiation diffusion by atmospheric particles whose diameters are much larger than the energy wavelength. Water droplets, commonly 5 to 100 µm in diameter, scatter all visible and reflective IR wavelengths about equally, hence white clouds.

**Absorption** - a thermodynamically irreversible transformation of radiant energy into heat.

Atmospheric absorption is due primarily to water vapor, carbon dioxide and ozone. These gases selectively absorb EMR in specific wavelength bands. Wavelength regions in which the atmosphere is particularly transmissive of energy are called *atmospheric windows*.

Figure 2.5 depicts the spectral transmittance of the atmosphere and shows the five “windows” used routinely in remote sensing. These windows are listed below:

### Atmospheric Windows

**Reflected EMR**
- **visible and near infrared** (0.3-1.3 µm) very high transmission (several small H₂O absorption features between 0.8 and 1.1 µm)
- **middle infrared** (1.5-1.8 µm and 2.0-2.6 µm) high transmission, but several very strong H₂O and CO₂ absorption bands at 1.4, 1.9, and 2.7 µm

**Emitted Thermal IR**
- **short-wavelength thermal infrared** (3.5-5 µm) popular window for night-time thermal sensing
- **long-wavelength thermal infrared** (8-14 µm) most frequently used thermal window

**Non-optical EMR**
- **microwave** (> 5.5 mm) transmission is virtually 100% (between 14 µm and 5.5 mm atmospheric transmission is very low)
Atmospheric Scattering 2.4

Atmospheric Transmissivity 2.5
ENERGY INTERACTIONS WITH EARTH SURFACE MATERIALS

EMR incident on any earth surface will interact in three fundamental ways - various fractions of the energy will be reflected, absorbed and/or transmitted.

\[ E_I (\lambda) = E_R (\lambda) + E_A (\lambda) + E_T (\lambda) \]

- \( E_I \) = incident energy
- \( E_R \) = reflected energy
- \( E_A \) = absorbed energy
- \( E_T \) = transmitted energy

\((\lambda)\) = denotes all components are a function of wavelength

Reflection, absorption, and transmission will vary for different earth features and help us to distinguish between them.

The wavelength dependency is critically important because two indistinguishable features in one wavelength region may be very different in another wavelength band - the foundation of multispectral remote sensing.

Specular Reflection - mirror like, where the angle of reflection equals the angle of incidence.

Diffuse Reflection - reflection is uniform in all directions (Lambertian).

EMR absorbed or transmitted by earth features are of little direct use in remote sensing except that the reflected energy we are interested in is reduced by these two mechanisms.
Solar Radiant Flux

For our purposes, the sun may be considered as a sphere of gas, nearly 1.4 million kilometers in diameter, which is heated by continuous nuclear reactions at its center. The spectral radiant flux output from the sun is complicated by the tremendous temperature variations which occur along its radius. Also, the solar atmosphere is opaque to certain wavelengths. Stated simply, the effective blackbody temperature (EBT) of the sun is wavelength dependent. In the wavelength region from 350 to 2500 nm, the EBT varies from 5,700 to 6,000 kelvin. At its peak exitance wavelength (487 nm), the sun can be best approximated by a blackbody source at 5,950 kelvin. For general discussion purposes, an average EBT of 6,000 kelvin can be used in the wavelength region 400-2500 nm. As show in Figure 2.6, more than 50 percent of the total solar energy present in the visible through middle-infrared spectrum occurs in the visible light region (400-700 nm).

2.6 Spectral Reflectance Characteristics of Earth Cover Types

BioPhysical Controls of Vegetation Reflectance

Energy Partitioning. From an energy balance viewpoint, all solar radiant flux incident upon any object is either reflected, transmitted, or absorbed. As a group, vegetation is unique in its three-segment partitioning of solar irradiance (Figure 2.7). In the visible part of the spectrum (400-700 nm), reflectance is low, transmittance is nearly zero, and absorptance is high. The fundamental control of energy-matter interactions with vegetation in this part of the spectrum is plant pigmentation.

In the longer wavelengths of the near-infrared portion of the spectrum (700-1350 nm), both reflectance and transmittance are high whereas absorptance is very low. Here the physical control is internal leaf structures. The middle-infrared sector (1350-2500 nm) of the spectrum for vegetation is characterized by transition. As wavelength increases, both reflectance and transmittance generally decrease from medium to low. Absorptance, on the other hand, generally increases from low to high. Additionally, at three distinct places in this wavelength domain, strong water absorption bands can be observed. The primary physical control in these middle-infrared wavelengths for vegetation is in vivo water content. Internal leaf structure plays a secondary role in controlling energy-matter interactions at these wavelengths.
Solar Spectral Exitance

Relative Spectral Exitance

Wavelength (µm)

6000K Blackbody Temperature

Spectral Partitioning by Vegetation

Transmittance

Absorptance

Reflectance

Percent Reflectance

Percent Transmittance

Wavelength (µm)
Visible Reflectance. The dominant plant pigments are the chlorophylls. These compounds exhibit pronounced absorptance of the bluish (400-500 nm) and reddish (600-700 nm) wavelengths (Figure 2.8.) This absorption of solar energy by vegetation is, of course, required in order to support photosynthesis. As noted above, transmittance by vegetation in the visible wavelengths is very low. Irradiance which has not been absorbed will be reflected. Thus, Chlorophyll-bearing vegetation appears green as a result of its minor reflectance peak in the 500-600 nm wavelengths.

There are other plant pigments, the carotenes and xanthophylls, which produce yellow or orange reflectances. Figure 2.9 shows the single, broad absorptance band, centered at about 450 nm, associated with these compounds. Although frequently present in green leaves, the solitary absorption feature produced by these pigments is usually masked by the chlorophyll absorptance. During stress or senescence, however, chlorophyll production usually declines and blue absorption (i.e. yellow reflectance) of the carotenes/xanthophylls may become obvious.

The anthocyanins are another type of plant pigment. They absorb the bluish and greenish wavelengths, giving rise to their red reflectance (Figure 2.9). These compounds are also frequently present in green foliage, but are masked by chlorophyll absorption. Some plant species (e.g. red maple *Acer rubrum*) produce large quantities of anthocyanin during autumn senescence at a time when chlorophyll production is declining. The resulting shift in spectral absorptance accounts for the bright red leaf color.

As plant senescence progresses, the changes in relative abundance of the various pigments are accompanied by shifts in spectral absorptance and reflectance. Figure 2.10 illustrates the temporally dynamic nature of visual foliar reflectance.

Near-Infrared Reflectance. Experiments by Moss (1951), Pearman (1966), Woolley (1971), Gausman (1977), and others have demonstrated that leaf reflectance occurs internally. The fundamental mechanism responsible for this phenomenon is the refractive index differences between the various internal leaf structures (cell walls, air spaces, chloroplasts, etc.). Leaves which were vacuum infiltrated with various liquids reflected less energy in the 400-2500 nm wavelengths than non-infiltrated leaves (Figure 2.11). Note that the near-infrared (NIR) reflectance was the most altered in these experiments, followed by the middle-infrared reflectance.
### Chlorophyll Compounds

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Relative Absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- **Chlorophyll-a**
- **Chlorophyll-b**

### Non-green Pigments

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Relative Absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- **α--Carotene**
- **Anthocyanin**
- **Lutein (Xanthophyll)**
# Introduction to Environmental Remote Sensing

## Senescence

- **Wavelength (µm):**
  - 0.4 to 1.1
- **Percent Reflectance:**
  - 0 to 60
- **Phases:**
  - Summer
  - Early fall
  - Mid-fall
  - Late fall

- **Colors:**
  - Green
  - Yellow-Green
  - Yellow
  - Brown

## NIR Foliar Reflectance

- **Wavelength (µm):**
  - 0.4 to 2.4
- **Percent Reflectance:**
  - 0 to 50
- **Voids:**
  - Filled with air (Refractive Index = 1.00)
  - Filled with water (Refractive Index = 1.33)
There are two common types of structural arrangements within leaves. The dorsiventral leaf structure, typical of dicots, has palisade mesophyll along the upper leaf side and spongy mesophyll composing the lower portion (Figure 2.12). The compact leaf structure typical of monocots, in contrast, presents a relatively densely-packed mesophyll lacking the long, prism-like palisade cells and containing very few large intercellular air voids. Internal leaf structure exerts little control on visible reflectance. In the infrared spectrum, dorsiventral leaves - containing numerous large air voids - reflect more long-wavelength radiation than compact leaves (Figure 2.13).

The important role these internal air voids play in controlling infrared reflectance is highlighted by observing leaf maturation. From a structural standpoint, dorsiventral leaves grow by pulling themselves apart internally (Figure 2.14). Immature dorsiventral leaves exhibit a compact, overall mesophyll arrangement. The lacunate mesophyll associated with older dorsiventral leaves contains many more air spaces. The relationships between spectral reflectance and leaf maturity are illustrated in Figure 2.15. Since young, immature leaves contain less chlorophyll and fewer air voids than older leaves, they reflect more visible light and less infrared radiation.

The most well-known near-IR reflectance difference between vegetation types is that which can be observed between broadleaf and needleleaf arboreal species. This very useful relationship, shown in Figure 2.16, exhibits indistinguishable spectral reflectances in the visible wavelengths, but easily recordable differences in the photographic infrared. Although stand conditions such as site index, age class, canopy closure, disturbance history, etc. will promote within-class differences, in general, broadleaf trees will reflect much more (> 10% more) NIR radiation than needleleaf trees. These large differences in NIR reflectance are the result of several factors:

1. At the leaf level of observation, the broad leaves have a dorsiventral internal leaf structure while the needle leaves have a compact internal structure.

2. At the plant level of observation, most broadleaf trees have a much higher leaf-area/stem-branch-trunk area ratio compared to needleleaf trees. The non-foliar stems, branches and trunks tend to absorb NIR radiation.

3. At the canopy level of observation, most well-stocked broadleaf canopies present an upper reflectance surface that is nearly
2.12 Leaf Structures

Dorsiventral Leaf Structure (typical of dicots)

Compact Leaf Structure (typical of monocots)

2.13 Effect of Leaf Structure on Reflectance

Dorsiventral

Compact
2.14 Dorsiventral Leaf Maturation

Young Leaf
Compact Mesophyll
(Few Air Spaces)

Older Leaf
Lacunate Mesophyll
(Many Air Spaces)

2.15 Leaf Maturity

[Graph showing percent reflectance vs. wavelength (µm) for new and old leaves]
Spectral Signatures of Deciduous and Coniferous Trees

unbroken foliar material (i.e. high NIR reflectance) with fewer dark shadows compared to the needleleaf canopy which, even when well stocked, presents many inter-tree gaps and shadows. In large part, this is due to the differences in growth forms between the two types: broadleaf trees tend to have a rounded or bulbous form compared to the near conical form of needleleaf trees.

Foliar infrared reflectance is also altered by the number of leaf layers present in the canopy. In the near infrared especially, there is very little absorption - any irradiance that is not reflected will be transmitted. The impact of these energy-matter interactions can be illustrated using the overly-simplistic reflectance model shown in Figure 2.17. In this example, it is assumed that all of the irradiance is divided equally between reflectance and transmittance.

As a consequence of minimal absorptance in the near infrared, there is a limited, but useful, relationship between foliar biomass and NIR reflectance (Figure 2.18). As the number of leaf layers increases (increasing leaf area), infrared reflectance increases, especially in the NIR. Note that visible light reflectance remains unchanged since transmission is near zero. Note that beyond a certain point, called the infinite or asymptotic reflectance level, increasing leaf area has no impact on spectral reflectance.

One digital processing technique that seeks to take advantage of these reflectance relationships in the visible and NIR is called the Normalized Difference Vegetation Index (NDVI). It uses image algebra and is defined as:

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$

That is, the difference between the red light reflectance and the near infrared reflectance divided by their sum. The division by the sum of the red light and the NIR light is an attempt to normalize this index so that it may be used for multi-temporal or inter-scene comparison work. The premise of the index is that only vegetation, among the three major classes of earth cover types, possesses a large difference between its red light reflectance (due to chlorophyll absorption) and its NIR reflectance (due to high NIR transmissivity and, therefore, added NIR reflectance from deep within a vegetation canopy.

Numerous studies, using multispectral imagery of various spatial resolutions, have related NDVI values to canopy leaf area index (LAI). LAI is the amount of leaf surface area per unit ground area, and is widely used to describe the photosynthetic and transpirational surface of plant canopies. Using high-spatial-resolution data...
NIR Reflectance Model

\[
0.5 + 0.125 + 0.031 = 0.656
\]

Leaf Area

Percent Reflectance

Wavelength (µm)
(pixels = 2.23 x 2.46 meters or 2.23 x 9.45) from the Compact Airborne Spectrographic Imager (CASI), Gong et al. (1995) demonstrated a very strong statistical relationship ($r^2 = 0.971$, rmse = 0.764) between measured LAI and predicted LAI (Figure 2.19). In the best case, they used NDVI values calculated from a NIR band at 761.4 - 770.2 nm and a red-light band at 601.0 - 609.8 nm. Other bands on the CASI instrument yielded somewhat lower $r$-squared values in relating the NDVI value to the measured LAI value ($r^2 = 0.970$, rmse = 0.848 and $r^2 = 0.968$, rmse = 1.151). Importantly, these investigators mention that, "NDVI starts to saturate before LAI reaches 6." The western montane forest canopies they were studying had LAI values that peaked between 8 and 13.

Using Thematic Mapper Simulator data (24 x 24 meter pixels), Peterson et al. (1987) also reported a very strong statistical relationship between measured LAI and the NIR/red ratio. This study also used montane forest canopies as its target that had LAIs that varied from 1 to 16. As shown in Figure 2.20, a log-linear relationship between the NIR/Red ratio and the measured leaf area index explained 91% of the variance ($r^2 = 0.91$, S.E. = 0.77). These researchers also noted that, "The LAI to Near IR/red relationship slowly became asymptotic, reaching a saturation level at about an LAI of ten."

Even at the coarse spatial resolution of the AVHRR instrument (pixels = 1.2 km²), Spanner et al. (1990) reported reasonably strong statistical relationships between measured LAIs of montane forest canopies and the NDVI (Figure 2.21). In their best fit from July 1987, the $r^2 = 0.789$ with a standard error of 0.044. These results were obtained with monthly-maximum-NDVI composite imagery, so the lower explanation of variance is not unexpected. These authors noted, "...penetration of light into the forest canopy becomes asymptotic above an LAI of 5-6, so that some asymptotic behavior should be inherent in the relationship at an LAI above 6."

**Middle-Infrared Reflectance.** In the middle-infrared (MIR) wavelengths, leaf reflectance is inversely related to *in vivo* water content (Figure 2.22). Overall reflectance increases as a leaf desiccates. The rise in middle-infrared reflectance, compared to the shorter wavelengths sectors, is the most substantial. Within the MIR wavelengths, the greatest reflectance changes occur in the major water absorption bands at 1.45, 1.92, and 2.7 micrometers. The minor water absorption bands at 0.96 and 1.2 micrometers become notable spectral features in the reflectance curves of multi-layer
**NDVI vs. LAI**

**High Spatial Resolution**

![Graph showing the relationship between Predicted LAI and Measured LAI. The graph includes a linear regression line with R^2 = 0.971. The data points indicate a strong positive correlation. Predicted LAI derived from NDVI where NIR = 761.4 - 770.2 nm and Red = 601.0 - 609.8 nm.]

**VI vs. LAI**

**Moderate Spatial Resolution**

![Graph showing the relationship between叶面积指数 (Leaf Area Index, LAI) and atmospherically corrected near IR/Red ratio. The equation y = 1.92x^{0.583}, R^2 = 0.91, S.E. = 0.77 is provided. Relationship between the atmospherically corrected near IR/Red ratio and the LAI of the forest stands.]

---

(c) 1999  David P. Lusch, Ph.D.
Figure 2.21: NDVI vs. LAI Coarse Spatial Resolution

The graph shows the relationship between leaf area index (LAI) and NDVI for July 1987. The equation is given as $y = 0.315x - 0.256$, with $R^2 = 0.789$ and S.E. = 0.044. The relationship indicates a strong positive correlation between LAI and NDVI. The graph is labeled as 'July 1987 NDVI'.

Figure 2.22: Leaf Moisture Content

The graph depicts the percent reflectance against wavelength (in micrometers) for different moisture content levels. The moisture content levels are labeled as wet, decreasing moisture content, and dry. The graph shows a decrease in percent reflectance as the wavelength increases, indicating a decrease in moisture content from wet to dry conditions.
canopies. Note that long-path length remote sensing of middle-infrared radiation must be accomplished in the appropriate “atmospheric windows” - 1.5 to 1.8 and 2.0 to 2.6 micrometers - in between the major water absorption bands (Figure 2.23).

**BioPhysical Controls of Soil Reflectance**

The spectral reflectance of soil is controlled, for the most part, by six variables: moisture content, organic matter content, particle size distribution, iron oxide content, soil mineralogy, and soil structure (Obukhov and Orlov, 1964; Bowers and Hanks, 1965; Shields *et al*., 1968; Baumgardner *et al*., 1970; Bowers and Smith, 1972; Peterson *et al*., 1979; Stoner and Baumgardner, 1980, 1981). Of these variables, moisture content and organic matter are the most important (Figure 2.24).

**Moisture Content.** The near-surface moisture content of soil is the most important reflectance factor due to its dynamic nature and large overall impact on soil reflectance. As shown in Figure 2.25, there is an inverse relationship between edaphic moisture content and soil spectral reflectance. Note the persistence of the water absorption bands (1.45 and 1.92 micrometers) even in the air-dried sample. This results from water films being held tightly onto the relatively large proportion of very fine silt and clay particles in this particular soil. Also notable is the strong hydroxyl absorption band at 2200 nm which many clay-rich soils will exhibit. Comparing soils from different natural drainage classes, the better drained soils are more reflective (Figure 2.26).

**Organic Matter Content.** Mineral soils, as distinct from organic soils, are dominantly mineral material with less than 20 percent organic carbon by weight. As shown in Figure 2.27, for mineral soils, as the organic matter content increases, soil reflectance decreases. As shown in Figure 2.28, some researchers have demonstrated a workable relationship between remotely sensed soil reflectance and organic carbon content. The reflectance of organic soils, on the other hand, is controlled primarily by state of decomposition of the plant material (Figure 2.29). Peat (fibric material) is composed of plant remains which have undergone only minimal decomposition. This type of organic soil is usually dark brown to reddish-brown. The highly decomposed sapric material (muck) is generally black. Organic soils of intermediate decomposition are classed as hemic soils.
2.23 Atmospheric Transmissivity

Transmission

Transmission [%]

1 μm 10 μm 100 mm 1 mm 1 m

Wavelength

O₃, H₂O, CO₂

2.24 Soil Reflectance

Six Controlling Factors

Most Important Factors
1. Moisture Content
2. Organic Matter Content

Other Factors
3. Particle Size (surface)
4. Iron Oxide Content
5. Mineralogy
6. Structure
Well — Moderately Well Drained
Somewhat Poorly — Poorly Drained
Very Poorly Drained

Wavelength (µm)

Percent Reflectance

Silt Loam Texture
sand 22%
silt 66%
clay 12%

Soil Drainage

Wavelength (µm)

Percent Reflectance

Soil Moisture Content

Percent Reflectance

Silt Loam Texture
sand 22%
silt 66%
clay 12%
Organic Matter Content

mineral soils

Low
Medium
High

Percent Reflectance

Wavelength (µm)

0 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4

0 5 10 15 20

0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4

2.27
Relationship between soil organic carbon and Landsat TM data in eastern Washington

Regression function comparing the association between measured s.o.c. content and observed Landsat TM values for the pooled Plaza and Pullman, Washington field sites (A) and the pooled Thera and St. John, Washington field sites.


Processing notes:

2 pixel by 2 pixel spatial average (28.5m x 2 = 57m)

Atmospheric correction performed (Chavez’s dark object subtraction)

DN’s converted to Radiances

Ratios: 1/4; 3/4; 5/4; 5/3

PC Transformation: PC1: greeness variation
PC2: soils variation
PC3: wetness variation

Regressed PC2 vs Soil Organic Carbon of pooled samples
**Particle Size Distribution.** The larger-diameter particle sizes (e.g. medium sand, coarse sand, etc.) exhibit pronounced interstitial voids. This increased surficial micro-roughness, compared to the fine particle sizes, presents many more “light traps” to any irradiance. Assuming the other soil factors are equal, the finer particle sizes will exhibit greater soil reflectances (Figure 2.30). With moisture content equilibrated, and the organic matter content naturally similar, the multi-sample data presented in Figure 2.31 illustrate the relationship between soil texture and spectral reflectance.

**Iron Oxide Content.** Iron oxide (Fe₂O₃) is one of the primary causes of the red colors in many soils. Iron oxide content and organic matter content are the two most important soil properties affecting the spectral reflectance characteristics of eroded soils, particularly in the 500 to 1200 nm region (Weismeiier *et al.*, 1984). The data presented in Figure 2.32 illustrate the relationship between iron oxide content and soil spectral reflectance. Chemically removing the extractable iron oxides from a soil sample results in increased reflectance especially at wavelengths less than 1100 nm. A broad absorption feature, centered at 900 nm and attributed to iron oxide, is obvious in this graph.

**BioPhysical Controls of Water Reflectance**

**Energy Partitioning.** There are three types of possible reflectance from a water body - surface (specular) reflectance, bottom reflectance, and volume reflectance (Figure 2.33). Of these, only volume reflectance contains information relating to water quality. For deep (>2 m), clear water bodies, volume reflectance is very low (6-8 percent) and is confined to the visible wavelengths (Figure 2.34). Transmittance in these cases is very high especially in the blue-green part of the spectrum, but diminishes rapidly in the near-infrared wavelengths. Absorptance, on the other hand, is notably low in the shorter visible wavelengths, but increases abruptly in the near-infrared sector. Shallow water (<2 m deep) transmits significant amounts of NIR radiation (Figure 2.35). As depth increases, the peak transmittance wavelength for clear water decreases and finally stabilizes at about 480 nm.

**Volume Reflectance.** Clear water reflects very little solar irradiance, but turbid water is capable of reflecting significant amounts of sunlight (Figure 2.36). It is notable that the peak-reflectance point shifts to longer wavelengths as turbidity increases (Figure 2.37). As shown in Figures 2.38 and 2.39, as the chlorophyll content of a water body increases (resulting from an increase in algae, phytoplankton, etc.) its
Soil Particle Size

Wavelength (µm)  Percent Reflectance

- Medium Silt
- Very Fine Sand
- Fine Sand
- Medium Sand
- Coarse Sand
- Very Coarse Sand

Soil Texture

Wavelength (µm)  Percent Reflectance

- Sandy Loam
- Fine Sandy Loam
- Very Fine Sandy Loam

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### Iron Oxides in Soil

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Percent Reflectance</th>
</tr>
</thead>
<tbody>
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<td>2.2</td>
<td>90</td>
</tr>
<tr>
<td>2.4</td>
<td>100</td>
</tr>
</tbody>
</table>

**Iron Oxide Absorption Band**

- Iron Oxides Present (<5%)
- Iron Oxides Chemically Removed

### Water Reflectance

- Solar Irradiance
- Scattered “Air Light”
- Surface Reflectance
- Bottom Reflectance
- Volume Reflectance
**Spectral Partitioning by Water**

- Transmittance
- Absorptance

**Water Transmittance**

- Deep, clear water

---

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Percent Reflectance vs. Wavelength (µm)

Water Turbidity

Total Solids (mg/l)

Percent Reflectance

Water Turbidity

Spectral Reflectance, Rv (%)

Chlorophyll in Water

Chlorophyll in Fresh Water

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2-38
blue-light reflectance decreases while its green-light reflectance increases. The “hinge point” in this relationship, over four orders of magnitude of concentration differences, remains relatively stable at 510-520 nm. Also noteworthy, is the asymptotic reflectance change in the blue wavelengths as chlorophyll concentration increases compared to the reflectance differences in the longer wavelengths.

**Clouds and Snow.** Snow and clouds can be easily differentiated only in the middle-infrared portion of the spectrum (Figure 2.40). Snow reflectance is unique. It is very high in the visible and NIR wavelengths, but plummets to near zero in the water absorption bands, and remains at relatively low levels between them. In contrast, most clouds act as non-selective scatterers and reflect significant amounts of solar irradiance across the 400-2500 nm spectrum.

**Summary**

The reflectance, absorptance, and transmittance characteristics of generalized vegetation, soil, and water features have been summarized using graphical examples from the research literature. This synthesis is designed to facilitate our understanding of the principal, physical controls of these energy-matter interactions. These relationships are assumed to be fundamental to fully comprehending any remotely-sensed data acquired in the 400-2500 nm spectrum.
Percent Reflectance vs. Wavelength (µm) for Snow and Clouds

- Clouds
- Snow

Key:
- 50 µm grain radii
- 200 µm
- 1000 µm

Reflection peaks at different wavelengths for each category.
References


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**Reference for Figure 2.39**

Chapter 3 Videography

Contents

3.1 Objectives
3.2 Introduction
3.3 Video Signal Recording
3.4 VCR Formats
3.5 Color Infrared Videography
3.6 Airborne Videography
3.1 Objectives

- Compare the spatial and spectral resolution of video technology with film-based systems
- List four advantages and two disadvantages of video remote sensing
- Describe two applications which could benefit from the use of airborne videography

3.2 Introduction

Video is a Latin word meaning *I see*. Most of us are familiar with audio, meaning *I hear*, systems in which the microphone converts sound waves into electrical signals. In a video system, the sensor (either a vidicon tube or a solid state array) in the camera converts light energy into electrical signals. The sensor is to a video system what the microphone is to an audio system. The raw video signal is a fluctuating DC voltage. Bright objects in the scene are represented by higher voltages; dark parts of the scene are represented by lower voltages.

Just as an audio signal can be recorded on tape, so to the video signal can be tape recorded. However, recording video signals is a more difficult task because of the much higher frequencies associated with video data. High-fidelity sound recording, for instance, captures a frequency range of about 20 to 20,000 Hz. In marked contrast, the frequency range of video extends to 4 MHz or more — 200 times the range of audio!

3.3 Video Signal Recording

The amplitude-modulated, DC-voltage video signal is converted into a frequency-modulated signal by the video cassette recorder (VCR). As illustrated in Figure 3.1, the FM circuit in the VCR uses a voltage-controlled oscillator (VCO) for this purpose. The voltage fluctuations of the incoming video signal causes the oscillator’s vibrational frequency to vary. For a VHS recording system, for example, the sync tip of the input video signal is locked at the voltage level which produces a 3.4 MHz oscillator output frequency. The video voltage associated with peak white, on the other hand, causes the oscillator frequency to increase to 4.4 MHz; this provides a total bandwidth of 1.0 MHz.

In North America, the format of video images is specified by the RS-170A standard from the National Television Standards Committee (NTSC). This requirement specifies that each
3.1 Video Recording

Video signal from camera (fluctuating DC voltage: black = 0 V, white = 1 V)

FM modulator (VCO)

To Tape

FM output signal

Hi-Fi audio recording captures a frequency range of 20-20,000 Hz

Video recording frequencies extend beyond 4 MHz -- more than 200 times the range of audio

Sync Tip

Video Signal Voltage

Peaks White

Luminance Signal Bandpass

1 2 3 4 5 6 MHz
A video picture (called a frame) will contain 525 scan-lines, which will be scanned in 1/30 second. Each frame is generated by interlacing two fields, each containing 262.5 scan-lines, which is produced in 1/60 second. If the vertical blanking interval — the time required for the scanning electron beam (in a video tube) to reposition itself from the bottom of one field to the top of the next — is taken into account, vertical resolution of NTSC video is limited to about 242 lines per field. Horizontal resolution is the amount of detail in the horizontal direction of the picture and is dependent primarily on the frequency bandwidth of the video signal. It is expressed as the number of lines that can be resolved in three-quarters of the picture width — a function of the 4:3 aspect ratio of video. For broadcast television, this bandwidth is fixed by the FCC (each channel is allocated a 6-MHz bandwidth). In remote sensing applications, the videographic imagery is generally not collected for broadcast purposes. In this context, the horizontal resolution of the data is determined by the quality of the video camera/lens system and the video cassette recorder.

The faster the magnetic tape can be moved across the gap of the recording head, the better the recording of high-frequency (i.e. rapidly varying) signals will be. Clearly, increasing the tape speed in order to record a 4-MHz signal would require an unrealistic amount of tape. This problem was solved by radically changing the tape scanning method. Whereas audio tape is pulled past a stationary recording head, video tape is usually moved past a rapidly rotating head. Hence, the relative tape speed is dramatically increased without using a prohibitive amount of tape.

The frequency-modulated video signal, called the luminance or Y signal, carries the black and white information of the scene. This achromatic data provides the spatial detail in the video image. The color information in the video signal, the chrominance (or chroma) signal, is converted by the VCR to a lower-frequency, non-modulated subcarrier. Two different color subcarrier frequencies are used, depending on the recording format.

3.4 VCR Formats

The portable VCR technology required for airborne videography is barely twenty years old. Sony introduced the 3/4-inch U-Matic format in 1969, and within three years it became the industrial standard. The 1/2-inch “consumer” formats, Beta and VHS, both were released in the late ’70s. Beta was the second format which
Sony marketed — hence their use of the second letter of the Greek alphabet to name the product. Originally, VHS stood for Vertical Helical Scan, a studio recording method. Later, VHS became a trademark of JVC, Inc as the Video Home System. These product names have now been extended in usage to represent two different, and unfortunately incompatible, video formats. In early 1987, Sony improved their 3/4-inch product line with the addition of the 3/4-inch SP U-Matic. Later that same year, JVC released a much-improved 1/2-inch format called Super VHS (S-VHS). Sony produced the newest professional format in 1988: Extended Definition (ED) Beta.

In addition to these consumer-grade and industrial formats, the early ’80s saw the introduction of professional component recorders. Sony developed the Betacam system, whereas Panasonic and RCA supported the M-format. These very expensive recorders use tape at six times the normal speed in order to record the chrominance signals separately from the luminance signal. Yet another professional format was released by Panasonic in 1985 — the VHS-based M-2 format. This special type of recorder uses metal-particle tape and is known for providing superb reproductions out to several generations. To date, these professional systems, mostly because of their cost, have not been used much in video remote sensing.

As mentioned earlier, the vertical resolution of video is determined primarily by the fixed number of interlaced scan lines. The horizontal resolution, in comparison, is determined in large part by the maximum recording frequency. Figure 3.2 shows that the 1/2-inch, VHS format uses a peak frequency of 4.4 MHz (Beta uses 4.8 MHz). This provides a maximum recorded horizontal resolution of about 240 lines, regardless of how many lines the video camera produced. The 3/4-inch, U-Matic format has a 5.4 MHz peak frequency which allows about 260 vertical lines to be recorded. With their 3/4-inch, SP U-Matic format, Sony provided a major improvement in recordable resolution. In this format, the peak recording frequency is 6.6 MHz, providing 340 lines of horizontal resolution. The S-VHS format boosts the peak recording frequency to 7.0 MHz, providing more than 400 lines of horizontal resolution. ED Beta uses a peak frequency of 9.3 MHz. It’s reported to be able to reproduce about 500 lines of resolution.

In order to use these higher signal frequencies, which are more difficult to record, improved types of magnetic tape were required. The more magnetically absorbent a tape is, the easier it is to record a high-frequency signal. Magnetic absorbency is called coercivity and is measured in oersteds. Standard VHS tape has a coercivity of about
3.2 Video Bandwidths

VHS
- Luminance: 1.0 MHz
- 240 lines
- Color
- 629kHz

U-Matic (conventional)
- Luminance: 1.6 MHz
- 260 lines
- Color
- 688kHz

Super Beta
- Luminance: 1.2 MHz
- 290 lines
- Color
- 688kHz

S-VHS
- Luminance: 1.6 MHz
- 420 lines
- Color
- 629kHz

ED Beta
- Luminance: 2.5 MHz
- 500 lines
- Color
- 688kHz
700 oersteds. The 3/4-inch formats, U-Matic and the SP U-Matic, have tape coercivities of around 650 and 720 oersteds, respectively. The S-VHS tape has a coercivity of at least 900 oersteds. The ED Beta system shifted to a metal tape having a coercivity of about 1450 oersteds.

The frequency bandwidth of the recorded video signal is analogous to the quantization level of a digital system. The larger the dynamic range, the better small reflectance differences in the scene can be recorded. With a broader frequency bandwidth, the system electronics in a VCR are better able to discriminate between closely-grouped frequencies associated with minor differences in scene brightness. This increased contrast helps to sharpen the appearance of the image.

Standard VHS has a 1.0 MHz luminance-signal bandwidth (see Figure 3.2). Black is recorded as a 3.4 MHz frequency and white is recorded as a 4.4 MHz signal. The S-VHS and the two U-Matic formats use a 1.6 MHz luminance-signal bandwidth. In the case of Super VHS, white is recorded as a 7.0 MHz signal while black is recorded as a 5.4 MHz frequency. ED Beta uses a 2.5 MHz bandwidth ranging from 6.8 MHz (black) to 9.3 MHz (white).

Both the S-VHS and ED Beta VCRs are capable of recording and playing back the luminance (Y) signal separately from the chrominance (C) signal. This avoids the mixing of these two signals inherent to the NTSC format. The separated Y/C signals can be displayed on special monitors. The results are TV pictures which appear somewhat sharper because the color component is more crisply displayed, especially along the edges of features.

3.5 Color Infrared Videography

A standard color video camera using vidicon tubes as its sensor is shown in Figure 3.3. Like all multispectral imaging devices, the camera decomposes the incoming radiant energy into three separate spectral paths and provides a separate detector for each channel. In the example shown here, dichroic mirrors are used for the beam splitter. These optical devices have preferred reflectivity — the “blue” mirror, for example, reflects bluish wavelengths of light, but freely transmits the greenish and reddish light. Other methods, such as prisms, can also be used as the beam splitter.

In the spring of 1983, researchers at the University of Minnesota developed the first single-camera, color infrared video
system (Meisner and Lindstrom, 1985). Two major modifications of a standard, three-tube, color video camera were made. First, the beam-splitter assembly was replaced with one that rejects blue light altogether, but separates the green, red and near infrared components using different dichroic mirrors (Figure 3.3). Second, the Saticon tube and its supporting electronics from the blue channel were removed and replaced with a silicon target tube which has sensitivity in the near infrared portion of the spectrum (Figure 3.4). This camera still produces a standard NTSC composite signal, so standard video cassette recorders can be used to capture the imagery.


In striking parallel with the development path of aerial photography, airborne videography has moved through black and white, B/W infrared, color, and color infrared capabilities. Everitt (1988) provides a succinct review of the historical development of videography. Table 3.1 lists the major advantages and disadvantages of videography.

Most airborne videography, like aerial photography, is acquired in the vertical mode (Figure 3.5). This can be accomplished with a clamp-on exterior mount, but is best done using a belly mount so that the video camera is afforded some environmental protection. Other necessary pieces of equipment include a portable VCR and some means of powering the system (batteries or connection to the aircraft power system). A small portable video monitor is, while not a necessity, a great advantage to ensure that the system is working and that the flight line is correct. Meisner (1986) and Vlcek (1988) should be consulted for more information about planning an airborne videography mission.
Video Detectors

Relative Sensitivity vs. Wavelength (µm)

Silicon Target Tube
Saticon Tube
Blue Green Red Near Infrared

Airborne Videography

Video Camera
Portable Video Cassette Recorder
5-inch Portable Color Monitor

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Table 3.1 Advantages and Disadvantages of Videography

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Near-real-time availability of the imagery</td>
<td>• Low spatial resolution</td>
</tr>
<tr>
<td>• Greater light sensitivity than film permitting narrow band imagery and longer wavelength sensitivity</td>
<td>• Difficult to obtain hard copy of the images</td>
</tr>
<tr>
<td>• Immediate potential for digital processing of the video signal</td>
<td>• Relatively narrow field of view</td>
</tr>
<tr>
<td>• Equipment is portable, versatile, easy to use, and has a low operating cost</td>
<td>• Near-infrared video systems have a vignetting problem</td>
</tr>
<tr>
<td>• Ability to view live imagery concurrent with its acquisition</td>
<td>• Calibration is difficult due to automatic gain control</td>
</tr>
<tr>
<td>• Ability to record “field notes” on the audio track</td>
<td></td>
</tr>
<tr>
<td>• High frame rate (30 per second) offers extreme endlap which can be useful in some situations (e.g. small, scattered clouds below the aircraft)</td>
<td></td>
</tr>
</tbody>
</table>
References


Chapter 4  Multispectral Scanner Systems

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4.10 Earth Observation System

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4.1 Objectives

- Define the term "pixel".

- Define the term "Digital Number (DN)".

- Explain the difference between IFOV and ground resolution.

- Describe the cause of geometric distortion from scanners.

- Compare imaging spectrometers to multispectral scanners.

- Explain the necessity of using polar-orbiting satellites for earth-resources observations.

- List the spectral sensitivities of the eight Landsat-7 ETM+ bands.

- Describe the potential information content of each spectral band of the Enhanced Thematic Mapper.

- Given a set of generalized spectral reflectance curves for selected features, predict the display color which will form using several different RGB band combinations.

- Compare the spatial, spectral, and revisit differences between Landsat-7 and SPOT-4.

- List the advantages of the off-nadir viewing capability of SPOT-4.

- List the spatial, spectral, and revisit characteristics of the AVHRR instrument on the NOAA Polar Orbiter satellites.

- Define the vegetation index concept and describe its use.

4.2 Introduction

Basic concepts of digital image data are presented to introduce the topic of scanning systems, their geometric distortions and the difference between imaging spectrometers and multispectral scanners. Satellite multispectral scanners are introduced with a comparison of the Landsat 7 ETM+ instrument and the HRVIR imager on SPOT 4. For historical completeness, the first- and second-generation Landsats (1-3 and 4-5) and the first SPOT series (1-3) are also described. The AVHRR instrument is briefly discussed and compared with the current Landsat and SPOT systems.
4.3 Multispectral Scanners

Scanning Systems

There are two approaches used "scan" an image from a remote platform. The first, across-track scanning, uses a rotating or oscillating mirror to sweep one or more detectors across the scene while the platform carries the imager along the flight tract (Figure 4.0a). The alternative method - along-track scanning - uses a fixed, linear array of numerous detectors which form the physical width of the scene. Each detector forms one column of data. Again, the platform motion develops the length of the image (Figure 4.0b). Notwithstanding these differences, all imagers have three hardware components in common: front-end optics, beam splitter and analog-to-digital converter (Table 4.1).

Concepts of Digital Image Data

- **Pixel** is a contraction of picture element, which is the area or cell from which radiance or landscape brightness is recorded by a multispectral scanner. (Note, the assigned pixel dimensions may not exactly correspond to the area from which the radiance measurements were made (i.e. the IFOV) if the system "over scans" - this was the case with the MSS instrument on Landsats 1-3).

- **Digital Number** (DN) is the relative radiance measurement or "brightness" value (BV), recorded as an integer, for an individual pixel in an individual spectral band.

- **IFOV** (instantaneous field-of-view) is the solid angle subtended by a detector element in an imaging device when the scanning motion is stopped. The IFOV is a system specification, usually presented in radians, milliradians or microradians.

- **Ground resolution** refers to the area of the earth's surface captured by the IFOV of a radiometer at a given flying height above the terrain:

\[ D = H' \beta \]

where  
- \( D \) = diameter of the ground area viewed  
- \( H' \) = flying height above the terrain  
- \( \beta \) = IFOV of the system expressed in radians
Across-track or Whiskbroom MSS system operation

Along-track or Pushbroom MSS system operation
<table>
<thead>
<tr>
<th><strong>TABLE 4.1 COMMON COMPONENTS OF MULTISPECTRAL SCANNERS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. SCANNING METHODS</strong></td>
</tr>
<tr>
<td>- Across - Track Scanning (Whiskbroom)</td>
</tr>
<tr>
<td>- Along - Track Scanning (Pushbroom)</td>
</tr>
<tr>
<td><strong>2. HARDWARE BASICS</strong></td>
</tr>
<tr>
<td><strong>- COLLECTION OPTICS</strong></td>
</tr>
<tr>
<td>- Includes the scan mirror for across-track scanners</td>
</tr>
<tr>
<td>- Determines the field-of-view (i.e. total image width)</td>
</tr>
<tr>
<td>- For a given detector size and flight altitude, determines the ground resolution</td>
</tr>
<tr>
<td><strong>- BEAM SPLITTER</strong></td>
</tr>
<tr>
<td>- Decompose incoming radiance into separate wavelength ranges (bands)</td>
</tr>
<tr>
<td>- Uses dichroic gratings, dichroic mirrors, or prisms</td>
</tr>
<tr>
<td><strong>- ANALOG-TO-DIGITAL CONVERTER</strong></td>
</tr>
<tr>
<td>- Analog = continuous signal</td>
</tr>
<tr>
<td>- Digital = sampled signal</td>
</tr>
<tr>
<td>- Radiometric Resolution (number of recorded radiance levels)</td>
</tr>
<tr>
<td>- $2^6 = 64$; $2^8 = 256$; $2^{10} = 1024$</td>
</tr>
<tr>
<td><strong>- Recorder and/or Transmitter</strong></td>
</tr>
<tr>
<td>- for Landsat 7:</td>
</tr>
<tr>
<td>- recorder = 350 Gb solid-state memory</td>
</tr>
<tr>
<td>- transmitter = X-Band @ 150 Mbs</td>
</tr>
</tbody>
</table>
Geometric Distortion

The causes of geometric distortion from scanners include:

- variations in the altitude, attitude, and velocity of a sensor's platform
- skew distortions due to the rotation of the Earth beneath the sensor during imaging
- displacement due to relief and curvature of the Earth
- inconsistent velocity of the sweep of the scanner mirror (across-track systems only)

Imaging Spectrometers

- Imaging spectrometers are instruments which acquire images in many, very narrow, spectral bands. These instruments have been used almost exclusively for research about spectral reflectance and target discrimination, but are becoming more commonly available - e.g. MODIS on Terra (formerly EOS AM-1).

- Multispectral scanners, like imaging spectrometers, produce several spectrally distinct images, but the bandpasses tend to be rather wide and the total number of bands is small (usually less than 10).
Practicum - Angular Resolving Power
Comparing your Eye to Landsat and SPOT

The resolving power of your eyes can be determined by viewing resolution targets from a fixed distance (say 5 meters). The worked example below shows the results of a typical image interpreter.

<table>
<thead>
<tr>
<th>High-Contrast Target</th>
<th>Low-Contrast Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 line-pairs cm⁻¹</td>
<td>3 line-pairs cm⁻¹</td>
</tr>
<tr>
<td>0.2 or 0.3 line width (mm)</td>
<td>0.6 line width (mm)</td>
</tr>
</tbody>
</table>

The spacing of these resolution targets is expressed in line-pairs per centimeter. The "line pair" is composed of a black bar immediately flanked by a white bar of the same width.

So, for a target with 3 line-pairs cm⁻¹, each individual bar must be

\[ \frac{1.67}{10 \text{ mm}} \text{ mm/line} \]

3 line-pairs = 6 lines 1 cm = 10 mm 10 mm / 6 lines = 1.67 mm/line

For our example result above, resolving 6 line-pairs per cm, each line is

\[ \frac{0.83}{10 \text{ mm}} \text{ mm/line} \]

6 line-pairs = 12 lines 1 cm = 10 mm 10 mm / 12 lines = 0.83 mm/line

We are all familiar with the system of measuring plane angles in degrees, but the unit of angular measure in the International System of Units (SI; the so-called metric system) is the radian (rad).

The radian is that unique angle which subtends an arc length which is just equal to the radius of a circle.

\[ 1 \text{ rad} = \frac{\text{arc length}}{\text{radius}} \]
The formula for the circumference of a circle is:

$$C = 2\pi r$$

Since one radian subtends an arc length equal to the radius, there must be $2\pi$ radians in a circle. There are also $360^o$ in a circle, so we can relate radians to degrees and vice versa:

How many degrees are there in one radian?

$$2\pi \text{ radians} = 360^o$$

$$\pi \text{ radians} = 180^o$$

$$1 \text{ radian} = 180^o / \pi = 57.296^o$$

Question 4. How many radians are there in one degree?

$$360^o = 2\pi \text{ radians}$$

$$1^o = 2\pi / 360^o$$

$$1^o = 0.01745 \text{ radians}$$

Note that this angular measure has no dimensions; it is the ratio of a length (the arc) to a length (the radius).

In remote sensing, we frequently express resolving power in terms of the angle (in radians) subtended between the imaging system and two targets spaced at the minimum resolvable distance:
Although we report the angular resolving power in terms of radians, in reality the minimum resolvable distance we measure is **NOT** the arc length, but rather the **chord length**.

Also, as you can see in the diagram, the reported altitude is **NOT** actually the radius. How serious are these discrepancies?

Let's find out by assuming a 10° field-of-view instrument is flown at an altitude of 1000 meters.

\[ \alpha = 10^\circ \quad 10^\circ = 0.1745 \text{ radians} \]

\[ \text{alt} = 1000 \text{ m} \]

\[ r = \frac{\text{alt}}{\cos \frac{\alpha}{2}} = \frac{1000 \text{ m}}{\cos 5^\circ} \]

\[ = 1000 \text{ m} / 0.9961947 \]

\[ \text{radius} = 1003.82 \text{ m} \]

\[ 0.1745 \text{ rad} = \frac{\text{arc length}}{\text{radius}} \]

\[ \text{arc length} = 0.1745 \times 1003.82 \text{ m} \]

\[ \text{arc length} = 175.17 \text{ m} \]

The **chord length** \( c \) can be calculated as follows:

\[ \tan \frac{\alpha}{2} = \frac{b \text{ (opposite side)}}{\text{alt} \text{ (adjacent side)}} \]

\[ b = \tan 5^\circ \times 1000 \text{ m} \]

since \( b = 1/2 \ c \) (the chord length).

\[ c = 2 \times (\tan 5^\circ \times 1000 \text{ m}) \text{ chord length} = 174.98 \text{ m} \]

So, you can see that the chord length is actually 0.19 m shorter than the arc length. But, this is only a 0.1% difference which is not significant for most remote sensing applications.
Most non-photographic remote sensing systems have fields of view which are too narrow to conveniently use radians. Instead, we express angular resolving power in **milliradians** (mrad, $10^{-3}$ radians). A useful relationship to remember is that at an altitude of 1000 units, a 1 mrad system can resolve 1 unit of length. The formula is simple:

$$\text{angular resolution (in mrad)} = \frac{\text{minimum resolvable distance}}{\text{altitude}} \times 1000$$

For example, a sensor with an angular resolution of 1 mrad could resolve high-contrast targets which were 10 m apart from an altitude of 10 km, but could also resolve targets spaced 1 m apart from an altitude of 1000 m.

$$1 \text{ mrad} = \frac{10 \text{ m}}{10,000 \text{ m}} = \frac{1 \text{ m}}{1000 \text{ m}}$$

Using this formula for angular resolution, let's calculate the resolving power of the interpreter's eyes from the opening example in **milliradians** (mrad).

$$= \frac{\text{width of bars resolved}}{\text{distance from target}} \times 1000 = \frac{0.83 \text{ mm}}{5000 \text{ mm}} \times 1000$$

$$= 0.166 \text{ mrad}$$

The minimum ground resolved distance for six of the bands of the ETM+ instrument on Landsat 7 is 30 meters from its nominal altitude of 705 km. What is the angular resolution of this system in **milliradians**?

$$\text{mrad} = \frac{30 \text{ m}}{705 \text{ km}} \times 1000$$

$$= \frac{30 \text{ m}}{705,000 \text{ m}} \times 1000$$

$$= 0.0426 \text{ mrad}$$
What is the angular resolution of the ETM+ expressed in microradians (µrad, \(10^{-6}\) radians)?

\[
42.6 \text{ µrad}
\]

How many times better is the resolution of the ETM+ instrument (30 m bands only) than the eyes of the interpreter in our example?

\[
\frac{0.166 \text{ mrad}}{0.0426 \text{ mrad}} = 3.9 \text{ times improvement}
\]
4.4 Landsat Satellites

1. Landsat 1, 2, and 3

The launch of the first Earth Resources Technology Satellite (ERTS-1) on July 23, 1972 marked the beginning of a program of remote sensing from space. Initially conceived in the late 1960s, this program was designed to demonstrate the feasibility of remotely sensing earth resources from unmanned satellites. Mission requirements were developed by scientists in the National Aeronautics and Space Administration and the U.S. Department of Interior. These included the acquisition of medium-resolution, multispectral data from systematic, repetitive observations taken at a constant local time. In addition, both photographic and digital data were to be produced and made available to interested users. Both the satellites and the program were renamed Landsat (for land satellite) with the launch of Landsat-2 on January 22, 1975. Although the satellites were designed for an operational lifespan of one year, they have greatly exceeded these original expectations. Landsat-1, which was retired in January, 1978, acquired more than 270,000 scenes of portions of the Earth during its five-and-a-half year operation. Landsat-2 acquired 185,105 scenes from January, 1975 to July, 1983 (nearly 8.5 years) while Landsat-3 acquired 324,655 scenes from March, 1978 to September, 1983.

2. Spacecraft and Orbital Characteristics

The actual vehicle for Landsats 1, 2, and 3 is a reconfigured Nimbus weather satellite (Figure 4.1). These butterfly-shaped satellites weigh 959 kg (2100 lb), are 3 meters (10 feet) high by 1.5 meters (5 feet) wide with solar panels 4 meters (13 feet) wide. These satellites were launched by a Thor-Delta rocket from Vandenberg Air Force Base in California.

The satellites were placed into a near-polar, circular orbit at a nominal altitude of 917 km (570 miles) (Figure 4.2). This orbit is sun-synchronous, which means that the angle between the sun, the center of the earth, and the satellite are held constant. To maintain this constant angle (37.5 degrees), the orbital plane of the satellite is inclined 99 degrees (measured clockwise from the equator) so that it rotates at a rate equivalent to the rate of the earth about the sun (Figure 4.3). This configuration insures that the spacecraft will cross over the same area of the Earth at a constant local time, thereby creating repeatable illumination conditions. A mid-morning (about 9:30 a.m. local time) overpass time was chosen as providing neither excessively long shadows nor shadowless conditions while avoiding the tendency of afternoon cloud buildup over terrestrial areas. The Sun’s rays strike the Earth at different angles during different times of
Landsat 1–3

4.1

Multispectral Scanner (MSS)

Return Beam Vidicon (RBV)

Landsat 1–3

Orbital Parameters

4.2

Altitude = 900 km (nominal)

Landsat at Noon Local Time

Earth Rotation

Equatorial Plane

Landsat at 9:42 A.M. Local Time
Orbit Plane rotates at the same rate as the mean rate of the Earth about the Sun.
the year and also vary by latitude. At 45° north latitude the solar elevation angle changes from 60° in June to 18° in December (Figure 4.4), thereby creating changing illumination conditions seasonally. In addition, the azimuth of solar illumination will change seasonally providing illumination from different directions (Figure 4.5).

It requires 103 minutes for the satellite to complete one orbit about the Earth. During a single orbit the Earth will have rotated 2,760 km (at the Equator) beneath the satellite. Thus, successive orbits will be displaced westward at a rate equivalent to the westward progress of the sun’s illumination (Figure 4.6). After the satellite completes a pass over Michigan the next pass would be over Montana. After 24 hours the satellite will have completed 14 orbits. The westward progression of the orbit will be such that the next pass will be one orbital pass to the west of first orbital pass (Figure 4.7). After 18 days, the satellite will have completed 251 orbits. The next orbital pass will then coincide with the first pass producing repetitive coverage on an 18-day cycle.

Data acquired by the satellite are segmented into scenes of about 185 km along track. This segmentation process is applied so that consistent scene centering is accomplished with the resulting scenes indexed by a worldwide system of paths and rows (Figures 4.8 and 4.9). Scenes acquired at about 45° latitude will have approximately 40% sidelap between adjacent paths with an arbitrary 10% endlap created from scenes acquired within a single pass (i.e. a small amount of redundant data will be produced for two scenes segmented from a single orbital pass).

3. Landsat 1 and 2 Sensor Systems

The payloads for Landsats 1 and 2 were identical and included two imaging instruments, a return beam vidicon (RBV) camera and a multispectral scanner (MSS).

The RBV system was designed to acquire high-resolution television-like images of the Earth. The system consisted of three cameras which were aligned to view the same 185 km by 185 km ground area (which coincides with the ground area coverage of the MSS). The three cameras obtained images simultaneously in three different broad spectral bands. Camera 1 (Band 1) measured reflected solar radiation from 0.475 to 0.575 µm (visible, yellow-green), camera 2 (Band 2) 0.580 to 0.680 µm (visible, green-red) and camera 3 (Band 3) 0.690 to 0.830 µm (visible red and reflected infrared). Images were generated by the RBV system by shuttering the cameras and storing the resulting image on the photosensitive surface of the camera tube. This surface is then scanned to produce a video signal for subsequent trans-
Seasonal Solar Angle Changes

Variations of Solar Illumination

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Landsat 1–3 Orbital Cycle

The Earth revolves 2,760 km to the east (at the equator) between passes.

Satellite ground tracks spaced 150 km apart at the equator.

Note: Orbit N, Day M+1 Occurs 14 Revolutions after Orbit N, Day M.

Landsat Orbital Tracks

Day 1 Repeats Every 18 Days

Orbit Number
mission to a ground receiving station. Because of early problems with the tape recorders on Landsats 1 and 2, only a limited quantity of RBV data were ever collected.

Contrary to pre-launch expectations, the MSS system became the primary data collection instrument utilized on Landsats 1 and 2. The multispectral scanner is a line-scanning device which utilized an oscillating mirror to scan a 185 km swath perpendicular to the satellite’s path. Each active scan produced by the mirror sweep scans six lines simultaneously, collecting data in four wavelength bands (Figures 4.10 and 4.11). The forward motion of the satellite during the mirror retrace is such to position the next six scan lines immediately below the last six lines, thus providing a continuous scan of the Earth beneath the satellite.

The MSS on Landsats 1 and 2 acquired data in four wavelength bands, labeled 4, 5, 6, and 7 (because the RBV bands were labeled 1-3). Band 4 detects reflected solar radiation from 0.5 to 0.6 µm (visible, green), Band 5 from 0.6 to 0.7 µm (visible, red), Band 6 from 0.7 to 0.8 µm (reflected infrared), and Band 7 from 0.8 to 1.1 µm (reflected infrared).

The scan mirror of the MSS reflected radiation coming from the surface of the Earth (and its atmosphere) onto the detectors through fiber optic bundles. Filters were utilized to permit only certain wavelengths to strike the detectors. Each detector produced a voltage, from zero to four volts, which is related to the amount of radiation that strikes the detector. In order to produce individual area measurements, the output voltage from each detector was sampled during each active scan (Figure 4.14). Individual measurements are taken from a ground area of approximately 79 m by 79 m, the instantaneous field of view (IFOV). The sampling rate was such that, in order to maintain proper spatial relationships, these measurements are formatted as if they were taken from an area of 56 m by 79 m. This latter area is called a Landsat pixel (picture element) (Figure 4.15). The voltages produced by each detector for each pixel were converted from an analog signal to a digital form by means of a multiplexer. The resulting numbers, from 0 to 63, called brightness values (BV) or digital numbers (DN), are directly related to the amount of solar radiation reflected from the surface of the Earth for a specific wavelength band. These data were transmitted to a ground receiving station where they were reformatted into computer compatible tapes and converted into image products.
Composite Total Area Scan for Any Band Formed by Repeated 6 Line Sweeps Per Active Mirror Cycle

Field of View = 11.56 Degrees

Note: Active Scan is West to East

MSS Scan Pattern

MSS Ground Scan Pattern
**Voltage to Digital Count Conversion**

Detector Voltage

Digital Counts (Brightness Values)

Number Samples per 185.2 km Line

**MSS Pixel Formatting**

Instantaneous Field of View of MSS

Sampling Interval of MSS

Landsat Picture Element (Pixel)

Energy Measurement made from a 5776 Square Meter Area

Formatted to 4408 Square Meter Area
4. Landsat 3 Sensor Systems

Based on the experience from sensor operation and subsequent analysis of data from Landsats 1 and 2, two system changes were made on Landsat 3. The three-camera, multispectral, RBV system was replaced by a two-camera, single spectral response system. Both cameras had the same broad-band spectral sensitivity, from 0.51 to 0.75 µm (green to near infrared) and were configured to produce side-by-side pictures approximately 99 km on a side, thus, they cover the same 185 km swath width as the MSS. Whenever two adjacent series of exposures were made, the resulting four images corresponded to a single MSS scene. To produce such an image format, the focal lengths of the cameras were doubled, thereby increasing the ground resolution to approximately 30 m.

A fifth channel (Band 8) was added to the MSS on Landsat 3. This thermal channel detected emitted radiation from 10.4 to 12.6 µm. The resulting quantized values are therefore related to apparent temperature. The ground resolution of the thermal detectors is 237 meters square, resulting in pixels that are approximately three times as large as those in bands 4, 5, 6, and 7. This channel failed shortly after the launch of Landsat 3 and very few scenes were ever acquired.

The geographical coverage of a single Landsat MSS scene is approximately 185 km on a side. A comparison of the coverage of a single Landsat scene with conventional aerial photography (assuming a 9-by-9 inch format, a 6-inch focal length lens, and 60% overlap with 30% sidelap) is given in Table 4.2.

<table>
<thead>
<tr>
<th>Table 4.2 Comparison of Landsat coverage with aircraft coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage of 1 Landsat scene</td>
</tr>
<tr>
<td>185 km by 178 km = 32,930 square kilometers</td>
</tr>
<tr>
<td>115 mi by 111 mi = 12,765 square miles</td>
</tr>
<tr>
<td>Standard aircraft coverage of 1 Landsat scene</td>
</tr>
<tr>
<td>Platform</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Low-altitude aircraft</td>
</tr>
<tr>
<td>Low-altitude aircraft</td>
</tr>
<tr>
<td>High-altitude aircraft</td>
</tr>
<tr>
<td>Commercial jet aircraft</td>
</tr>
<tr>
<td>Military aircraft</td>
</tr>
</tbody>
</table>
In response to the needs for improving the characteristics of the original multispectral scanner (MSS), NASA developed a second-generation of Landsat satellites. This program was a significant advance in remote sensing technology with the addition of the Thematic Mapper (TM) instrument, along with the MSS, on Landsats 4 and 5.

Landsat 4 was launched in July 1982; Landsat 3 continued operation until September 1983. Early on, Landsat 4 developed solar array and communications problems that restricted its use to MSS acquisition only. Landsat 5, a twin of Landsat 4, was launched ahead of original plans in March 1984.

Operational responsibility for the Landsat program was transferred from NASA to NOAA in January 1983 (for the MSS, and September 1984 for the TM). The Earth Observation Satellite Company (EOSAT), a private-sector joint venture, began operating the Landsat system under government contract in October 1985.

1. Spacecraft and Orbital Characteristics

The spacecraft vehicle for Landsats 4 and 5 was the newly designed Multimission Modular Spacecraft. The Landsat 4/5 configuration (Figure 4.16) was originally designed to be retrievable by the space shuttle, but this was never attempted.

Compared to the earlier Landsat satellites, Landsat 4/5 is in a lower orbit (705 km), with a slightly later equatorial crossing time - 9:45 a.m (Figure 4.17). Landsat 4/5 have a 16-day repeat cycle. The lower orbit was necessary to produce the higher ground resolution of the TM (30 meters versus 80 meters for MSS). The 9:45 acquisition time was chosen to optimize the scanning characteristics of the TM sensor. Because of these orbital differences, a second Worldwide Reference System (WRS-2) was created for indexing Landsat 4 and 5 coverage data (Figure 4.18).

2. Thematic Mapper (TM) Characteristics

The Thematic Mapper was configured to improve the spatial, spectral and radiometric resolution compared to the MSS. A comparison of the sensor characteristics of the TM and MSS systems is presented in Table 4.3. The TM has been configured with seven spectral bands (Figure 4.19, 4.20, 4.21, 4.22, 4.23, 4.24 and
Landsat 4–5

Ground Track
Altitude = 705 Km (nominal)
Inclination = 98.2°
Mean Solar Time = 9:45 A.M. (approximate local)
Direction Of Travel
Orbit Period = 98.9 Minutes
Worldwide Reference System (WRS)

Landsat 4,5

Great Lakes Scene Centers
4.25, compared to four on the MSS. Comparative band regions are narrower on the TM and include sensitivities into the middle infrared and thermal infrared regions of the electromagnetic spectrum. The ground resolution (except for the thermal band) has been changed from approximately 80 meters to 30 meters. The number of quantization levels has been increased from 64 to 256.

The present configuration of the TM sensor was primarily designed for monitoring vegetation. Specific sensor characteristics were derived from an analysis of research efforts designed to determine optimum spectral resolution for monitoring vegetation from space, and consideration of political, technical and economic limitations.

<table>
<thead>
<tr>
<th>Band No.</th>
<th>Spectral Sensitivity (micrometers)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>TM</strong></td>
<td><strong>MSS</strong></td>
</tr>
<tr>
<td>1</td>
<td>0.45 - 0.52</td>
<td>0.5 - 0.6&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>2</td>
<td>0.52 - 0.60</td>
<td>0.6 - 0.7</td>
</tr>
<tr>
<td>3</td>
<td>0.63 - 0.69</td>
<td>0.7 - 0.8</td>
</tr>
<tr>
<td>4</td>
<td>0.76 - 0.90</td>
<td>0.8 - 1.1</td>
</tr>
<tr>
<td>5</td>
<td>1.55 - 1.75</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>10.40 - 12.50</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>2.08 - 2.35</td>
<td>--</td>
</tr>
</tbody>
</table>

| IFOV     | 30 m (Bands 1 - 5, 7)             | 80 m (Bands 1 - 4)             |
|          | 120 m (Band 6)                    |                                |

| BV Levels | 256 | 64 |

<sup>1</sup>Band numbers 1, 2, and 3 were utilized for the Return Beam Vidicon Cameras on Landsat 1 and 2.
Spectral resolution (i.e., the width and placement of spectral bands) has been shown to be highly correlated with successful vegetation monitoring. Within the reflective portion of the electromagnetic spectrum (including the visible and reflective infrared between 0.38 and 3.00 µm), five primary regions and two transition regions have been identified. These wavelength regions, useful for monitoring green vegetation, are listed in Table 4.4 in order of descending overall usefulness. The spectral channels utilized in the TM are presented in Table 4.5 for comparison with these primary spectral findings. Additional research has identified the interval

<table>
<thead>
<tr>
<th>Number</th>
<th>Wavelength</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>0.74 - 1.10</td>
<td>Direct biomass sensitivity</td>
</tr>
<tr>
<td>2nd</td>
<td>0.63 - 0.69</td>
<td>Direct \textit{in vivo} chlorophyll sensitivity</td>
</tr>
<tr>
<td>3rd</td>
<td>1.35 - 2.50</td>
<td>Direct \textit{in vivo} foliar water sensitivity</td>
</tr>
<tr>
<td>4th</td>
<td>0.37 - 0.50</td>
<td>Direct \textit{in vivo} carotenoid and chlorophyll sensitivity</td>
</tr>
<tr>
<td>5th</td>
<td>0.50 - 0.62</td>
<td>Direct/indirect and slight sensitivity to chlorophyll</td>
</tr>
<tr>
<td>6th</td>
<td>0.70 - 0.74</td>
<td>Indirect and minimal sensitivity to vegetation; perhaps valuable non-vegetational information</td>
</tr>
<tr>
<td>7th</td>
<td>1.1 - 1.3</td>
<td></td>
</tr>
</tbody>
</table>
between 1.55 and 1.75 µm (corresponding to TM band 5) as the region best suited for monitoring plant canopy water status. The placement of spectral bands, in relation to reflectance of green vegetation, are shown for the MSS (Figure 4.26) and the TM (Figure 4.27).

### Table 4.5  TM Bandwidths for Monitoring Vegetation

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (µm)</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM1</td>
<td>0.45 - 0.52</td>
<td>Sensitivity to chlorophyll and carotenoid concentrations</td>
</tr>
<tr>
<td>TM2</td>
<td>0.52 - 0.60</td>
<td>Slight sensitivity to chlorophyll plus the green region characteristics</td>
</tr>
<tr>
<td>TM3</td>
<td>0.63 - 0.69</td>
<td>Sensitivity to chlorophyll</td>
</tr>
<tr>
<td>TM4</td>
<td>0.76 - 0.90</td>
<td>Sensitivity to vegetational density or biomass</td>
</tr>
<tr>
<td>TM5</td>
<td>1.55 - 1.75</td>
<td>Sensitivity to water in plant leaves</td>
</tr>
<tr>
<td>TM6</td>
<td>10.40 - 12.50</td>
<td>Thermal properties</td>
</tr>
<tr>
<td>TM7</td>
<td>2.08 - 2.35</td>
<td>Sensitivity to water in plant leaves</td>
</tr>
</tbody>
</table>
**Multispectral Scanner Band Sensitivities**

![Multispectral Scanner Band Sensitivities](image)

**Thematic Mapper Band Sensitivities**

![Thematic Mapper Band Sensitivities](image)
1. Introduction

In 1992, the US Congress authorized the procurement, launch and operation of a new Landsat satellite. At 11:36 am on April 15, 1999, the latest member of the Landsat family was launched into orbit (Figure 4.28). No other remote sensing system, public or private, fills the role of Landsat in global change research or in civil and commercial applications. Landsat 7 will fulfill its mission by providing repetitive, synoptic coverage of continental surfaces using spectral bands in the visible, near-infrared, short-wave infrared, and thermal infrared regions of the electromagnetic spectrum. Five of its eight bands are acquired at a spatial resolution of 30 meters.

The primary new features on Landsat 7 are:

- a panchromatic band with 15 m spatial resolution
- on board, full aperture, 5% absolute radiometric calibration
- a thermal IR channel with 60 m spatial resolution

The Landsat Program is committed to provide Landsat digital data to the user community in greater quantities, more quickly and at a lower cost than at any previous time in the history of the program.

The continuation of the Landsat mission is important for several reasons. Repetitive, broad-area coverage is needed for observation of seasonal changes on regional, continental and global scales. Other systems afford frequent global coverage (e.g. AVHRR), but none provide global coverage at the 30-meter spatial resolution of Landsat 7. Unlike the ocean and atmosphere, characterizing the land surface is distinguished by high-spatial-frequency processes that require a high spatial resolution. Both man-made (deforestation) and natural changes (glacial recession) are often initiated at scales requiring high resolution for early detection.

The Landsat 7 system offers the unique capability to seasonally monitor important small-scale processes on a global scale, such as the inter- and intra-annual cycles of vegetation growth; deforestation; agricultural land use; erosion and other forms of land degradation; snow accumulation and melt and the associated fresh-water reservoir replenishment; and urbanization. The other systems affording global coverage do not provide the resolution needed to observe these processes in detail and only the Landsat system provides a 26-plus year record of these processes.
2. Orbit

The orbit of Landsat 7 is repetitive, circular, sun-synchronous, and near-polar at a nominal altitude of 705 km at the Equator. The spacecraft crosses the Equator from north to south on the descending orbital node at 10:00 AM +/- 15 minutes on each pass. Each orbit takes nearly 99 minutes, and the spacecraft completes just over 14 orbits per day, covering the entire Earth between 81 degrees north and south latitude every 16 days. Figure 4.29 illustrates the orbit characteristics of Landsat 7.

The TERRA spacecraft (formally known as EOS-AM) is scheduled for launch on October 4, 1999 on an Atlas-IIAS expendable launch vehicle from Vandenberg Air Force Base in Lompoc, California. TERRA will be injection into an identical 705 kilometer, sun synchronous orbit as Landsat 7. This same-day orbit configuration will space the satellites ideally 15 minutes apart (i.e. equatorial crossing times of 10:00 to 10:15 AM for Landsat 7 and 10:30 for TERRA). A multispectral data set having both high (i.e. 30 meter) and medium-to-coarse (i.e. 250 to 1000 meter) spatial resolution will thus be acquired on a global basis repetitively and under nearly identical atmospheric and plant physiological conditions.

3. Swathing Pattern

Landsat 7 orbits the Earth in a preplanned ground track. The ETM+ sensor onboard the spacecraft obtains data along the ground track at a fixed width or swath as depicted in Figure 4.30. The 16-day Earth coverage cycle for Landsat 7 is shown in Figure 4.31. The adjacent swath to the west of a previous swath is traveled by Landsat 7 one week later (and the adjacent swath to the east occurred one week earlier and will recur nine days later).

Every 16 days, a Landsat satellite returns to its starting point and repeats the cycle. Working together, Landsats 5 and 7 will offer repeat coverage of any location every eight days. At the equator, the ground track separation is 172 km, with a 7.6 percent overlap. This overlap gradually increases (due to the fixed 185 km swath width) as the satellites approach the poles, reaching 54 percent at 60° latitude (Table 4.6).
Ground Track

Altitude = 705 Km (nominal)

Inclination = 98.2°

Mean Solar Time = 9:45 A.M. (approximate local)

Orbit Period = 98.88 Minutes

Directions Of Travel

Landsat 7–5 Orbital Parameters

Landsat 7 ETM+
Swath Pattern

Sensor Swath Width is 185 km. Data is framed into 170 km increments (scenes) along track.
Ground Track

Altitude = 705 Km (nominal)

Inclination = 98.2°

Mean Solar Time = 9:45 A.M. (approximate local)

Direction of Travel

Orbit Period = 98.9 Minutes

Landsat 4–5

Orbital Parameters

Landsat 7

ETM+

16-Day Coverage Pattern
4. Landsat 7 Worldwide Reference System

The standard worldwide reference system as defined for Landsat 4 and 5 (WRS-2) was preserved for Landsat 7. The WRS-2 indexes orbits (paths) and scene centers (rows) onto a global grid system comprising 233 paths by 248 rows. The term row refers to the latitudinal center line across a frame of imagery along any given path.

The 16-day ground coverage cycle for Landsats 4 and 5 was accomplished in 233 orbits. Thus, for Landsats 4 and 5 (and now Landsat 7), the WRS-2 system is made up of 233 paths numbered 001 to 233, east to west, with Path 001 crossing the equator at 64.60 degrees west longitude.

Landsat 4, 5 and 7 scenes are chosen at 23.92-second increments of spacecraft time in both directions calculated from the equator in order to create 248 Row intervals per complete orbit. Note that this is the same as the Landsat 1 through 3 WRS-1

<table>
<thead>
<tr>
<th>Latitude (degrees)</th>
<th>Image Sidelap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.3</td>
</tr>
<tr>
<td>10</td>
<td>8.7</td>
</tr>
<tr>
<td>20</td>
<td>12.9</td>
</tr>
<tr>
<td>30</td>
<td>19.7</td>
</tr>
<tr>
<td>40</td>
<td>29.0</td>
</tr>
<tr>
<td>50</td>
<td>40.4</td>
</tr>
<tr>
<td>60</td>
<td>53.6</td>
</tr>
<tr>
<td>70</td>
<td>68.3</td>
</tr>
<tr>
<td>80</td>
<td>83.9</td>
</tr>
</tbody>
</table>
system. The Rows have been positioned in such a way that Row 60 coincides with the equator during the descending node on the day side part of the orbit and Row 184 during the ascending node. Row one of each Path starts at 80 degrees, 47 minutes north latitude and the numbering increases southward to a maximum latitude 81 degrees, 51 minutes south (Row 122) and then turns northward, crosses the equator (Row 184), and continues to a maximum latitude of 81 degrees, 51 minutes north (Row 246). Row 248 is located at latitude 81 degrees 22 minutes north whereupon another Path begins.

5. The Long Term Acquisition Plan

The Long Term Acquisition Plan (LTAP) is used to direct the acquisition by Landsat 7 of Worldwide Reference System (WRS) scenes around the world for archiving in the U.S. EROS Data Center. The WRS land data base identifies those WRS scenes containing land or shallow water which will be imaged at least once every year. Table 4.7 shows the WRS scenes for Brazil that are included in the LTAP.

6. Enhanced Thematic Mapper Plus

The earth observing instrument on Landsat 7, the Enhanced Thematic Mapper Plus (ETM+), replicates the capabilities of the highly successful Thematic Mapper instruments on Landsats 4 and 5. The ETM+ also includes new features that make it a more versatile and efficient instrument for global change studies, land cover monitoring and assessment, and large area mapping than its design forebears (Table 4.8).

The ETM+ instrument is a fixed “whisk-broom”, eight-band, multispectral scanning radiometer capable of providing high-resolution imaging information of the Earth’s surface. It detects spectrally-filtered radiation in VIS, NIR, SWIR, LWIR and panchromatic bands (Table 4.9) from the sun-lit Earth in a 183 km-wide swath when orbiting at its nominal altitude of 705 km.

The ETM+ scanner contains 2 focal planes. The primary focal plane consists of optical filters, detectors, and preamplifiers for 5 of the 8 ETM+ spectral bands (bands 1–4 and 8). The second focal plane is cooled and includes the optical filters, infrared detectors, and input stages for ETM+ spectral bands 5, 6, and 7 (Figures 4.32 and 4.33).
ETM+ Optics

Cold Focal Plane
Prime Focal Plane
Scan Mirror
(7 scans per second)
Radiator to Deep Space
Relay Optics
Scan Line Correction Mirrors
Telescope
Radiation
705 km
185 km
Direction of Travel
(groundtrack)

ETM+ Detector Array

Band
Detectors
32
16
16
16
16
16
16
8

Prime Focal Plane
Cold Focal Plane

Detector Row Spacing
(42.5 μm/1° FOV)
Along-track direction

Band Spacing
(42.5 μm/1° FOV)
Cross-track Direction (Instrument Scan)
Reverse
Forward

© 1999 David P. Lusch, Ph.D.
On board solar calibration and payload correction data allow the ground processing segment to radiometrically correct the data to an absolute accuracy of 5% and to geometrically register a scene to within 250 meters. Nominal ground sample distances (i.e. “pixel” sizes) are 15 meters in the panchromatic band, 30 meters in the VIS, NIR and SWIR bands and 60 meters in the LWIR band.

Landsat 7 will collect data in accordance with the Worldwide Reference System, which has catalogued the world’s land mass into 57,784 scenes, each 183 km wide by 170 km long. The ETM+ will produce approximately 3.8 gigabits of data for each
### Table 4.8  ETM+ Technical Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: opto-mechanical scanner</td>
<td></td>
</tr>
<tr>
<td>Spatial resolution:</td>
<td>15/30/60 m</td>
</tr>
<tr>
<td>Spectral range:</td>
<td>0.45-12.5 µm</td>
</tr>
<tr>
<td>Number of bands:</td>
<td>8</td>
</tr>
<tr>
<td>Temporal resolution:</td>
<td>16 days</td>
</tr>
<tr>
<td>Size of image:</td>
<td>183 x 170 km</td>
</tr>
<tr>
<td>Swath:</td>
<td>183 km</td>
</tr>
<tr>
<td>Stereo:</td>
<td>no</td>
</tr>
<tr>
<td>Programmable:</td>
<td>yes</td>
</tr>
<tr>
<td>Quantization:</td>
<td>Best 8 of 9 bits</td>
</tr>
<tr>
<td>On-board data storage:</td>
<td>~375 Gb (solid state)</td>
</tr>
</tbody>
</table>

### Table 4.9  ETM+ Bands

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Bandpass (Micrometers)</th>
<th>Resolution (Meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.45 to .515</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>.525 to .605</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>.63 to .690</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>.75 to .90</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>1.55 to 1.75</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>10.40 to 12.5</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>2.09 to 2.35</td>
<td>30</td>
</tr>
<tr>
<td>Pan</td>
<td>.52 to .90</td>
<td>15</td>
</tr>
</tbody>
</table>
Wideband data downlink

Landsat 7 carries the ETM+ instrument and a solid state recorder (SSR). The ETM+ data stream is separated into two formats. Format 1 (channel, also referred to as channel I, contains bands 1–6; format 2 (channel Q, also referred to as channel Q, contains bands 6, 7, and 8 (PAN). Each format is transferred at 75 Mbps to a switching unit where the data are modulated and either (1) downlinked in real-time to a Landsat Ground Station (LGS) via an X-band link at a combined aggregate rate of 150 Mbps, or (2) recorded on the SSR.

The data recorded on the SSR can be played back using one or two 150 Mbps bitstreams and downlinked to a LGS via the X-band link. When the spacecraft flies over a LGS, it downlinks two 150 Mbps data streams, either 1 real-time and 1 playback, or 2 playbacks. Therefore, when the data are transmitted to the LGS, it is a combined rate of 300 Mbps: a 150 Mbps bitstream from the ETM+ and a separate 150 Mbps bitstream from the SSR or two 150 Mbps bitstreams from the SSR.

The primary receiving station is at the US Geological Survey’s (USGS) EROS Data Center (EDC) in Sioux Falls, South Dakota, USA. All substantially cloud-free, land and coastal scenes will be acquired by EDC through the real-time downlink or by playback from the solid state recording device. The capacities of the satellite, instrument and ground system will be sufficient to allow for continuous acquisition of all substantially cloud-free scenes at EDC. In addition, a world-wide network of receiving stations will be able to receive real-time, direct downlink of image data via X-band. Each station will be able to receive data only for that part of the ETM+ ground track where the satellite is in sight of the receiving station.

Initial Events

Landsat 7 was launched on April 15, 1999. Just three days later, on Sunday, April 18, the ETM+ instrument acquired its first scene (primary focal plane only). The ETM+ out-gassing process was successfully completed by April 30. The cool-down period, which started upon completion of out-gassing, was completed over the next 48 hours. Initial thermal analysis of the cold focal plane indicates that it is stable at 91 Kelvin (its design specification).
A Landsat 7 underflight of Landsat 5 was successfully completed during the period of June 1-3, 1999. This project was collected Landsat 5 and Landsat 7 data simultaneously to cross-calibrate the two Landsat systems. Several ground station operators (Australia, Argentina, Brazil, Canada, ESA, South Africa, and Saudi Arabia) participated by collecting Landsat 5 data. In addition, Space Imaging collected Landsat 5 data of Canada, USA, and Mexico. These data were sent to the EROS Data Center for processing and analysis. The NASA Landsat 7 Project Science Office has responsibility for analyzing these data to cross-calibrate between ETM+ and the Landsat 5 Thematic Mapper. Results of these analyses will be distributed as they become available.

By June 28, 1999, Landsat 7 was positioned in its nominal operational orbit at an altitude of 705 kilometers. The final maneuvering process placed Landsat 7 in an orbit consistent with and eight paths to the east of Landsat 5. This results in a Landsat 7 and Landsat 5 overflight of the same location eight days apart during routine operations.

When the nominal orbit was achieved, the Landsat 7 program entered into a pre-operational phase during which Landsat 7 acquired data according to the nominal duty cycle. The first 16-day cycle was completed on July 14, 1999.

The On-orbit Initialization and Verification, conducted over a 90 day period, was completed on August 2, 1999. This process stabilized the ETM+, positioned the spacecraft in the correct orbit, and allowed the on-board and ground systems to interact and undergo appropriate testing. Performance of both the Landsat 7 spacecraft and the ETM+ instrument met or exceeded specifications for almost all system requirements.
### Summary of the
Orbital characteristics of the Landsat Family

#### Landsat 1-3

- **altitude:** 907-915 km
- **inclination:** 99.2°
- **orbit:** Near-polar, sun synchronous
- **equatorial crossing time:** 0930 AM (descending node)
- **period of revolution:** 103 minutes
- **repeat coverage:** 18 days

#### Landsat 4-5

- **altitude:** 705 km
- **inclination:** 98.2°
- **orbit:** Near-polar, sun synchronous
- **equatorial crossing time:** 0930 AM (descending node)
- **period of revolution:** 99 minutes
- **repeat coverage:** 16 days

#### Landsat 7

- **altitude:** 705 km
- **inclination:** 98.2°
- **orbit:** Near-polar, sun synchronous
- **equatorial crossing time:** 1000 AM (descending node)
- **period of revolution:** 99 minutes
- **repeat coverage:** 16 days
10. LANDSAT 7 DATA POLICY

October 31, 1994
Revised: September 19, 1997

INTRODUCTION

Section 105 of Public Law (P.L.) 102-555, The Land Remote Sensing Policy Act of 1992, states, "The Landsat Program Management (LPM), in consultation with other appropriate United States Government agencies, shall develop a data policy for Landsat 7...". The law also identifies goals for the policy. This document, in accordance with the law, establishes a data policy for Landsat 7 that covers the acquisition, processing, archival, distribution, and pricing policy for Landsat 7 system development and operations are contained in the Management Plan for the Landsat Program.

As required by P.L. 102-555, this Data Policy is designed to achieve the following:

1. Ensure that unenhanced data are available to all users at the cost of fulfilling user requests;

2. Ensure timely and dependable delivery of unenhanced data to the full spectrum of civilian, national security, commercial, and foreign users and the National Satellite Land Remote Sensing Data Archive (NSLRSDA);

3. Ensure that the United States retains ownership of all unenhanced data generated by Landsat 7;

4. Support the development of the commercial market for remote sensing data;

5. Ensure that the provision of commercial value-added services based on remote sensing data remains exclusively the function of the private sector; and

6. To the extent possible, ensure that the data distribution system for Landsat 7 is compatible with the Earth Observing System Data and Information System (EOSDIS).

The Landsat 7 system will comprise a spacecraft carrying an Enhanced Thematic Mapper Plus (ETM+) instrument and a ground segment consisting of mission operations, data capture, ground processing, data archiving, and data product distribution elements. The ETM+ is a nadir-pointing, eight spectral band instrument designed to
provide data continuity with the Thematic Mapper instruments on Landsats 4 and 5.

ACQUISITION

Data acquisition by the ETM+ on Landsat 7 will be directed the mission goal of acquiring and updating periodically a global archive of daytime, substantially cloud-free images of land areas. In addition to the periodic global archive acquisitions, Landsat 7 will acquire every daytime scene on every pass over the United States. However, the Landsat operator will modify the acquisition schedule for the global archive mission and the standing order for scenes of the United States to accommodate time-critical observations and other requests based on the following order of priorities:

1. Spacecraft and instrument health and safety
2. Time critical acquisitions related to national security, natural disasters, and environmental emergencies
3. Time-critical acquisitions to support large campaigns and other key US Government (USG) programs
4. Acquisitions critical to the global archive mission
5. Acquisition requests from individuals and commercial entities

Conflicts in the acquisition schedule will be resolved by the Landsat operator according to the priorities listed above and policy guidelines established by the Landsat Coordinating Group (LCG) acting on behalf of the Landsat Program Management. Non-time critical requests for acquisitions will be received by the EOSDIS Distributed Active Archive Center (DAAC) at the US Geological Survey's EROS Data Center (EDC) in Sioux Falls, South Dakota. Requests for time critical acquisitions will be received directly by the Landsat operator.

The primary USG ground station will be located at EDC. The ground station will have the capability to capture both real-time and recorded data via direct transmission from Landsat 7. Secondary USG ground stations will be located in the Fairbanks, Alaska area, and Svalbard, Norway. The secondary station(s) will serve as backup for the primary station and ensure that the requirement for scene acquisitions is met. In addition, the Landsat 7 system will be capable of transmitting data in real-time to other, non-USG* ground station. USG ground stations will operate according to the data acquisition priorities defined in this document. Non-USG
stations will receive data upon request and limited by the allocation of spacecraft assets for providing direct transmission data. These direct downlink resources will be scheduled in a balanced and equitable manner consistent with the achievement of the global archive mission goal.

The Landsat 7 operator will develop a standard ground station agreement which each non-USG operator must sign to be authorized to receive Landsat 7 data. This agreement will include conditions such as: provision for acquisition of scheduling and availability of the direct downlink; the use of non-USG ground stations as contingency backups or supplements for USG data acquisitions; retention of ownership of by USG of all unenhanced data from Landsat 7; the reception, archiving and cataloging of remotely received data; the availability of these data; exchange of metadata and image data between the non-USG ground station and the EDC-DAAC; the technical services available to the ground station; and fees associated with access to data. The Landsat 7 operator will endeavor to provide all requested coverage with the ETM+ sensor within the coverage circle of authorized ground stations, within the limits of the Landsat 7 system's resources and in accordance with conflict resolution guidelines.

Processing EDC will generate Level 0R data files, metadata, and browse images for all Landsat 7 data received by the Landsat 7 Ground Station at EDC. The EDC-DAAC will provide access to the Landsat 7 metadata and browse images on a nondiscriminatory basis and will generate Level10R, Level 1R, and Level 1G data products on request (see Attachment for descriptions of the data products) for distribution to Landsat data users.

Data processing beyond Level 1 products distributed through EDC is the responsibility of the users and will be accomplished with user-owned capabilities or those available from private sector suppliers.

*Non-USG is defined as the Landsat international ground station (IGS) and other ground stations built and/or operated by government-sponsored organizations, commercial entities, or any combination thereof.

ARCHIVE
EDC will archive, at a minimum, all Landsat 7 Level10R data files, metadata, and browse images generated at EDC, and metadata and browse products provided to EDC by the Landsat 7 non-USG ground stations.

DISTRIBUTION
Landsat 7, Level 0R, Level 1R and Level 1G data products will be distributed in a timely manner on a nondiscriminatory basis, within the
technical limitations of the system. The USG will impose no restrictions on subsequent use, sale, or redistribution of data from Landsat 7.

Should demand for data products exceed the daily capacity at EDC, orders will be processed based on the same priorities as data acquisition.

EDC will provide standard services associated with distribution of Landsat 7 data including distribution in defined, standard product format(s). Data will be available on physical media and via electronic transfer.

**PRICING**

All users will be charged standard prices for the products/services provided. Prices will be reviewed and established by LPM once per year. It is the intent of LPM to distribute Level 0R data for no more than $500 per scene.

**ATTACHMENT: LANDSAT 7 PROCESSING DEFINITIONS**

**METADATA**

Descriptive information pertaining to the associated data files or data products. Information includes location and spatial coverage of the digital image data, acquisition date, associated file content, and data quality. Metadata are generated for the Level 0R data files and for the Level 0R, 1R, and 1G data products.

**BROWSE IMAGES**

Sub-sampled Level 0R digital image of the Earth that can be viewed on a scene basis to quickly assess general ground area coverage, data quality, and the spatial relationships between ground area coverage and cloud coverage. A browse image provides a coarse spatial resolution image with a reduced data volume to facilitate screening of the archived Landsat 7 data.

**CALIBRATION**

File Parameters required to radiometrically and geometrically correct Level 0R digital image data to generate Level 1R or 1G data products. The parameters are based on calibration of the ETM+ and the Landsat 7 spacecraft.

**LEVEL 0R**

Data File Level 0R digital image data (see description below); payload correction data from the spacecraft including...
attitude, ephemeris high frequency jitter data, and ETM+ and spacecraft
temperatures; mirror scan correction data; a geolocation table; and
internal calibration lamp data.

LEVEL 0R
Data Product Level 0R data files packaged and formatted for
distribution to Landsat 7 data users along with the associated metadata
and calibration parameter file. Data products are generated on request
by a data user. A user may specify a subset of a Level 0R digital image
or a subset of the data files for distribution.

LEVEL 1R
Data Product A radiometrically corrected ETM+ digital Earth
image along with the files containing metadata, calibration parameters,
payload correction data, mirror scan correction data, a geolocation
table, and internal calibration lamp data. The digital image pixels are not
resampled, for geometric correction and registration. Level 1R data
products are generated on request and the data are packaged and
formatted for distribution to the data user.

LEVEL 1G
Data Product A radiometrically corrected and geometrically
corrected ETM+ digital Earth image along with metadata, calibration
parameters, and a geolocation table. The radiometrically corrected
pixels are resampled for geometric correction and registration to a user-
specified map projection. Level 1G data products are generated on
request and the data are packaged and formatted for distribution to the
data user.
4.8 SPOT Satellites

The SPOT satellite program is discussed via summary graphics and tables outlining the orbit, sensor and data-product characteristics of the SPOT system (see Tables 4.10-4.11 and Figures 4.34-4.40).

The Next Generation: SPOT 4

SPOT 4 was launched from Kourou, French Guiana on March 24, 1998. SPOT 4 has some new instrumentation in addition to all the features of the original three SPOT satellites. New features of SPOT 4 include:

- an enhanced, push-broom, multispectral imager, the HRVIR, which provides a middle infrared band (1.58-1.75 µm), on-board registration of all bands and the two HRVIR imagers are programmable for independent image acquisition.

- on-board recording systems with greater storage capacity (solid state memory)

- a 5 year design life.

SPOT 4 also carries a new instrument, VEGETATION, which provides a wide swath (2,250 km), high temporal resolution, high radiometric resolution, but low spatial resolution (1.36 km²) (Table 4.11). The VEGETATION instrument features similar bands as the HRVIR instrument, as well as a blue band (B0: 0.43-0.47 µm) for atmospheric correction and water penetration.
### TABLE 4.10 SPOT SATELLITE CHRONOLOGY

- SPOT 1: launched 2/22/86  
  retired 12/31/90  
  re-used in 1997

- SPOT 2: launched 1/22/90

- SPOT 3: launched 9/25/93  
  lost 11/14/97

- SPOT 4: launched 3/24/98

### TABLE 4.11 SPOT 4 VEGETATION INSTRUMENT

- Wide field-of-view, 4-band imaging radiometer
  - Swath width = 2,250 km
    - @ latitude $\geq 35^\circ$ = daily coverage
    - Equatorial zone = every other day coverage

- Spectral Resolution

  - Blue (0.43 - 0.47 mm)  
    Band No. 0
  - Red (0.61 - 0.68 mm)  
    Band No. 2
  - NIR (0.78 - 0.89 mm)  
    Band No. 3
  - MIR (1.58 - 1.75 mm)  
    Band No. 4

- Spatial Resolution = 1.36 km² (1.165 x 1.165 km)

- Radiometric Resolution = 10-bit (DN range 0-1023)
### SPOT 1–4

#### SPOT 1-3

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (µm)</th>
<th>Pixel Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAN</td>
<td>0.51–0.73</td>
<td>10 m</td>
</tr>
<tr>
<td>1</td>
<td>0.50–0.59</td>
<td>20 m</td>
</tr>
<tr>
<td>2</td>
<td>0.61–0.68</td>
<td>20 m</td>
</tr>
<tr>
<td>3</td>
<td>0.79–0.89</td>
<td>20 m</td>
</tr>
</tbody>
</table>

#### SPOT 4

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (µm)</th>
<th>Pixel Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.50–0.59</td>
<td>20 m</td>
</tr>
<tr>
<td>2</td>
<td>0.61–0.68</td>
<td>10 m</td>
</tr>
<tr>
<td>3</td>
<td>0.79–0.89</td>
<td>20 m</td>
</tr>
<tr>
<td>4</td>
<td>1.58–1.75</td>
<td>20 m</td>
</tr>
</tbody>
</table>

### Orbital Mechanics

- **Altitude:** 830 km (nominal)
- **Inclination:** 98.7°
- **Mean Solar Time:** 10:30 A.M.
- **Orbit Period:** 101.4 minutes
SPOT Off–Nadir Viewing

Plane mirror steerable by ground control

CCD Detector arrays (2)

off-nadir viewing

nadir viewing

off-nadir viewing

Satellite Ground Track

Regions Observed

Observable Strip

SPOT Revisit Capabilities

One pass each on days:

D+10

D+5

D

D–5

11 out of 26 days

7 out of 26 days

zone observed

latitude = 45°

latitude = 0°

latitude = 0°
**Percentage Reflectance**

- **Vegetation**
- **Dry Soil**
- **Clear Water**

**HRV Multispectral (XS)**

- Wavelength (µm): 0.4, 0.6, 0.8, 1.0, 1.2, 1.4
- Reflectance values: 0, 10, 20, 30, 40, 50, 60, 70, 80

**HRV Panchromatic (P)**

- Wavelength (µm): 0.4, 0.6, 0.8, 1.0, 1.2, 1.4
- Reflectance values: 0, 10, 20, 30, 40, 50, 60, 70, 80

**Parallax**

- Pass on day A
- Pass on day B
4.9 AVHRR

The U.S. National Oceanic and Atmospheric Administration (NOAA) operates a series of polar-orbiting satellites for meteorological applications. Known as the NOAA polar-orbiting satellite program, there are currently two satellites operating (NOAA-14, and -15), each carrying six major instruments (Table 4.12). Of concern to remote sensing studies is the Advanced Very High Resolution Radiometer (AVHRR). This instrument has been built in three versions: a 4-, 5-, or 6-channel scanning radiometer with sensitivity in the visible (0.58-0.68µm), near-infrared (0.73-1.10 µm), middle-infrared (1.58-1.64 µm), and different sectors of the thermal infrared (Figure 4.41) region. The AVHRR instrument has a ground resolution of 1.1 km with a swath width of about 2700 km (Figure 4.42, Table 4.13).

Figure 4.43 summarizes the spatial and spectral differences between the Landsat MSS and TM instruments, the SPOT HRV sensor, and the NOAA AVHRR radiometer.
### Table 4.12 NOAA Polar-Orbiting Satellites

<table>
<thead>
<tr>
<th>Presently Active</th>
<th>Launch Date</th>
<th>Data Available From</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA - 14</td>
<td>12-30-94</td>
<td>12-30-94 to Present</td>
</tr>
<tr>
<td>NOAA - 15</td>
<td>5-13-98</td>
<td>5-13-98 to Present</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decommissioned</th>
<th>Launch Date</th>
<th>Data Availability Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIROS - N</td>
<td>10-13-78</td>
<td>10-19-78 to 1-30-80</td>
</tr>
<tr>
<td>NOAA - 6</td>
<td>6-27-79</td>
<td>6-27-79 to 3-5-83</td>
</tr>
<tr>
<td>NOAA - 7</td>
<td>6-23-81</td>
<td>8-19-81 to 6-7-86</td>
</tr>
<tr>
<td>NOAA - 8</td>
<td>3-28-83</td>
<td>6-20-83 to 7-12-84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7-1-85 to 10-31-85</td>
</tr>
<tr>
<td>NOAA - 9</td>
<td>12-12-84</td>
<td>2-25-85 to 11-7-88</td>
</tr>
<tr>
<td>NOAA - 10</td>
<td>9-17-86</td>
<td>11-17-86 to 9-17-91</td>
</tr>
<tr>
<td>NOAA - 11</td>
<td>9-24-88</td>
<td>11-8-88 to 9-13-94</td>
</tr>
<tr>
<td>NOAA - 12</td>
<td>5-14-91</td>
<td>9-1-91 to 12-15-94</td>
</tr>
<tr>
<td>NOAA - 13</td>
<td>8-9-93</td>
<td>8-9-93 to 8-21-93</td>
</tr>
</tbody>
</table>

**Orbit Characteristics**

Altitude
- 833 km (NOAA-6, 8, 10, 12 and 15)
- 870 km (TIROS-N; NOAA-7, 9, 11, 13, and 14)

Period of orbit
- 101.5 min (833 km altitude)
- 102.3 min (870 km altitude)

Orbit inclination
- 98.9°

Orbits per day
- 14.2 (833 km) or 14.1 (870 km)

Distance between orbits
- 25.5° (approx. 2,700 km)

Overpass times
- NOAA - 14 1330 (ascending) and 0130 (descending) LST
- NOAA - 15 1930 (ascending) and 0730 (descending) LST
AVHRR Spectral Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>NOAA-6, -8, -9, -11, -12 and -14</th>
<th>NOAA-7, -9, -11, -12 and -14</th>
<th>NOAA-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.58—0.68</td>
<td>0.58—0.68</td>
<td>0.58—0.68</td>
</tr>
<tr>
<td>2</td>
<td>0.72—1.10</td>
<td>0.72—1.10</td>
<td>0.725—1.00</td>
</tr>
<tr>
<td>3A</td>
<td></td>
<td>3.55—3.93</td>
<td>1.58—1.64</td>
</tr>
<tr>
<td>4</td>
<td>10.5—11.5</td>
<td>10.3—11.30</td>
<td>10.30—11.30</td>
</tr>
<tr>
<td>5</td>
<td>11.5—12.50</td>
<td>11.50—12.50</td>
<td>11.50—12.50</td>
</tr>
</tbody>
</table>

Swath Width and Orbit Types of the AVHRR Instrument

Orbit Type:
- Ascending = S Hemisphere to N Hemisphere
- Descending = N Hemisphere to S Hemisphere

Satellite ground track

2,700 km
<table>
<thead>
<tr>
<th>Table 4.13 AVHRR Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan angle from nadir</td>
</tr>
<tr>
<td>Optical FOV</td>
</tr>
<tr>
<td>IFOV, at nadir</td>
</tr>
<tr>
<td>IFOV, off-nadir maximum</td>
</tr>
<tr>
<td>along track</td>
</tr>
<tr>
<td>across track</td>
</tr>
<tr>
<td>Swath width</td>
</tr>
<tr>
<td>Repeat coverage</td>
</tr>
<tr>
<td>Spectral Channels</td>
</tr>
<tr>
<td>NOAA-6,8 and 10</td>
</tr>
<tr>
<td>NOAA-7, 9, 11, 12, and 14</td>
</tr>
<tr>
<td>NOAA-15</td>
</tr>
<tr>
<td>1 0.58-0.68</td>
</tr>
<tr>
<td>2 0.72-1.10</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>3 3.55-3.93</td>
</tr>
<tr>
<td>4 10.5-11.5</td>
</tr>
<tr>
<td>-----</td>
</tr>
</tbody>
</table>
4.10 Earth Observing System

The Earth Observing System (EOS) is a series of Earth-orbiting satellites which will provide global observation of the land surface, atmosphere, and oceans over 15 years or more. EOS is part of NASA's Earth Science Enterprise (formerly Mission To Planet Earth) program which provides measurement systems and research initiatives to further the acquisition and synthesis of environmental data to address scientific issues related to global change and Earth system science.

Complete information and details on the satellites and instruments included in EOS can be found in the MTPE/EOS Reference Handbook. This document can be directly accessed at the following Internet address:


EOS is complemented by missions and instruments from international partners, including Japan, Brazil, the European Space Agency (ESA), and ESA member countries. Together, these NASA and international programs form the basis for a comprehensive International Earth Observing System (IEOS).

The first EOS-sponsored satellite, the polar-orbiting TERRA spacecraft (formally known as EOS AM-1) is scheduled for launch on October 4, 1999 (Figure 4.44). Its descending node equatorial crossing will be 10:30 AM. TERRA will fly four instruments:

ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer (Figure 4.45, Table 4.14)
A three-radiometer sensor package with three vis/NIR, six SWIR, and five thermal IR channels with 15, 30, and 90 m resolution, respectively, and a 60 km swath.

MISR - Multi-angle Imaging Spectrometer
Thirty-six channel instrument; nine pushbroom cameras with discrete view angles (up to +/- 70°) in four spectral bands (0.443 to 0.865 µm) with resolution to 275 m to 1.1 km.

MODIS - Moderate Resolution Imaging Spectrometer (Figure 4.46, Table 4.15)
Thirty-six channel imaging radiometer (0.7 µm to 14.3 µm) with 250 m, 500 m, or 1 km resolution and 2,300 km swath width.

MOPITT - Measurement of Pollution in the Troposphere
Eight channel, cross-track scanning, gas correction radiometer operating at three wavelengths (2.2, 2.3, and 4.7 µm)
ASTER Instrument

Advanced Spaceborne Thermal Emission and Reflection Radiometer
A suite of three advanced optical radiometers that operate in the visible and near infrared, the short-wavelength infrared, and the thermal infrared.

MODIS Instrument

Moderate Resolution Imaging Spectro-radiometer
An imaging radiometer employing a cross-track scan mirror and collecting optics, and a set of individual detector elements to provide imagery of the Earth’s surface and cloud cover in 36 discrete spectral bands.
### TABLE 4.10 ASTER INSTRUMENT SPECTRAL CHARACTERISTICS

<table>
<thead>
<tr>
<th>VNIR</th>
<th>SWIR</th>
<th>TIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1: 0.52 - 0.60 mm N nadir looking</td>
<td>Band 4: 1.600 - 1.700 mm</td>
<td>Band 10: 8.125-8.475 mm</td>
</tr>
<tr>
<td>Band 2: 0.63 - 0.69 mm N nadir looking</td>
<td>Band 5: 2.145 - 2.185 mm</td>
<td>Band 11: 8.475 - 8.825 mm</td>
</tr>
<tr>
<td>Band 3: 0.76 - 0.86 mm N nadir looking</td>
<td>Band 6: 2.185 - 2.225 mm</td>
<td>Band 12: 8.925 - 9.275 mm</td>
</tr>
<tr>
<td>Band 3: 0.76 - 0.86 mm B backward looking</td>
<td>Band 7: 2.235 - 2.285 mm</td>
<td>Band 13: 10.25 - 10.95 mm</td>
</tr>
<tr>
<td></td>
<td>Band 8: 2.295 - 2.365 mm</td>
<td>Band 14: 10.95 - 11.65 mm</td>
</tr>
<tr>
<td></td>
<td>Band 9: 2.360 - 2.430 mm</td>
<td></td>
</tr>
</tbody>
</table>

**Ground Resolution:**
- 15 m
- 30 m
- 90 m
<table>
<thead>
<tr>
<th>Band#</th>
<th>Bandwidth (nm)</th>
<th>Primary Uses</th>
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<tbody>
<tr>
<td>1</td>
<td>620 - 670</td>
<td>Land/Cloud Boundaries</td>
</tr>
<tr>
<td>2</td>
<td>841 - 876</td>
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<tr>
<td>3</td>
<td>459 - 479</td>
<td>Land/Cloud Properties</td>
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<td>545 - 565</td>
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<tr>
<td>5</td>
<td>1230 - 1250</td>
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</tr>
<tr>
<td>6</td>
<td>1628 - 1652</td>
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<tr>
<td>7</td>
<td>2105 - 2155</td>
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<td>8</td>
<td>405 - 420</td>
<td>Ocean Color/Phytoplankton/Biogeochemistry</td>
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<td>9</td>
<td>438 - 448</td>
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<td>483 - 493</td>
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<td>743 - 753</td>
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<td>862 - 877</td>
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<td>17</td>
<td>890-920</td>
<td>Atmospheric Water Vapor</td>
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<td>18</td>
<td>931 - 941</td>
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<td>19</td>
<td>915 - 965</td>
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<tr>
<td>Band#</td>
<td>Bandwidth (µm)</td>
<td>Primary Uses</td>
</tr>
<tr>
<td>-------</td>
<td>----------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>20</td>
<td>3.660 - 3.840</td>
<td>Surface/Cloud Temperature</td>
</tr>
<tr>
<td>21</td>
<td>3.929 - 3.989</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>3.929 - 3.989</td>
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<tr>
<td>23</td>
<td>4.020 - 4.080</td>
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<tr>
<td>24</td>
<td>4.433 - 4.498</td>
<td>Atmospheric Temperature</td>
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<td>25</td>
<td>4.482 - 4.549</td>
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<td>26</td>
<td>1.360 - 1.390</td>
<td>Cirrus Clouds/Water Vapor</td>
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<tr>
<td>27</td>
<td>6.535 - 6.895</td>
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</tr>
<tr>
<td>28</td>
<td>7.175 - 7.475</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>8.400 - 8.700</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>9.580 - 9.880</td>
<td>Ozone</td>
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<tr>
<td>31</td>
<td>10.780 - 11.280</td>
<td>Surface/Cloud Temperature</td>
</tr>
<tr>
<td>32</td>
<td>11.770 - 12.270</td>
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</tr>
<tr>
<td>33</td>
<td>13.185 - 13.485</td>
<td>Cloud Top Temperature</td>
</tr>
<tr>
<td>34</td>
<td>13.485 - 13.785</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>13.785 - 14.085</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>14.085 - 14.385</td>
<td></td>
</tr>
</tbody>
</table>
## Contents

5.1 Objectives
5.2 Introduction to Thermal Infrared Energy
5.3 Thermal Energy Detectors
5.4 Thermal Sensors
5.5 Interpreting Thermal Imagery
5.1 Objectives

- List the portions of the electromagnetic spectrum used for thermal sensing.
- Explain the difference between apparent and kinetic temperatures.
- List several sources of distortion in thermal IR imagery.
- Describe the characteristics of clouds and smoke on thermal IR data.
- Describe the diurnal temperature cycles of vegetation, soil, and water.
- List several applications of thermal IR data.
- List the spatial, spectral, and revisit characteristics of the thermal data from Landsat TM, ETM+ and NOAA AVHRR.

5.2 Introduction

A brief introduction to thermal infrared energy is presented along with the definition of pertinent terms. Thermal infrared detectors are described before thermal sensing is presented. A section on interpreting thermal infrared imagery is presented next.

Definitions

Heat

The kinetic energy of the random motion of particles of matter causing collisions that result in changes of energy state and the subsequent emission of electromagnetic radiation (Radiant Flux).

Amount of heat

Measured in calories (one calorie = the amount of heat required to raise the temperature of one gram of water one °C)

Concentration of heat

Measured by temperature
<table>
<thead>
<tr>
<th><strong>Kinetic Temperature</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration of kinetic heat as measured by a thermometer in contact with the object.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Radiant Temperature</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration of radiant flux; it can be sensed remotely. Also known as Apparent Temperature. The total exitance (W m⁻²) is proportional to the fourth power of kinetic temperature times emissivity. <strong>Thermal infrared radiation is sensed remotely by electronic detection means rather than by photochemical means (i.e. film).</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Conduction</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The transfer of heat through a material by molecular interaction.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Convection</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The transfer of heat through the physical movement of heated matter.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Radiation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The transfer of heat in the form of electromagnetic waves. Unlike conduction and convection, radiative transfer of heat can occur through (or within) a vacuum.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Thermal Conductivity</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>A measure of the ease of heat transfer; a measure of the rate at which heat will pass through a material: (W m⁻¹ K⁻¹).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Thermal Capacity</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The ability of a material to store heat energy; calculated as the product of density and specific heat (cal cm⁻³ °C⁻¹).</td>
</tr>
</tbody>
</table>
Blackbody Radiation

Stefan - Boltzmann Law for a Blackbody:

\[ W = \sigma T^4 \]

- \( W \) = total radiant exitance (W m\(^{-2}\))
- \( \sigma \) = Stefan - Boltzmann constant \( (5.6697 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}) \)
- \( T \) = temperature of the blackbody (K)

Wien's Displacement Law

\[ \lambda_{\text{max}} = \frac{2,898 \text{ } \mu \text{m} \text{ K}}{T} \text{ (Kelvin)} \]

Note: \( \lambda_{\text{max}} \) is inversely proportional to temperature

Planck's Blackbody Law

\[ M_\lambda = \frac{3.74151 \times 10^8}{\lambda^5 \left( e^{1.43879 \times 10^4 / \lambda T} - 1 \right)} \]

Radiation From Real Materials

A blackbody is a theoretical, perfect absorber and perfect emitter. Real materials are not blackbodies so their emitting ability is less than perfect. The emitting ability of a material is called emissivity (\( \varepsilon \)):

\[ \varepsilon_\lambda = \frac{\text{exitance of an object at } T}{\text{exitance of a blackbody at } T} \]
\[ \varepsilon \text{ ranges from } 0 \text{ to } 1: \]

- \textit{Blackbody} \[ \varepsilon = 1 \]
- \textit{Graybody} \[ \varepsilon < 1, \text{ but constant at all wavelengths} \]
- \textit{Selective Radiator} \[ \varepsilon < 1, \text{ but varies with wavelength} \]

\textbf{Kirchhoff's Law}

\[ \varepsilon_\lambda = A_\lambda \] (under conditions of thermal equilibrium)

"Good emitters are good absorbers"

As discussed in Chapter 2,

\textbf{Absorptance + Reflectance + Transmittance = 1}

(1)

Kirchhoff's Law states that \textbf{Absorptance = Exitance}

(2)

So, \textbf{Exitance + Reflectance + Transmittance = 1}

(3)

Since most objects of remote sensing observation are opaque to thermal infrared wavelengths,

\textbf{Transmittance = 0}

and Eq. 3 above becomes: \textbf{Exitance + Reflectance = 1}

(4)

This relationship states that Emissivity and Reflectance of thermal infrared wavelengths are \textit{inversely related} to one another. The greater an object's Reflectivity, the lesser its Emissivity is. That's why blackbodies are black -- as the perfect emitter, a blackbody, according to Eq. 4, \textit{must} also be the the perfect absorber (i.e. no reflectance). Note that Reflectivity and Emissivity must be compared at the same wavelengths.
Stefan-Boltzmann Law applied to real materials:

\[ W = \varepsilon \sigma T^4 \]

Emissivity varies with different materials. Two objects with the same kinetic temperature can have very different exitances (i.e. apparent temperature).

Thermal IR sensors detect radiant temperature \( (T_{\text{rad}}) \); most users are interested in kinetic temperature \( (T_{\text{kin}}) \).

\[ T_{\text{rad}} = \varepsilon^{2.5} T_{\text{kin}} \]

Thermal IR sensors detect thermal radiation from the surface of objects (about 50 µm in depth). This surface layer may have a different temperature compared to the internal bulk temperature (e.g. evaporative cooling of a soil surface).

Atmospheric Effects

Two major (and two minor) atmospheric windows (> 50% transmission) occur in the thermal IR portion of the spectrum (Figure 5.1):

- short wavelength 3.4 - 4.2 µm
- thermal window 4.6 - 4.8 µm
- long wavelength 8.1 - 9.4 µm
- thermal window 9.8 - 13.2 µm

For certain applications, it is important to note that the short wavelength thermal bandpass is subject to “contamination” from reflected solar infrared, whereas the long wavelength thermal bandpass is not (Figure 5.2).

Consult the blackbody curves shown in Figure 5.3. It appears that the earth (ambient, 290 K), even at its peak wavelength, emits considerably less radiation than the sun does. In fact, at its peak wavelength, the sun emits greater than 3 million times more radiation per micrometer than the earth emits at its peak wavelength. Comparing the radiant output from the sun and the earth at the earth’s peak wavelength, we can observe that the sun emits almost 450 times more radiant flux per micrometer than the earth does.
Introduction to Digital Remote Sensing

5.1 Atmospheric Transmittance

In the Thermal Infrared

- O₃
- H₂O
- CO₂

Transmittance

Wavelength (µm)

0.2
0.4
0.6
0.8
1.0

0
2
4
6
8
10
12
14

5.2 Sun vs Earth Power Relationship

In the Thermal Infrared

Solar Irradiance

Reflected Solar Flux (ρ = 0.1)

Terrestrial Emitted Flux (κ = 1.0, T = 300K)

Terrestrial Emitted Flux (κ = 0.85, T = 300K)

Power Relationship

Spectral Radiant Exitance W m⁻² µm⁻¹

3.5
3.7
4.0
4.5
4.65

3
4
5
6
7
8
9
10
11
12
13
14

0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

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Blackbody Emittance Curves
On the basis of these facts, you might conclude that thermal infrared sensing during the daytime would be dominated by reflected solar radiation rather than emitted earth radiation and, therefore, would be useless for recording terrestrial temperature data. Such a conclusion is not correct; daytime thermal IR sensing can be effectively done, if the correct bandpass is used. The apparent contradiction between Figure 5.3 and the above statement that daytime thermal IR sensing can be accomplished results from the faulty assumption that all of the radiant power emitted by the sun reaches the earth. It doesn’t!

The sun is a sphere of gas nearly 1.4 million kilometers in diameter which is heated by continuous nuclear reactions at its center. The spectral radiant flux from the sun is complicated by the tremendous temperature variations which occur along its radius. Another complication is the opacity of the solar atmosphere to certain wavelengths. Stated simply, the effective, blackbody temperature of the sun is wavelength dependent. Measurements of solar irradiance from outside the earth’s atmosphere provide the data presented in Table 5.1.

At its peak exitance wavelength (0.487 μm), the sun can best be approximated by a blackbody source at 5950 K (Table 5.1). Using Planck’s Blackbody Law, the spectral radiant exitance of the sun’s surface can be calculated to be:

\[
M_\lambda = 9.59 \times 10^7 \text{ W m}^{-2} \text{ μm}^{-1}
\]

at \( \lambda = 0.487 \text{ μm} \) and \( T = 5950 \text{ K} \)

At the top of the earth’s atmosphere, some 150 million kilometers away from the sun, solar irradiance has been measured to be:

\[ 2,072.2 \text{ W m}^{-2} \text{ μm}^{-1} \]

Obviously, much less radiation reaches one square meter of the earth’s upper atmosphere than left one square meter of the sun’s surface. The reduction factor (F) by which radiant flux emitted from the solar surface is decreased by the time it reaches the top of earth’s atmosphere is:

\[
F = \frac{9.59 \times 10^7 \text{ W m}^{-2} \text{ μm}^{-1}}{2072.2 \text{ W m}^{-2} \text{ μm}^{-1}} = 4.63 \times 10^4
\]
This reductions factor \( F \) applies at any wavelength and is dimensionless. The spectral radiant exitance of the sun at 9.6 µm (the wavelength of the earth’s peak spectral exitance) can be calculated in a similar fashion. At 9.6 µm, the sun is best approximated by a blackbody temperature of 5000K (Table 5.1).

\[
M_\lambda = 1.31 \times 10^4 \, \text{W m}^{-2} \mu\text{m}^{-1}
\]

at \( \lambda = 9.6 \, \mu\text{m} \) and \( T = 5000 \, \text{K} \)

<table>
<thead>
<tr>
<th>Bandpass (µm)</th>
<th>Effective Blackbody Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20 - 0.25</td>
<td>5000</td>
</tr>
<tr>
<td>0.26 - 0.34</td>
<td>5500</td>
</tr>
<tr>
<td>0.35 - 0.44</td>
<td>5700</td>
</tr>
<tr>
<td>0.45 - 0.47</td>
<td>5900</td>
</tr>
<tr>
<td>0.48 - 0.49</td>
<td>5950</td>
</tr>
<tr>
<td>0.50 - 0.54</td>
<td>5900</td>
</tr>
<tr>
<td>0.55 - 0.64</td>
<td>5800</td>
</tr>
<tr>
<td>0.65 - 0.94</td>
<td>5700</td>
</tr>
<tr>
<td>0.95 - 1.29</td>
<td>5800</td>
</tr>
<tr>
<td>1.30 - 4.50</td>
<td>6000</td>
</tr>
<tr>
<td>4.60 - 5.90</td>
<td>5500</td>
</tr>
<tr>
<td>6.00 - 20.0</td>
<td>5000</td>
</tr>
</tbody>
</table>
Applying the reduction factor (F), yields:

\[
\frac{1.31 \times 10^4 \text{ W m}^{-2} \mu\text{m}^{-1}}{4.63 \times 10^4} = 0.28 \text{ W m}^{-2} \mu\text{m}^{-1}
\]

For the earth, assuming an ambient temperature of 300 K, Planck’s Blackbody Law gives:

\[M_\lambda = 31.2 \text{ W m}^{-2} \mu\text{m}^{-1}\]

at \(\lambda = 9.6 \mu\text{m}\) and \(T = 300 \text{ K}\)

These calculations show that at 9.6 \(\mu\text{m}\), the earth’s emitted radiation is more than 100 times more powerful than the incoming solar infrared irradiance. Figure 5.2 shows the “cross-over” region of the spectrum, where the earth becomes the more powerful radiator compared to the sun, to be 3.70 - 4.65 \(\mu\text{m}\).

### 5.3 Thermal Energy Detectors

**Thermal Detectors (Bolometers)**

These devices change their own temperature in response to incident thermal radiation and usually their electrical resistance is a function of their temperature.

**Advantages:**
- very accurate
- response is not wavelength dependent

**Disadvantages:**
- incapable of rapid response
- lower thermal sensitivity

**Photon (or Quantum) Detectors**

Incident radiation excites electrical charge carriers within the detector material which change an electrical characteristic of the responsive element. This process is carried out without any significant temperature change in the responsive element.

There are two types of photon detectors:
1. **Photoconductive** - Change in incident radiation causes a change in the electrical resistance of the detector. Requires a bias voltage supply; the electronic noise of the supply limits the detector performance.

2. **Photovoltaic** - Change in incident radiation causes a change in the output voltage of the detector. These detectors have a better signal-to-noise ratio (SNR) than the photoconductive types, but only a limited number of materials are available:
   
   - Silicon (Si)
   - Indium Antimonide (InSb)
   - Germanium (Ge)

Advantage of Photon Detectors:

- very rapid (< 1 µsec) response time

Disadvantages of Photon Detectors:

- narrow spectral sensitivity
- necessity for cooling in order to improve SNR

---

### 5.4 Thermal Sensors

**Thermal Radiometers**

A non-imaging device; the basic form of radiant temperature sensor. For any such device, the ground resolution of the instrument at any given flying altitude is a function of the *Instantaneous Field Of View (IFOV)*.

\[
\text{Diameter of the ground} = H \beta
\]

\[
\text{resolution cell}
\]

where:

- \( H \) = flying height above terrain
- \( \beta \) = IFOV (cone angle) in radians

**Thermal Scanners**

Imaging devices which produce a two-dimensional record of surface radiant temperature. Aircraft scanners typically use a rotating mirror and usually have a large angular acceptance angle (90° - 120°). The data are most often recorded on magnetic tape, although some instruments provide in-flight imagery (CRT display or black & white strip photos).
5.5 Interpreting Thermal Imagery

Interpreting Thermal Imagery

- The diurnal cycles of radiant temperatures for vegetation, soil, and water are shown in Figure 5.4.

- Polished metals have very high reflectance in the thermal IR, so their emissivity is very low (< 0.10) [Kirchhoff’s Law].

- Water has very low reflectance in the thermal IR, so its emissivity is very high (> 0.95).

- Water has the highest thermal capacity of any substance: 1.00 @ 15°C

  dry air = 0.24  
sandy soil = 0.24  
moist clay soil = 0.35

- The thermal inertia of water is similar to that of many soils and rock types:

  water = 0.037  
soils = 0.024 - 0.042  
shale = 0.034  
sandstone = 0.054

- By day, water presents a cooler radiant temperature compared to the surrounding landscape, while at night water presents a warmer radiant temperature compared to its surroundings. Why?

  1. Water has the highest thermal capacity (ability to store heat) of all landscape substances. So in the daytime, water bodies stay cooler than terrestrial objects because water can absorb a lot of energy with very little temperature change. It takes about four times as much energy to change the temperature of a shallow water body by 1°C compared to that required to change the temperature of rocks or soil by the same amount.

  2. Radiation losses (at night) from the free water surface causes cooling. Cooler water is slightly more dense than warmer water causing convection currents to set up which mix the water layers. This helps water bodies to maintain a relatively warm radiant temperature at night.
Diurnal $T_{rad}$ Cycles

Radiant Temperature

- Rocks & Soils (Typical)
- Vegetation
- Standing Water
- Metallic Objects

Midnight
Local Dawn
Noon
Local Sunset
Midnight

5.4
Note that convection does not operate to transfer heat in soils and rocks (their heat must be conducted to the surface and earth materials are generally poor conductors).

- Moist soil is generally cooler than dry soil due to evaporative cooling and the large heat capacity of water.

- Vegetation is cooler than dry soil during the day due to transpiration; it's warmer than dry soil at night because there is no transpiration and the high thermal capacity of the in vivo moisture maintains the absorbed heat of the day.

- Thermal images containing clouds record the radiant temperature of their constituents: water droplets or ice particles. In most cases, due to their altitude in the atmosphere, clouds exhibit a cold to very cold signature (usually dark grey to black).

- Smoke plumes are usually invisible on thermal imagery. Hence, the thermal signatures of the surface features beneath the smoke plumes are recorded. This makes thermal imagery, particularly real time data, very useful for forest fire control work.

- Apparent thermal inertia ($\Delta T_{rad}$)

Thermal inertia cannot be measured by remote sensing methods because the three parameters needed to calculate it, conductivity, density, and thermal capacity, must be measured by contact techniques. But the maximum and minimum radiant temperature can be measured and for corresponding pixels (i.e. the same ground area): $T_{rad\ max} - T_{rad\ min} = \Delta T_{rad}$. Since the area is the same, $\varepsilon$ is the same and $\Delta T_{rad}$ is approximately equal to $\Delta T_{kinetic}$.

$\Delta T_{rad}$ is low for materials with high thermal inertia.

$\Delta T_{rad}$ is high for materials with low thermal inertia.

\[
\text{Apparent Thermal Inertia} = \frac{1 - \text{Albedo}}{\Delta T_{rad}}
\]
Contents

6.1 Objectives
6.2 Introduction
6.3 Color Science
6.4 Color Formation Exercise
6.1 Objectives

- List the additive and subtractive primary colors
- Given the color continuum chart, determine the complement of any primary color
- Given a set of generalized spectral reflectance curves, predict the color that each feature will form in both a (NIR, R, G) false-color composite and a (SWIR, NIR, R) false-color composite
- Define the vegetation index concept and describe its use.
- Define the moisture index concept and describe its use and limitations.

6.2 Introduction

The theory of color science is briefly discussed, especially with respect to additive and subtractive color formation. Satellite imagery is illustrated with respect to the formation of colors from various earth surface features portrayed in three different types of color composites.

6.3 Color Science

In 1666, Sir Isaac Newton laid the foundation of color science when he discovered that white sunlight was composed of a mixture of all colors of the spectrum (Figure 6.1). The visible region of the electromagnetic spectrum extends from about 400 to 700 nanometers wavelength. EMR of these wavelengths produces a psychophysical response through the normal human eye called “color”. All spectral colors from violet to deep red are “contained” in the visible region of the EMR. Sir William Herschel is credited with the discovery of the infrared portion of the electromagnetic spectrum (Figure 6.2).

The visible light spectrum can be visualized as consisting of three main parts. The portion containing wavelengths longer than about 580 nm includes all the reddish light; wavelengths between 490 and 580 nm contain greenish light; and wavelengths shorter than 490 nm include all the bluish light. The full range of colors can be produced from a beam of white light by varying the proportions of the reddish, greenish, and bluish parts independently.
### Visible Electromagnetic Radiation

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Apparent Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-430</td>
<td>400-490 bluish Violet</td>
</tr>
<tr>
<td>430-475</td>
<td>Blue</td>
</tr>
<tr>
<td>475-510</td>
<td>490-580 greenish Cyan</td>
</tr>
<tr>
<td>510-560</td>
<td>Green</td>
</tr>
<tr>
<td>560-590</td>
<td>Yellow</td>
</tr>
<tr>
<td>590-620</td>
<td>580-700 reddish Orange</td>
</tr>
<tr>
<td>620-700</td>
<td>Red</td>
</tr>
</tbody>
</table>

#### Discovery of Infrared

Sir William Herschel (1738–1822)
There are two methods used to reproduce color:

- additive color formation using the additive primaries
  - blue
  - green
  - red

- subtractive color formation using the subtractive primaries
  - cyan
  - magenta
  - yellow

These six primary colors are only points on the continuum of spectral colors, but they are the compliments of one another (Figure 6.3).

### 6.4 Color Formation Exercise

**Objective.** Predict the color that common earth-surface features will form in both a (R, G, B) true-color composite and a (NIR, R, G) false-color composite.

**Materials.** Ten generalized spectral reflectance curves and a glossary of color terms; three color composites of a Landsat TM scene extract from the vicinity of Manaus, Brazil.

One of the complicating factors which inhibits our understanding of the false-color rendition of landscape targets is the nearly unlimited number of subtle reflectivity differences in the various wavelengths which can, and do, affect the appearance of the landscape on three-band digital displays. However, we must come to grips with at least a few “standard” color/target relationships if we expect to become proficient image interpreters.

In the following exercise, you will gain experience in interpreting both true-color and false-color renditions of reflectance data. In order to maintain our perspective on multispectral reflectance, very generalized spectral reflectance curves in the wavelength range of 0.4 to 0.9 µm are presented. These curves simulate real objects, but their identity is not labeled in order that, for the present, we may concentrate solely
Additive Primaries
Blue
Green
Red

Subtractive Primaries
Yellow
Magenta
Cyan

Additive and Subtractive Colors are Complementary
Blue = Magenta + Cyan
Green = Yellow + Cyan
Red = Yellow + Magenta
Yellow = Red + Green
Magenta = Blue + Red
Cyan = Blue + Green

Subtractive Primaries
Yellow ABSORBs Blue
Magenta ABSORBs Green
Cyan ABSORBs Red
in spectral reflectance without reference to other image interpretation clues (e.g. texture, pattern, association or location).

In order to simplify reality, this exercise assumes that reflectance exists only in one of four magnitudes. These are shown on the Y-axes of the graphs as $L$ - very little reflectance, $M$ - moderate reflectance, $H$ - high reflectance or $VH$ - very high reflectance. Four bands will be considered on the x-axes:

- Blue band: 0.4 - 0.5 $\mu$m
- Green band: 0.5 - 0.6 $\mu$m
- Red band: 0.6 - 0.7 $\mu$m
- NIR band: 0.7 - 0.9 $\mu$m

Any three of these four bands may be displayed on either the red ($R$), green ($G$) or blue ($B$) channels of a computer color display. If we assign Red, Green and Blue bands, respectively, to the $R$, $G$, $B$ color space we can make a true-color composite. The "standard" false-color composite (one that simulates the appearance of a color infrared airphoto, is made be displaying the NIR, Red and Green bands, respectively, on the $R$, $G$, $B$ display channels.

For the band numbering scheme of Landsat TM and ETM+, the true-color composite is the 3,2,1; the "standard" false-color composite (FCC) is a 4,3,2; and a popular high-contrast composite is the 5,4,3. For the SPOT HRVIR, no true color composite can be made directly from the available bands since no blue reflectance is measured. The HRVIR "standard" FCC is the 3,2,1, while the high-contrast FCC is the 4,3,2.

Your task is to record the relative amount of reflectance in each band in the spaces provided to the right of each graph. Make a mental judgement of the color that this arrangement will form in the two cases (i.e. the true-color composite and the "standard" FCC). Then consult the color glossary provided at the end of the exercise to see what the correct answer is, based on the relative amounts of Red, Green and Blue light in the display. All correct answers are contained in the glossary, but not all glossary entries are correct answers for this exercise.

Write the color name beneath the $R$, $G$, $B$ column for each composite.
Question 1.

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.5</td>
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<td>.6</td>
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<td>.7</td>
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</tr>
<tr>
<td>.8</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>.9</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

TRUE COLOR
(R) ________  (R) ________
(G) ________  (G) ________
(B) ________  (B) ________

Display Color  Display Color

Question 2.

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>.4</td>
<td></td>
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<td></td>
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<td>.5</td>
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<tr>
<td>.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TRUE COLOR
(R) ________  (R) ________
(G) ________  (G) ________
(B) ________  (B) ________

Display Color  Display Color

Question 3.

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.5</td>
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<td>.8</td>
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</tr>
<tr>
<td>.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TRUE COLOR
(R) ________  (R) ________
(G) ________  (G) ________
(B) ________  (B) ________

Display Color  Display Color
**Question 4.**

![Graph showing relative reflectance vs. wavelength (µm)]

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TRUE COLOR**

(R) __________ (G) __________ (B) __________

**ST'D FCC**

(R) __________ (G) __________ (B) __________

**Display Color**

**Question 5.**

![Graph showing relative reflectance vs. wavelength (µm)]

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TRUE COLOR**

(R) __________ (G) __________ (B) __________

**ST'D FCC**

(R) __________ (G) __________ (B) __________

**Display Color**

**Question 6.**

![Graph showing relative reflectance vs. wavelength (µm)]

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TRUE COLOR**

(R) __________ (G) __________ (B) __________

**ST'D FCC**

(R) __________ (G) __________ (B) __________

**Display Color**

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6-8
Question 7.

![Graph showing Relative Reflectance vs Wavelength (µm)]

**TRUE COLOR**
- (R) __________
- (G) __________
- (B) __________

**ST'D FCC**
- (R) __________
- (G) __________
- (B) __________

Display Color
- Display Color

---

Question 8.

![Graph showing Relative Reflectance vs Wavelength (µm)]

**TRUE COLOR**
- (R) __________
- (G) __________
- (B) __________

**ST'D FCC**
- (R) __________
- (G) __________
- (B) __________

Display Color
- Display Color

---

Question 9.

![Graph showing Relative Reflectance vs Wavelength (µm)]

**TRUE COLOR**
- (R) __________
- (G) __________
- (B) __________

**ST'D FCC**
- (R) __________
- (G) __________
- (B) __________

Display Color
- Display Color
Question 10.

<table>
<thead>
<tr>
<th>Relative Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
</tr>
<tr>
<td>H</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>L</td>
</tr>
</tbody>
</table>

Wavelength (µm)

<table>
<thead>
<tr>
<th>TRUE COLOR</th>
<th>ST'D FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R) _____</td>
<td>(R) _____</td>
</tr>
<tr>
<td>(G) _____</td>
<td>(G) _____</td>
</tr>
<tr>
<td>(B) _____</td>
<td>(B) _____</td>
</tr>
</tbody>
</table>

Display Color  Display Color
<table>
<thead>
<tr>
<th>Color Glossary</th>
<th>Display Color</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>VH</td>
<td>VH</td>
<td>VH</td>
<td></td>
</tr>
<tr>
<td>Light Grey</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Dark Grey</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Strong Blue</td>
<td>L</td>
<td>L</td>
<td>VH</td>
<td></td>
</tr>
<tr>
<td>Pale Cyan</td>
<td>H</td>
<td>VH</td>
<td>VH</td>
<td></td>
</tr>
<tr>
<td>Strong Cyan</td>
<td>L</td>
<td>VH</td>
<td>VH</td>
<td></td>
</tr>
<tr>
<td>Strong Green</td>
<td>L</td>
<td>VH</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Dark Green</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Very Dark Green</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Light Yellowish-Green</td>
<td>M</td>
<td>VH</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Dark Yellowish-Green</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Strong Yellow</td>
<td>VH</td>
<td>VH</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Dark Yellow</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Reddish-Orange</td>
<td>VH</td>
<td>M</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Light Reddish-Gray</td>
<td>VH</td>
<td>H</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Dark Reddish-Gray</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Strong Red</td>
<td>VH</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Dark Red</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>reddish Brown</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Strong Reddish-Magenta</td>
<td>VH</td>
<td>L</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Pale Magenta</td>
<td>VH</td>
<td>H</td>
<td>VH</td>
<td></td>
</tr>
<tr>
<td>Magenta</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Dark Magenta</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td></td>
</tr>
</tbody>
</table>
In this portion of the exercise, you will explore additive color formation in the context of a Landsat TM 5,4,3 composite. The TM 5,4,3 composite (or the SPOT HRVIR 4,3,2 composite) displays one image from each of the three spectral zones that are important for vegetation analysis (Visible, Near-Infrared and Shortwave Infrared). As such, this type of composite usually portrays the maximum amount of information about a vegetated landscape that can be created with "raw" imagery (as opposed to using, for example, the Tasseled Cap transformation or one or more band ratios). Table 6.1 provides a partial glossary of the color hues which dominate this 5,4,3 composite. Note that white is formed by the mixing of Very High strengths of Red, Green, and Blue. Black, on the other hand, is the sum of little or no Red, Green, and Blue light.

Table 6.2 introduces the concept of the Vegetation Index (VI), which is sensitive to the relative difference in reflectance between the near-infrared band (TM 4 or HRVIR 3) and the red light channel (TM 3 or HRVIR 2). Consulting Figure 6.4, you can observe that, of the major classes of earth-surface features, only vegetation exhibits a large reflectance contrast in these two bands with the near-infrared (TM 4 or HRVIR 3) reflectance dominating. This index helps to summarize the vegetative state of a landscape facet. A Very High VI implies a vigorous, high-biomass area of vegetation. Lower VIs suggest either 1) less vigorous plant growth, 2) lower biomass per unit area, or 3) plant senescence. Extremely low VIs, or reversals where the red reflectance dominates, are typical of non-vegetated surfaces.

Table 6.3 provides guidance in the physical interpretation of the shortwave-infrared reflectance (TM 5 or HRVIR 4) . In this portion of the spectrum, the influence of water (i.e. moisture content) is dominant. High water content results in low reflectance. Caution must be exercised, however, since other factors also play a role in controlling reflectance in the SWIR. Internal leaf structure, for instance, influences foliar reflectance in this portion of the spectrum. SWIR bands are also very sensitive to shadows, since atmospheric scattering is nil in the SWIR.

Using the TM 5,4,3 composite image with the appropriate overlay and Tables 6.1 - 6.3, complete the interpretation form provided (page 6-15).
Percent Reflectance

Thematic Mapper Bands

Wavelength (µm)

Thematic Mapper Band Sensitivities

- vegetation
- dry soil
- clear water
### Table 6.1 Additive Color Glossary

<table>
<thead>
<tr>
<th>Color</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pale Blue</td>
<td>H</td>
<td>H</td>
<td>VH</td>
</tr>
<tr>
<td>Purple</td>
<td>M</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Pale Magenta</td>
<td>VH</td>
<td>H</td>
<td>VH</td>
</tr>
<tr>
<td>Lt. Magenta</td>
<td>H</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Lt. Yellow-Green</td>
<td>M</td>
<td>VH</td>
<td>L</td>
</tr>
<tr>
<td>Dk. Yellow-Green</td>
<td>M</td>
<td>H</td>
<td>L</td>
</tr>
<tr>
<td>Green</td>
<td>L</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>reddish-Brown</td>
<td>M</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Blue-Black</td>
<td>L</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>Black</td>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>White</td>
<td>VH</td>
<td>VH</td>
<td>VH</td>
</tr>
</tbody>
</table>

### Table 6.2 Vegetation Index

<table>
<thead>
<tr>
<th>Band 4 BV</th>
<th>Band 3 BV</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
<td>L</td>
<td>VH</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>M</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>all others</td>
<td></td>
<td>(non-vegetative)</td>
</tr>
</tbody>
</table>

### Table 6.3 Moisture Index

<table>
<thead>
<tr>
<th>Band 5 BV</th>
<th>Possible Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
<td>Very Dry</td>
</tr>
<tr>
<td>H</td>
<td>Dry</td>
</tr>
<tr>
<td>M</td>
<td>Moist</td>
</tr>
<tr>
<td>L</td>
<td>Very Moist</td>
</tr>
</tbody>
</table>
### TM 5,4,3 Composite Interpretation

<table>
<thead>
<tr>
<th>Location</th>
<th>Color</th>
<th>5 BV</th>
<th>4 BV</th>
<th>3 BV</th>
<th>VI</th>
<th>MI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Dark Green</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Strong Green</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Dk. Yellowish-Green</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Lt. Yellowish-Green</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Pale Magenta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Magenta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Dark Magenta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>White</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Location | Color            | Earth Cover Type
---|------------------|-------------------
A  | Dark Green       |                   
B  | Strong Green     |                   
C  | Dk. Yellowish-Green |               
D  | Lt. Yellowish-Green |               
E  | Pale Magenta     |                   
F  | Magenta          |                   
G  | Dark Magenta     |                   
H  | White            |                   |
Question 1.

ANSWERS

Question 2.

Question 3.
**ANSWERS**

**Question 4.**

- **TRUE COLOR**
  - (R)  __________
  - (G)  __________
  - (B)  __________

- **STD’D FCC**
  - (R)  __________
  - (G)  __________
  - (B)  __________

- **Display Color**
  - Black
  - Strong Red

![Relative Reflectance Diagram](image)

**Question 5.**

- **TRUE COLOR**
  - (R)  __________
  - (G)  __________
  - (B)  __________

- **STD’D FCC**
  - (R)  __________
  - (G)  __________
  - (B)  __________

- **Display Color**
  - Dark Green
  - Strong Reddish-Magenta

![Relative Reflectance Diagram](image)

**Question 6.**

- **TRUE COLOR**
  - (R)  __________
  - (G)  __________
  - (B)  __________

- **STD’D FCC**
  - (R)  __________
  - (G)  __________
  - (B)  __________

- **Display Color**
  - Strong Red
  - Strong Yellow

![Relative Reflectance Diagram](image)
ANSWERS

Question 7.

![Graph showing relative reflectance vs. wavelength (µm)]

TRUE COLOR
(R) M
(G) L
(B) L

STD FCC
(R) VH
(G) M
(B) L

Relative Reflectance
Wavelength (µm)

Display Color
Reddish Brown

Display Color
Reddish-Orange

Question 8.

![Graph showing relative reflectance vs. wavelength (µm)]

TRUE COLOR
(R) H
(G) H
(B) L

STD FCC
(R) VH
(G) H
(B) H

Display Color
Dark Yellow

Display Color
Lt. Reddish-Gray

Question 9.

![Graph showing relative reflectance vs. wavelength (µm)]

TRUE COLOR
(R) VH
(G) VH
(B) VH

STD FCC
(R) VH
(G) VH
(B) VH

Display Color
White

Display Color
White
Question 10.

**TRUE COLOR**

- (R) VH
- (G) VH
- (B) VH

**ST'D FCC**

- (R) L
- (G) VH
- (B) VH

**Display Color**

- White
- Strong Cyan
# ANSWERS

**TM 5,4,3 Composite Interpretation**

<table>
<thead>
<tr>
<th>Location</th>
<th>Color</th>
<th>Earth Cover Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Dark Green</td>
<td>Forest</td>
</tr>
<tr>
<td>B</td>
<td>Strong Green</td>
<td>Healthy Pasture</td>
</tr>
<tr>
<td>C</td>
<td>Dk. Yellowish-Green</td>
<td>Pasture; less moist and somewhat stressed compared to B [note the lower NIR reflectance]</td>
</tr>
<tr>
<td>D</td>
<td>Lt. Yellowish-Green</td>
<td>Pasture; less moist compared to B (shorter grasses ?)</td>
</tr>
<tr>
<td>E</td>
<td>Pale Magenta</td>
<td>Bare soil; lower moisture / organic matter compared to F</td>
</tr>
<tr>
<td>F</td>
<td>Magenta</td>
<td>Bare soil; nominal moisture / organic matter</td>
</tr>
<tr>
<td>G</td>
<td>Dark Magenta</td>
<td>Bare soil; higher moisture / organic matter compared to F</td>
</tr>
<tr>
<td>H</td>
<td>White</td>
<td>Bare soil; freshly disturbed -- low moisture / organic matter</td>
</tr>
</tbody>
</table>
Chapter 7  Digital Image Processing

Contents

7.1 Objectives

7.2 Introduction

7.3 Image Rectification and Restoration
   1. Geometric Correction
   2. Radiometric Correction
   3. Noise Removal

7.4 Image Enhancement
   1. Contrast Stretching
   2. Level Slicing
   3. Edge Enhancement
   4. Ratioing (including vegetation indexes)
   5. Principal Components Transformations
   6. Intensity/Hue/Saturation Color Transformation

7.5 Image Classification
   1. Introduction to Image Classification
   2. Spectral Pattern Recognition
      A Geometric Interpretation
      The Statistical Approach
   3. Unsupervised Clustering

7.6 Accuracy Assessment Techniques
7.1 Objectives

- Define image classification.
- List the two basic approaches to classifying remotely sensed imagery.
- Explain which of the various image elements are predominately used in digital image processing.
- Describe the minimum-distance-to-means classification process.
- Describe the maximum-likelihood classification process.
- Explain the concept of unsupervised clustering as a classification technique.
- Describe at least one accuracy assessment technique and explain why it is used.

7.2 Introduction

Digital images are first discussed with respect to rectification and restoration and then image enhancement (Table 7.1, 7.2, 7.3, and 7.4). Under Image classification, both supervised, minimum distance-to-the-means and maximum likelihood, and unsupervised techniques are introduced (Figure 7.1). The final topic includes a brief discussion of accuracy assessment techniques.

Table 7.1 Image Processing Sequence of Remotely Sensed Data

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Image Restoration</td>
</tr>
<tr>
<td>2.</td>
<td>Image Enhancement</td>
</tr>
<tr>
<td>3.</td>
<td>Image Classification</td>
</tr>
<tr>
<td>4.</td>
<td>Accuracy Assessment</td>
</tr>
</tbody>
</table>
### 7.3 Image Rectification and Restoration


- Geometric Correction
- Radiometric Correction
- Noise Removal

#### Table 7.2 Image Restoration

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Periodic Noise Removal</td>
</tr>
<tr>
<td>• Random Noise Removal</td>
</tr>
<tr>
<td>• Atmospheric (Haze)Correction</td>
</tr>
<tr>
<td>• Geometric Correction</td>
</tr>
<tr>
<td>• Radiometric Correction</td>
</tr>
</tbody>
</table>
7.4 Image Enhancement


- Contrast Stretching
- Level Slicing
- Edge Enhancement
- Ratioing
- Vegetation Indexes
- Principal Components Transformations
- Intensity/Hue/Saturation Color Transformation

Table 7.3 Image Enhancement

- Contrast Stretching
- Density Slicing
- Edge Enhancement
- Spatial and Directional Filtering
- Band Ratios
- Data Transformations
  - Principal Components
  - Canonical Analysis
7.1

Digital Data

Unsupervised Clustering

Classification Technique

Manual Interpretation

Clustering

Supervised Preprocessing

Statistics

Histograms

Enhancement

Digital Image

Ancillary Data

Training Site Selection

Manual Image Interpretation

Ancillary Data

Cluster Assignment

Digital Classification

Accuracy Assessment

Report Of Accuracy

Classified Image
Table 7.4 Basic Image Statistics
(see Figure 7.2)

- MINimum / MAXimum value
- Range
- Frequency
- Histogram (graph of Frequency distribution)
- Mean, Median, Mode
- Normal (Gaussian) Population Density Function (Bell-shaped curve)
- Variance
- Covariance
- Standard Deviation
Descriptive Statistics

7.2

- Skewness

- Mean
- Median
- Mode

+ Skewness

- Mean
- Median
- Mode

Mean
Median
Mode

68.27%
95.45%
99.73%
1. Introduction to Image Classification

A fundamental goal of remote sensing analysis is the classification of an image or scene. Classification, the partitioning of the image into discrete, pre-determined classes, can be accomplished either manually (photo or image interpretation) or with the aid of computers (digital processing). Both approaches require the use of decision rules. These rules (or keys) are generally derived from an analysis of areas considered representative of the various classes. Photointerpreters utilize image elements such as size, shape, shadow, tone or color, texture, pattern, site, and association to characterize a particular class, whereas digital techniques rely on numerical parameters.

Classification by both techniques will be illustrated for a Landsat MSS sub-scene acquired on February 26, 1979 over Wexford County, Michigan. A fairly direct visual classification technique would characterize each class by tone: white = snow, gray = hardwoods, and black = pines. The image would then be portioned into classes based upon tonal comparisons. The decision rule is simple; assign each area to the class with the same, or most similar, gray tone. The numeric equivalent of this technique would utilize digital values, obtained from a densitometer, or brightness values from the Landsat CTT in place of gray tones (Figure 7.3).

The decision rule may now be stated mathematically; assign the unknown area \( x \) to the class to which the distance is numerically minimum (\( H \)). Distances are simply the absolute value of the unknown area minus the class to which it is being compared (Figure 7.3):

\[
d = | x - H |
\]

The use of tone in the above analysis was chosen since it illustrated the concept of spectral pattern recognition. Of the three major image characteristics (spectral, spatial, and temporal attributes), spectral patterns are the most commonly utilized feature in digital classification.

2. Spectral Pattern Recognition

A Geometric Interpretation

When more than one band of Landsat MSS data are to be analyzed, individual bands may be represented by color images and superimposed to create color composite images. This technique is
7.3

Landsat MSS Image Gray Scale

Snow → X → Hardwoods → Pines

White 120 110 100 80 60 40 20 0
Gray Lead to Black

d
limited to three bands for any single composite. It is also not capable of rendering the full range of tonal information available from the MSS data. Digital classification techniques utilize the full range of spectral data (brightness values) available from multiple bands simultaneously.

Although the computer operates strictly in a numerical mode, graphical techniques will be used to introduce geometric concepts in image classification (this technique is adopted from one presented by Lillesand and Kiefer, 1979). The portrayal of spectral responses, and thus spectral patterns, is limited to two dimensions, whereas computer implementation of these techniques is mathematical and can be applied to almost any number of bands.

All subsequent data represent digital brightness values extracted from the CCT corresponding to a subscene. Individual areas, called “training sites,” were identified from ancillary data sources (maps and aerial photography) as being “representative” of the various cover types. These sites, therefore, represent a sample of pixels which will be utilized to characterize (numerically) the individual cover types. Individual pixel values have been plotted onto a two-dimensional graph; letters indicate to which category the value pertains (Figure 7.4). Band 6 brightness values are plotted on the x axis with the corresponding value for band 5 on the y axis. Visually, each class displays a variable range of possible values, although the spectral responses tend to form discernible patterns. These three training sites will be utilized to illustrate several classification strategies.

An extension of the tonal classification technique, illustrated in Figure 7.3, utilizes two or more brightness values (the numerical equivalent of gray tones). Each class is characterized by a set of mean values obtained from the pixels located within the training areas in each spectral band. The decision rule is a direct extension of the one band (gray tone) technique: assign an unknown pixel to the class with the same, or most similar, brightness values (gray tone). This strategy, known as the minimum distance-to-means classifier, is illustrated in Figure 7.5. Class means were determined and those for band 5 and band 6 are shown as a + on Figure 7.5. To classify an unknown pixel, such as points 1, 2, and 3, the distance between the unknown pixel and the mean value for each class is determined. For point 1, these distances are shown by lines connecting the point to each class mean position. The decision rule would be: assign the unknown pixel to the “closest” (i.e. minimum distance) class. Point 1 would therefore be classified as belonging to the hardwood class.
Training Site Pixel Values

Minimum Distance-to-Means Classification
The mathematics for expressing the distance measure numerically are illustrated in Figure 7.6. Since the x (BV6) and y (BV5) axes are perpendicular, the Pythagorean theorem for right triangles can be used. Since the square of the hypotenuse is equal to the sum of the squares of the sides:

\[ d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \]

For n dimensions, or bands, the generalization is:

\[ d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + \ldots + (n_2 - n_1)^2} \]

or, expressed in terms of BVs:

\[ d = \sum_{i=1}^{n} (BV_i - \overline{BV})^2 \]

Therefore, the formula for calculating the distance between an unknown pixel and mean value for a specific class, using 4 band MSS data, would be:

\[ d = \sqrt{(BV4 - \overline{BV4})^2 + (BV5 - \overline{BV5})^2 + (BV6 - \overline{BV6})^2 + (BV7 - \overline{BV7})^2} \]

Note also that the above formula for one dimension, \( d = \sqrt{(x_2 - x_1)^2} \) is equivalent to the distance measure developed for the one band tonal classification. Although the calculation of distance as presented above, known as Euclidean distance, may be intuitively the “best” measure, other distance measures have been applied in remote sensing data analysis.

While the minimum distance-to-means classifier is relatively straightforward, its reliance on mean values alone to characterize classes ignores the variance exhibited within the classes. For example, point 2 (Figure 7.5) would be classified as belonging to jack pine, the closest class mean, when, in fact, it “appears” to belong to the red pine class. The classification strategy is thus insensitive to differential variance exhibited by classes.
Geometric Derivation of Distance

Mean Value for a Specific Class $(BV_6, BV_5)$

Unknown Pixel $(BV_6, BV_5)$

$(X_2, Y_2)$

$(X_1, Y_1)$

$(X_2, Y_1)$

$X_2 - X_1$

$Y_2 - Y_1$

$d$

$x$

$y$

$(BV_6)$

$(BV_5)$

$7.6$
Statistically, the simplest measure of variability for a set of data values is the range. The minimum and maximum values (i.e. range) are obtained from the training set and are used to bound a category. Thus, a rectangular decision region, for each class, is defined by the class range (Figure 7.7). The decision is straightforward: assign an unknown pixel to the class decision region in which it occurs. By introducing a measure of variability, this strategy would now assign point 2 (Figure 7.7) to the red pine class. Note that point 1 is also classified as red pine and that point 3 lies in two decision regions. Overlapping decision regions commonly occur whenever classes display correlation between bands. Both hardwoods and red pine are highly correlated in band 5 and band 6, thus producing a positively slanted series of pixel observations. It can be seen that highly correlated categories are ill-defined by rectangular decisions regions. The more general situation for this classifier occurs whenever opposite sides of the class boundaries are parallel to each other, but not necessarily to the coordinate axis, producing parallelograms (Figure 7.8), or, for multi-dimensional data sets, parallelepipeds.

The Statistical Approach

Statistical decision theory, as opposed to the geometric techniques presented above, quantitatively account for both variance and correlation in the data set. With parametric techniques, the distribution of the various categories must be specified, with the most common assumption being that the data is normally (Gaussian) distributed. Probability density functions are used to compute the statistical probability that an unknown pixel belongs to a particular category. The decision rule is to assign the unknown pixel to the category with the highest probability. For the univariate case, the maximum likelihood classifier will function as illustrated in Figure 7.9. Note that point 3, from Figure 7.5, is closer to the mean for the hardwood class but has a higher probability of belonging to the more variable red pine class. The estimated probability density function for the univariate case (ie. considering only one band of data as in Figure 7.9) is:

$$p(x|c_i) = \frac{1}{(2\pi)^{1/2}S_i} \exp \left(-\frac{1}{2} \frac{(x - m_i)^2}{S_i^2}\right)$$

where:

- $p(x|c_i) =$ probability that $x$ is from class $i$
- $m_i =$ the mean BV for class $i$
- $S_i =$ the variance for class $i$
Parallelepiped Classification

7.7

Rectangular Decision Regions

Band 5 Brightness Value

Band 6 Brightness Value

Parallelepiped Classification

7.8

Parallelogram Decision Regions

Band 5 Brightness Value

Band 6 Brightness Value

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Probability Density Functions

p(3 | RP)  
p(3 | H)

22  31  36
Mean (Red Pine)  Point 3  Mean (Hardwood)

Hardwood
Red Pine

Band 5 BV

7.9
and the decision rule is: decide that \( x \) is from class \( i \) if and only if:

\[ p(x|c_i) \geq p(x|c_j) \text{ for all } j. \]

Note that each category is characterized entirely by its mean(s) and variance (-covariance).

Whenever two bands of data are analyzed, the bivariate probability density function is utilized to compute probabilities:

\[ p(x_1, x_2|c_i) = \frac{1}{2\pi (s_{11} s_{22} - s_{12}^2)^{1/2}} \]

where: \( m_{ij} \) = the mean BV in band \( j \) (for class \( i \));
\( s_{ij} \) = the variance in band \( j \) (for class \( i \));
\( s_{ijk} \) = the covariance between bands \( j \) and \( k \) (for class \( i \)).

The probability density function for two bands may be thought of as defining a series of points of equal probability about the mean (Figure 7.10). The center of a class is determined by the mean and shape by the covariance matrix, points of equal probability are therefore elliptical (hyperellipsoids for more than two bands). The maximum likelihood decision rule would classify points 2 and 3 as red pine and point 1 as hardwood (Figure 7.10). Probability density functions for more than two bands are presented in the section on matrix notation.

The formal derivation of the maximum likelihood decision rule is based upon the Bayesian principal to minimize the average loss over the entire classification process. The Bayesian technique is theoretically an optimum classifier which applies two additional weighting factors to a probability; an \( a \) priori probability of occurrence and a loss function. If, as is often the case, the \( a \) priori probabilities are unknown and assumed equal, and if the loss due to an incorrect classification is simply defined as being inversely proportional to the \( a \) priori probability, then the Bayes optimal strategy generalizes to the maximum likelihood classifier previously presented.

Matrix algebra provides a means for condensing large mathematical manipulations into a much smaller set of symbols. Vectors, matrices, and their manipulations (matrix algebra) are commonly used in multivariate statistical analysis. Therefore, many of the image classification techniques will be presented in matrix notation.
Maximum Likelihood Classification

Lines of Equal Probability

Band 5 Brightness Value

Band 6 Brightness Value
A Landsat scene is recorded on a computer-compatible tape as a Matrix L, composed of four-dimensional spectral vectors, \( P_{ij} \), which represent brightness values of individual pixels in four MSS bands:

\[
L = \begin{bmatrix}
P_{1,1} & \ldots & P_{1,3548} \\
\vdots & \ddots & \vdots \\
\vdots & & \vdots \\
P_{2983,1} & \ldots & P_{2983,3584}
\end{bmatrix}
\]

where \( L \) = Landsat MSS scene; and

\[
P_{ij} = \begin{bmatrix}
BV4_{ij} \\
BV5_{ij} \\
BV6_{ij} \\
BV7_{ij}
\end{bmatrix}
\]

where \( P_{ij} \) = four-dimensional vector corresponding to a single pixel and defined by the digital counts (or brightness values) in the four MSS bands.

Pixels located within a training site, \( x_c \), are used to estimate a mean spectral vector for a specific category:

\[
x_c = \begin{bmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{bmatrix}
\]

where

\[
x_i = [BV4_i, BV5_i, BV6_i, BV7_i]
\]

and \( n = \) sample size

The mean spectral vector, \( X_c \), of class \( c \), is defined as the arithmetic means, \( BV_c \), of the brightness values, in four bands, from the pixels within the training site:
The computation of the mean spectral vector is:

\[ \mathbf{X}_c = \frac{1}{n}(\mathbf{X}_c'1) \]

The variance-covariance matrix, \( S_c \), for a training site class is defined as follows:

\[
S_c = \begin{bmatrix}
\text{var}(BV4) & \text{cov}(BV4,BV5) & \text{cov}(BV4,BV6) & \text{cov}(BV4,BV7) \\
\text{cov}(BV5,BV4) & \text{var}(BV5) & \text{cov}(BV5,BV6) & \text{cov}(BV5,BV7) \\
\text{cov}(BV6,BV4) & \text{cov}(BV6,BV5) & \text{var}(BV6) & \text{cov}(BV6,BV7) \\
\text{cov}(BV7,BV4) & \text{cov}(BV7,BV5) & \text{cov}(BV7,BV6) & \text{var}(BV7)
\end{bmatrix}
\]

The computation of the variance-covariance matrix is:

\[
S_c = \frac{1}{n} \mathbf{X}_c' \mathbf{X}_c - \frac{1}{n}(\mathbf{X}_c'1)(1'\mathbf{X}_c)
\]

The probability density function, employed in the maximum likelihood classifier, for a particular class is:

\[
p(P_{ij}|C) = \frac{1}{(2\pi)^{n/2}|S_c|^{1/2}} \exp \left( - \frac{1}{2}(P_{ij} - \mathbf{X}_c)' S_c^{-1} (P_{ij} - \mathbf{X}_c) \right)
\]

where:
- \( p(P_{ij}|C) \) = probability of pixel \( P_{ij} \) belonging to class \( C \)
- \( n \) = dimension of vector, \( P_{ij} \) (4 in the case of Landsat MSS data)
- \( X_c \) = mean spectral vector for class \( C \)
- \( S_c \) = variance-covariance matrix for class \( C \)

3. Unsupervised Clustering

Most clustering algorithms involve two passes through the entire data set. During the first pass, clusters are created by an iterative process. The final cluster means, form the first pass, are then utilized to assign each pixel in the data set to a cluster based on quadratic distance.
Figure 7.11 is a diagrametic representation of the method used to create clusters during the first pass. Pixel values are read, one at a time, and assigned to an existing cluster or used to create a new cluster.

After the entire data set has been processed, cluster means are frozen. During the second pass, pixels are assigned to a cluster based on quadratic distance. If \( r > R \), the pixel is unclassified.

The following example utilizes data from the Wexford County test site (Table 7.5) to illustrate the assignment of individual pixels to specific clusters. Figure 7.12 is a plot of mean brightness values for the 27 clusters, while Table 7.6 lists the mean brightness values, by band, for each cluster. To classify pixel A, the quadratic distance between it and each cluster mean would be calculated as:

\[
d = \sqrt{(w_2 - w_1)^2 + (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}
\]

where:
- \( d \) = quadratic distance
- \( w, x, y, z \) = BVs in four bands
- \( _2 \) = unknown pixel
- \( _1 \) = cluster mean

The following values are obtained:

<table>
<thead>
<tr>
<th>cluster no.</th>
<th>( d )</th>
<th>cluster no.</th>
<th>( d )</th>
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<td>1</td>
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<tr>
<td>13</td>
<td>163.38</td>
<td>26</td>
<td>160.87</td>
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</table>
if \( r < r_{\text{max}} \), \( P \) is assigned to a current cluster using \( r_{\text{min}} \)

if \( r > r_{\text{max}} \)
  if \( C_n < C_N \), a new cluster is formed
  if \( C_n = C_N \)
    if \( C_{\text{small}} < C_{\text{min}} \), \( C_s \) is deleted and the new cluster replaces it
    if \( C_{\text{small}} \geq C_{\text{min}} \), the new pixel \( P \) is discarded

at merger \( M \), distance \( D \) between all cluster means are computed
if \( D < D_{\text{min}} \), the two clusters are merged systematically.
Digital Counts (Brightness Values)

Spectral Band

Non-Forest
Red Pine
Jack Pine
Red, Jack and Mixed Pines
Non-Forest with more than 25% Forest

Brightness Value Plot for 27 Clusters
Based on these measures of distance, pixel A would be classified as belonging to cluster number 22. Note also that pixel A is least like (maximum distance) cluster number 18, which is most like pixel B, jack pine.

Upon completion of assigning each pixel to a cluster the analyst must assign appropriate category labels to each cluster or group of clusters. This is usually accomplished by reference to supplemental data such as existing maps or aerial photography.
Table 7.5  Digital Data from the Wexford County test site

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<th>Band</th>
<th>Row</th>
<th>SNOW Pixels</th>
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<th>BOUNDARY B</th>
<th>JACK PINE B</th>
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Column  | 123 124 125 126 127 128 129 130 131 132 133 |
Table 7.6  Results of clustering Wexford County test data

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<td>6</td>
<td>33.44</td>
<td>85.09</td>
<td>40.58</td>
<td>92.16</td>
<td>126.95</td>
<td>21.08</td>
</tr>
<tr>
<td>7</td>
<td>30.26</td>
<td>66.24</td>
<td>34.98</td>
<td>70.74</td>
<td>97.21</td>
<td>22.10</td>
</tr>
<tr>
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<td>#21</td>
<td>#22</td>
<td>#23</td>
<td>#24</td>
</tr>
<tr>
<td>%</td>
<td>6.80</td>
<td>4.34</td>
<td>5.43</td>
<td>8.35</td>
<td>3.62</td>
<td>3.48</td>
</tr>
<tr>
<td>4</td>
<td>61.59</td>
<td>19.18</td>
<td>24.68</td>
<td>114.73</td>
<td>65.05</td>
<td>15.76</td>
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<tr>
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<td>72.91</td>
<td>17.68</td>
<td>23.35</td>
<td>126.97</td>
<td>77.00</td>
<td>12.79</td>
</tr>
<tr>
<td>6</td>
<td>72.88</td>
<td>32.59</td>
<td>36.17</td>
<td>126.33</td>
<td>74.49</td>
<td>24.50</td>
</tr>
<tr>
<td>7</td>
<td>58.13</td>
<td>34.99</td>
<td>36.00</td>
<td>92.27</td>
<td>58.49</td>
<td>26.58</td>
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<tr>
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<tr>
<td>4</td>
<td>15.90</td>
<td>31.90</td>
<td>37.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>12.79</td>
<td>30.00</td>
<td>41.04</td>
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<td></td>
</tr>
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<td>6</td>
<td>29.14</td>
<td>35.00</td>
<td>43.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>32.76</td>
<td>31.00</td>
<td>37.58</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Both researchers and potential users of remotely-sensed data require procedures to assess the accuracy of classifications derived from remote-sensing sources. This need has been recognized by the remote sensing community and has been addressed on numerous occasions, including a national working conference, "Landsat Classification Accuracy" (Mead and Szajgin, 1981, 1982).

A broad spectrum of statistical sampling techniques has been proposed to test mapping accuracies. Most assume that a contingency table (Figure 7.13) has been produced from a random sample of individual pixels or clusters compared to "known" cover conditions. Previously, classification accuracy was computed as the ratio of the sum of the diagonal elements to the total sum of elements (Figure 7.14). Although simple to compute, this technique has been shown to over-estimate the true accuracy of the classification. To compensate for this random inflation of accuracy, the Kappa Coefficient of Agreement has been suggested as a standard as a measure of classification accuracy (Figure 7.15). The kappa or KHAT index will range from 0, no reduction in error, to 1, complete reduction of error, compared to the error from a completely random classifier (Figure 7.16). Several small computer programs have been written to allow for the ease of computing the Kappa statistic.

For research purposes, complete enumeration of the test population, to facilitate a pixel-by-pixel comparison, has also been proposed. The use of complete enumeration, in the form of photo-interpreted cover-type maps, to evaluate the accuracy of Landsat classifications were compared with assessments made directly from the aerial photography. A computerized, geographic information system was utilized to compare the Landsat classifications with the cover-type maps on a pixel-by-pixel basis. Error maps of pixels which were similarly mis-classified by a variety of algorithms contained a larger number of errors than were verified from the aerial photography. For two test sites, only 67 and 52 percent of the pixels which were originally considered to be in error were substantiated as being in error. Discrepancies between the two results were determined to be primarily caused by definitional differences between the cover-type maps and the Landsat classifications, especially with regard to minimum-type size. Since Landsat classifications are typically compared with existing cover-type maps in an effort to replace photo-interpretation techniques or to provide an updating procedure, managers should be aware of the basic differences and limitations associated with these direct comparisons.
### Confusion Table Format

#### LANDSAT CLASSIFICATION

<table>
<thead>
<tr>
<th>COVER TYPE (Map)</th>
<th>Red 1 Pine</th>
<th>Jack Pine</th>
<th>Pine Mixtures</th>
<th>Swamp Conifers</th>
<th>Other 3</th>
<th>Total 5</th>
<th>Percent Correct 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Pine 2</td>
<td>[ ] 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jack Pine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pine Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swamp Conifers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total 6</strong></td>
<td>[ ] 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Percent Correct 9</strong></td>
<td>[ ] 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 - columns correspond to classes, as determined from the Landsat classification, and show which cover type classes they actually represent.

2 - rows correspond to classes, as determined from the cover type map, and show into which Landsat classes it was placed.

3 - includes hardwoods and all non-forest categories.

4 - values along the diagonal represent correctly classified pixels.

5 - the total count for a class from the cover type map.

6 - the total number of pixels for a particular Landsat class.

7 - the total number of pixels for the entire sample.

8 - the accuracy for a single class, considering omission errors only, ratio of the number of correct classifications for that row to the row total (expressed as a percent).

9 - the accuracy for a single class, considering commission errors only, ratio of the number of correct classifications for that column to the column total (expressed as a percent).

10 - overall classification accuracy, ratio of the sum of diagonal values to the total number of sample points (expressed as a percent).
## Landsat Classification Performance

<table>
<thead>
<tr>
<th>TYPE MAP</th>
<th>Red Pine</th>
<th>Jack Pine</th>
<th>Pine Mixes</th>
<th>Hardwoods</th>
<th>Grass</th>
<th>Water</th>
<th>Other</th>
<th>Total</th>
<th>Percent Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. Pine</td>
<td>66</td>
<td>21</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>103</td>
<td>64.1</td>
</tr>
<tr>
<td>J. Pine</td>
<td>2</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>26</td>
<td>84.6</td>
</tr>
<tr>
<td>Mixtures</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>14</td>
<td>35.7</td>
</tr>
<tr>
<td>Hwds.</td>
<td>1</td>
<td>8</td>
<td>0</td>
<td>166</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>176</td>
<td>94.3</td>
</tr>
<tr>
<td>Grass</td>
<td>1</td>
<td>13</td>
<td>21</td>
<td>7</td>
<td>61</td>
<td>0</td>
<td>5</td>
<td>108</td>
<td>56.5</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>29</td>
<td>0</td>
<td></td>
<td>29</td>
<td>100</td>
</tr>
<tr>
<td>Other</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>16</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>75</td>
<td>64</td>
<td>26</td>
<td>186</td>
<td>69</td>
<td>30</td>
<td>25</td>
<td>475</td>
<td></td>
</tr>
<tr>
<td><strong>Percent Correct</strong></td>
<td><strong>88.0</strong></td>
<td><strong>34.4</strong></td>
<td><strong>19.2</strong></td>
<td><strong>89.2</strong></td>
<td><strong>88.4</strong></td>
<td><strong>96.7</strong></td>
<td><strong>64.0</strong></td>
<td></td>
<td><strong>76.8</strong></td>
</tr>
</tbody>
</table>
Kappa Coefficient of Agreement

\[ \hat{K} = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} x_{i+} x_{+i}}{N^2 - \sum_{i=1}^{r} x_{i+} x_{+i}} \]

Where + represents summation over the index.

For computational purposes, the following form is often used:

\[ \hat{K} = \frac{\theta_1 - \theta_2}{1 - \theta_2} \]

where \( \theta_1 = \sum_{i=1}^{r} \frac{x_{ii}}{N} \) and \( \theta_2 = \sum_{i=1}^{r} \frac{x_{i+} x_{+i}}{N^2} \)
### Summary of Landsat Classification Performance

#### Wexford County test site

<table>
<thead>
<tr>
<th>Rank</th>
<th>Classification scheme</th>
<th>Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>April, visual interpretation</td>
<td>0.744</td>
</tr>
<tr>
<td>2</td>
<td>June, maximum likelihood</td>
<td>0.700</td>
</tr>
<tr>
<td>3</td>
<td>February, minimum distance</td>
<td>0.686</td>
</tr>
<tr>
<td>4</td>
<td>February, maximum likelihood</td>
<td>0.682</td>
</tr>
<tr>
<td>5</td>
<td>February, unsupervised clustering</td>
<td>0.678</td>
</tr>
</tbody>
</table>

#### Crawford County test site

<table>
<thead>
<tr>
<th>Rank</th>
<th>Classification scheme</th>
<th>Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>June, maximum likelihood</td>
<td>0.623</td>
</tr>
<tr>
<td>2</td>
<td>February, maximum likelihood</td>
<td>0.563</td>
</tr>
<tr>
<td>3</td>
<td>February, minimum distance</td>
<td>0.562</td>
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<tr>
<td>4</td>
<td>February, unsupervised clustering</td>
<td>0.561</td>
</tr>
<tr>
<td>5</td>
<td>April, visual interpretation</td>
<td>0.549</td>
</tr>
</tbody>
</table>
absolute altitude—Altitude above the actual surface of a planet or natural satellite, either land or water.

absolute orientation—The scaling, leveling, and orientation to ground control (in a photogrammetric instrument) of a relatively oriented stereoscopic model or group of models.

absorbed light—Light rays that are neither reflected nor transmitted when directed toward opaque or transparent materials.

absorption—The thermodynamically irreversible transformation of radiant energy into heat.

absorption band—A range of wavelengths (or frequencies) in the electromagnetic spectrum within which radiant energy is absorbed by a substance.

accommodation—The faculty of the human eye to adjust itself to give sharp images for different object distances. The ability of the eyes to bring two images into superimposition for stereoscopic viewing.

accuracy—The closeness of results of observations, computations, or estimates to the true values or to values which are accepted as being true.

achromatic—Devoid of hue, or transmitting light without showing its constituent colors.

actinic light—A part of the spectrum that causes chemical changes to take place in light sensitive photographic emulsions. The light that creates images on light sensitive material.

active—Denotes a source of radiation external to the surface or object.

active microwave—A system or a sensor that provides its own source of EMR in the microwave region (1mm to 1m), to detect and/or locate objects, measure altitude and to acquire imagery of the terrain. Examples are synthetic and real aperture radar, radar scatterometer and radar altimeter.

active system—A system having its own source of EMR as, for example, a radar.

acuity, visual—A measure of the human eye’s ability to separate details in viewing an object.

acutance—An objective measure of the ability of a photographic system to show a sharp edge between contiguous areas of low and high illuminance.

adaptation—The faculty of the human eye to adjust its sensitivity to varying intensities of illumination.
additive color process—a method for creating essentially all colors through the addition of light of the 3 additive color primaries (blue, green, and red) in various proportions.

adjustment—the determination and application of corrections to observations, for the purpose of reducing errors or removing internal inconsistencies in derived results.

aerial—of or pertaining to operations in or from the air or atmosphere.

aerial camera—a camera specially designed for aerial use.

aerial film—a specially designed roll film supplied in many lengths and widths to fit aerial cameras.

aerial photograph—any photograph taken from the air. sometimes called aerial photo or air photograph.

aerial photograph, oblique—a photograph taken with the camera axis directed between the horizontal and the vertical. high oblique—an oblique photograph in which the apparent horizon is shown. low oblique—an oblique photograph in which the horizon is not shown.

aerial photograph, vertical—an aerial photograph made with the optical axis of the camera approximately perpendicular to the earth’s surface and with the film as nearly horizontal as is practicable.

aerial photographs, composite—air photographs made with a camera having one principal lens and two or more surrounding and oblique lenses symmetrically placed. the several resulting photographs may be rectified in printing to permit assembly as verticals with the same scale.

aerial photographs, overlapping—two or more aerial photographs to which a portion of the total area projected thereon is common. such photographs are used for stereoscopic studies and for making mosaics.

aerial photography—the art, science, or process of taking aerial photographs.

aerial reconnaissance—the securing of information by aerial photography or by visual observation from the air.

aerial survey—a survey using aerial photographs as part of the surveying operation; also, the taking of aerial photographs for surveying purposes.

aerospace—of or pertaining to both the earth’s atmosphere and space.

air base—an imaginary line connecting the points in space at which successive photos in a flight strip were taken; specifically, the length of such a line.

airborne (device)—any device transported by an aircraft.

air speed—the speed of an aircraft relative to the surrounding atmosphere.
algorithm—A statement of the steps to be followed in the solution of a problem. An algorithm may be in the form of a word description, an explanatory note, or a labeled diagram or flowchart. It usually refers to the coded instructions used by a computer to complete some operation.

altimeter—An instrument which indicates the vertical distance above a specified datum plane; when unmodified, usually means an aneroid barometer which utilizes relative pressure of the atmosphere.

altitude—Height above a datum; the datum is usually mean sea level.

altitude, absolute—Height above the surface of the Earth as distinguished from altitude, height above sea level. It is sometimes referred to as radar or radio altitude.

analytical phototriangulation—A phototriangulation procedure in which the spatial solution is obtained by computational routines. When performed with aerial photographs, the procedure is referred to as analytical aerotriangulation.

angle of drift—The angular difference between the true heading of an aircraft and its ground track.

angle of field—A property of a lens. The angle subtended by lines that pass through the center of the lens and locate the diameter of the maximum image area within the specified definition of the lens. Also called angular field.

angle of incidence—The angle at which EMR strikes a surface as measured from the normal to the surface at the point of incidence (limits 0 to 90 degrees).

angle of reflection—The angle which EMR reflected from a surface makes that is perpendicular (normal) to the surface.

angle of refraction—The angle made by the refracted ray with the incident ray when a ray of light passes through a transparent substance. The refracted ray is bent at an angle from the line of the incident ray.

angle of sun.—The angle of the sun above the horizon. Not only the quantity of light (lumens) being reflected to the aerial camera, but also the spectral quality of the light are influenced by sun-angle. Also called sun elevation, sun elevation angle.

angstrom (Å)—Unit of linear measurement equal to $10^{-10}$ m. In SI = 0.1 nanometers.

annotated photograph—A photograph on which planimetric, hypsographic, geologic, cultural, hydrographic, or vegetation information has been added to identify, classify, outline, clarify, or describe features that would not otherwise be apparent in examination of an unmarked photograph.

annotation—Any marking on illustrative material for the purpose of clarification, such as numbers, letters, symbols, and signs.
annual (thermal) wave—Annual cycle of heating and cooling of the upper 3-5m of soils, in response to the yearly progression of the seasons. Below this point, constant annual temperatures, at any given depth, may be observed. See diurnal wave.

antenna—The device that radiates EMR from a transmitter and receives EMR from other antennae or other sources.

aperture—The opening in a lens diaphragm through which light passes.

apparent horizon—In general, the apparent or visible junction of earth and sky, as seen from any specific position. Also called the apparent, visible, or local horizon.

astigmatism—An aberration affecting the sharpness of images for objects off the axis in which rays passing through different meridians of the lens come to a focus in different planes. Thus, an extra-axial point object is imaged as two mutually perpendicular short lines located at different distances from the lens.

attitude—The angular orientation of a camera, or of the photograph taken with that camera, with respect to some external reference system. The angular orientation of an aerial or space vehicle with respect to a reference system.

axis, optical—In a lens element, the straight line which passes through the centers of curvature of lens surfaces. Also called principal axis. In an optical system, the line formed by the coinciding principal axes of the series of optical elements.

axis of tilt—The line along which a tilted photo intersects the plane of an imaginary vertical photo taken with the same camera from the same point, and along which the tilted photo has the same scale as would the vertical photo.

azimuth—The direction of a line given as an angle measured clockwise from a reference direction, usually north. Direction at right angles to the antenna beam. In side-looking radar, the direction parallel to ground track.

band—A selection or range of wavelengths or frequencies.

bar scale—A graduated line on a map, plan, photograph, or mosaic, by means of which actual ground distances may be determined. Also called graphic scale.

base direction—The direction of the vertical plane containing the air base, which might be expressed as bearing or an azimuth.

base, photo—The distance between the principal points of two adjacent prints of a series of vertical aerial photographs.

bayonet mount—A device used to facilitate changing camera parts. Each part has prongs that fits into the mount and locks them into place.

bearing—Direction of a line measured as an acute angle from a reference meridian.
**benchmark**—A standard reference location or value used for calibration purposes. A point used in surveying or mapping, usually giving altitude (elevation above mean sea level or some other reference).

**blackbody**—An ideal emitter which radiates energy at the maximum possible rate per unit area at each wavelength for any given temperature.

**blackbody radiation**—The electromagnetic radiation emitted by an ideal black body; it is the theoretical maximum amount of radiant energy of all wavelengths which can be emitted by an object at a given temperature.

**blow-up**—Photographic slang meaning to enlarge or an enlargement.

**bolometer**—An instrument that measures the intensity of radiant energy by employing a thermally sensitive electrical resistor.

**boresight camera**—A camera mounted with its optical axis parallel to the axis of a sensor, such as an infrared spectrometer or radar, to photograph the area being sensed, thus providing location data.

**brightness**—The attribute of visual perception in accordance with which an area appears to emit more or less light.

**brightness range**—The ratio of the apparent brightness of highlights to the deepest shadow in the actual scene as measured from the camera station.

**brilliance**—The degree of intensity of a color.

**cadastral map**—A map showing the boundaries of subdivisions of land, usually with the bearings and lengths thereof and the areas of individual tracts, for purposes of describing and recording ownership. A cadastral map may also show culture, drainage, and other features relating to the value and use of land.

**cadastral survey**—A survey relating to land boundaries and subdivisions, made to create units suitable for transfer or to define the limitations of title.

**calibrated focal length**—The act or process of determining certain specific measurements in a camera or other instrument or device by a comparison with a standard, for use in correcting or compensating errors or for purposes of record.

**calibration**—The act or process of comparing certain specific measurements in an instrument with a standard.

**camera**—A lightproof chamber or box in which the image of an exterior object is projected upon a sensitized plate or film, through an opening usually equipped with a lens or lenses, shutter, and variable aperture.

**camera, aerial**—A camera specially designed for aerial use.
camera axis—In a single-lens camera, the photography perpendicular. In a multiple-lens camera, the photography perpendicular of the central perspective unit or the photography perpendicular of the transformed photograph.

camera calibration—The determination of the calibrated focal length, the location of the principal point with respect to the fiducial marks, the point of symmetry, the resolution of the lens, the degree of flatness of the focal plane, and the lens distortion effective in the focal plane of the camera and referred to the particular calibrated focal length.

camera, continuous-strip—A camera in which a continuous-strip exposure is made by rolling the film continuously past a narrow slit opening at a speed of the aircraft.

camera, ground—A camera designed for terrestrial use. Also called terrestrial camera.

camera magazine—The removable part of a camera in which the unexposed and exposed portions of film are contained.

camera, mapping—A camera specially designed for the production of photographs to be used in surveying. The prefixes mapping and surveying indicate that a camera is equipped with means for maintaining and indicating the interior orientation of the photographs with sufficient accuracy for surveying purposes. A mapping camera may be either an aerial mapping camera or a terrestrial mapping camera.

camera, metric—A specially constructed and calibrated camera used to obtain geometrically accurate photographs for use in photogrammetric instruments.

camera, multiband—A camera that exposes different areas of one film or more than one film, through one lens and a beam splitter, or two or more lenses equipped with different filters, to provide two or more photographs in different spectral bands.

camera, multiple-assembly—An assembly of two or more cameras mounted so as to maintain a fixed angle between their respective optical axes.

camera, multiple-lens—A camera with two or more lenses, the axes of the lenses being systematically arranged at a fixed angle to cover a wide field by simultaneous exposures in all chambers. In most such cameras the oblique lenses are arranged symmetrically around a central lens.

camera, panoramic—A camera with a very wide angle of view, up to horizon to horizon, usually equipped with a moving (sweeping) lens.

camera, photogrammetric—A general term applicable to cameras used in any of the several branches of photogrammetry.

camera port—The opening in the body or hull of a remote sensor platform through which the camera is operated.
camera, stereometric—A combination of two cameras mounted with parallel optical axes on a short, rigid base; used in terrestrial photogrammetry for taking photographs in stereoscopic pairs.

camera, surveying—A camera specifically designed for obtaining photographs to be used in surveying. The camera is equipped with a mechanism to maintain and to indicate the interior orientation of the photographs with sufficient accuracy for surveying purposes.

camera, terrestrial—A camera designed for use on the ground.

camera, trimetrogon—An assembly of three cameras equipped with wide-angle Metrogon lenses, in which one of the cameras is vertical and the other two are 60-degree obliques.

Cartesian coordinates—A coordinate system in which the locations of points in space are expressed by reference to three planes, called coordinate planes, no two of which are parallel.

cartography—Map and chart construction.

cartridge, film—A light-tight container which must be loaded with film in the dark but may be placed in the camera during daylight or under artificial light.

cassette—A container for roll film which may be loaded in the darkroom and used subsequently for daylight loading of the camera. A container to hold magnetic tape.

ceiling—The height above the earth’s surface of the lowest layer of clouds or obstruction phenomena that is reported as broken, overcast, or obscuration and not classified as thin or partial. The maximum altitude at which an aircraft can fly.

cell, photoelectric—A device by which light is transformed into electrical energy. It can be used to activate a camera shutter or other device, or to measure the intensity of light.

center line—A line drawn from the center point of a vertical photo through the transposed center point from an overlapping photo.

center, photograph—The center of a photograph as indicated by the images of the fiducial marks of the camera. In a perfectly adjusted camera the photograph center and the principal point are identical.

center point—The point at the exact center of a photo, corresponding in position to the optical axis of the camera; it is sometimes referred to as the optical center, or principal point.

change detection—a process of comparing two or more images to determine differences.

chart—a map specifically designed for use in navigation.

chroma—the color dimension on the Munsell scales that correlates most closely with saturation.

classification—the process of assigning individual pixels to categories on the basis of spectral-reflectance characteristics.
closure or closing error—The amount by which a quantity obtained by a series of related measurements differs from the true or fixed value of the same quantity.

cluster—A homogenous group of units which vary “like” one another. “Likeness” is usually determined by the association, similarity, or distance among the measurement patterns associated with the units.

cluster analysis—Statistical analysis of observed units or values to show the likely groupings for unsupervised classification or to indicate confidence for supervised classification.

coated lens—A lens whose air-glass surfaces have been coated with a transparent film of such thickness and index of refraction as to minimize the light loss due to reflection.

color—That property of an object which is dependent on the wavelength of the light it reflects or, in the case of a luminescent body, the wavelength of light that it emits. White light is a balanced mixture of all the visible spectral colors.

color balance—The proper intensities of colors in a color print, positive transparency, or negative, that give a correct reproduction of the gray scale.

color composite—A color picture produced by assigning one of the primary colors to each of three spectral band images.

color infrared (film)—A three layer color film sensitized to green, red and near-infrared. Conventional color film is sensitive to blue, green and red.

color photography—Photography in which either the direct-positive or the negative-positive color process is used.

color sensitivity—The sensitivity of a photographic emulsion to light of various wavelengths.

compilation—The production of a new map from existing maps, aerial photographs, surveys, new data, or other sources.

composite photograph—A photograph made by assembling the separate photographs, made by the several lenses of a multiple-lens camera in simultaneous exposure, into the equivalent of a photograph taken with a single wide-angle lens.

computer compatible tape (CCT)—The magnetic tape upon which the digital data from multispectral scanner images are recorded.

contact print—A print made from a negative or a diapositive in direct contact with sensitized material.

contact size—A print, either positive or negative, of the same size as the negative or positive from which it was made.

contour—On land, an imaginary line on a surface connecting points of equal elevation; also, the line representing this feature on a map or chart (properly called contour line).
**contour interval**—The difference in elevation between adjacent contours.

**contrast**—The difference between highlights and shadows. The ratio of reflecting power between the highlights and shadows of a print determines the contrast.

**contrast filter**—A color filter so chosen as to make a colored subject stand out very sharply from surrounding objects.

**contrast stretching**—The process of increasing the contrast of images by digital or optical processing.

**control**—A system of points with established positions or elevations, or both, which are used as fixed references in positioning and correlating map features. Control is generally classified in four orders (with first order denoting highest quality) according to the precision of the methods and instruments used in establishing it, and the accuracy of the resultant positions and elevations. Often called basic control.

**control, geodetic**—Control which takes into account the size and shape of the earth; implies a reference spheroid representing the geoid and horizontal—and vertical-control datums.

**control, ground**—Control obtained by ground surveys as distinguished from control obtained by photogrammetric methods; may be for horizontal or vertical control, or both. Ground (in-situ) observations to aid in interpretation of remote sensor data.

**control, horizontal**—Control with horizontal positions only. The positions may be referred to the geographic parallels and meridians or to other lines of reference, such as plane coordinate axes.

**control, photogrammetric**—Control, established by photogrammetric methods as distinguished from control established by ground methods. Also called minor control.

**control point**—Any station in a horizontal and/or vertical control system that is identified on a photograph and used for correlating the data shown on that photograph.

**control strip**—A strip of aerial photographs taken to aid planning and accomplishing later aerial photography, or to serve as control in assembling other strips. A strip of film used for control of exposure, development, or both.

**control, vertical**—Control with elevations only; usually referred to mean sea level.

**convergence of evidence**—The bringing together of several types of information in order that a conclusion may be drawn in the light of all available data. In remote sensing, often implies increase in scale to obtain more information about a smaller area.

**coordinate systems, State plane**—A series of grid coordinate systems prepared by the U.S. Coast and Geodetic Survey for the entire United States, with a separate system for each State. Each State system consists of one or more zones. The grid coordinates for each zone are based on, and mathematically adjusted to, a map projection. The Lambert conformal conic projection with two standard parallels is used for zones of predominant east-west extent and
limited north-south extent. The transverse Mercator projection is used for zones of predominant north-south extent and limited east-west extent.

**coordinates**—Linear or angular quantities which designate the position of a point in a given reference or grid system.

**coordinate, geographic**—A system of spherical coordinates for describing the positions of points on the earth. The declinations and polar bearings in this system are the latitudes and longitudes respectively.

**coordinates, grid**—A plane-rectangular coordinate system based on and mathematically adjusted to a map projection in order that geographic positions (latitudes and longitudes) may be readily transformed into plane coordinates and the computations relating to them made by the ordinary methods of plane surveying.

**coordinates, photograph**—A system of coordinates, either rectangular or polar, describing the position of a point on a photograph.

**coordinates, plane-rectangular**—A system of coordinates in a horizontal plane, used to describe the positions of points with respect to an arbitrary origin by means of two distances perpendicular to each other. A plane-rectangular coordinate system is used in mapping areas so small that the errors introduced by substituting a plane for the curved surface of the earth will be within the required accuracy.

**coordinates, space**—A three-dimensional system of rectangular coordinates in which the x- and y-coordinates lie in a reference plane tangent to the earth at a selected point and the z-coordinate is perpendicular to that plane. Used in the extension of horizontal and vertical control through a series of overlapping vertical photographs from an initial point of tangency of the reference plane. The use of the term “space coordinates,” should be strictly limited to a three-dimensional rectangular coordinate system which has not been adjusted to the vertical and horizontal control data.

**coordinates, spherical**—A system of polar coordinates in which the origin is the center of a sphere and the points all lie on the surface sphere. The polar axis of such a system cuts the sphere at its two poles. In photogrammetry, spherical coordinates are useful in defining the relative orientation of perspective rays or axes and make it possible to state and solve, in simple forms, many related problems.

**corresponding images**—A point or line in one system of points or lines homologous to a point or line in another system. Corresponding image points (sometimes incorrectly called conjugate points) are the images of the same object point on two or more photographs.

**course**—The direction in which a pilot attempts to fly an aircraft; the line drawn on a chart or map as the intended track. The direction of a course is always measured in degrees from the true meridian, and the true course is always meant unless it is otherwise qualified (e.g., as a magnetic or compass course).

**coverage**—The ground area represented on aerial photographs, photomosaics or maps.
coverage, stereoscopic—Aerial photographs taken with sufficient overlap to permit complete stereoscopic examination.

crab—The condition caused by failure to orient the camera so that the axis perpendicular to the long dimension of the film is parallel to the track of the airplane. This is indicated in vertical photography by the sides of the photographs not being parallel to the principal-point base line. Any turning of an airplane which causes its longitudinal axis to vary from the track of the plane.

crop—to trim or cut off parts of the picture. Usually accomplished by masking the image area during printing.

crown closure—A photo measure or estimate of the density of a forest stand. As seen on the vertical photograph, crown closure is the percentage of ground are occupied by tree crowns.

crown diameter, visible—The apparent diameter of a tree crown image on a vertical aerial photograph.

culture—a term applied to all the works of humans that are shown on a map.

data—the plural of datum. Numerical or quantitative notations.

data collection (device)—Any device designed for the collection of usually digital data.

datum—Any numerical or geometrical quantity or set of such quantities that can serve as a reference or a base for measurement of other quantities. For a group of statistical references, the plural form is data; as geographic data for a list of latitudes and longitudes. Refers to a direction, level, or position from which angles, heights, depths, speeds, or distances are conventionally measured.

datum, horizontal-control—The position on the spheroid of reference assigned to the horizontal control (triangulation and traverse) of an area and defined by (1) the position (latitude and longitude) of one selected station in the area, and (2) the azimuth from the selected station to an adjoining station. The horizontal-control datum may extend over a continent or be limited to a small area. A datum for a small area is usually called local datum and is given a proper name.

datum, horizontal plane—a plane perpendicular to the direction of gravity; any plane tangent to the geoid or parallel to such a plane.

datum, vertical-control—Any level surface (as, for example, mean sea level) taken as a surface of reference from which to reckon elevations; also called the datum level. Although a level surface is not a plane, the vertical-control datum is frequently referred to as the datum plane.

definition—the degree of sharpness, that is, distinctness of small detail in the picture image, negative, or print.
delineation—The visual selection and distinguishing of mapworthy features on various possible source materials by outlining the features on the source material, or on a map manuscript (as when operating a stereoscopic plotting instrument); also, a preliminary step in compilation. The delineation of features on a photograph.

density slicing—The process of converting the continuous gray tone of an image into a series of density intervals, or slices, each corresponding to a specific digital range.

details (mapping)—The small items or particulars of information (shown on a map by lines, symbols, and lettering) which, when considered as a whole, furnish the comprehensive representation of the physical and cultural features of the earth’s surface. The greater the omission of details, the more generalized the map.

develop—To subject to the action of chemical agents for the purpose of bringing to view the invisible or latent image produced by the action of light on a sensitized surface; also, to produce or render visible in this way.

diaphragm—The physical element of an optical system which regulates the quantity of light traversing the system. The quantity of light determines the brightness of the image without affecting the size of the image.

diapositive—A positive image on a transparent medium such as glass or film; a transparency. The term originally was used primarily for a transparent positive on a glass plate used in a plotting instrument, a projector, or a comparator, but now is frequently used for any positive transparency.

diazo—Refers to a series of UV sensitive salts which when processed in ammonia vapors yield a specific dye in inverse proportion to the amount of UV exposure. A positive reproduction of a black-and-white transparency is produced when exposed in contact with a diazo film where the diazo film is exposed in direct proportion to the transparency of the black-and-white film.

digital data—Of or relating to data in the form of numerical digits; a readout in numerical digits; data displayed, recorded, or stored in binary notation.

digitize—to use numeric values to represent data.

digitization—the process of converting an image recorded originally on photographic material into numeric format.

direct positive—the positive image obtained by exposure in the camera with subsequent chemical treatment to develop and “reverse” the tones of the image.

displacement—Any shift in the position of an image on a photograph which does not alter the perspective characteristics of the photograph (i.e., shift due to tilt of the photograph, scale change in the photograph, and relief of the objects photographed).

display—the graphic presentation of the output data of a device or system as, for example, on a radar scope. The cathode ray tube is a widely used display device for the output of “electronic” sensors.
diurnal (thermal) wave—The daily temperature rise of surficial materials under the heating of the sun. In soils, this thermal change is restricted to about the first 30 cm; below this point relatively constant daily temperatures exist at any given depth. See annual wave.

drift—The horizontal displacement of an aircraft, caused by the force of wind, from the track it would have followed in still air. Sometimes used to indicate a special condition of crab wherein the photographer has continued to make exposures oriented to the predetermined line of flight while the airplane has drifted from that line.

electromagnetic energy—see electromagnetic radiation, the preferred term.

electromagnetic radiation (EMR)—Energy propagated through space or through material media in the form of advancing oscillations of in-phase, plane-polarized electric and magnetic fields. The term radiation, alone, is used commonly for this type of energy, although it actually has a broader meaning. Also called electromagnetic energy.

electromagnetic spectrum—The ordered array of known electromagnetic radiations extending from the shortest cosmic ray, through gamma rays and X-rays, across ultraviolet, visible, infrared and microwave radiation, and extending into the wavelengths of radio energy.

elevation—Vertical distance from the datum, usually mean sea level, to a point or object on the earth’s surface. Not to be confused with altitude, which refers to points or objects above the earth’s surface.

emissivity—The ability of a material, in comparison to that of a blackbody, to emit radiant energy. It is the ratio of the exitance of a real object at some temperature divided by the exitance of a theoretical blackbody at the same temperature.

emittance—the obsolete term for the radiant flux per unit area emitted by an object. See exitance, the preferred term.

emulsion—A suspension of a light-sensitive silver salt (especially silver chloride or silver bromide) in a colloidal medium (usually gelatin), which is used for coating photographic films, plates, and papers.

end lap—The overlap of aerial or space photographs or images along (foreward) the flightline or track of the platform.

enhancement, image—The process of altering the appearance of an image for the purpose of extraction of additional information. It may be accomplished by digital or photographic (optical) methods.

environment—The complex of physical, chemical and biotic factors that act upon an organism or an ecological community. An external condition or the sum of such conditions, in which a piece of equipment or a system operates (e.g. temperature environment). These environments are usually typified by a range of values, and may be either natural or artificial.
**equator**—In a system of polar or spherical coordinates, the great circle of a sphere which is perpendicular to the polar axis.

**exitance**—The radiant flux per unit area ($\text{Wm}^{-2}$) emitted by an object. Replaces the obsolete term **emittance**.

**exposure**—The total quantity of light received per unit area on a sensitized plate or film; may be expressed as the product of the light intensity and the exposure time, in units of (for example) meter-candle-seconds or watts per square meter. The act of exposing a light-sensitive material to a light source.

**exposure interval**—The time interval between the taking of successive photographs.

**exposure time**—The time during which a light-sensitive material is subjected to the action of light.

**eyepiece**—In an optical device, the lens group which is nearest the eye and with which the image formed by the preceding elements is viewed.

**f-number**—A representation of the speed of a lens, defined by focal length divided by diameter.

**factor, filter**—The amount that film exposure must be increased to off-set the reduction in light resulting from the use of a filter. A filter absorbs part of the light passing through it; therefore, less light reaches the film. The lens diaphragm must be opened wider or the shutter longer for correct exposure of the film. A filter factor of 2 means that the normal exposure must be double.

**false-color, image**—A color image in which the dye color is not the same as scene color. Infrared Ektachrome film produces false color images since the infrared exposure is represented as red, the red exposure as green, and the green exposure as blue.

**far infrared**—A term for the longer wavelengths of the infrared region, from 15 $\mu$m to 1 mm, the generally accepted shorter wavelength limit of the microwave part of the EM spectrum. This spectral region is severely limited in remote sensing because the atmosphere transmits very little radiation between 15 $\mu$m and the millimeter regions.

**fiducial marks**—Index marks (usually 4), rigidly connected with the camera lens through the camera body, which form images on the negative. The marks are adjusted so that the intersection of lines drawn between opposite fiducial marks define the principal point.

**field-of-view**—The solid angle through which an instrument is sensitive to radiation. Due to various effects, diffraction, etc., the edges are not sharp. In practice they are defined as the “half-power” points, i.e., the angle outwards from the optical axis, at which the energy sensed by the radiometer drops to half its on-axis value.

**film**—The sensitized material and its base, which is exposed in a camera.
**film cassette**—A reloadable film container, usually used for perforated roll film, which may be installed in or removed from the camera magazine in daylight or under artificial illumination.

**film speed**—That property of film which determines how much exposure must be allowed for a given light source in order to secure a negative of correct density and contrast.

**filter**—Any material which, by absorption or reflection, selectively modifies the radiation transmitted through an optical system. Such a filter may operate by polarization, scattering, etc., and may also be electronic. The filter usually is interposed between the film and the scene being photographed, but it may form part of the film itself.

**filter factor**—A number indicating the exposure increase necessary when using a filter, as compared to the exposure necessary under the same conditions without the filter.

**filtering**—The decomposition of a signal into its harmonic components. The separation of a wanted component of a time series from any unwanted residue (noise).

**fix**—To render a developed photographic image permanent by removing the unaffected light-sensitive material. To establish the position of a point of observation by a surveying procedure. Also, the point thus established.

**flatness**—Lack of contrast in print or negative, generally due to flat, even lighting, overexposure, or incorrect concentration of developer.

**flicker method**—The alternate projection of corresponding photographic images onto a tracing-table, platen or projection screen, or into the optical train of a photogrammetric instrument.

**flight altitude**—The vertical distance above a given datum, usually mean sea level, of an aircraft in flight or during a specified portion of a flight. In aerial photography, when the datum is mean ground level of the area being photographed, this distance is called flight height or sometimes absolute altitude.

**flight attitude**—The spatial orientation of an aircraft, rocket, satellite, spacecraft, or other vehicle in flight.

**flight characteristics**—A characteristic exhibited by an aircraft, rocket, spacecraft, or other vehicle during flight, such as a tendency to stall or yaw, an ability to remain stable at certain speeds.

**flight (flightline) map**—The map on which are indicated the desired lines of flight and/or the positions of exposure stations previous to the taking of air photographs, or the map on which are plotted, after photography, selected air stations and the groundtracks joining them.

**flight strip**—A succession of overlapping aerial photographs taken along a single course.

**flightpath**—The path made or followed in the air or in space by an aircraft, rocket, etc.; the continuous series of positions occupied by a flying body; more strictly, the path of the center of gravity of the flying body, referred to the Earth or other fixed reference.
floating mark—A mark seen as occupying a position in the three-dimensional space formed by the stereoscopic fusion of a pair of photographs and used as a reference mark in examining or measuring the stereoscopic model. Index mark—A real mark (such as a cross or dot) lying in the plane or the object space of a photograph and used singly as a reference mark in certain types of monocular instruments, or as one of a pair to form a floating mark.

focal length—The distance measured along the optical axis from the optical center of the lens to the plane of critical focus of a very distant object.

focal length-calibrated—An adjusted value of the equivalent focal length, computed to equalize the positive and negative values of distortion over the entire field used in the aerial camera. Also stated as the distance along the lens axis from the interior perspective center to the image plane; the interior center of the perspective being selected so as to equalize the positive and negative values of lens distortion over the field. The calibrated focal length is used when determining the setting of diapositives in plotting instruments and in photogrammetric computations based on linear measurements on the negative, such as those made with a precision comparator.

focal length, equivalent—Same as focal length but measured to the plane of best average definition throughout the angular field of the lens-calibrated focal length; an adjusted value of the focal length which distributes the effect of lens distortion throughout the entire area of the photograph. It usually minimizes the effect of distortion for the purpose of determining the best principal distance setting for stereoplotters.

focal plane—The plane (perpendicular to the axis of the lens) in which images of points in the object field of the lens are focused.

focus—To make the camera adjustments necessary to have the focal plane of the lens and film or ground-glass coincide. The point at which the rays from a point source of light reunite and cross after passing through a camera lens. In practice, the plane in which a sharp image of any scene is formed.

focus, fixed—A focus that cannot be adjusted, as in an ordinary box camera. Aerial cameras, with few exceptions, are focused at infinity and must be flown at an altitude greater than the hyperfocal distance. Fixed-focus head cameras are normally focused at the hyperfocal distance, thus permitting all objects from infinity to one-half the hyper-focal distance to be sharply defined.

fog—A fault photographic negative seen as a veil over the whole negative, as darkened patches, or as an obscuring of shadows (light areas in the negative). It may be due to light reaching the negative accidentally (light fog), or to an error in compounding or using solutions (chemical or dichroic fog), or to gradual degeneration of the film or developer with age.

form line—An approximate, or uncontrolled contour line.

frame—Any individual member of a continuous sequence of photographs. One complete television picture consisting of two fields of interlaced scanning lines.
**frequency**—Number of oscillations or wavelengths that pass a point per unit time.

**full aperture**—The maximum opening of a lens or lens diaphragm.

**generation**—The number of reproduction steps in which a negative or positive photographic copy is separated from the original. The original is the first generation, any positive made from that negative is a second generation copy.

**geodesy**—The science which deals mathematically with the size and shape of the earth, and the earth’s external gravity field, and with surveys of such precision that overall size and shape of the earth must be taken into consideration.

**geodetic coordinates**—Quantities which define the position of a point on the spheroid of reference with respect to the planes of the geodetic equator and of a reference meridian.

**geodetic datum**—A datum consisting of five quantities, the latitude and longitude and elevation above the reference spheroid of an initial point, a line from this point, and two constants which define the reference spheroid.

**geoid**—The figure of the earth; the mean sea level conceived as extended continuously through all the continents.

**geometric accuracy**—Four types: Geographic—the ability to locate a point using standard latitude and longitude coordinates; Positional—the ability to locate a point in an image by using a map; Scene registration—the ability to superimpose the same point in two images of a scene taken at the same time (different spectral bands); Temporal registration—the ability to superimpose a point in two images of the same scene taken at different times (same or different spectral bands).

**geometric correction**—The removal of sensor, platform, or scene induced geometric errors such that the data conform to a desired projection. This involves the creation of a new digital image by resampling the input digital image.

**geostationary (satellite)**—A satellite so placed into orbit above the Earth that it rotates with the Earth and thus remains fixed over the same area.

**gray body**—A radiating surface whose radiation has essentially the same spectral energy distribution as that of a blackbody at the same temperature, but whose emissive power is less.

**gray scale**—A monochrome strip of shades ranging from white to black with intermediate shades of gray. The scale is placed in a setup for a color photograph and serves as a means of balancing the separation negatives and positive dye images.

**grid line**—One of the lines in a grid system; a line used to divide a map into squares. East-west lines in a grid system are x-lines, and north-south lines are y-lines.

**ground-based (device)**—A piece of equipment or mechanism situated on the ground (usually used in conjunction or support of an aerial or a space mission).
ground-check—The process of collecting or providing information concerning the actual state of the ground usually at the time of a remote sensing overflight.

ground control—Accurate data on the horizontal and/or vertical positions of identifiable ground points.

ground data—Supporting data collected on the ground, and information derived therefrom, as an aid to the interpretation of remotely-recorded surveys, such as airborne imagery.

ground information—Information derived from ground data and surveys to support interpretation of remotely sensed data.

ground resolution—The area of the earth's surface encompassed by the IFOV of a radiometer at a given flight altitude above terrain:

\[ D = H' \beta \]

where

- \( D \) = diameter of the ground area viewed
- \( H' \) = flying height above the terrain
- \( \beta \) = IFOV of the system (expressed in radians)

ground speed—The rate of motion of an aircraft or space vehicle along its track with relation to the ground; The resultant of the heading and air speed of an aircraft and the direction and velocity of the wind.

ground support—Services and information provided to an aerial or space mission from the ground.

ground survey—A survey made by ground methods, as distinguished from an aerial survey.

hard copy—Information recorded on a sheet (map, picture, chart, graphics, etc.) in such a manner that it may be stored or transported.

heading—Azimuth of the longitudinal axis of an aircraft.

heat-sensing (device)—An instrument used to detect and sense heat.

high oblique—An oblique photo which shows the horizon line.

high-oblique photograph—An oblique photograph in which the apparent horizon is included within the field of view.

horizon—in general, the apparent or visible junction of earth and sky, as seen from any specific position. Also called the apparent, visible, local, or sensible horizon.

horizon photograph—A photograph of the horizon, taken simultaneously with a vertical photograph and used to determine the relative tilt between adjacent photographs.

horizontal-control datum—The position on the spheroid of reference assigned to the horizontal control (triangulation and traverse) of an area and defined by (1) the position (latitude and
longitude) of one selected station in the area, and (2) the azimuth from the selected station to an adjoining station. The horizontal-control datum may extend over a continent or be limited to a small area. A datum for a small area is usually called a local datum and is given a proper name.

**hue**—The attribute of a color by virtue of which it differs from gray of the same brilliance, and which allows it to be classed as red, yellow, green, blue, or intermediate shades of these colors.

**humidity**—Degree of wetness, especially of the atmosphere. Relative humidity—Ratio of water vapor present, at a given temperature, to the greatest amount possible at the temperature. Absolute humidity—The weight of water vapor contained in a given volume of air, in grains per cubic foot or grams per cubic meter. Specific humidity—The weight of water vapor per unit weight of the moist air.

**image**—The representation of an object produced by the optical, electro-optical, optical mechanical, or electronic recordation of reflected or emitted EMR. The term is generally used when the EMR from a scene is not directly recorded on film. See **imagery**.

**image compression**—An operation which preserves all or most of the information in the image and which reduces the amount of memory needed to store an image or the time needed to transmit an image.

**image enhancement**—The manipulation of image density to more easily see certain features of the image.

**image, latent**—The invisible image, recorded by light action upon the film or plate, which is made visible in development.

**image motion**—In aerial photography, the movement of the platform during the exposure which blurs and degrades the photographic image.

**image-motion compensator**—A device installed with certain aerial cameras to compensate for the forward motion of an aircraft while photographing ground objects. True image-motion compensation must be introduced after the camera is oriented to the flight track of the aircraft and the camera is fully stabilized.

**image processing**—Encompasses all the various operations which can be applied to photographic or image format data. These include, but are not limited to, image compression, image restoration, image enhancement, preprocessing, quantization, spatial filtering, and other image pattern recognition techniques.

**image restoration**—A process by which a degraded image is restored to its original condition. Image restoration is possible only to the extent that the degradation transform is mathematically invertible.

**imagery**—The products of image-forming instruments (analogous to photography). The term is generally used when the EMR from a scene was not directly recorded on film.
inch (in.)—Exactly 2.540 centimeters.

index map—A map of smaller scale on which are depicted the location (with accompanying designations) of specific data, such as larger-scale topographic quadrangles or geodetic control. A map showing the location and numbers of flight strips and photographs. Photo index—A mosaic (not an index map) made by assembling individual photographs, with accompanying designations, into their proper relative positions and copying the assembly photographically at a reduced scale.

infrared (IR)—Pertaining to or designating the portion of the EM spectrum with wavelengths beyond the red end of the visible spectrum from 0.7 to 14 µm. It is divided into three regions: near, middle, and thermal IR.

infrared film—A color or a black and white film which responds to photographic infrared radiation.

infrared, middle—Pertaining to or designating the portion of the EM spectrum with wavelengths from 1.35 to 5.0 µm.

infrared, near—Pertaining to or designating the portion of the EM spectrum with wavelengths from 0.7 to 1.35 µm.

infrared, photographic—Pertaining to or designating the portion of the EM spectrum with wavelengths from 0.7 to about 0.98 µm that can be sensed directly by photographic films. Photographic IR is a subset of the near IR spectral region.

infrared scanner—An optical-mechanical scanning device which operates in one or more spectral bands of the infrared EMR range.

infrared, thermal—Pertaining to or designating the portion of the EM spectrum with wavelengths from about 3.0 to 14 µm. The thermal IR region contains two useful bands: short-wavelength thermal (3.4 to 4.8 µm) and long-wavelength thermal (8.1 to 13.2 µm).

instantaneous field-of-view (IFOV)—The solid angle through which a detector is sensitive to radiation. For a radiometer, it is determined by the focal length of the instrument's optical system and the size of it's detector element. In a scanning radiometer, it is the solid angle subtended by the detector element when the scanning motion is stopped.

instrument—A device that measures, detects, or otherwise performs to provide information about quantities or conditions.

instrumentation—The installation and use of electronic, gyroscopic, and other instruments for the purpose of detecting, measuring, recording, telemetering, processing, or analyzing different values or quantities as encountered in the flight of a rocket or spacecraft. The assemblage of such instruments in an aircraft, rocket, spacecraft, other vehicle or place.

interface—A common boundary between two parts of a system, whether material or non-material. To join or work together, coordinate, either physically or mentally.
**interpupillary distance**—The distance between the pupils of the eyes of an individual. Also called eye base and interocular distance.

**intervalometer**—A timing device for automatically operating the shutter of a camera at any predetermined interval.

**irradiance**—The measure of radiant flux incident on a surface, expressed in Wm\(^{-2}\).

**key, photointerpretation**—A device designed to aid in the rapid, accurate identification of an object and in judging its significance from its appearance in a picture.

**knot**—A nautical mile per hour, 1.1508 statute miles per hour.

**latent image**—An invisible image produced by the physical or chemical effect of light upon matter (usually silver halide or halides), which can be rendered visible by the subsequent chemical process of photographic development.

**latitude**—Angular distance north or south of the Equator measured along a meridian.

**leader**—A strip of film at the beginning of a roll of film which is used for loading the camera.

**legend**—A description, explanation, table of symbols, and other information, printed on a map or chart to provide a better understanding and interpretation of it. The title of a map or chart formerly was considered part of the legend, but this usage is obsolete.

**lens**—A piece, or combination of pieces (elements) of glass or other transparent material shaped to form all but the simplest cameras.

**lens distortion**—An aberration affecting the position of images off the axis in which objects at different angular distances from the axis undergo different magnifications.

**lens element**—One lens of a complex lens system. In a photographic lens, the terms front element and rear element are often used.

**light**—Visible radiation (about 0.4 to 0.7 \(\mu m\) in wavelength) considered in terms of its luminous efficiency, i.e., evaluated in proportion to its ability to stimulate the sense of sight.

**light, actinic**—Light that is capable of causing photochemical change in a photographic emulsion. The wavelength of actinic light varies with the sensitivity of the material. Blue and violet are normally considered to be the most actinic of visible light rays because all commonly used photographic materials are highly sensitive to these colors.

**line, center**—A line extending from the true center point overlapping aerial photographs through each of the transposed center points.

**line, flight**—A line drawn on a map or chart to represent the track over which an aircraft has been flown or is to fly. The line connecting the principal points of vertical aerial photographs.

**line, rhumb**—A line which has constant bearing on the globe.
**lithosphere**—The solid part of the Earth or other spatial body. Distinguished from the atmosphere and the hydrosphere.

**loran**—An acronym for **long-range navigation**; it is a low-frequency aid to navigation operating in the 90 to 110 kHz range.

**low oblique**—An oblique photo which does not show the horizon line; the term is restricted by some writers, however, to photos more nearly vertical than horizontal (camera axis less than 45 degrees from vertical).

**magazine**—A container for rolled film or photographic plates, attached to the camera body; those used with aerial cameras are equipped with automatic mechanisms that advance and position the photographic material for exposure.

**magnetic declination**—The angle between true (geographic) north and magnetic north (direction of the compass needle). The magnetic declination varies for different places and changes continuously, but very slowly, with respect to time.

**magnification**—The ratio of the size of an image to the size of the object, normally the ratio of a linear quantity in the image to a corresponding linear quantity in the object.

**map**—A representation in a plane surface, at an established scale, of the physical features of (natural, artificial, or both) a part or all of the earth’s surface with the means of orientation indicated. Also, similar representation of certain features to satisfy specific requirements. Frequently the word “map” is preceded by an adjective which explains what type of information the map is designed primarily to present. Many types and scales of maps are made to serve numerous purposes.

**map (verb)**—To prepare a map or engage in a mapping operation.

**map, base**—A map showing certain fundamental information, used as a base upon which additional data of specialized nature are compiled. Also, a map containing all the information from which maps showing specialized information can be prepared: a source map.

**map, cadastral**—A map showing the boundaries of subdivisions of land, usually with the bearings and lengths thereof and the areas of individual tracts, for purposes of describing and recording ownership. A cadastral map may also show culture, drainage, and other features relating to the value and use of land.

**map, contour**—A topographic map which portrays relief by means of contour lines.

**map grid**—Two sets of parallel lines at right angles drawn on a plane surface and used as a rectangular coordinate system (a reference system) for plotting position and scaling distances and directions in surveying and mapping. A map grid may or may not be based on a map projection.

**map, hydrographic**—A map showing a portion of the waters of the earth, including shorelines, the topography along the shore and of the submerged portions, and as much of the topography of the surrounding country as is necessary for the purpose intended.
map, planimetric—A map presenting only the horizontal positions for the features represented: distinguished from a topographic map by the omission of elevation contours.

map projection—A systematic drawing of lines on a plane surface to represent the parallels of latitude and the meridians of longitude of the earth or a section of the earth.

map, special-purpose—Any map designed primarily to meet specific requirements. Usually the map information portrayed on a special-purpose map is emphasized by omitting or subordinating nonessential or less important information. A word or phrase is usually employed to describe the type of information which a special-purpose map is designed to present, i.e., route, tax, or index map.

map, topographic—A map which represents the horizontal and vertical positions of the features represented; distinguished from a planimetric map by the addition of relief in measurable form. A topographic map uses contours or comparable symbols to show mountains, valleys, and plains; and, in the case of hydrographic charts, symbols and numbers to show depths in bodies of water.

marginal information—The notations printed in the margins or borders of mosaics, plans, or especially, maps.

mean sea level (MSL)—The average level of the sea, as calculated from a large number of observations taken at equal intervals of time.

meteorology—The study of dealing with the phenomena of the atmosphere. This includes not only the physics, chemistry, and dynamics of the atmosphere, but is extended to include many of the direct effects of the atmosphere upon the earth’s surface.

meter (m)—The basic unit of length of the metric system, defined as 1.650.763.73 wavelengths in vacuo of the unperturbed transition 2p 10—5d in krypton u. Effective 1 July 1959 in the U.S. customary system of measures, 1 yard = 0.9144 meter, exactly, or 1 meter = 0.094 yards = 39.37 inches. The standard inch is exactly 25.4 millimeters.

metric system—The international standard system of weights and measures. The meter, kilogram, and second are the fundamental units of measures of length, mass, and time, respectively. Officially referred to as the International System of Units (abbreviated SI).

microwave—EM radiation between 1 meter and 1 millimeter in wavelength or 0.3 to 300 GHz in frequency. The portion of the electromagnetic spectrum in the millimeter and centimeter wavelengths, bounded on the short wavelength side by the far infrared (at 1 mm) and on the long wavelength side by very high-frequency radio waves. Passive systems operating at these wavelengths sometimes are called microwave systems. Radar is an active microwave system. The exact limits of the microwave region are not defined.

Mie scattering—Scattering produced by atmospheric particulates having diameters about equal to the wavelengths of the interacting EMR.
**mission**—The dispatching of one or more aircraft to accomplish one particular task. A single flight of an aircraft engaged in photographic reconnaissance. A flight of one or more space vehicles to accomplish one or more objectives.

**mosaic**—An assemblage of overlapping aerial or space photographs or images whose edges have been matched to form a continuous pictorial representation of a portion of the earth’s surface.

**mosaic, controlled**—A mosaic which is laid to ground control and in which prints are used which have been ratioed and rectified.

**mosaic, semi-controlled**—A mosaic composed of corrected or uncorrected prints laid to a common basis of orientation other than ground control.

**mosaic strip**—A mosaic consisting of one strip of photographs or images taken on a single flight.

**mosaic, uncontrolled**—A mosaic composed of uncorrected prints, the detail of which has been matched from print to print without ground control or other orientation.

**mosaicking**—The assembling of photographs or other images whose edges are cut and matched to form a continuous photographic representation of a portion of the earth’s surface.

**mottled**—Covered with irregular spots; said of negatives, prints, or image texture.

**mount, aerial camera**—A device which supports a camera in an aircraft for vertical and/or oblique photography.

**multiband system**—A system for simultaneously observing the same target with several filtered bands, through which data can be recorded. Usually applied to cameras, may be used for scanning radiometers which utilize dispersant optics to split wavelength bands apart for viewing by several filtered detectors.

**multi-lens camera**—A camera having two or more lenses pointing at the same target which, when used with different film/filter combinations, produces multiband photographs. A camera having two or more lenses pointed at an angle to one another, and taking two or more overlapping pictures simultaneously.

**multispectral**—Generally used for acquisition of remote sensing data in two or more spectral bands.

**multispectral (line) scanner**—A remote sensing device which operates on the same principle as the infrared scanner except that it is capable of recording data in the ultraviolet and visible portions of the spectrum as well as the infrared.

**nadir**—That point on the celestial sphere vertically below the observer, or 180 degrees from the zenith. That point on the ground vertically beneath the perspective center of the camera lens.

**nadir, ground**—The point on the ground vertically beneath the perspective center of the camera lens.
nadir, photograph—That point at which a vertical line through the perspective center of the camera lens pierces the plane of the photograph.

nautical chart—A map especially designed for the mariner, on which are shown navigable waters and the adjacent or included land, if any, and on which are indicated depths of water, marine obstructions, aids to navigation, and other pertinent information.

nautical mile (knot)—A unit of distance used principally in navigation. For practical navigation it is usually considered the length of 1 minute of any great circle of the earth, the meridian being the great circle most commonly used. Because of various lengths of the nautical mile in use throughout the world, due to differences in definition and the assumed size and shape of the earth, the International Hydrographic Bureau in 1929 proposed a standard length of 1852 meters, which is known as the international nautical mile.

near infrared—Pertaining to or designating the portion of the EM spectrum with wavelengths from 0.7 to 1.35 µm. The term emphasizes the radiation reflected from plant materials, which peaks around 0.85 micrometers. It is also called solar infrared, as it is only available for use during the daylight hours.

negative—A photographic image on film, plate, or paper, in which the tones are reversed. A film, plate, or paper containing such a reversed image.

negative, color—A photographic image on film, plate, or paper, in which the colors appear as the complements of those in nature. A film, plate, or paper containing such an image.

oblique—Any position, or direction that is slanted, inclined, or not perpendicular.

oblique photograph—A photograph taken with the camera axis intentionally directed between the horizontal and the vertical. A high-oblique photograph is one in which the apparent horizon is included within the field of view, whereas a low-oblique photograph does not include the apparent horizon within the field of view.

optical axis—In a lens element, the straight line which passes through the centers of curvature of the lens surfaces. Also called principal axis. In an optical system, the line formed by the coinciding principal axes of the series of optical elements.

orbit—The path of a body or particle under the influence of a gravitational or other force. For instance, the orbit of a celestial body is its path relative to another body around which it revolves. To go around the earth or other body in an orbit.

orientation—Direction or arrangement with respect to other detail. The direction in which the photograph is turned with respect to observer, map, etc. A single photo is best oriented for study when turned so that the shadows are cast toward the observer.

origin—The reference position from which angles or distances are reckoned.

orthophotographic projection—Projection by parallel rays onto a plane at right angles to the rays.
orthophoto map—A photomap made from an assembly of orthophotographs. It may incorporate special cartographic treatment, photographic edge enhancement, color separation, or a combination of these.

orthophoto mosaic—An assembly of orthophotographs forming a uniform scale mosaic.

orthophoto scope—A photomechanical device, used in conjunction with a double-projection anaglyphic instrument, for producing orthophotographs.

over exposure—The result of too much light being permitted to act on a light-sensitive material, with either too great a lens aperture or too slow a shutter speed or both.

overlap—The area common to two successive photos along (foreward) the same flight strip; the amount of overlap is expressed as a percentage of photo area.

overlapping pair—Two photographs taken at different exposure stations in such a manner that a portion of one photograph shows the same terrain as shown on a portion of the other photograph.

panchromatic—Used for films that are sensitive to broad band (e.g., entire visible part of spectrum) EMR, and for broadband photographs.

passive—Applied to EMR emitted from an object or surface; also used for reflected natural EMR.

passive system—A sensing system that detects or measures radiation reflected or emitted by the target.

pattern—in a photo image, the regularity and characteristic placement of tones or textures. The relations between any more-or-less independent parameters of a response; e.g., the pattern in the frequency domain of the response from an object.

pattern recognition—Concerned with, but not limited to, problems of: pattern discrimination, pattern classification, feature selection, the pattern identification, cluster identification, feature extraction, filtering, enhancement, and pattern segmentation.

perpendicular, photograph—The perpendicular from the interior perspective center to the plane of the photograph.

perspective—Representation, on a plane or curved surface, or natural objects as they appear to the eye. The appearance of such objects to the eye.

photo base—Air base reduced to photo scale; measured as the mean distance between center points and transposed center points on a stereopair of photos.

photogeology—The interpretation of the geology of an area from an analysis of landforms, drainage, tones, and vegetation distribution on aerial photographs.
photogrammetric survey—A method of surveying that uses either ground photographs or aerial photographs.

photogrammetry—The art or science of obtaining reliable measurements by means of photography.

photograph—A picture formed by the action of light on a base material coated with a sensitized solution which is chemically treated to fix the image points at the desired density. Usually now taken to mean the direct action of EMR on the sensitized material.

photograph axes—The preferred term is fiducial axes.

photograph center—The center of a photograph as indicated by the images of the fiducial mark or marks of the camera. In a perfectly adjusted camera, the photograph center and the principal point are identical.

photograph, composite—A photograph made by assembling the separate photographs made by each lens of a multiple lens camera in a simultaneous exposure into the equivalent of a photograph taken with a single wide-angle lens.

photograph horizon—A photograph of the horizon taken simultaneously with another photograph for the purpose of obtaining an indication of the orientation of the other photograph at the instant of exposure.

photograph perpendicular—The perpendicular from the interior perspective center to the plane of the photograph.

photographic interpretation—The act of examining photographic images for the purpose of identifying objects and judging their significance.

photographic interpreter (PI)—An individual specially trained or skilled in photographic interpretation. Photointerpreter, photo interpreter, and image interpreter are other widely used terms.

photography—The art of process of producing images or sensitized material through the action of light. The term photography is sometimes incorrectly used in place of photographs, however, the distinction between the process and the product is a valuable one and should be observed.

photomap—A single photo, composite, or mosaic showing coordinates and marginal information: normally reproduced in quantity.

photosensitive—A term used to describe substances whose chemical composition is altered by the action of light.

phototopography—The science of surveying in which the detail is plotted entirely from photographs taken at suitable ground stations.
phototriangulation—The process of the extension of horizontal and/or vertical control whereby the measurements of angles and/or distance on overlapping photographs are related into a spatial solution using the perspective principles of the photographs.

pitch—A rotation of an aircraft about the horizontal axis normal to its longitudinal axis so as to cause a nose-up or nose-down attitude. A rotation of the camera or of the photograph-coordinate system about either the photograph axis or the exterior Y; tip or longitudinal tilt.

type—A contraction of a picture element. In Landsat, an integrated radiance mapping unit.

Planck's Law—A mathematical expression for the variation of monochromatic radiant flux as a function of wavelength for a blackbody at a given temperature.

planimetric map—A map which presents only the horizontal positions for features represented.

polarization—The direction of the electric vector in an EM wave. Waves may be plane-polarized, or linearly polarized, in which case the electric vector is in the same direction at all points in the wave. They may also be circularly or elliptically polarized, in which case the direction of the electric vector at some point changes with time (circular) or both direction and amplitude change in a relative manner (elliptical).

polarizing filter—A filter which passes light waves vibrating in one polarization direction only. Used over camera lenses to cut down or remove rays of any or all other polarization direction(s) when they may constitute objectionable reflections from glass, water, or other highly reflecting surfaces.

positive—A photographic image having approximately the same rendition of light and shade as the original subject. A film, plate, or paper containing such an image.

positive, direct—A positive image obtained directly without the use of a negative.

precision—A quality associated with the refinement of instruments and measurements, indicated by the degree of uniformity or identity of repeated measurements.

precision camera—An indefinite term sometimes applied to any camera used for photogrammetric purposes. May be construed as meaning a camera that can be calibrated.

preprocessing—Commonly used to describe corrections and processing done to image data before information extraction. Includes geometric and radiometric correction, mosaicking, resampling, and formatting.

primary color—Any one of three colors—red, yellow, or blue—used for producing an extensive range of colors by additive mixtures.

principal plane—The vertical plane through the internal perspective center containing the photograph perpendicular of a tilted photograph.
processing—The operations necessary to produce negatives, diapositives, or prints from exposed film, plates, or papers. The manipulation of data by means of computer or other device.

projection, map—A systematic drawing of lines on a plane surface to represent the parallels of latitude and the meridians of longitude of the earth or a section of the earth. A map projection is frequently referred to as a projection but the complete term should be used unless the context clearly indicates the meaning.

pseudoscopic view—A reversal of the normal stereoscopic effect, causing valleys to appear as ridges and ridges as valleys.

radar—Acronym for radio detection and ranging. A method, system, or technique, including equipment components, for using beam, reflected, and timed EMR to detect, locate, and (or) track objects, to measure altitude and to acquire a terrain image. In remote sensing of the earth’s or a planetary surface, it is used for measuring, and often, mapping the scattering properties of the surface.

radial—A line or direction from the radial center of a photograph to any other point on the photograph.

radial triangulation—The aerotriangulation procedure, either graphical or analytical, in which directions form the radial center, or approximate radial center, of each overlapping photograph are used for horizontal-control extension by the successive intersection and resection of these direction lines. A radial triangulation also is correctly called a radial plot or a minor-control plot. If made by analytical methods, it is called an analytical radial triangulation. A radial triangulation is assumed to be graphical unless prefixed by the word analytical. A graphical triangulation is usually laid out directly onto ground control plotted on a map, map projection, or map grid; but it may be first laid out independently of such control and later adjusted to it as a unit. In the latter case, the scale and azimuth of the radial triangulation unit are not known until it is adjusted to the ground control. The radial center for near-vertical photographs may be the principal-point, the nadir point, or the isocenter. A radial triangulation is assumed to be made with principal points as radial centers unless the definitive term designates otherwise (as, for example, nadir-point triangulation or nadir-point plot, the isocenter triangulation or isocenter plot. The adjective radial is not necessary in these four terms). The adjective analytical is required to designate that the triangulation is by analytical and not graphical methods (e.g., analytical nadir-point triangulation).

radiance—The accepted term for radiant flux in power units (e.g. watts) and not for flux density per solid angle (e.g. watts/cm²sr) as often found in publications.

radiant temperature—Concentration of the radiant flux from a material. Radiant temperature is the product of the kinetic temperature multiplied by the emissivity to the one-fourth power.

radiation—The emission and propagation of energy through space or through a material medium in the form of waves; e.g., the emission and propagation of EM waves, or of sound and elastic waves. The process of emitting radiant energy.
Rayleigh scattering—Scattering by particles small in size compared with the wavelengths being scattered, e.g., scattering of blue light by the atmosphere.

reconnaissance—A general examination or survey of the main features, or certain specific features, of a region, usually as a preliminary to a more detailed survey.

reconnaissance photography—Aerial photography taken primarily for purposes other than making maps, charts, or mosaics.

rectification—The process of projecting a tilted or oblique photograph onto a horizontal reference plane, the angular relation between the photography and the plane being determined by ground reconnaissance. Transformation is the special process of rectifying the oblique images from a multiple-lens camera to equivalent vertical images by projection onto a plane that is perpendicular to the camera axis. In this case, the projection is onto a plane determined by the angular relations of the camera axis and not necessarily onto a horizontal plane.

reference spheroid—A spheroid determined by revolving an ellipse about its shorter (polar) axis and used as a base for geodetic surveys of a large section of the earth (such as the Clarke Spheroid of 1866, which is used for geodetic surveys in the United States). The spheroid of reference is a theoretical figure whose dimensions closely approach the dimensions of the geoid; the exact dimensions are determined by various considerations of the section of the earth’s surface concerned.

reflectance—The ratio of the radiant energy reflected by a body to that incident upon it.

reflection—EMR neither absorbed nor transmitted is reflected. Reflection may be diffuse, when the incident radiation is scattered upon being reflected from the surface, or specular, when all or most angles of reflection equal the angle of incidence.

refraction—The bending of EMR rays when they pass from one medium to another having a different index of refraction or dielectric coefficient. EMR rays also bend in media that have continuous variations in their indices of refraction or dielectric coefficients.

registration (image)—The process of superimposing two or more images or photographs so that equivalent geographic points coincide. Registration may be done digitally or photographically.

relative humidity—Ratio of water vapor present, at a given temperature, to the greatest amount possible at that temperature.

relative tilt—The tilt of a photograph with reference to an arbitrary plane, not necessarily a horizontal plane, such as that of the preceding or subsequent photograph in a strip. Also defined as the angle between the photograph perpendicular and a reference direction, such as the photograph perpendicular of the preceding or subsequent photograph in a strip.

remote sensing—In the broadest sense, 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; e.g., the utilization at a distance (as from
aircraft, spacecraft, or ship) of any device and its attendant display for gathering information pertinent to the environment, such as measurements of force fields, electromagnetic radiation, or acoustic energy. The technique employs such devices as the camera, lasers, radiometers, scanners, and radio frequency receivers, radar systems, sonar, seismographs, gravimeters, magnetometers, and scintillation counters. The practice of data collection in the wavelengths from ultraviolet to radio regions. This restricted sense is the practical outgrowth from airborne photography.

**rendezvous**—To assemble or cause to assemble at a certain place and time.

**representative fraction (R.F.)**—The relation between map or photo distance and ground distance, expressed as a fraction (1/25,000) or often as a ratio (1:25,000) (1 inch on map = 25,000 inches on ground).

**reproduction**—The processes involved in printing copies from an original drawing. The principal processes are photography, lithography, (or engraving), and printing. Also, a printed copy of an original drawing, made by any of the processes of reproduction.

**resolution**—The ability of an entire remote sensor system, including lens, antennae, display, exposure, processing, and other factors, to render a sharply defined image. It may be expressed as line pairs per millimeter or meters, or in many other manners. In radar, resolution usually applies to the effective beamwidth and range measurement width, often defined as the half-power points. For infrared line scanners the resolution may be expressed as the instantaneous field-of-view. Resolution also may be expressed in terms of temperature or other physical property being measured. If expressed in size of object, or distances on the ground, the distance is termed ground resolution.

**resolution cell**—The element on the ground distinguishable on the image, usually consisting of the half-power beamwidth distance by the half-power pulse duration. As some systems use other discrimination techniques, however, different definitions may apply.

**resolution target**—Regularly spaced pairs of light and dark bars that are used to evaluate the resolution of images or photographs.

**resolving power**—A mathematical expression of lens definition, usually stated as the maximum number of line pairs per millimeter that can be resolved (that is, seen as separate lines) in an image.

**return beam vidicon (RBV)**—A modified vidicon television camera tube, in which the output signal is derived from the depleted electron beam reflected from the tube target.

**rhumb line**—A line (curved) on the surface of the earth, crossing all meridians at a constant angle. Also called a loxodromic curve. On a Mercator projection, the rhumb line is represented by a straight line.

**roll**—A rotation of an aircraft about its longitudinal axis so as to cause a wing-up or wing-down
attitude. A rotation of a camera or a photograph-coordinate system about either the photograph x axis or the exterior X axis.

**satellite**—An attendant body that revolves about another body. A man-made object that revolves about a spacial body.

**scale**—The full range of tones of which a photographic paper is capable of reproducing is called the scale of the paper, it is also termed dynamic range. The ratio of a distance on a photograph or map to its corresponding distance on the ground. Scale may be expressed as a ratio, 1:24,000; a representative fraction, 1/24,000; or an equivalence, 1 in. = 2,000 ft.

**scale, graphic**—A graduated line on the margin of a map, chart, mosaic, etc., by means of which scaled distances may be measured in terms of actual ground distances. Also called bar scale.

**scale, gray**—A term used to describe the various tonal graduations on a photographic medium, cathode ray tube, or other display medium or device.

**scale height**—A measure of the relationship between density and temperature at any point in an atmosphere; the thickness of a homogeneous atmosphere which would give the observed temperature or pressure.

**scale, tree crown**—A simple measuring device printed on a transparent templet for measuring diameters of tree crowns and dimensions of other small objects. It may be designed in the form of a micrometer wedge or with small circular dots of graduated sizes.

**scanner**—Any device that scans, and by this means produces an image. A radar set incorporating a rotatable antenna, or radiator element, motor drives, mounting, etc., for directing a searching radar beam through space and imparting target information to an indicator.

**scanning**—The sweep of a mirror, prism, antenna, or other element across the track (direction of flight); may be straight, circular, or other shape. The motion of the radar antenna assembly when searching for targets.

**scanning radiometer**—A radiometer, which by the use of a rotating or oscillating plane mirror, can scan a path normal to the movement of the radiometer. The mirror directs the incoming radiation to a detector, which converts it into an electrical signal. This signal is amplified to stimulate a device such as a tape recorder, or glow tube, or CRT that can be photographed to produce a picture. When the system is moved forward at velocity V and altitude H, a suitable V/H ratio may be established, so that consecutive scans are just touching. This is often called an IR-imager, but is only so restricted because of the optical materials used, all-reflective optics being as useful in the UV and visible regions. They may all be single or multiple-band.

**scanning radiometer (microwave)**—A scanning device which operates in the microwave region of EMR, or portions of it, by systematically breaking up an image into picture elements (or pixels) and reducing some attribute of each picture element.

**scattering**—The process by which small particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions. The process by which a
rough surface diffusely reflects EMR incident upon it.

**scene**—The area on the ground that is covered by an image or photograph.

**sensitivity, color**—The sensitivity of a photographic emulsion to light of various wavelengths.

**sensor**—Any device which gathers EMR or other energy and presents it in a form suitable for obtaining information about the environment. Passive sensors, such as thermal infrared and microwave, utilize EMR produced by the surface or object being sensed. Active sensors, such as radar, supply their own energy source. Aerial cameras use natural or artificially produced EMR external to the object or surface being sensed.

**shadow**—Obscurity within the area or space from which direct EMR from a source is excluded by an interposed opaque body. A no-return area extending in range from an object which is elevated above its surroundings. The object obstructs the beam, preventing illumination of the area behind it. Radar shadows are analogous to shadows caused by visible light.

**shutter**—The mechanism of a camera which, when set in motion, permits light to reach the sensitized surface of the film or plate for a predetermined length of time.

**sidelap**—The area common to two photos in adjacent flight strips; the amount is expressed as a percentage of the total photo area. Also called overlap.

**sidelooking radar**—An all weather, day/night remote sensor which is particularly effective in imaging large areas of terrain. It is an active sensor, as it generates its own energy which is transmitted and received to produce a photo-like picture of the ground. Also referred to as sidelooking airborne radar, abbr. SLAR.

**signature**—Any characteristic or series of characteristics by which a material may be recognized. Used in the sense of spectral signature.

**signature analysis techniques**—Techniques which use the variation in the spectral reflectance or emittance of objects as a method of identifying the objects.

**slotted templet**—A templet on which the radials are represented as slots cut in a sheet of cardboard, metal, or other material.

**slotted templet triangulation**—A graphic radial triangulation using slotted templets.

**space coordinates**—May refer to any general three-dimensional coordinate system used to define the position of a point in the object space, as distinguished from the image of the point on a photograph.

**spacecraft**—Devices, manned and unmanned, which are designed to be placed into an orbit about the earth or into a trajectory to another celestial body. Generally considered to be maneuverable, as contrasted to satellites, which are placed in “fixed” orbits.

**spatial model**—A term applied to the three-dimensional image seen by stereoscopic methods.
**spectral band**—An interval in the electromagnetic spectrum defined by two wavelengths or frequencies.

**spectral colors**—The continuous band of pure colors in the visible spectrum are divided, for convenience, into seven basic spectral colors: violet, indigo, blue, green, yellow, orange, and red.

**spectral discrimination**—The ability to differentiate between segments of spectrum.

**spectral reflectance**—The reflectance of electromagnetic energy at specified wavelength intervals.

**spectrum**—In physics, any series of energies arranged according to wavelength (or frequency). The series of images produced when a beam of radiant energy is subject to dispersion. A rainbow-colored band of light is formed when white light is passed through a prism or a diffraction grating. This band of colors results from the fact that the different wavelengths of light are bent in varying degrees by the dispersing medium and is evidence of the fact that white light is composed of colored light of various wavelengths.

**speed, emulsion**—A measure of the sensitivity of the emulsion. It determines the exposure required to produce the desired density of image.

**speed, ground**—The velocity of an aircraft along its track with relation to the ground; the resultant of the heading and air speed of an aircraft and the direction velocity of the wind.

**speed, lens**—The ratio of the equivalent focal length to the diameter of the entrance pupil at the maximum diaphragm opening.

**spheroid of reference**—See spheroid or ellipsoid under geoid.

**State Plane Coordinate Systems**—See coordinate systems, state plane.

**stationary orbit**—An orbit in which an equatorial satellite revolves about the primary at the same angular rate as the primary rotates on its axis. From the primary, the satellite thus appears to be stationary over a point on the primary.

**Stefan-Boltzmann law**—One of the radiation laws; it states that the amount of energy radiated per unit time from a unit surface area of an ideal black body is proportional to the fourth power of the absolute temperature of the black body.

**stereo base**—A line representing the distance and direction between complementary image points on a stereopair of photos correctly oriented and adjusted for comfortable stereoscopic vision under a given stereoscope, or with the unaided eyes.

**stereogram**—A stereopair of photos or drawings correctly oriented and permanently mounted for stereoscopic examination.

**stereopair**—A pair of photos which overlap in area and are suitable for stereoscopic examination.
stereophotogrammetry—Photogrammetry utilizing stereoscopic equipment and methods.

stereoscope—A binocular optical instrument for assisting the observer to view two properly oriented photographs or diagrams to obtain the mental impression of a three-dimensional model.

stereoscopic base—The length of the air base as represented on a photograph.

stereoscopic image—That mental impression of a three-dimensional object which results from stereoscopic vision.

stereoscopic model—The mental impression of a three-dimensional model which results from viewing two overlapping perspective views.

stereoscopic pair—Two photographs of the same area taken from different camera stations so as to afford stereoscopic vision; frequently called stereopair.

stereoscopic plotting instrument—An instrument for plotting a map or obtaining spatial solutions by observation of stereoscopic models formed by stereopairs of photographs.

stereoscopic vision—Binocular vision which enables the observer to view an object simultaneously from two different perspectives (as stations) to obtain the mental impression of a three-dimensional model.

stereoscopy—The science or art which deals with three-dimensional effects and the methods by which these effects are produced.

stereotriangulation—The use of stereoscopic plotting instruments to establish horizontal and (or) vertical control data by orientation of the stereoscopic pairs fo photographs in a continuous strip. Orientation of the initial model is by reference to ground control established by survey aperture.

stereo triplet—A series of three photos, the end members of which overlap sufficiently on the central one to provide complete stereoscopic coverage for the latter.

strip—Any number of photos taken along a photo flight line, usually at an approximately constant altitude.

strip radial triangulation—A direct radial triangulation in which the photographs are plotted in flight strips without reference to ground control and the strips are later adjusted together to the ground control.

subtractive color process—A method of creating essentially all colors through the subtraction of light of the 3 subtractive color primaries (cyan, magenta and yellow) in various proportions through use of a single white light source.

sun synchronous—An earth satellite orbit in which the orbit plane is near polar and the altitude such that the satellite passes over all places on earth having the same latitude twice daily at the same local sun time.
survey—The act or operation of making measurements for determining the relative positions on, above, or beneath the earth’s surface; also, the results of such operations; also, an organization for making surveys.

surveying camera—See camera, surveying.

symbol—A diagram, design, letter, or abbreviation, placed on maps and charts, which (by convention, usage, or reference to a legend) is understood to stand for or represent a specific characteristic or object.

target—The distinctive marking or instrumentation of a ground point to aid in its identification on a photograph. In photogrammetry, target designates a material marking so arranged and placed on the ground as to form a distinctive pattern over a geodetic or other control-point marker on a property corner on line, or at the position of an identifying point above an underground facility or feature. In radar, an object returning a radar echo to the receiver.

telemetry—The science of measuring a quantity or quantities, transmitting the measured value to a distant station, and there interpreting, indicating, or recording the quantities measured.

telephoto lens—A lens comprising a positive front element and a negative rear element; the focal length of the combination is greater than the distance from the front lens surface to the focal plane.

terrain—An area of ground considered as to its extent and topography.

terrestrial photograph—A photograph taken by a camera located on the ground. Sometimes called a ground photograph, although this is not a preferred term.

texture—in remote sensing, pertaining to emitted or infrared radiation in the 4.5 to 13.5 wavelength range; any sensible heat; or pertaining to heat, as thermal capacity, emissivity or conductivity.

thermal infrared—Pertaining to or designating the portion of the EM spectrum with wavelengths from about 3.0 to 14 µm. The thermal IR region contains two useful bands: short-wavelength thermal (3.4 to 4.8 µm) and long-wavelength thermal (8.1 to 13.2 µm). The spectral limits represent the envelope of energy emitted by the earth, behaving as a greybody, with a surface temperature around 290 K (27 °C).

thermal capacity (heat capacity)—The ability of a material to store heat; product of density and specific heat at constant pressure (cal cm⁻³ °C⁻¹).

thermal conductivity—The ability of material to conduct heat as a consequence of molecular motion. A measure of the rate at which heat will pass through a material (W m⁻¹ K⁻¹).

thermal inertia—Sometimes referred to as the thermal contact coefficient, it is a measure of the rate of heat transfer and is the product of thermal conductivity and thermal capacity.

thermal radiation—The electromagnetic radiation emitted by a hot black-body, such as the
filament of lamp.

tilt—The angle between the optical axis of the camera and the plumb line for a given photo.

tilt displacement—Displacement of images, on a tilted photograph, radially outward or inward with respect to the isocenter, according as the images are, respectively, on the low or high side of the isometric parallel (the low side is the one tilted closer to the earth, or the object plane).

tilt, x- and y—Tilt expressed as resultant rotations about each of two stationary rectangular axes lying in a horizontal plane, and the x-tilt being the resultant rotation about the x-axis and the y-tilt the resultant rotation about the y-axis. In an aircraft, the x-axis is the longitudinal axis of the aircraft, lengthwise through the fuselage; the y-axis is the transverse axis, from wingtip to wingtip.

time, Greenwich mean—Mean solar time of the meridian of Greenwich, England, used by most navigators and adopted as the prime basis of standard time throughout the world.

tolerance—The allowable variation from a standard or from specified conditions.

tone—Each distinguishable shade variation from black to white.

topography—Features of the surface of the earth considered collectively as to form. A single feature (such as a mountain or valley) is called a topographic feature. Topography is subdivided into hypsography (relief features), hydrography (water and drainage features), and culture (man-made features).

track—The actual path of an aircraft above, or a ship on, the surface of the earth. The course is the path which is planned; the track is the path which is actually taken. The azimuth of this path generally is referred to the true meridian.

transmittance—The ratio of the radiant energy transmitted through a body to that incident upon it.

transparency—The light-transmitting capability of a material. A positive image upon glass or film, intended to be viewed by transmitted light, either black-and-white or in color; also called a diapositive.

tree height, visible—That part of the total height of a tree discernible on an aerial photograph, limited by the observer’s stereoscopic acuity and by the point in a tapering tree crown where the crown diameter is too small to register as photo detail.

triangulation—An operation in surveying which consists of extending the survey from a measured base line by measuring the angles in a network of triangles at least one of which includes the base line as one of its sides.

triangulation, radial—A method of triangulation using overlapping aerial photographs. The center of each photograph serves as a station from which directions to points imaged are traced or measured and used to extend the triangulation. Also called a radial plot or minor control plot.
ultraviolet absorbing filter—A haze cutting filter used mainly in photography with color films to avoid expressive bluishness and loss of contrast in the pictures; usual designations are U.V.; Haze; Wratten 2A.

ultraviolet radiation—EMR of shorter wavelength than visible radiation but longer than X-rays; roughly, radiation in the wavelength interval between 10 and 4000A.

ultraviolet rays—Radiant energy in the ultraviolet portion of the EM spectrum.

uncontrolled mosaic—A mosaic made without correction for distortion of any type.

underexposure—The result of insufficient light being allowed to pass through the lens to produce all the tones of an image; or of sufficient light being allowed to pass for too short a period of time.

value (color)—Degree of lightness, one of the attributes, along with hue and saturation, that may be thought of as the dimensions of color.

vertical—Perpendicular, or at right angle to the plane of the horizon.

vertical photograph—An aerial photograph made with the camera axis vertical (or as nearly vertical as practical) in an aircraft.

video—In general, used to mean television, or used in the transmission or reception of the television image. Specifically, pertains to the bandwidth and spectrum position of the signal which results from television scanning and which is used to reproduce a picture.

view—The appearance to the eye, on a photograph, etc., of a scene or an aspect of something; and act of viewing or inspection.

vignette—The interference, by the lens mounting or other obstruction, with oblique rays, which causes a reduction in the effective diaphragm area. A process of regulating the distribution of light which reaches the print in such a way that the image obtained fades out toward the edges.

vignetting—A gradual reduction in density of parts of a photographic image caused by the stopping of some of the rays entering the lens. Thus, a lens mounting may interfere with the extreme oblique rays. An antivignetting filter is one that gradually decreases in density from the center toward the edges; it is used with aerial wide-angle lenses to produce a photograph of uniform density by cutting down the overexposure of the photograph center.

vignetting filter—A filter which gradually decreases in density from the center toward the edges. It is used in certain cases in photography or printing processes to produce a photograph of uniform density.

visibility—The greatest distance toward the horizon at which prominent objects (such as mountains, buildings, and towers) can be seen and identified by the unaided eye.

visible radiation—EMR of the wavelength interval to which the human eye is sensitive, the spectral interval from approximately 0.4 to 0.7 um.
**vision, binocular**—Simultaneous vision with both eyes.

**wave**—A disturbance which is propagated in a medium in such a manner that at any point in the medium the quantity serving as measure of disturbance is a function of time, while at any instant the displacement at a point is a function of the position of the point.

**wavelength**—Wavelength = velocity/frequency. In general, the mean distance between maximums (or minimums) of a roughly periodic pattern. Specifically, the least distance between particles moving in the same phase of oscillation in a wave disturbance. Optical and IR wavelengths are measured in nanometers (10-9m). Micrometers (10-6m) and Angstroms (10-19m).

**white**—An object is said to be white if it reflects all wavelengths of the visible spectrum equally. White light is a wavelength intensity distribution which creates a hueless sensation to the eye.

**wing photograph**—A photograph taken by one of the side or wing lenses of a multiple-lens camera.

**x-axis**—A horizontal axis in a system of rectangular coordinates; that line on which distances to the right or left (east or west) of the reference line are marked, especially on a map, chart, or graph.

**X-ray**—Nonnuclear EMR of very short wavelength, lying within the interval of 0.1 to 100A (between gamma rays and ultra-violet radiation).

**y-axis**—A vertical axis in a system of rectangular coordinates; that line on which distances above or below (north or south of) a reference line are marked, especially on a map, chart, or graph.

**yaw**—The rotation of an aircraft about its vertical axis so as to cause the aircraft’s longitudinal axis to deviate from the flight line. Sometimes called crab. The rotation of a camera or a photograph coordinate system about either the photograph z axis or the exterior z axis.