

NA-267A1

Commonwealth Science Council

**WORKSHOP ON REMOTE SENSING
FOR COASTAL AND FORESTRY RESOURCE MANAGEMENT**

Colombo, Sri Lanka

June 4 - 11, 1997

presented by

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NA 267

MA 267

organised by

Commonwealth Science Council, UK



Natural Resources, Energy & Science Authority of Sri Lanka



**Commonwealth Secretariat Workshop in Sri Lanka
Workshop on Remote Sensing**

Proposed Outline

Day 1 - Morning

Course Overview

- Introductions
- Discussion of course content

Basic Principles of Remote Sensing

- Brief history of remote sensing
- Electromagnetic radiation and radiation laws
- Energy interactions in the atmosphere and at the surface
- Resolution - spatial, spectral, radiometric and temporal

Day 1 - Afternoon

Earth-Observation Satellites and Sensors

- Landsat MSS and TM - orbits, sensors and image interpretation
- SPOT HRV - orbits, sensors and image interpretation
- IRS - orbits, sensors and image interpretation
- AVHRR & GOES - orbits, sensors and image interpretation

Activities:

- Designing a satellite for Sri Lanka - group discussions and presentations

Day 2 - Morning

Introduction to Digital Image Analysis

- Nature of digital data
- Preprocessing
- Image enhancement
- Supervised classification
- Unsupervised classification

Day 2 - Afternoon

Image Interpretation

- Accuracy assessment
- Land cover and land use mapping

Activities:

- Exercise on digital image analysis
- Demonstration of digital image analysis

Day 3 - Morning

Digital Image Analysis - Other Analysis Techniques

- Spatial filtering
- Spectral ratios
- Principal Components Analysis
- Change detection

Day 3 - Afternoon

Image Interpretation

Case Study - Land use change and sustainable development in Indonesia



Activities:

- Exercises on visual and/or digital image interpretation

Day 4 - Morning

Introduction to Radar Imagery

- Basic principles - SLAR systems, wavelengths, bands, polarizations
- Characteristics - scattering, geometry, surface roughness, vegetation response
- Radar sensors

Day 4 - Afternoon

Radar Satellites and Sensors

- Scasat
- Shuttle Imaging Radar
- ERS-1 & 2; JERS-1
- RADARSAT

Activities:

- Radar image interpretation

Day 5 - Morning

Introduction to Geographic Information Systems (GIS)

- Characteristics of a GIS
- Raster and vector data
- Digital elevation models
- Integration of remote sensing data with a GIS

Day 5 - Afternoon

Data Integration

- Global Positioning Systems

Activities:

Global Positioning System exercise

Day 6 - Morning

Student Presentations

Day 6 - Afternoon

Project Design & Wrap-up

- Discussion of possible projects
- Answers to questions posed by participants

Acknowledgments

The figures and tables used in this workshop are from the following remote sensing and geographic information systems textbooks:

- Aronoff, S., 1993. *Geographic Information Systems: A Management Perspective*, WDL Publications, Ottawa, Canada 294 p.
- Campbell, J.B., 1987. *Introduction to Remote Sensing*, Guilford Press, NY (G 70.4 C23)
- Environmental Systems Research Institute, 1993. *Understanding GIS: the ARC/INFO Method*, Longman Scientific and Technical, Harlow, Essex, England, variously paged.
- Huxhold, W.E. and A.G. Levinsohn, 1995. *Managing Geographic Information System Projects*, Oxford University Press, New York, 247 p.
- Jensen, J.R., *Introductory Digital Image Processing: A Remote Sensing Perspective*, Prentice Hall, Upper Saddle River, New Jersey, 316 pp.
- Lillesand, T.M. and R.W. Kiefer, 1994. *Remote Sensing and Image Interpretation*, Wiley and Sons, 3rd edition (G 70.4 L54)
- Maguire, D.J., M.F. Goodchild, and D.W. Rhind, eds., 1991. *Geographical Information Systems: Principles and Applications*, Longman Scientific and Technical, London, UK
- Richards, J.A., 1993. *Remote Sensing Digital Image Analysis: An Introduction*, Springer-Verlag, New York, 2nd edition (G 70.4 R53)
- Sabins, F.F., Jr., 1987. *Remote Sensing: Principles and Interpretation*, Wiley and Sons (G70.4 S15)
- Tomlin, C.D., 1990. *Geographic Information Systems and Cartographic Modeling*, Prentice Hall, Englewood Cliffs, N.J., 249 p.

Basic Principles of Remote Sensing

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Definitions of Remote Sensing

Group of techniques for collecting image or other forms of data about an object from measurements made at a distance from the object, and the processing and analysis of the data.

(CCRS - RESORS)

Remote sensing is the measurement and analysis of electromagnetic radiation reflected from, transmitted through, or absorbed and scattered by the atmosphere, the hydrosphere and by material at or near the land surface, for the purpose of understanding and managing the Earth's resources and environment.

(Larry Morley - Teledetection International)

The acquisition of information about an object, without being in physical contact with that object.

(Christine Hutton - CCRS)

Remote Sensing: the science and art of obtaining useful information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation.

(Lillesand, Thomas M. and Ralph W. Kiefer, "Remote Sensing and Image Interpretation" John Wiley and Sons, Inc, 1979, pp1.)

Remote sensing is the collection of natural resources and environmental information using images acquired by sensors on board aircraft or spacecraft.

(Bob Ryerson - CCRS)

Source: http://www.ccrs.nrcan.gc.ca/ccrs/whtisrs/rs_defne.html

INTRODUCTION TO REMOTE SENSING

1. **Definitions of Remote Sensing**

2. **History of Remote Sensing**

What has been the driving force?

3. **Military Developments**

- photography & balloons
- US Civil War photography from balloons
- 1930s development of mapping from aerial photography
- W.W.I photography from balloons and aircraft
- W.W.II mapping - photo-reconnaissance
- 1950s development of radar reconnaissance
- Vietnam thermal imagery and radar
- 'Cold War' U2 & spy satellites
- Gulf War high resolution VIR / radar / thermal

4. **Remote Sensing from Space**

- October 4, 1957 ?
- April 1, 1960 TIROS-1
- Humans in space
- Spy satellites
- Resource satellites visible and infrared
- Radar satellites
- High spatial resolution satellites

Unconventional Definitions of Remote Sensing !!

Advanced colouring-in.

(Rob Preston, Queensland Forest Service, Australia)

The art of dividing up the world into little multi-coloured squares and then playing computer games with them to release unbelievable potential that's always just out of reach.

(Jon Huntington, CSIRO Exploration, Geoscience, Australia)

Remote sensing is the most expensive way to make a picture.

(Andrew Bashfield, Intergraph Corporation)

Seeing what can't be seen, then convincing someone that you're right.

(David Pairman, Landcare Research, New Zealand)

A completely useless endeavour, designed to employ people who have no productive skills but are criminally capable.

(Tom Alföldi, Canada Centre for Remote Sensing)

télédéception

(Ferdinand Bonn, University of Sherbrooke)

How to stay informed by being out of touch.

(John Mobbs, Australian Defense Force Academy)

Astronomy in the wrong direction.

(Tom Alföldi, Canada Centre for Remote Sensing)

Staying as far away from the problem as possible.

(G. Archer, World Bank)

Source: http://www.ccrs.nrcan.gc.ca/ccrs/whtisrs/rs_udefe.html

Electromagnetic Radiation (EMR)**Introduction**

- record the interaction of EMR with surface features
- understand the nature of EMR as well as its behaviour or interaction with the atmosphere and surface features

Electromagnetic Spectrum

Electromagnetic Energy consists of:

- (i) Electric Field
 - varies in magnitude
 - perpendicular to the direction of propagation
- (ii) Magnetic Field
 - perpendicular to the electrical field
 - in phase with electrical field

Properties of EMR: (i) Wavelength
 (ii) Frequency
 (iii) Amplitude

- EMR possesses characteristics described by two theories that relate wavelength, frequency and energy

1. Wave Theory

Three measurements define the wave character of EMR:

- a) Wavelength (λ)
- b) Wave Frequency (ν)
- c) Wave Velocity (c) 3×10^8 m/sec

Formula: $c = \lambda \nu$

Inverse relationship between wavelength and frequency.

2. Particle Model

- proposes that EMR is composed of many discrete units called photons or quanta

Formula: $Q = h \nu$
 where Q = energy of a quantum (Joules)
 h = Planck's constant (6.626×10^{-34} Jsec)
 ν = frequency (kilohertz)

Direct relationship between energy and frequency.

3. Wave + Particle Model

Wave Theory $c = \lambda \nu$ solve for ν $\nu = c/\lambda$

Substitute: Particle Theory $Q = h \nu$ $Q = hc/\lambda$

Inverse relationship between energy and wavelength.

Interactions with the Atmosphere

- effects dependent on altitude, wavebands recorded and environment

Scattering

a) Rayleigh Scatter

- particles are small relative to wavelength
- affects shorter wavelengths (e.g., small dust particles, N₂, O₂)

b) Mie Scatter

- particle size approx. equal to wavelength
- longer wavelengths in or near the visible spectrum (e.g., dust, pollen, smoke)

c) Non-selective Scatter

- large particles
- affects all visible and near-infrared wavelengths equally (e.g., water droplets)

Refraction

- occurs at contact points between air masses of different densities (e.g., humidity, temperature)

Absorption

- loss of energy to atmospheric components (H₂O, O₃, CO₂)
- wavelength dependent

Atmospheric Windows

- wavelength ranges where the atmosphere is particularly transmissive of energy
e.g., visible to near-infrared (0.4 μm - 1.1 μm)
thermal (3 - 5 μm) (8 - 14 μm)

Interactions with the Atmosphere

1. Reflection
2. Absorption
3. Transmission

Proportions depend on

- nature of the surface
- wavelength
- angle of illumination

Energy Equation:

$$E_i(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda)$$

Spectral Reflectance (Albedo): $\rho_\lambda = [E_R(\lambda)/E_i(\lambda)] \times 100$ **Spectral Reflectance Curve**

- describes the spectral properties of an object
- function of space and time

IMAGE RESOLUTION

A) SYSTEM VARIABLES

- (i) Sensor Components
- (ii) Platform Conditions

B) TARGET VARIABLES

- (i) Contrast in the Scene (target verses background)
- (ii) Shapes (regular shapes favour high spatial resolution)
- (iii) Regular Patterns
- (iv) Extent and Uniformity of Background

C) ATMOSPHERIC CONDITIONS

RESOLVING POWER

A) SPATIAL RESOLUTION

- (i) the capability of a sensor to distinguish between small objects
- (ii) the **dimensions** of the ground area sensed at any instant in time

B) RADIOMETRIC RESOLUTION

- (i) the capability of a sensor to distinguish small differences in **energy intensity**
- (ii) the number of **discrete levels** into which an analog signal can be divided
(e.g., 8 bit data = 256 levels)

C) SPECTRAL RESOLUTION

- (i) **Number** of Wavebands Sensed
- (ii) **Width** of Wavebands Sensed

Spatial, Radiometric and Spectral Resolution are all **interrelated** (i.e., changes in one will affect the others, in terms of the characteristics/quality of the data recorded).

D) TEMPORAL RESOLUTION

- (i) **Time** of year that data is acquired (seasonality) (optimize for application)
- (ii) **Repetitive** Coverage

Signal Noise and the Signal to Noise (S/N) Ratio

Data quality is directly related to the noise level relative to the signal strength. Thus, the quality of multispectral data can be expressed by the signal-to-noise ratio which is specific to each waveband. The S/N directly affects the radiometric resolution of the data and is closely related to spatial and spectral resolution.

S/N is also affected by: the detector performance quality;
spectral radiance of the ground features;
atmospheric attenuation;
design of the system's optical components; and
the noise of the system electronics.

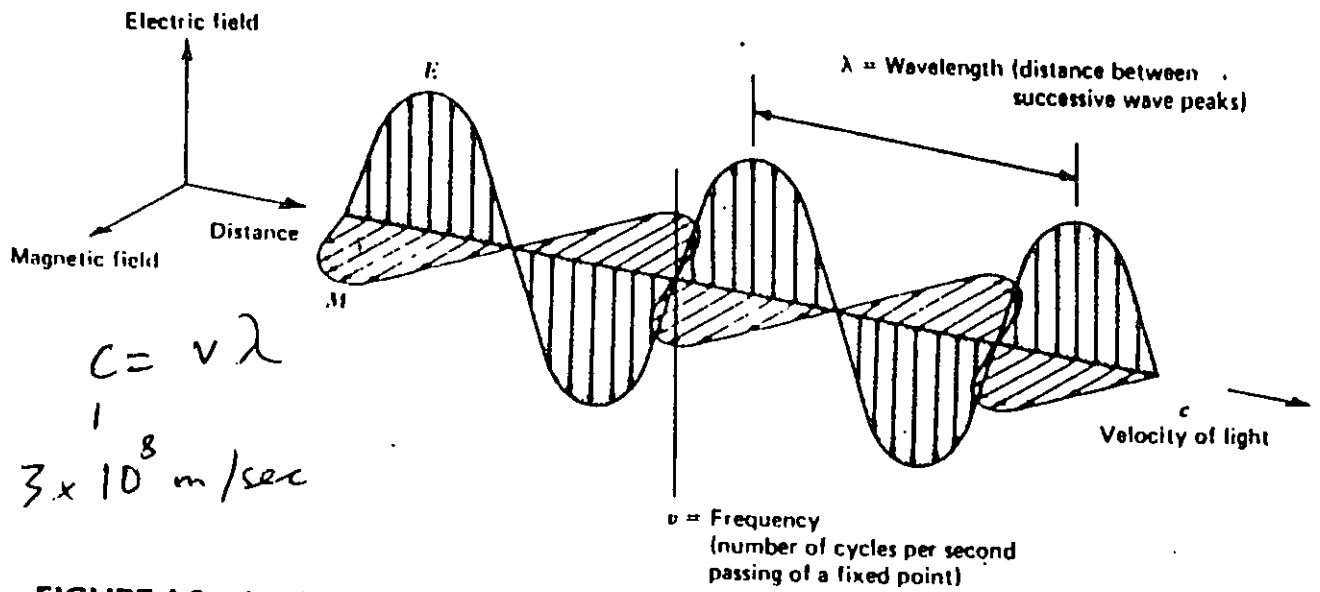


FIGURE 1.2 An electromagnetic wave. Components include a sinusoidal electric wave (E) and a similar magnetic wave (M) at right angles, both being perpendicular to the direction of propagation.

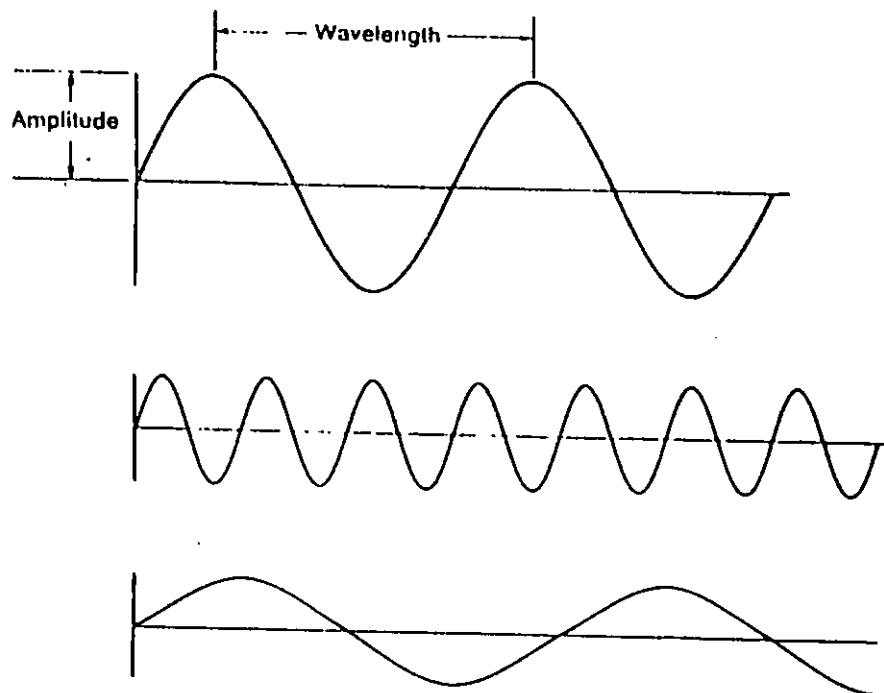


Figure 2.2. Amplitude, frequency, and wavelength. The center diagram represents high frequency, short wavelength; the bottom diagram shows low frequency, long wavelength.

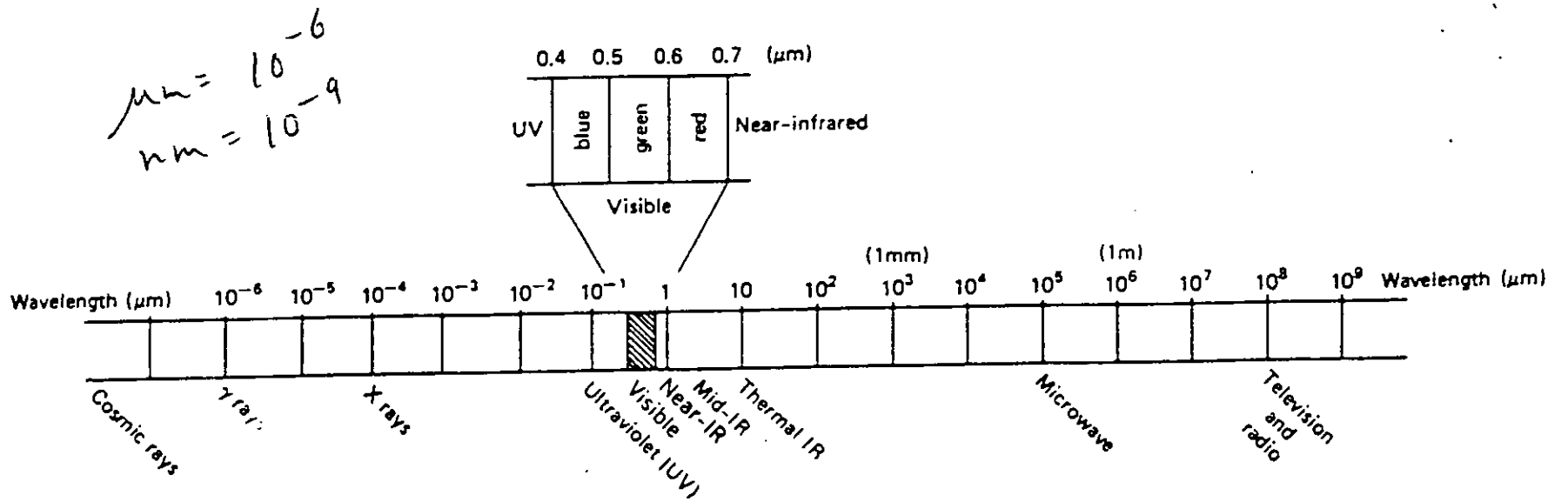


FIGURE 1.3 The electromagnetic spectrum.

$1 \text{ Hz} = 1 \text{ cycle/sec}$
 $\text{MHz} = 10^6$
 $\text{GHz} = 10^9$

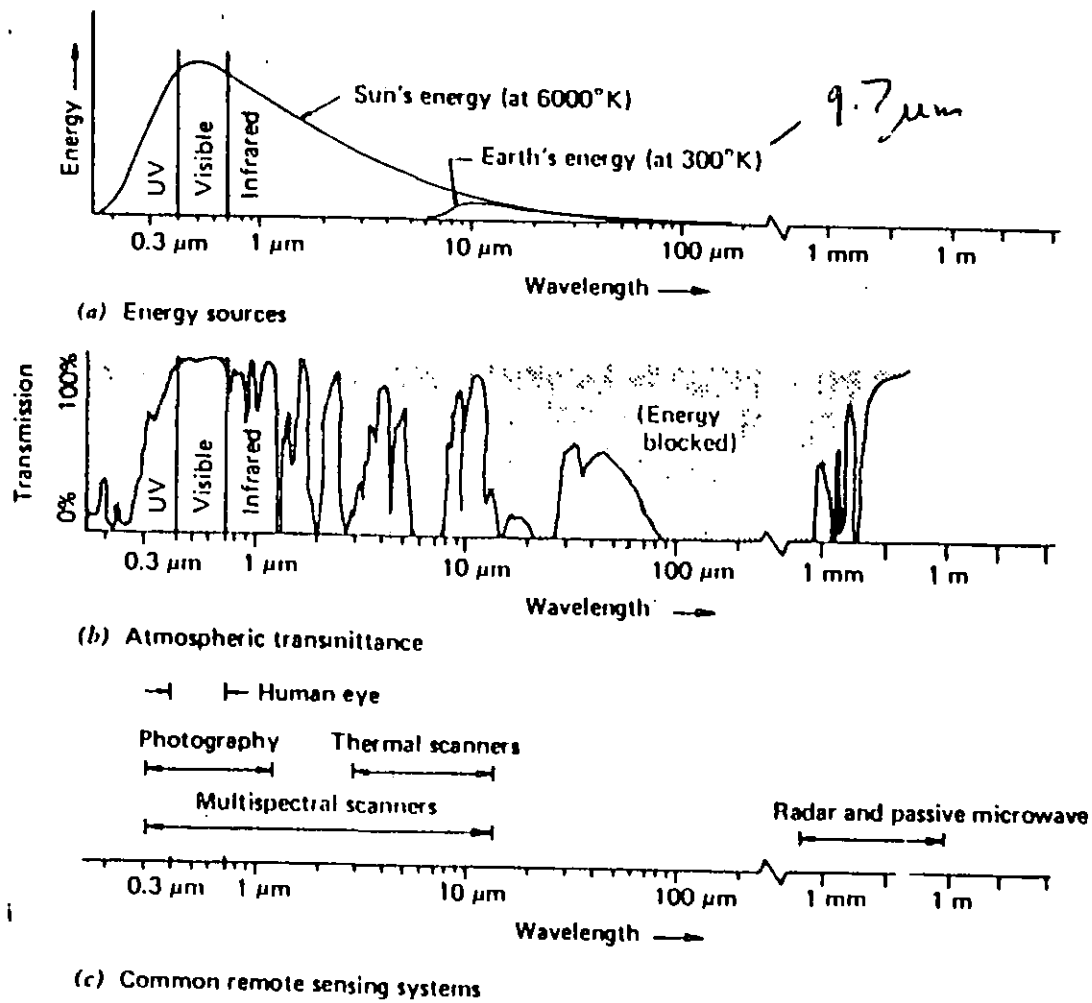


FIGURE 1.5 Spectral characteristics of (a) energy sources, (b) atmospheric effects, and (c) sensing systems. (Note that wavelength scale is logarithmic.)

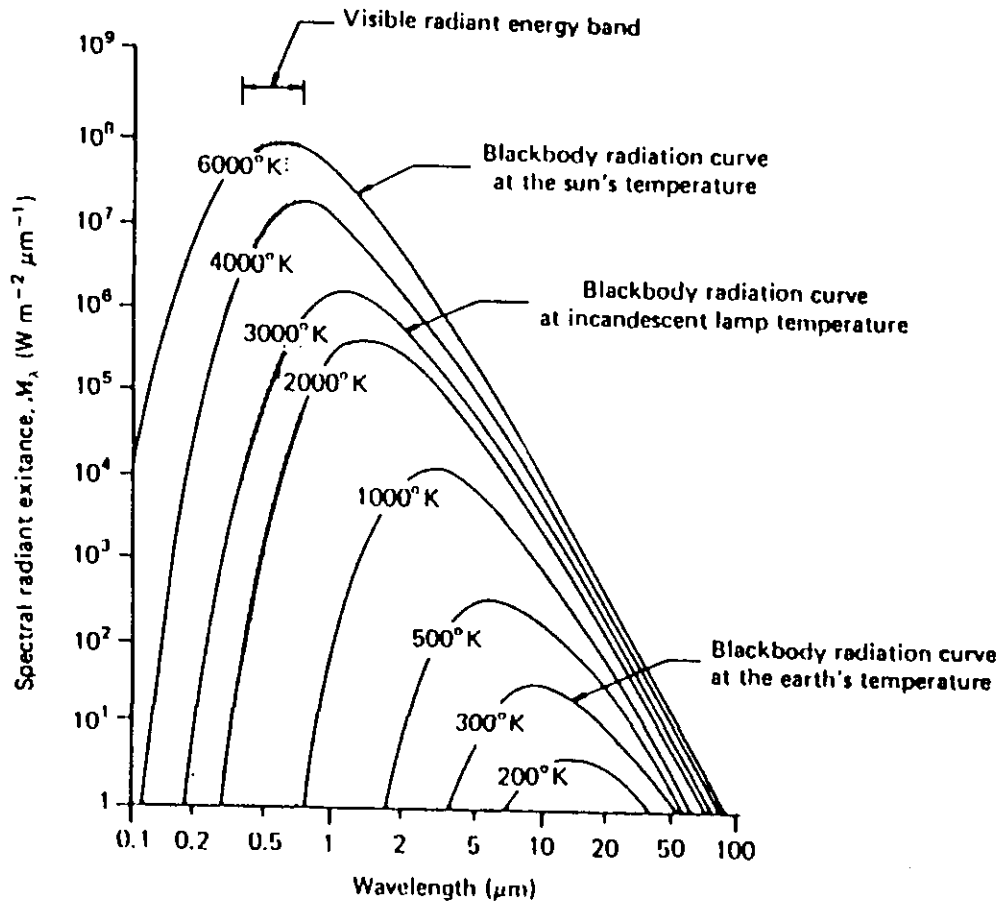
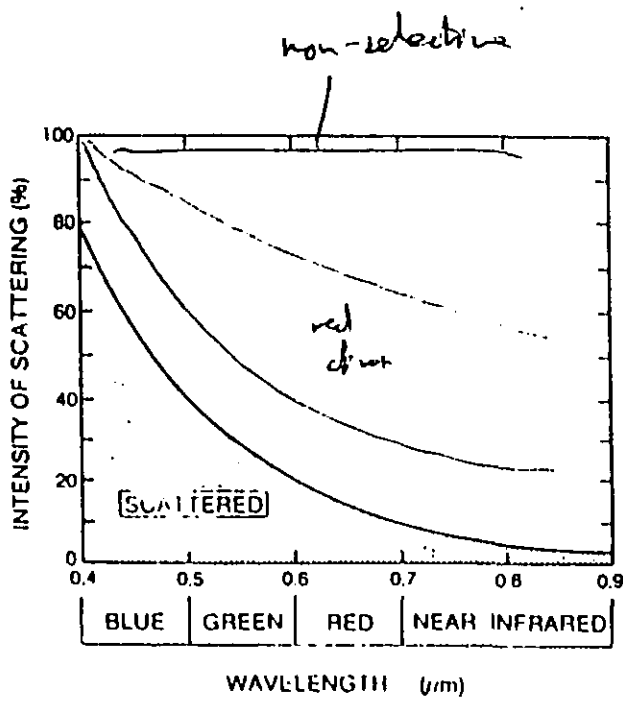


FIGURE 1.4 Spectral distribution of energy radiated from blackbodies of various temperatures. (Note that spectral radiant exitance, M_λ , is the energy emitted per unit wavelength interval. Total radiant exitance, M , is given by the area under the spectral radiant exitance curves.)



Rayleigh $\lambda < 1$ - air molecules, N_2, O_2
 Mie 0.1 - 10 - smoke, fumes, haze
 Non-selective > 10 - dust, fog, clouds.

Figure 2.7. Rayleigh scattering. Amount of scattering increases greatly as wavelength becomes shorter.

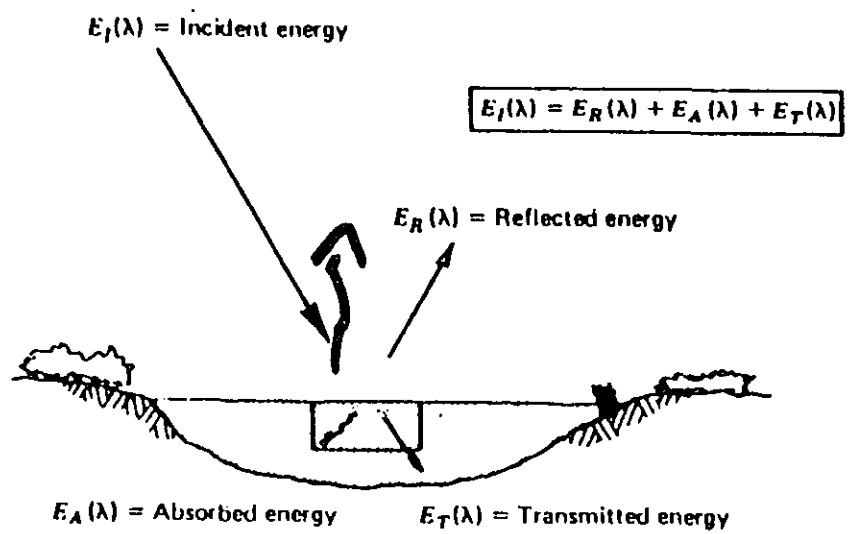
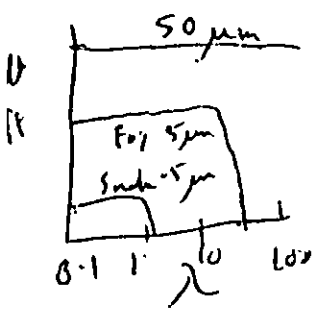


FIGURE 1.6 Basic interactions between electromagnetic energy and an earth surface feature.

$$E_H(\lambda) = E_i(\lambda) - [E_A(\lambda) + E_T(\lambda)]$$

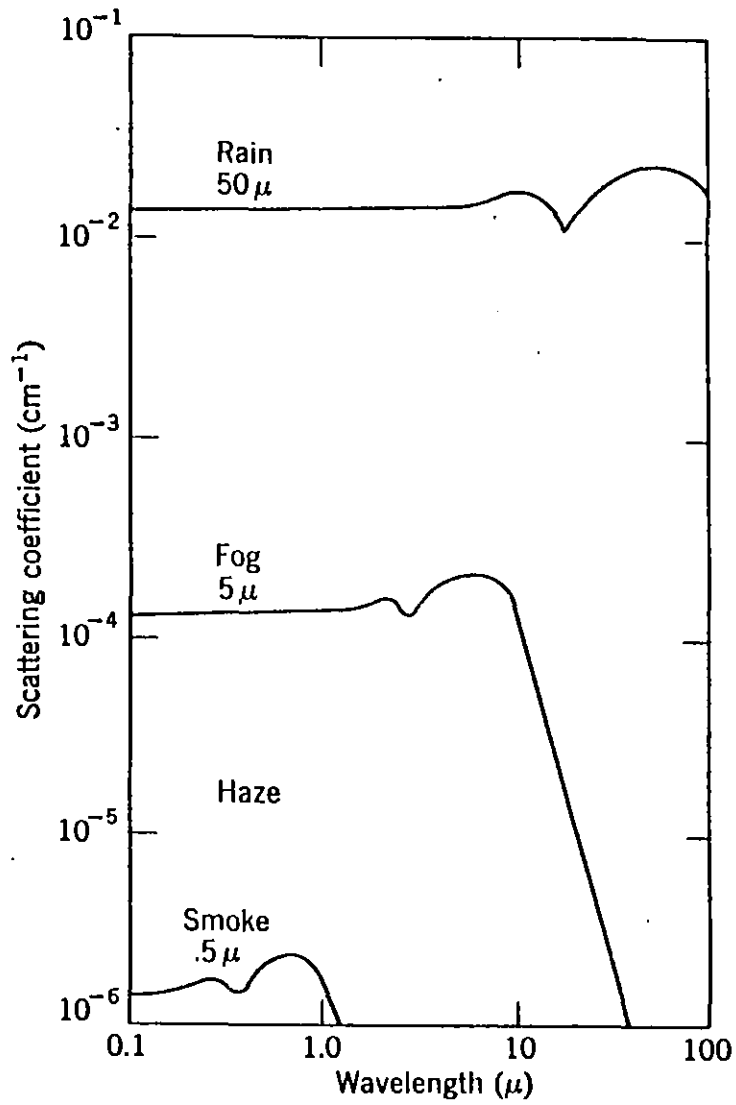


FIGURE 5.3 The scattering coefficient as a function of wavelength and particle size.

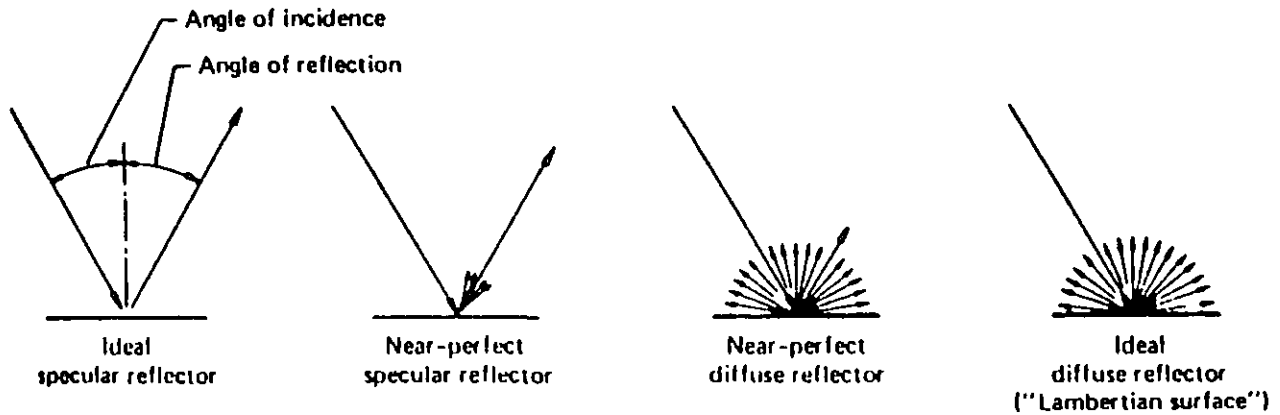


FIGURE 1.7 Specular versus diffuse reflectance. (We are most often interested in measuring the diffuse reflectance of objects.)

The reflectance characteristics of earth surface features may be quantified by measuring the portion of incident energy that is reflected. This is measured as a function of wavelength and is called *spectral reflectance*, ρ_λ . It is mathematically defined as

$$\rho_\lambda = \frac{E_R(\lambda)}{E_I(\lambda)} = \frac{\text{energy of wavelength } \lambda \text{ reflected from the object}}{\text{energy of wavelength } \lambda \text{ incident upon the object}} \times 100$$

where ρ_λ is expressed as a percentage.

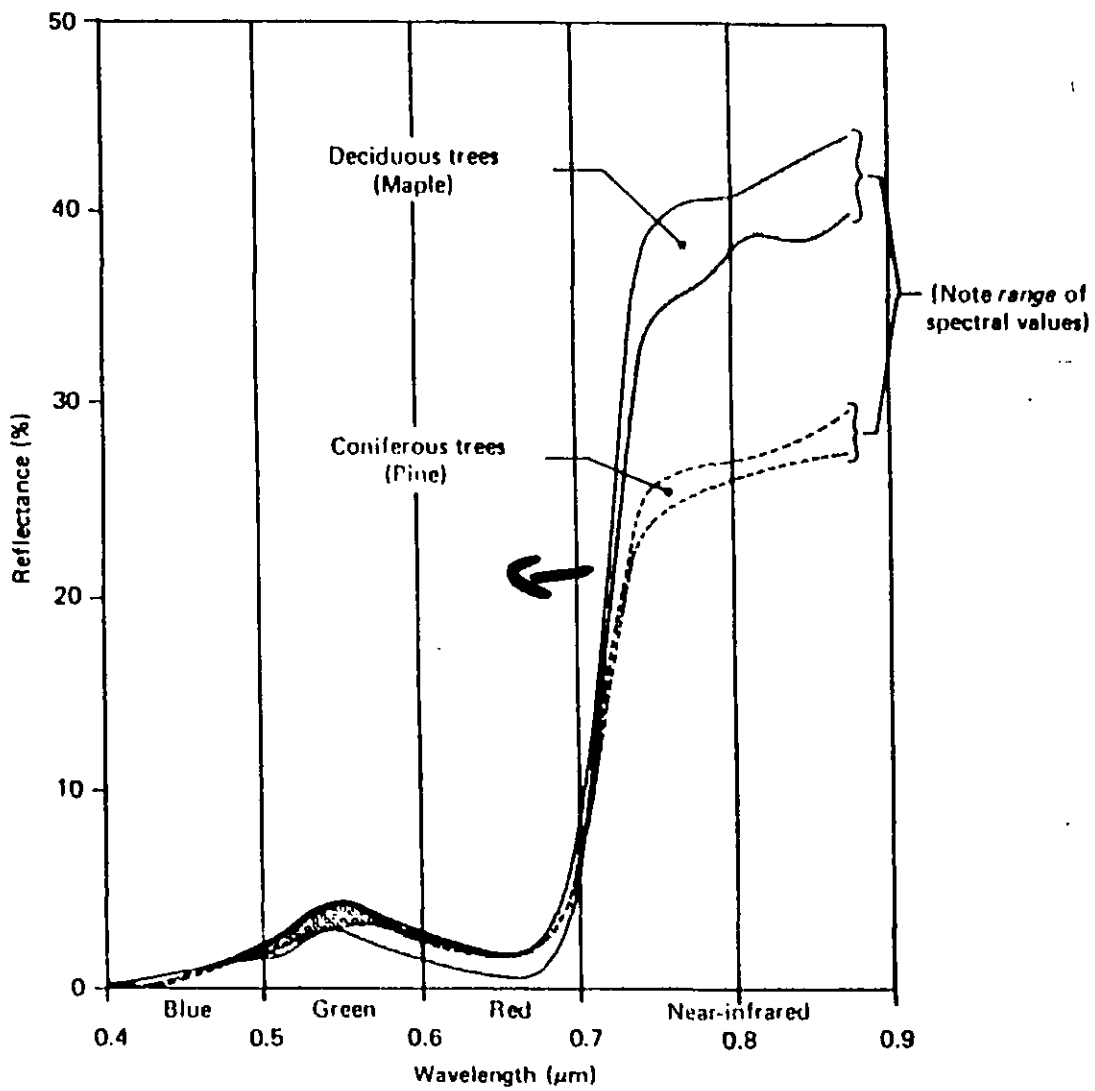


FIGURE 1.8 Generalized spectral reflectance envelopes for deciduous (broad-leaved) and coniferous (needle-bearing) trees. (Each tree type has a range of spectral reflectance values at any wavelength.) (Adapted from [17].)

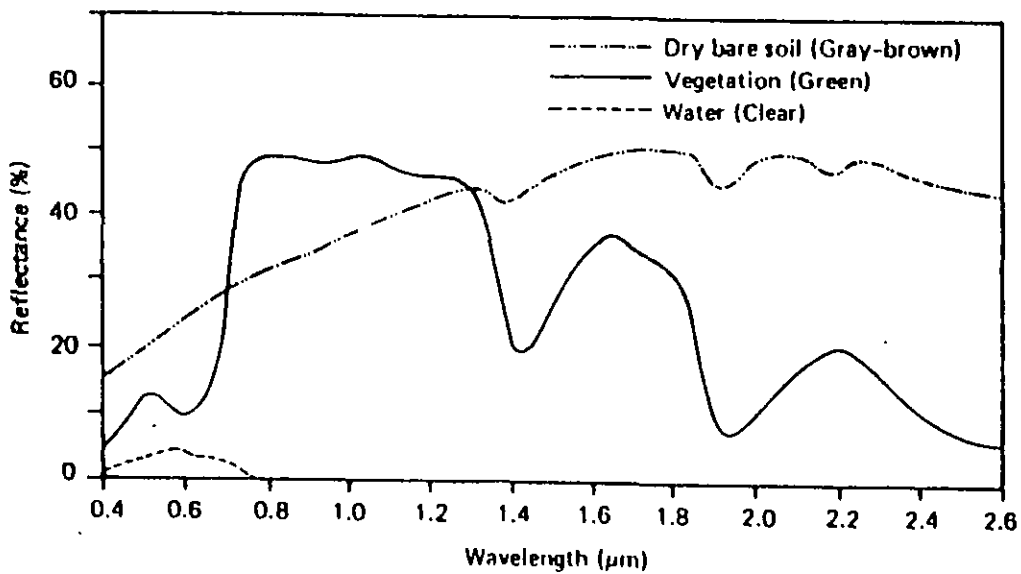
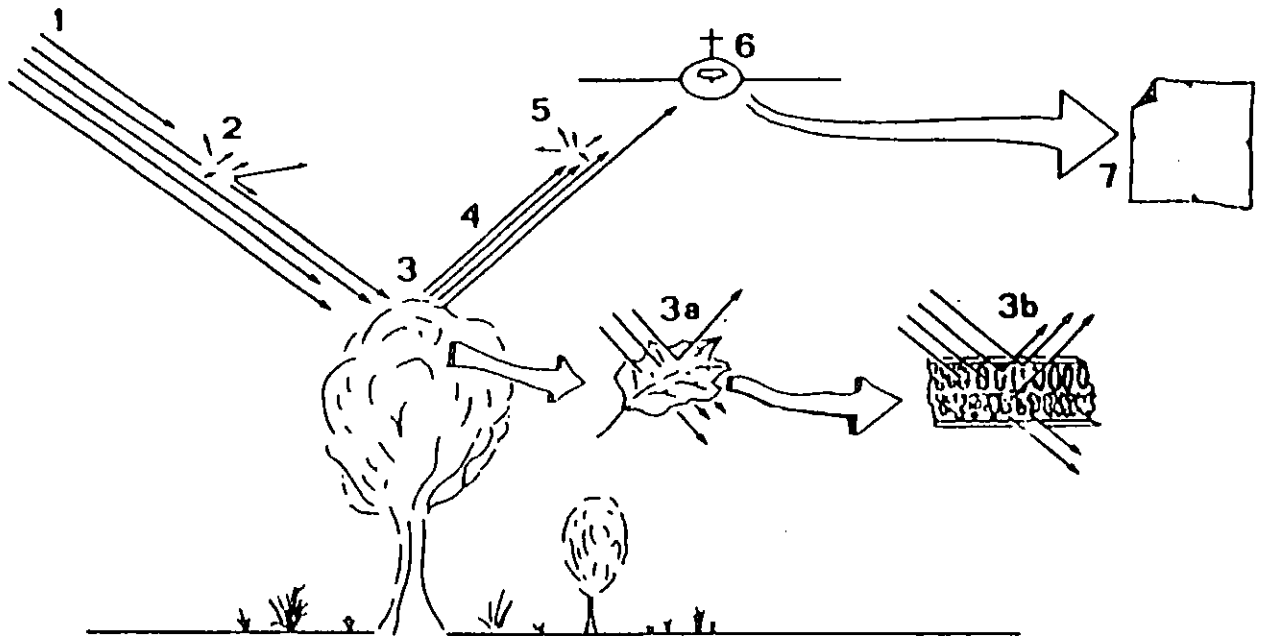


FIGURE 1.10 Typical spectral reflectance curves for vegetation, soil, and water. (Adapted from [27].)



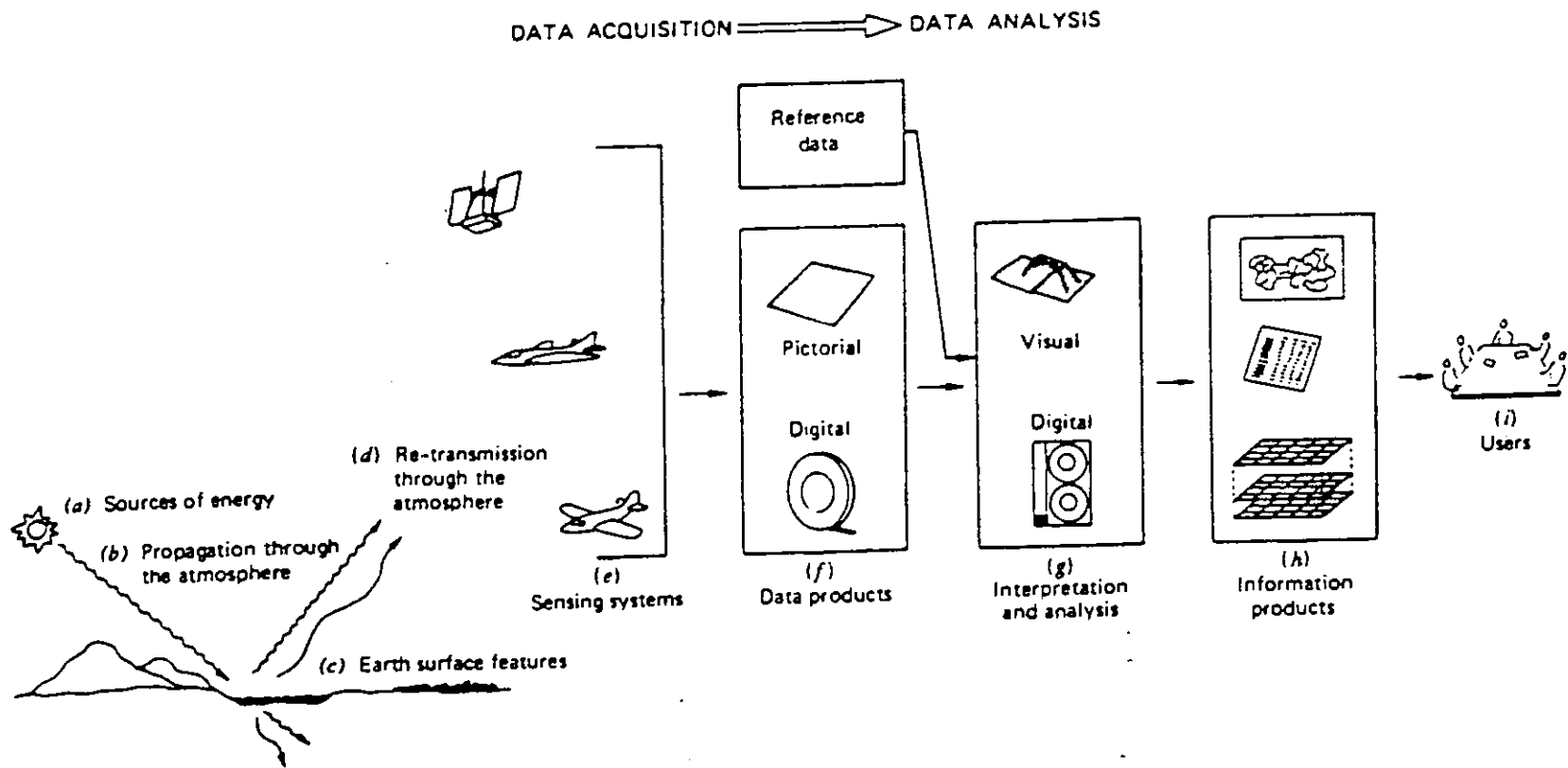
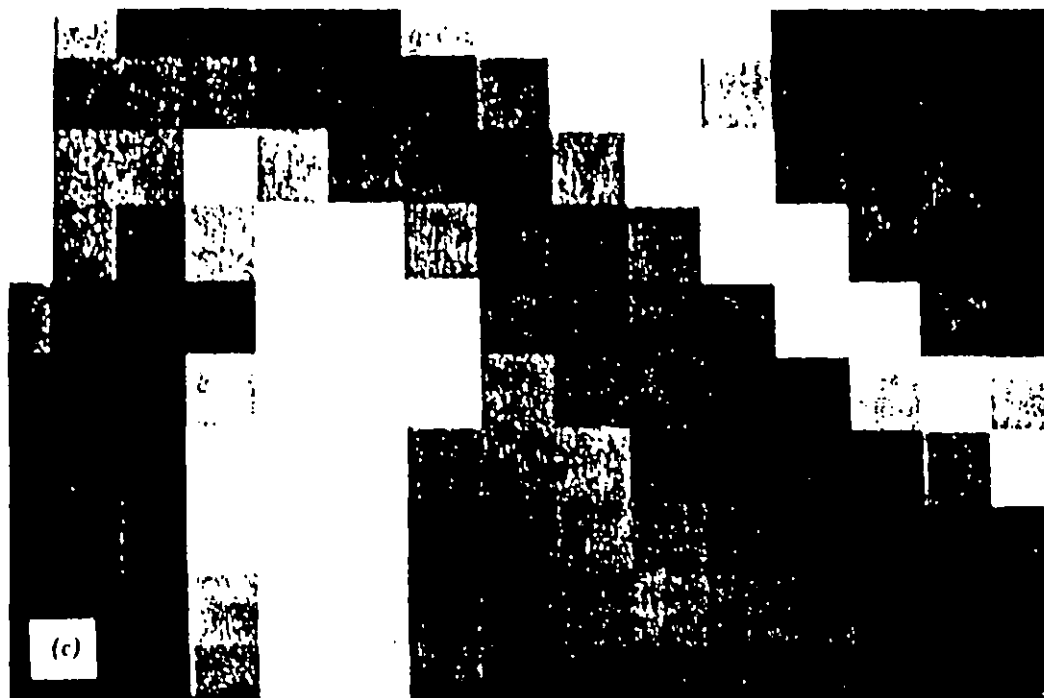


FIGURE 1.1 Electromagnetic remote sensing of earth resources.



54	40	31	27	27	28	39	51	52	50	45	25	24	24	23
55	37	37	35	31	27	26	35	58	66	38	13	17	21	19
56	40	39	45	39	32	27	26	36	52	50	28	14	13	14
52	39	33	42	49	48	36	31	26	33	51	51	31	16	16
42	34	24	30	60	67	49	33	27	28	31	47	51	35	24
26	29	26	44	76	76	49	37	33	30	29	29	44	52	44
14	31	36	50	85	70	36	37	38	30	25	29	28	40	52
20	31	39	51	72	56	35	35	37	35	31	27	29	31	36
21	26	36	46	58	49	37	35	36	37	34	33	26	29	30
21	20	29	43	54	53	40	31	30	32	30	29	24	22	27

(d)

FIGURE I.11

(continued)

GREEN. RED INFRARED

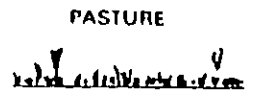
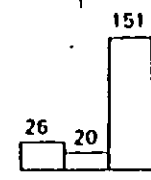
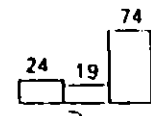
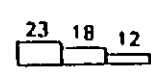
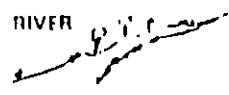
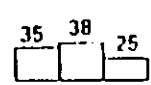
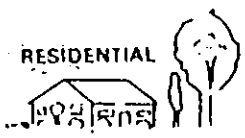
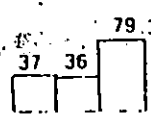
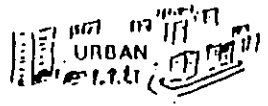
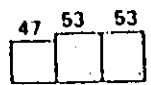
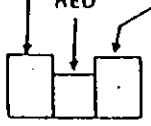


Figure 2.15. Spectral signatures.

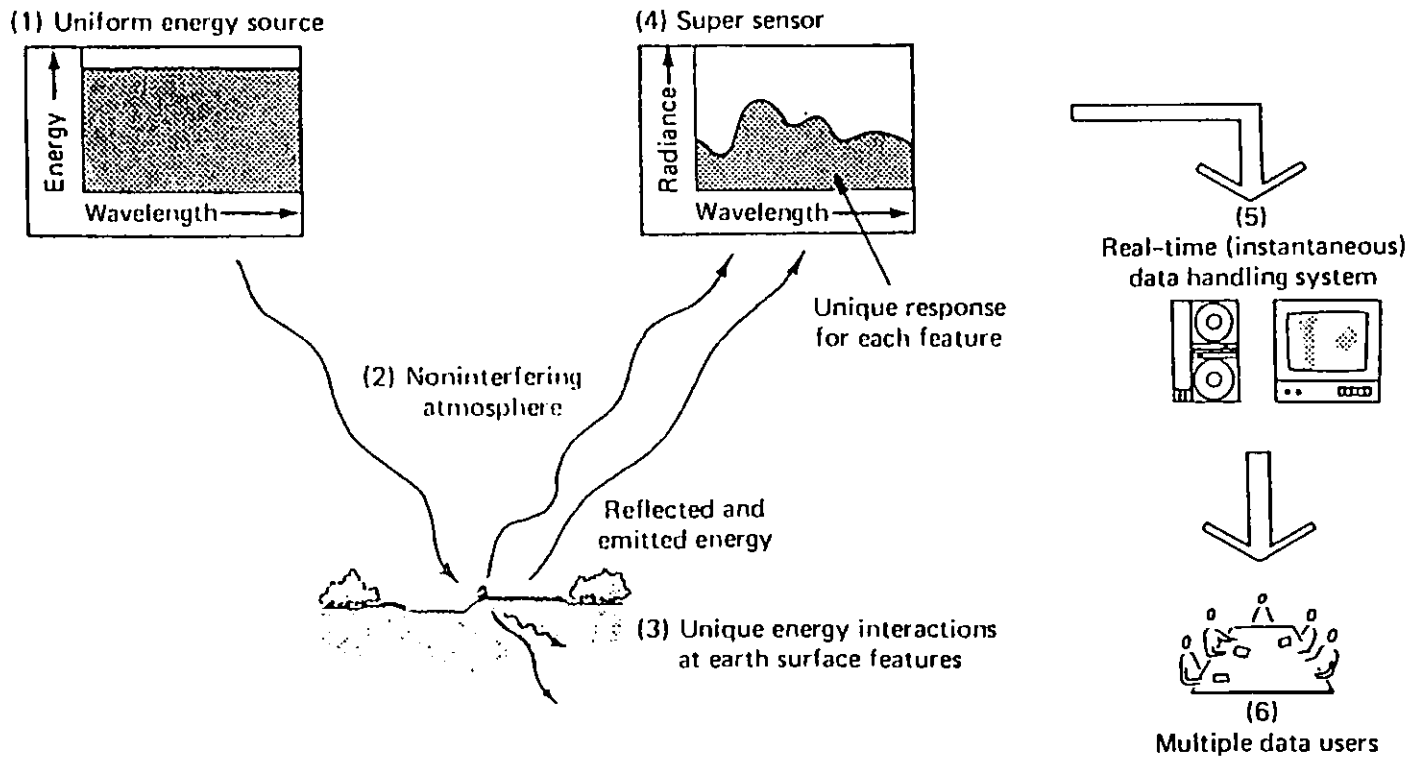


Figure 1.16 Components of an ideal remote sensing system.

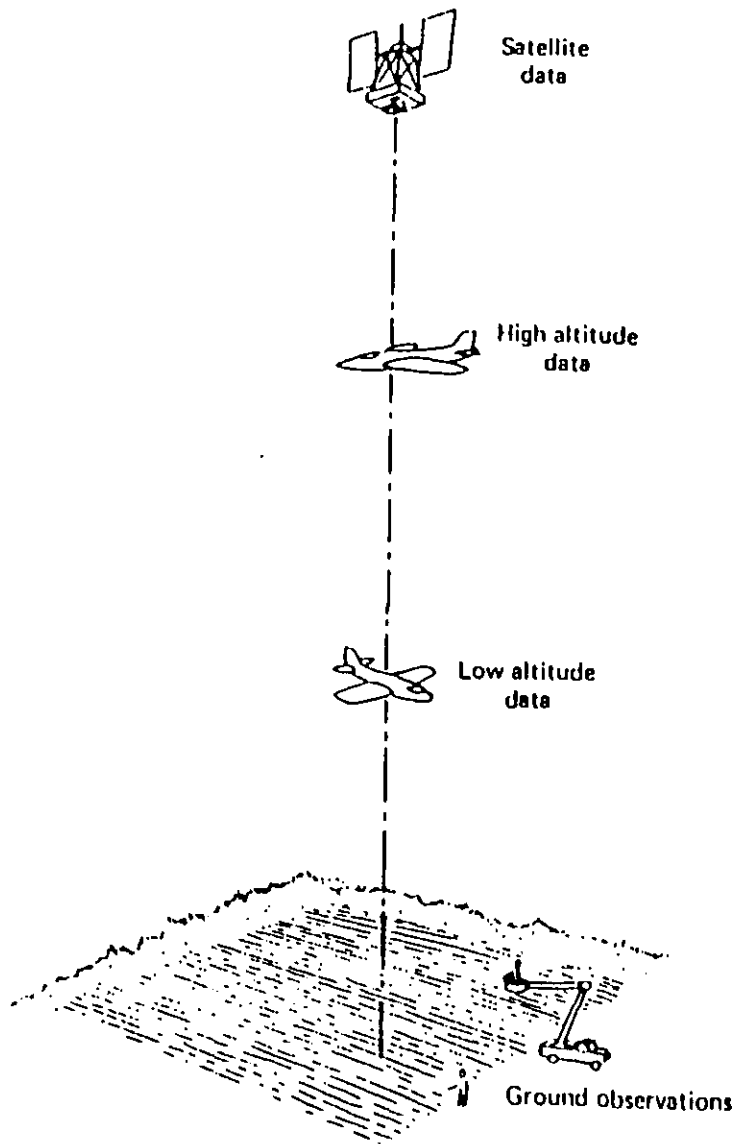


FIGURE I.15 Multistage remote sensing concept.

Earth-Observation Satellites and Sensors

Remote Sensors

Technology

Five basic sensor types:

- a) photographic cameras (film/digital)
- b) television/video cameras
- c) multispectral sensors
- d) radiometers
- e) radar systems

Wavelength of Operation

Sensor Type	Photographic & Video Cameras	MSS, Imaging Spectrometers & Radiometers	Radiometers	Radar Systems
Wavelength	Near UV, Visible, Near and Middle Infrared	Far Infrared	Microwave	
Energy source	Passive/Reflected	Passive/Emitted	Active/Reflected	

Energy source

- Active/Passive

Temporal Capability

- generally, as wavelength increases, sensing becomes less sensitive to:
 - a) time of day; and
 - b) weather conditions

Platform

Table 2-2. Characteristics of Selected Multispectral Remote Sensing Systems

Band	Bandwidth (μm)	IFOV (m)	Quantization (bits)	Off Nadir Viewing	Temporal Resolution (days)	Altitude (km)	Total Data Rate (Mbits/s)	Number Pixels per Line	Swath Width (km)
Landsat Multispectral Scanner (MSS) on ERTS 1, 2 and Landsat 3, 4, and 5									
4 ^a	0.50-0.60	79 × 79	6-8	No	18	917	15	2340	185
5	0.60-0.70								
6	0.70-0.80								
7	0.80-1.10								
8 ^b	10.4-12.6	240 × 240							
Landsat Thematic Mapper (TM) on Landsat 4 and 5									
1	0.45-0.52	30 × 30	8	No	16	705	85	3000	185
2	0.52-0.60	30 × 30							
3	0.63-0.69	30 × 30							
4	0.76-0.90	30 × 30							
5	1.55-1.75	30 × 30							
6	10.4-12.5	120 × 120							
7	2.08-2.35	30 × 30							
NOAA Advanced Very High Resolution Radiometer (AVHRR -12) Local Area Coverage (LAC) Data									
1	0.58-0.68	1100 × 1100	8	No	Daily	861 and 845	—	—	2700
2	0.725-1.10	1100 × 1100							
3	3.55-3.93	1100 × 1100							
4	10.3-11.3	1100 × 1100							
5	11.5-12.5	1100 × 1100							
Daedalus DS-1260 Multispectral Scanner									
1	0.38-0.42	Variable	8	No	Variable	Variable	—	799	Variable
2	0.42-0.45	Variable							
3	0.45-0.50	Variable							
4	0.50-0.55	Variable							
5	0.55-0.60	Variable							
6	0.60-0.65	Variable							
7	0.65-0.70	Variable							
8	0.70-0.79	Variable							
9	0.80-0.89	Variable							
10	0.92-1.10	Variable							
11	8.50-13.5	Variable							
Daedalus DS-1268 Multispectral Scanner									
1	0.42-0.45	Variable	8	No	Variable	Variable	—	799	Variable
2	0.45-0.52	Variable							
3	0.52-0.60	Variable							
4	0.60-0.62	Variable							
5	0.63-0.69	Variable							
6	0.69-0.75	Variable							
7	0.76-0.90	Variable							
8	0.91-1.05	Variable							
9	1.55-1.75	Variable							
10	2.08-2.35	Variable							
11	8.50-14.0	Variable							

Table 2-2. Characteristics of Selected Multispectral Remote Sensing Systems (Continued)

Band	Bandwidth (μm)	IFOV (m)	Quantization (bits)	Off Nadir Viewing	Temporal Resolution (days)	Altitude (km)	Total Data Rate (Mbits/s)	Number Pixels per Line	Swath Width (km)
Daedalus Airborne Multispectral Scanner (AMS)									
1	0.42-0.45	Variable	8-12	No	Variable	Variable	—	714	Variable
2	0.45-0.52	Variable							
3	0.52-0.60	Variable							
4	0.60-0.63	Variable							
5	0.63-0.69	Variable							
6	0.69-0.75	Variable							
7	0.76-0.90	Variable							
8	0.91-1.05	Variable							
9	3.00-5.50	Variable							
10	8.50-12.5	Variable							
NASA Calibrated Airborne Multispectral Scanner (CAMS)									
1	0.42-0.52	Variable	8	No	Variable	Variable	—	700	Variable
2	0.52-0.60	Variable							
3	0.60-0.63	Variable							
4	0.63-0.69	Variable							
5	0.69-0.76	Variable							
6	0.76-0.90	Variable							
7	1.55-1.75	Variable							
8	2.08-2.35	Variable							
9	10.5-12.5	Variable							
NASA Thermal Infrared Multispectral Scanner (TIMS)									
1	8.20-8.60	Variable	8	No	Variable	Variable	—	800	Variable
2	8.60-9.00	Variable							
3	9.00-9.40	Variable							
4	9.40-10.2	Variable							
5	10.2-11.2	Variable							
6	11.2-12.2	Variable							
French SPOT High Resolution Visible Sensor Systems (HRV) 1, 2, and 3									
Multispectral Mode									
1	0.50-0.59	20 × 20	8	Yes	Variable	832	25	3000	60
2	0.61-0.68	20 × 20							
3	0.79-0.89	20 × 20							
Panchromatic Mode									
1	0.51-0.73	10 × 10	8	Yes	Variable	832	25	6000	60
Indian IRS-1A and IRS-1B Linear Imaging Self Scanning Camera (LISS)									
LISS I									
1	0.45-0.52	72 × 72	8	No	22	904	—	—	148
2	0.52-0.59	72 × 72							
3	0.62-0.68	72 × 72							
4	0.77-0.86	72 × 72							
LISS II, consists of two CCD cameras									
1-4	Same as above	36.25 × 36.25	8	No	22	904	—	—	74 per sensor

Table 2-2. Characteristics of Selected Multispectral Remote Sensing Systems (Continued)

Band	Bandwidth (μm)	IFOV (m)	Quantization (bits)	Off Nadir Viewing	Temporal Resolution (days)	Altitude (km)	Total Data Rate (Mbits/s)	Number Pixels per Line	Swath Width (km)
European Remote Sensing Satellite (ERS-1) Active Microwave Instrument (AMI), Operates in three Modes									
SAR Image Mode									
	5.3 GHz C-band	$\leq 26.3 \times 30^c$	8	—	35	785	—	—	100
SAR Wave Mode									
	5.3-GHz C-band	$\leq 26.3 \times 30$	8	—	35	785	—	—	9.6–12
SAR Wind Scatterometer									
	5.3 GHz ± 52 kHz	≥ 45 km	8	—	35	785	—	—	500
RADARSAT Synthetic Aperture Radar (SAR) Operates in Seven Modes Using HH Polarization									
Standard	5.3-GHz C-band	25×28^c	—	—	4–6	793–821	85	—	100
Wide 1	5.3-GHz C-band	$48–30 \times 28$	—	—	4–6	793–821	85	—	165
Wide 2	5.3-GHz C-band	$32–25 \times 28$	—	—	4–6	793–821	85	—	150
Fine	5.3-GHz C-band	$11–9 \times 9$	—	—	4–6	793–821	85	—	45
ScanSAR N	5.3-GHz C-band	50×50	—	—	4–6	793–821	85	—	305
ScanSAR W	5.3-GHz C-band	100×100	—	—	4–6	793–821	85	—	510
Extended H	5.3-GHz C-band	$22–19 \times 28$	—	—	4–6	793–821	85	—	75
Extended L	5.3-GHz C-band	$63–28 \times 28$	—	—	4–6	793–821	85	—	170
Sea-Viewing Wide-Field-of-View Sensor (SeaWiFS)—Proposed EOS Earth Probe									
1	0.402–0.422	1130×1130	10	No	daily	705	—	—	2800
2	0.433–0.453	1130×1130	—	—	—	—	—	—	—
3	0.480–0.500	1130×1130	—	—	—	—	—	—	—
4	0.500–0.520	1130×1130	—	—	—	—	—	—	—
5	0.545–0.565	1130×1130	—	—	—	—	—	—	—
6	0.660–0.680	1130×1130	—	—	—	—	—	—	—
7	0.745–0.785	1130×1130	—	—	—	—	—	—	—
8	0.845–0.885	1130×1130	—	—	—	—	—	—	—
		Secondary product at 4.5×4.5 km	—	—	—	—	—	—	—
Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (JPL)									
	244 bands from 4–2.5 μm	20×20	12	No	Variable	20 km	20.4	—	11 km
Compact Airborne Spectrographic Imager (CASI) [Itres Research of Calgary, Alberta, Canada]									
	288 User-specified bands	Variable	8	No	Variable	Variable	Unknown	578	Variable
Multispectral Electro-optical Imaging System (MEIS)									
	8 User-specified bands	Variable	8	No	Variable	Variable	8.75	1024	Variable

^a MSS bands 4, 5, 6, and 7 were renumbered Bands 1, 2, 3, and 4 on Landsat 4 and 5.

^b MSS band 8 was present only on Landsat 3.

^c Range and azimuth resolution in meters.

Earth-Observation Satellites 1 Landsat MSS and TM

Lecture Outline

1. Introduction

2. History of the Landsat Satellites

Satellite	Launch	Decommissioned
ERTS 1 / Landsat 1	Jul. 23, 1972	Jan. 6, 1978
Landsat 2	Jan. 22, 1975	Feb. 25, 1982
Landsat 3	Mar. 5, 1978	Mar. 31, 1983
Landsat 4	July 16, 1982	?
Landsat 5	Mar. 1, 1984	
Landsat 6	Oct. 5, 1993	Failed on launch

3. Orbits and Coverage for Landsat 1 - 3

a) Orbit

- **sun-synchronous**

- What does this mean?

- satellite keeps pace with the rotation of the earth so that it is always in the sun on its descending orbit when it collects data

- Why has this been done?

- sun illumination is nearly constant for adjacent ground stations one day apart
 - sun illumination is nearly constant for repeat yearly coverage

- **near-polar at 900 km**

- What?

- does not go right over the pole - only covers to 82° N and 82° S.

- Why?

- orbital dynamics do not permit this to happen

- **nominal 9:42 a.m. equator crossing & approximate mean sun time**

- What?

- satellite is always acquiring data in mid-morning

- Why?

- less cloud cover than later in the day

- **14 orbits / 24 hours with period of 103.15 min**

What?

- timing to remain sun-synchronous at 900 km altitude

Why?

- relates to geometric and gravitational relationships

- **adjacent orbits on successive days**

What?

- path on Day 2 is always west of and adjacent to the path on Day 1

Why?

- provides similar spectral characteristics which aids in making mosaics

- **side-lap between orbits**

What?

- | | | |
|--------------------------|-----|-------|
| • minimum at the equator | 14% | 26 km |
| • maximum at 82° N | 85% | |
| • latitude 43°N | 40% | |

Why?

- because of the orbital pattern
- provides similar spectral characteristics which aids in making mosaics

b) Coverage

- **swath width**

What?

- 185 km coverage

Why?

- appropriate coverage to maintain near-vertical view
- data generated is within capability for data transmission rates

- **18-day repeat coverage**

What?

- takes 18 days to provide complete imagery of the globe (cloud-cover permitting)

Why?

- based on altitude of spacecraft, swath coverage and number of orbits per day

4. Orbits and Coverage for Landsat 4 - 5

a) Orbit

- sun-synchronous

- near-polar at **705 km**

Why?

- improved ground resolution
- potentially retrievable by the space shuttle

- nominal **9:45 a.m.** equator crossing
- **14.5 orbits / 24 hours** with period of **98.9 min**
Why?
 - due to lower orbit
- **adjacent swaths imaged 7 days apart**
What?
 - path on Day 8 is west of and adjacent to the path on Day 1
- Why?
 - better pattern to minimize problem of cloud cover

b) Coverage

- swath width 185 km
- **16-day repeat coverage**
Why?
 - different altitude compared with Landsat 1 - 3

4. Landsat Sensors

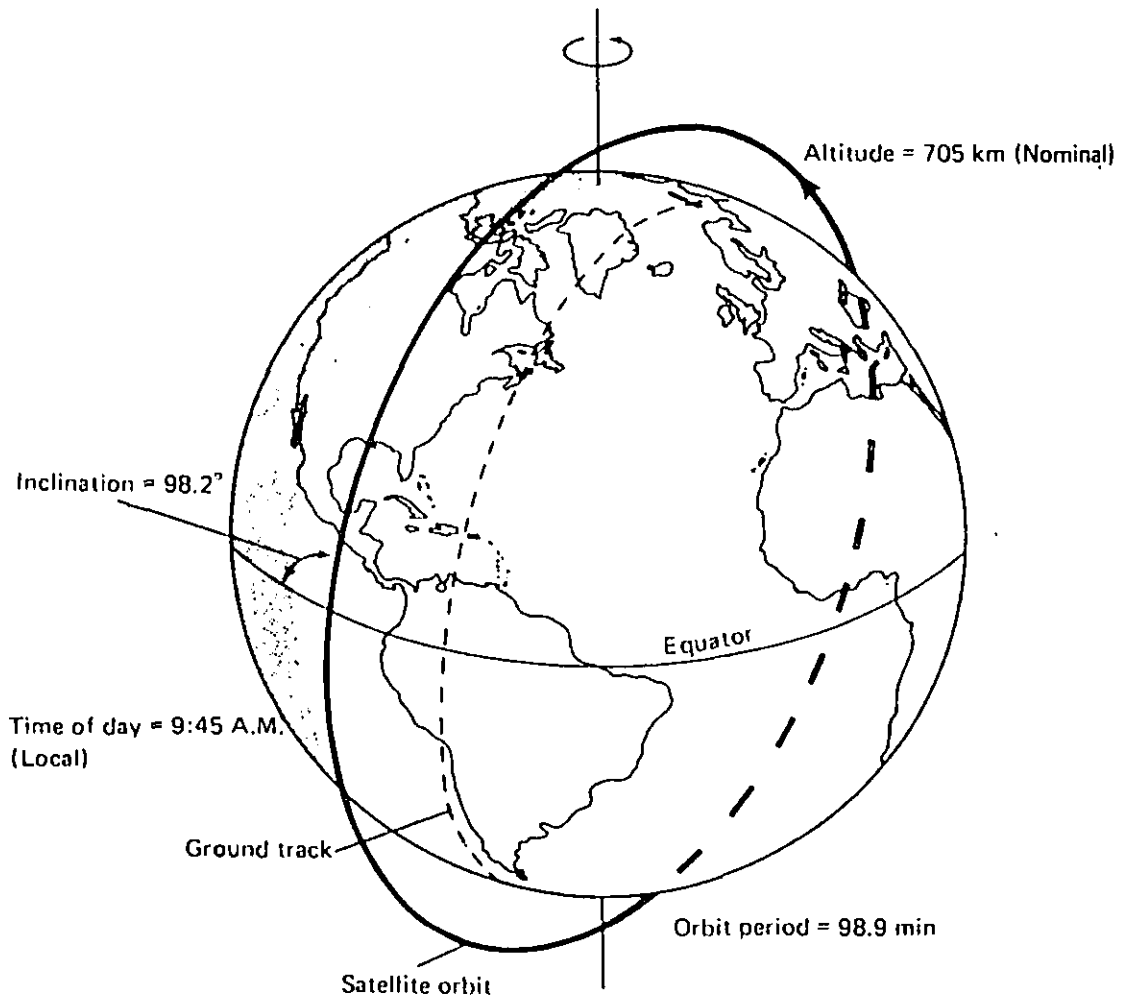
a) Multispectral Scanner

Mission	Band	Wavelengths	Spectral Region	Spatial Resolution
3 - 5	MSS1	0.5 - 0.6	Green	80 m x 80 m
	MSS2	0.6 - 0.7	Red	80 m x 80 m
	MSS3	0.7 - 0.8	Near IR	80 m x 80 m
	MSS4	0.8 - 1.1	Near IR	80 m x 80 m

b) Thematic Mapper

Mission	Band	Wavelengths	Spectral Region	Spatial Resolution
4 & 5	TM1	0.45 - 0.52	Blue	30 m x 30 m
	TM2	0.52 - 0.60	Green	30 m x 30 m
	TM3	0.63 - 0.69	Red	30 m x 30 m
	TM4	0.76 - 0.90	Near IR	30 m x 30 m
	TM5	1.55 - 1.75	Mid IR	30 m x 30 m
	TM6	10.4 - 12.5	Thermal IR	120 m x 120 m
	TM7	2.08 - 2.35	Mid IR	30 m x 30 m

c) Data Collection Platform



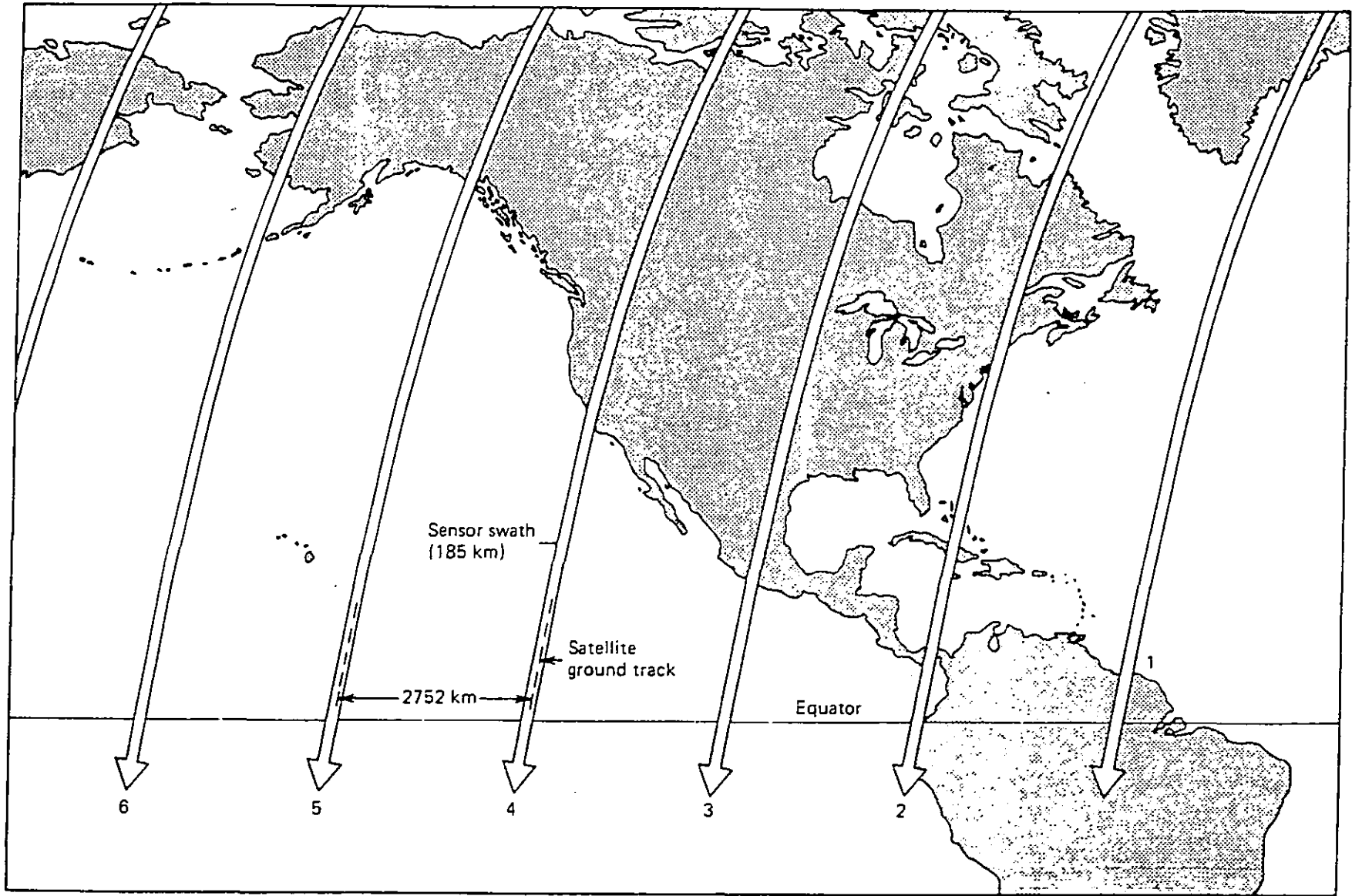


FIGURE 9.20 Spacing between adjacent Landsat-4 or -5 orbit tracks at the equator. The earth revolves 2752 km to the east at the equator between passes. (Adapted from NASA diagram.)

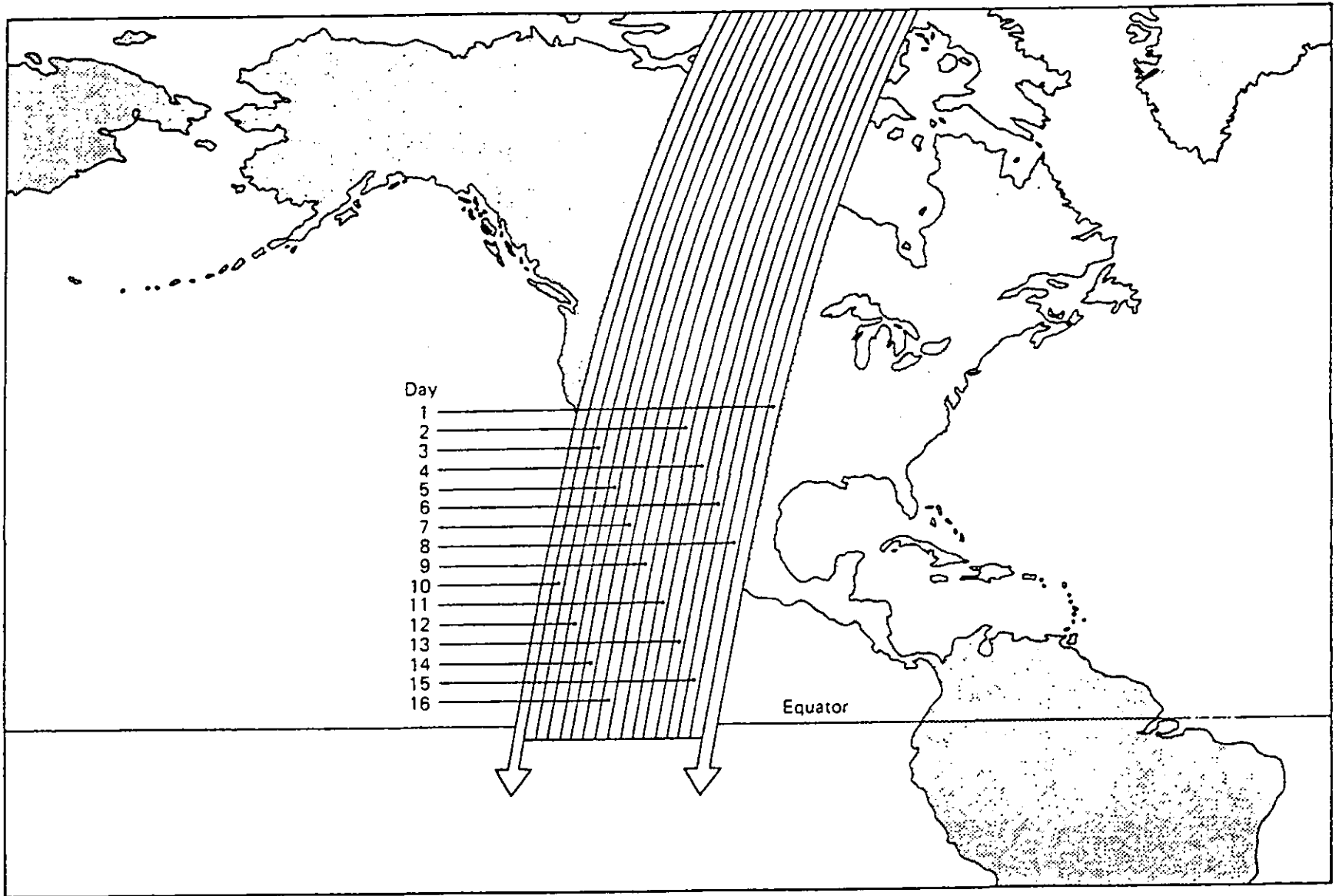


FIGURE 9.21 Timing of adjacent Landsat-4 or -5 coverage tracks. Adjacent swaths are imaged 7 days apart. (Adapted from NASA diagram.)

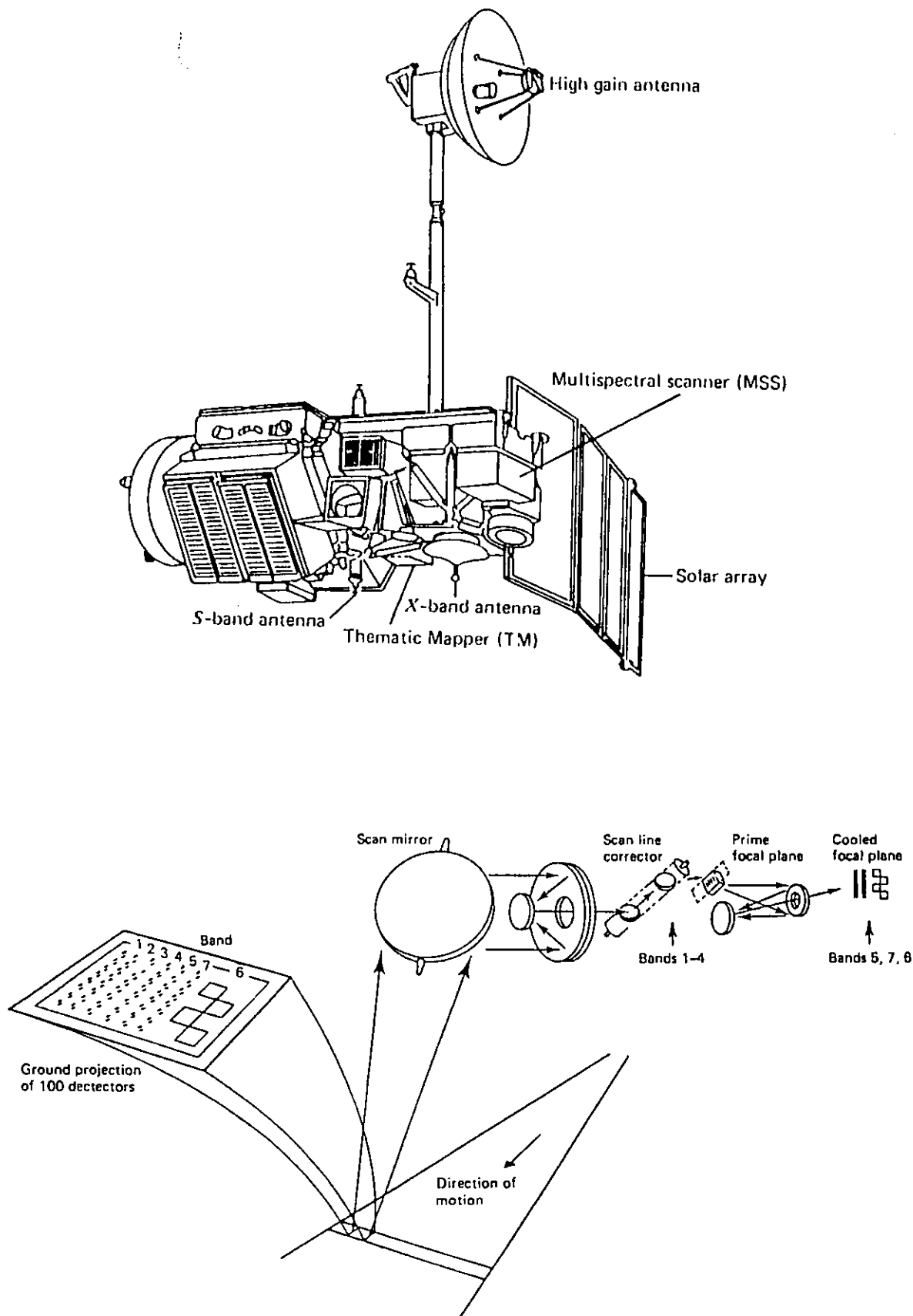


FIGURE 9.23 TM optical path and projection of detector IFOVs on earth surface. (Adapted from NASA diagram.)

Earth-Observation Satellites 2 Système Pour Observation de la Terre SPOT

1. Introduction

2. History of the SPOT Satellites

Satellite	Launch	Decommissioned
SPOT - 1	Feb. 21, 1986	Dec. 31, 1990
SPOT - 2	Jan. 21, 1990	?
SPOT - 3	Sep. 25, 1993	

3. Orbits and Coverage for SPOT 1 - 3

a) Orbit

- sun-synchronous
- near-polar at 832 km
- nominal 10:30 a.m. equator crossing & approximate mean sun time
- 14 orbits / 24 hours with period of 101.46 min
- 26 day repeat cycle
- side-lap between orbits

b) Coverage

- Nadir Viewing

- swath width

- What?

- 60 km coverage
- 117 km with two sensors operating

- Why?

- data generated is within capability for data transmission rates

- **26-day repeat coverage**

- Off-Nadir Viewing

- What?

- sensor looks to + or - 27°

- Why?

- increased coverage

equator	7 passes in 26 days
45° N	11 passes in 26 days

- stereoscopic view

- **swath width**

- What?

- 60 km - 80 km coverage within a 950 km wide strip

- Why?

- greatly increased coverage

- **3-day repeat coverage**

- **Revisit Capability**

- What?

- look at the same ground area from two different positions in space

- Why?

- stereoscopic view for mapping

4. SPOT Sensors

High Resolution Visible (HRV) Sensor

Mode	Band	Wavelengths	Spectral Region	Spatial Resolution
XS	1	0.50 - 0.59	Green	20 m x 20 m
	2	0.61 - 0.68	Red	20 m x 20 m
	3	0.79 - 0.89	IR	20 m x 20 m
Pan	1	0.51 - 0.73	G - R +	10 m x 10 m

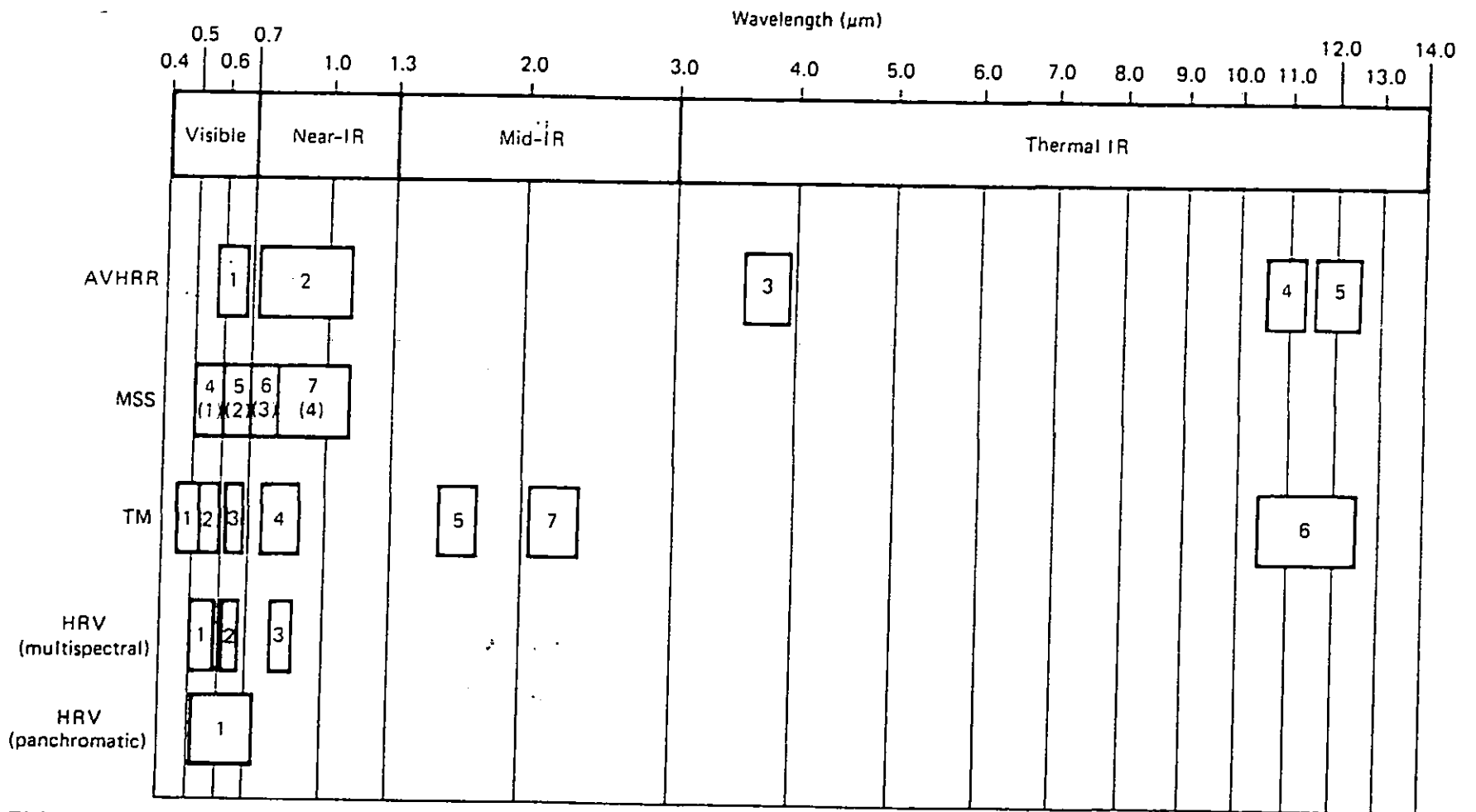
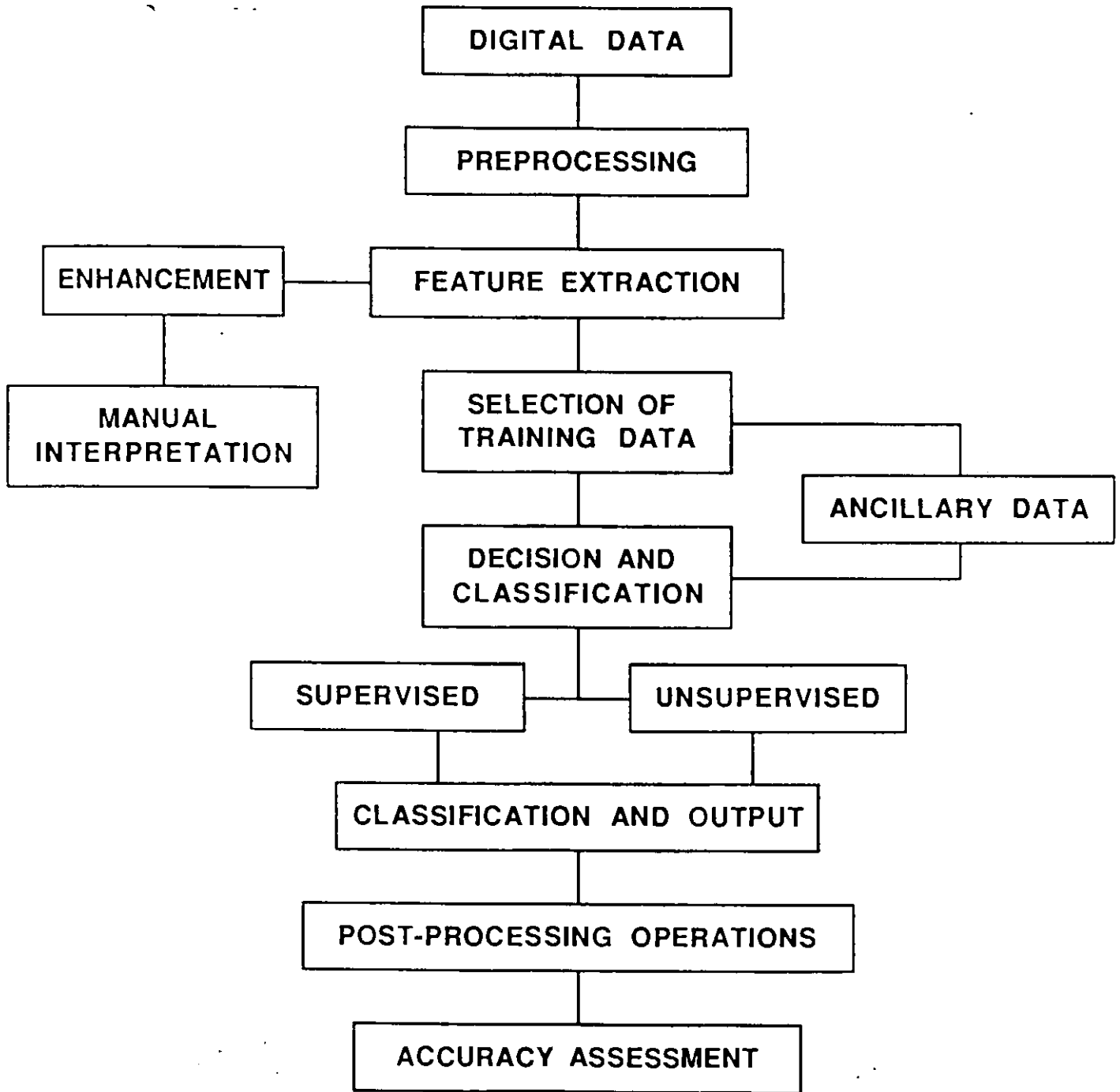


FIGURE 9.38 Summary of spectral sensitivity of NOAA AVHRR, Landsat MSS, Landsat TM, and SPOT HRV.

Introduction to Digital Image Analysis



Idealized Sequence for Digital Analysis

CAMPBELL (1987)

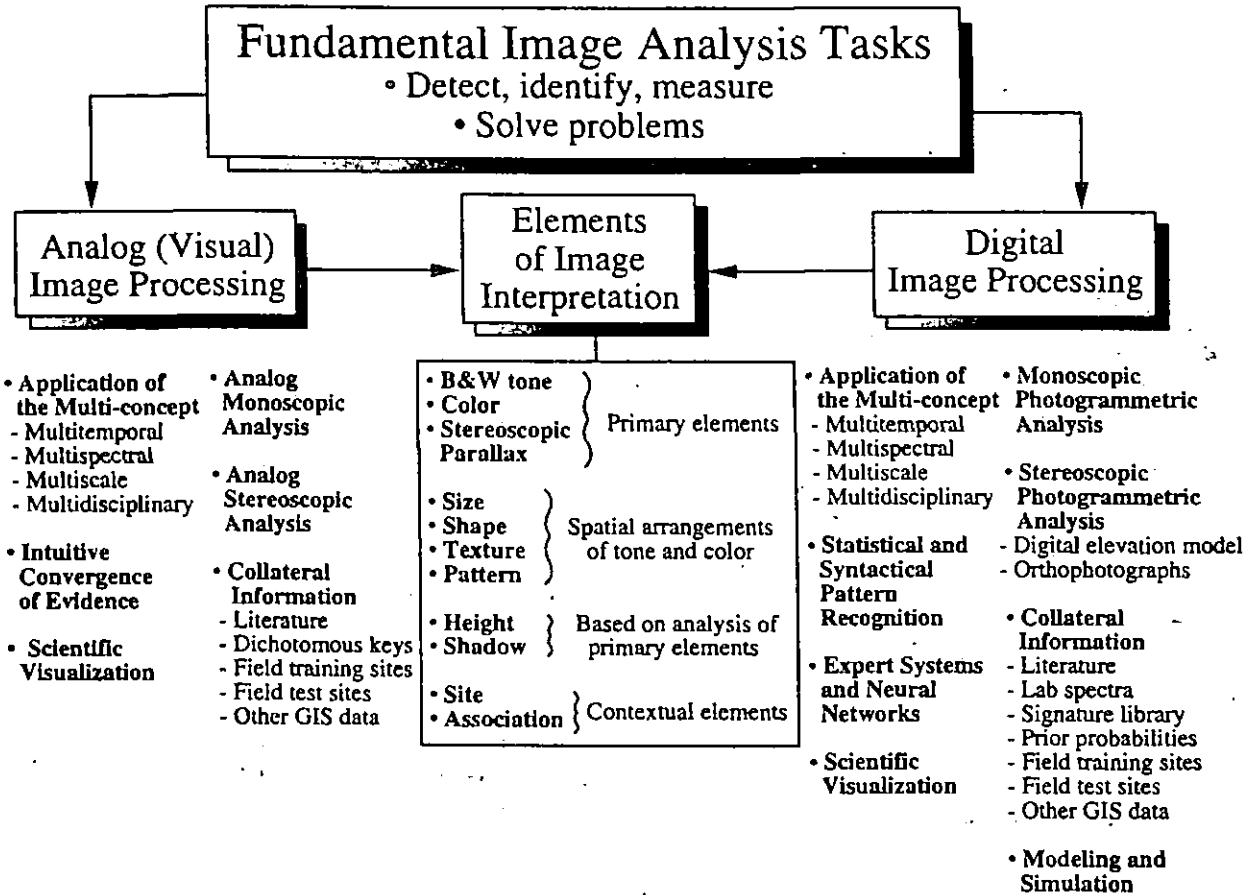


Figure 1-2 This conceptual diagram identifies analog (visual) and computer-assisted digital image processing of remotely sensed data that rely on the analysis of the fundamental elements of image interpretation. Visual analysis at the present time incorporates many more of the complex elements in the analysis of remote sensing images.

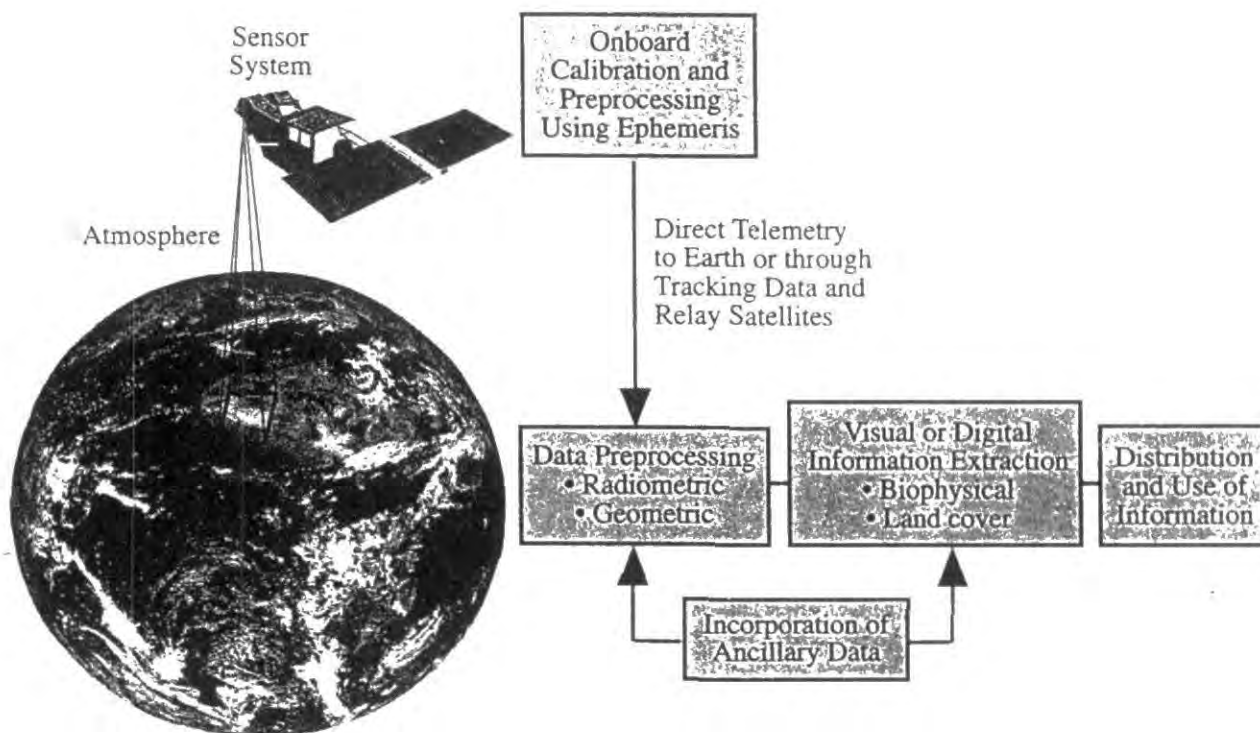


Figure 2-10 Overview of how remotely sensed data are turned into useful information. Once the remotely sensed data are collected, both onboard and ground preprocessing is performed to remove geometric and radiometric distortions. This may involve the use of ephemeris and/or ancillary data. The data are then analyzed visually or digitally to extract meaningful biophysical or land-use/land-cover information.

General Steps Used to Extract Land Cover Information from Digital Remote Sensor Data

- State the Nature of the Classification Problem**
- Define the region of interest
 - Identify the classes of interest from a Land Cover Classification System
- Acquire Appropriate Remote Sensing and Ground Reference Data**
- Select remotely sensed data based on the following criteria:
 - Remote sensing system considerations
 - Spatial, spectral, temporal, and radiometric resolution
 - Environmental considerations
 - Atmospheric, soil moisture, phenological cycle, etc.
 - Obtain initial ground reference data based on
 - *a priori* knowledge of the study area
- Image Processing of Remote Sensor Data to Extract Thematic Information**
- Radiometric correction (or normalization)
 - Geometric rectification
 - Select appropriate image classification logic and algorithm
 - Supervised
 - Parallelepiped and/or minimum distance
 - Maximum likelihood
 - Others (e.g., fuzzy maximum likelihood)
 - Unsupervised
 - Chain method
 - Multiple pass ISODATA
 - Others (e.g., fuzzy c-Means)
 - Hybrid involving ancillary information
 - Extract data from initial training sites using most bands (if required)
 - Select the most appropriate bands using feature selection criteria
 - Graphical (e.g., co-spectral plots)
 - Statistical (e.g., transformed divergence, TM-distance)
 - Extract training statistics from final band selection (if required)
 - Extract thematic information
 - By class (supervised)
 - Label pixels (unsupervised)
- Error Evaluation of the Land Cover Classification Map (Quality Assurance)**
- Obtain additional reference test data based on the following criteria:
 - *a posteriori* knowledge of the study area
 - Stratified random sample
 - Assess statistical accuracy of the classification map
 - Overall percent accuracy
 - Kappa coefficient
 - Accept or reject hypotheses
- Distribute Results if the Accuracy is Acceptable**
- Digital products
 - Analog (hard-copy) products
 - Error evaluation report
 - Image and map lineage report

Figure 8-1 General steps required to extract land-cover information from digital remote sensor data.

Table 3-1. Image Processing Functions Found in Many Image Processing Systems

Preprocessing

1. Radiometric correction (of error introduced by the sensor system and environmental effects)
2. Geometric correction (image-to-map, or image-to-image)

Display and Enhancement

3. Black & white, color-composite display
4. Density slice
5. Magnification, reduction, roam, pan
6. Transects
7. Contrast manipulation
8. Image algebra (band ratioing, image differencing, etc.)
9. Spatial filtering
10. Edge enhancement
11. Principal components
12. Linear combinations (e.g., Kauth transform)
13. Texture transforms
14. Frequency transformations (Fourier, cosine, Hadamard, Walsh etc.)
15. Digital elevation models (DEMs)
16. Three-dimensional transformations
17. Animation
18. Image compression

Information Extraction

19. Supervised classification
20. Unsupervised classification
21. Contextual classification
22. Incorporation of ancillary data during classification
23. Radar image processing
24. Hyperspectral data analysis
25. Soft copy photogrammetry to extract digital elevation models
26. Soft copy photogrammetry to extract orthophotographs
27. Expert system and/or neural network image analysis

Image Lineage

28. Complete image or output GIS file history

Image and Map Cartographic Composition

29. Scaled postscript level II output of images and maps

Geographic Information Systems (GIS)

30. Raster (image) based GIS
31. Vector (polygon) based GIS (must allow polygon comparison)

Integrated Image Processing and GIS

32. Complete image processing systems (Functions 1 through 23)
33. Complete image processing systems and GIS (Functions 1 to 33)

Utilities

34. Network (Internet, local talk, etc.)
-

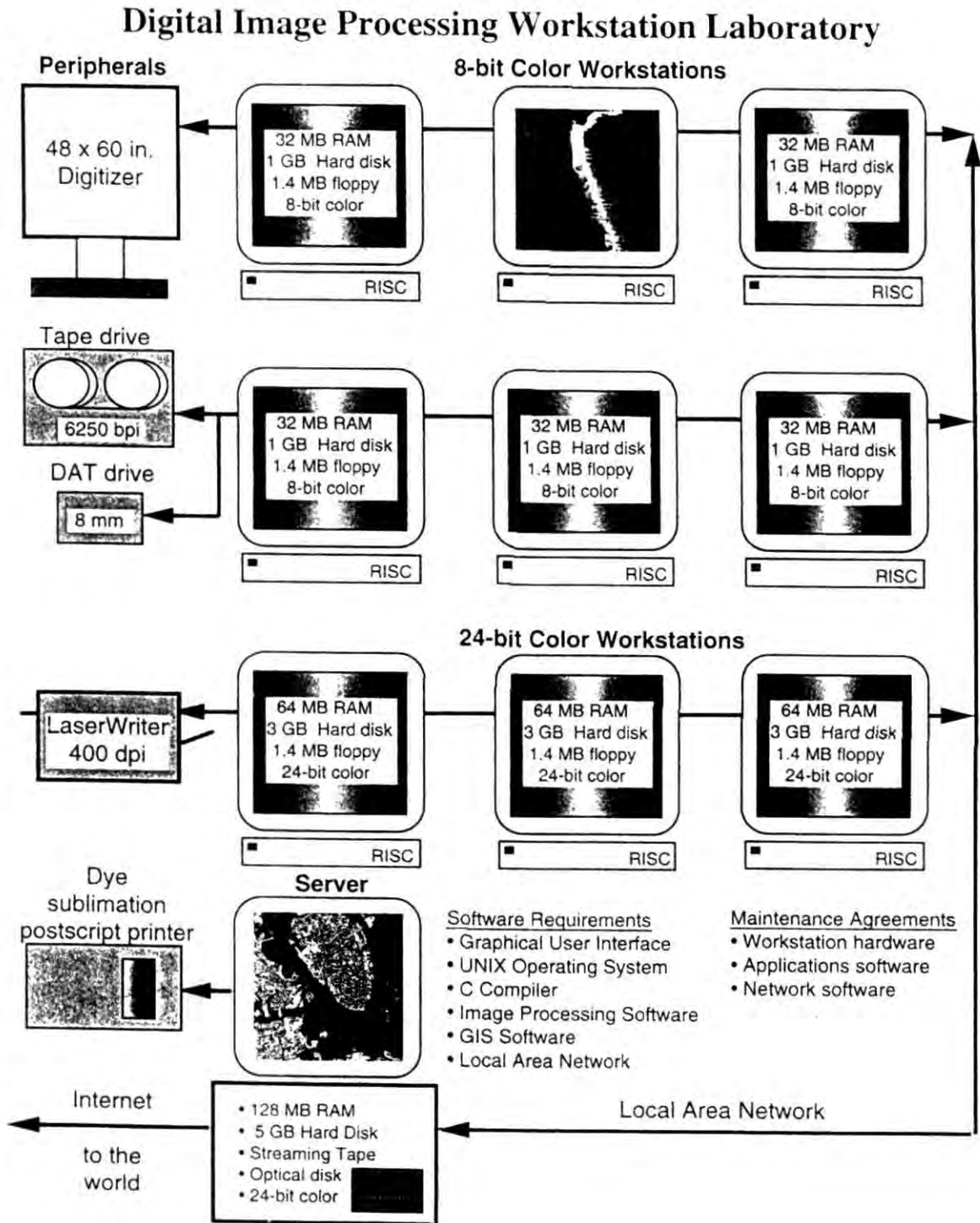


Figure 3-1 A hypothetical digital image processing laboratory consisting of 8- and 24-bit color workstations. Reduced instruction set (RISC) computer workstations and peripheral devices (e.g., digitizer, tape drives, and dye sublimation printer) communicate via a local area network (LAN). Communication with the outside world is via Internet. Each workstation has sufficient random access memory (RAM) and hard disk space. UNIX is the operating system of choice in this workstation environment. Digital image processing and GIS software ideally reside on each workstation (increasing the speed of execution), but may reside on the server. Compilers and network software normally reside on the server. Large remote sensing data sets may be placed on the server and accessed by all workstations, minimizing redundant data storage.

DIGITAL IMAGE PROCESSING**Introduction**

- increases our ability to examine, display and analyse remotely sensed data
- provides an "OBJECTIVE" approach (mathematical or statistical) to interpretation

ANALYST - decision maker

COMPUTER - mathematical computations

Image Statistics**1. Univariate Statistics**

- Mean
- Variance
- Standard deviation

2. Multivariate Statistics

- Covariance
- Correlation

Image Statistics**1. Univariate Statistics**

- measures of central tendency
- do not give any information about relationships between pixel values in different bands

a) Mean

$$\mu_k = \frac{\sum_{i=1}^n BV_{ik}}{n}$$

Example: MSS Band 1; Pixels 1 - 5

$$\mu_1 = \frac{\sum_{i=1}^5 BV_{i1}}{5}$$

$$\mu_1 = \frac{130 + 165 + 100 + 135 + 145}{5}$$

$$\mu_1 = 135$$

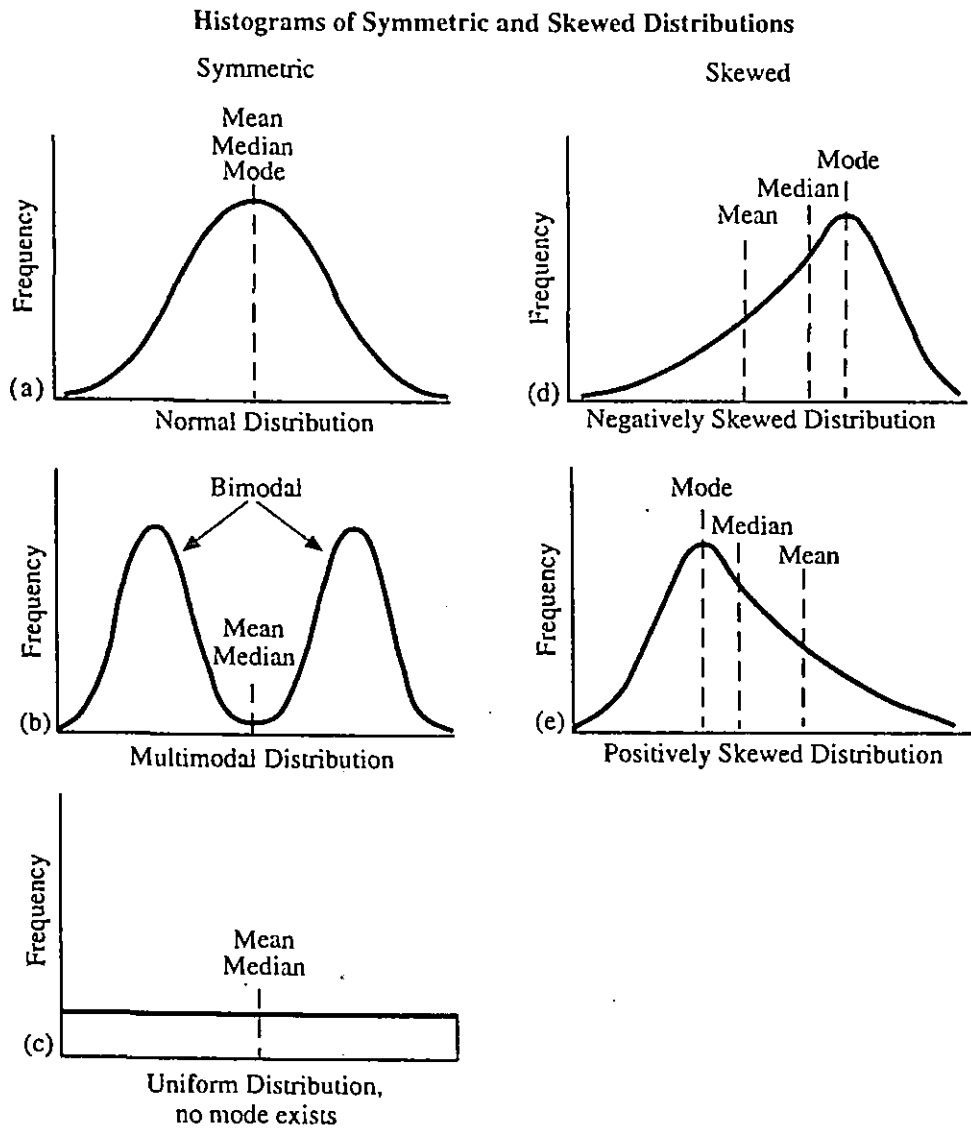


Figure 4-1 Relative position of measures of central tendency for commonly encountered frequency distributions (modified from Griffith and Amrhein, 1991).

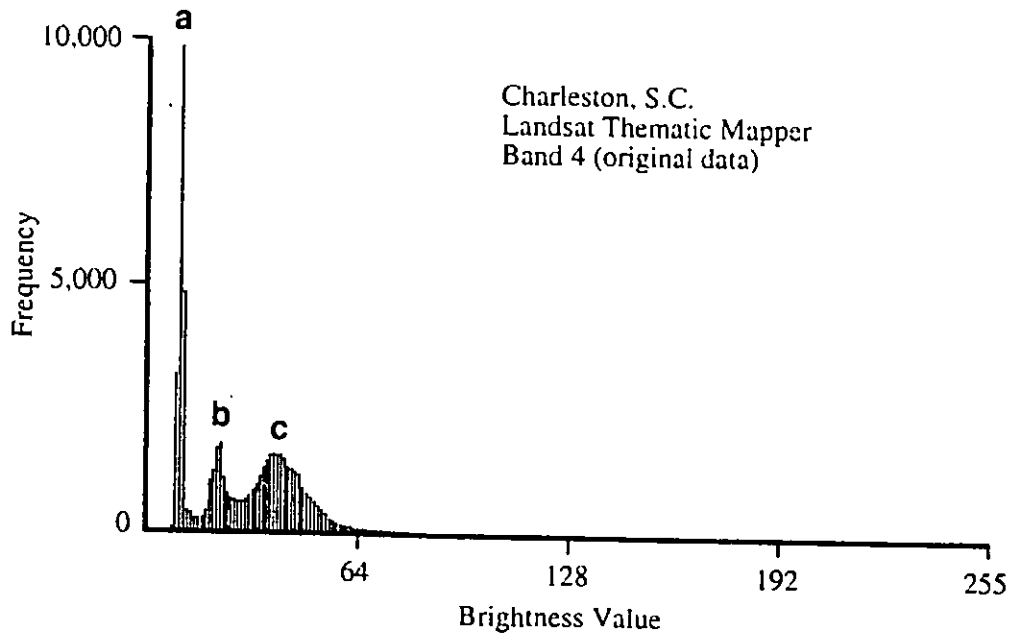


Figure 4-2 A multimodal histogram of the brightness values of a Charleston, S.C. Landsat Thematic Mapper band 4 image obtained on November 9, 1982. The peaks in the histogram correspond to dominant types of land cover in the image, including: (a) water pixels, (b) wetland, and (c) upland.

b) Variance . . .

$$\text{var}_k = \frac{\sum_{i=1}^n (BV_{ik} - \mu_k)^2}{n-1}$$

$$\text{var}_k = \frac{n(\sum_{i=1}^n BV_{ik}^2) - (\sum_{i=1}^n BV_{ik})^2}{n(n-1)}$$

Example: MSS Band 1; Pixels 1 - 5

$$\text{var}_1 = \frac{5(\sum_{i=1}^5 BV_{i1}^2) - (\sum_{i=1}^5 BV_{i1})^2}{5(5-1)}$$

$$\text{var}_1 = \frac{5(93,375) - (675)^2}{20}$$

$$\text{var}_1 = 562.5$$

c) Standard Deviation (S_k)

$$s_k = \text{var}_k^{1/2}$$

Example: MSS Band 1; Pixels 1 - 5

$$s_1 = (562.5)^{1/2}$$

$$s_1 = 23.72$$

2. Multivariate Statistics

Provide several important functions in digital image analysis:

- give insight into data quality
 - are the data likely to be suitable for the planned task?
- give insight into data redundancy
 - are pixel values in different bands correlated with each other or do they vary independently?
- provide information for principal components analysis (PCA), feature selection and image classification.

a) Covariance

- a measure of mutual interaction - "the joint variation of two variables about their common mean."

$$\text{COV}_{kl} = \frac{\sum_{i=1}^n (BV_{ik} - \mu_k)(BV_{il} - \mu_l)}{n-1}$$

$$\text{COV}_{kl} = \frac{\sum_{i=1}^n (BV_{ik} \cdot BV_{il}) - \frac{\sum_{i=1}^n BV_{ik} \sum_{i=1}^n BV_{il}}{n}}{n-1}$$

$$\text{COV}_{kl} = \frac{n \sum_{i=1}^n (BV_{ik} \cdot BV_{il}) - \sum_{i=1}^n BV_{ik} \sum_{i=1}^n BV_{il}}{n(n-1)}$$

Covariance (cont.)Example: MSS Bands 1 and 2; Pixels 1 - 5

$$\text{COV}_{1,2} = \frac{5 \sum_{i=1}^5 (BV_{i1} \bullet BV_{i2}) - \sum_{i=1}^5 BV_{i1} \sum_{i=1}^5 BV_{i2}}{5(5-1)}$$

$$\text{COV}_{1,2} = \frac{5(31860) - (675)(232)}{20}$$

$$\text{COV}_{1,2} = 135$$

Example: MSS Bands 2 and 3; Pixels 1 - 5

$$\text{COV}_{1,2} = \frac{5 \sum_{i=1}^5 (BV_{i2} \bullet BV_{i3}) - \sum_{i=1}^5 BV_{i2} \sum_{i=1}^5 BV_{i3}}{5(5-1)}$$

$$\text{COV}_{1,2} = \frac{5(44485) - (232)(935)}{20}$$

$$\text{COV}_{1,2} = 275.25$$

b) Correlation (r_{kl})

- "the ratio of the covariance of two variables to the product of their standard deviations."
- -estimates (by means of a unitless number) the degree of interaction between two variables.

$$r_{kl} = \frac{\text{COV}_{kl}}{s_k s_l}$$

Example: MSS Bands 1 and 2; Pixels 1 - 5

$$r_{1,2} = \frac{\text{COV}_{1,2}}{s_1 s_2}$$

$$r_{1,2} = \frac{135.0}{(23.72)(16.27)}$$

$$r_{1,2} = 0.35$$

Example: MSS Bands 2 and 3; Pixels 1 - 5

$$r_{2,3} = \frac{\text{COV}_{2,3}}{s_2 s_3}$$

$$r_{2,3} = \frac{275.25}{(16.27)(31.74)}$$

$$r_{2,3} = 0.53$$

Calculation of Common Image Statistics**Table 1. Sample Data Set of Landsat MSS Brightness Values**

Pixel	Band 1 (green)	Band 2 (red)	Band 3 (infrared)	Band 4 (infrared)
(1,1)	130	57	180	205
(1,2)	165	35	215	255
(1,3)	100	25	135	195
(1,4)	135	50	200	235
(1,5)	145	65	205	235

Table 2. Univariate Statistics for the Sample Data Set

	Band 1 (green)	Band 2 (red)	Band 3 (infrared)	Band 4 (infrared)
Mean m_k	135	46.4	187	222
Std. Dev., s_k	23.72	16.27	31.74	23.87
Variance, Var_k	562.5	264.8	1007.5	570
Minimum	100	25	135	195
Maximum	165	65	215	255

Table 3. Computation of Covariance between Bands 1 and 2 and Bands 2 and 3 of the Sample Data

Band 1 (green)	(Band 1) ²	Band 2 (red)	Band 3 (infrared)	B1 x B2	B2 x B3
130	16,900	57	180	7,410	10,260
165	27,225	35	215	5,775	7,525
100	10,000	25	135	2,500	3,375
135	18,225	50	200	6,750	10,000
145	21,025	65	205	9,425	13,325
675	93,375	232	935	31,860	44,485

Table 4. Variance-Covariance Matrix for the Sample Data Set

	Band 1	Band 2	Band 3	Band 4
Band 1	562.5			
Band 2	135	264.8		
Band 3	718.75	275.25	1007.5	
Band 4	537.5	64	663.75	570

Table 5. Correlation Matrix for the Sample Data Set

	Band 1	Band 2	Band 3	Band 4
Band 1				
Band 2	0.35			
Band 3	0.95	0.53		
Band 4	0.94	0.16	0.87	

Reference Jensen, J.R., 1993. Introductory Digital Image Processing Prentice-Hall, Englewood Cliffs, New Jersey, pp. 77-86.

IMAGE PREPROCESSING

Image Restoration: "produces a corrected image that is as close as possible, both geometrically and radiometrically, to the radiant energy characteristics of the original scene" (Jensen, 1996)

RADIOMETRIC ERRORS

- **Instrument**

- **Problem:** line drop-out (detector fails to function during a scan)
Solution: take average of the line above and below the drop-out line
- **Problem:** n-line striping (detector goes out of adjustment)
Solution: compute histograms over a homogeneous area and apply corrections
- **Problem:** striping (e.g., differences between 16 detectors in a Landsat TM image)
Solution: filtering or Fourier transform
- **Problem:** banding (e.g. differences between east-west and west-east scans)
Solution: filter or adjust values to provide correction
- **Problem:** line-start or line-end errors
Solution: apply horizontal adjustment

- **Atmosphere**

1. - **Problem: Attenuation by scattering and absorption**

- **Solutions:**
 - do nothing
(OK for land-cover mapping)
 - take *in-situ* measurements
(required for biophysical measurements)
 - model atmosphere
(correct for date, sun altitude, lat. & long.)
 - model atmosphere + *in situ* measurements
(absolute radiometric calibration)
 - use multiple looks or multiple bands
(relative radiometric calibration)

Absolute Radiometric Correction

- Takes into account:
- Rayleigh scattering
 - Mie scattering
 - absorption (water, carbon dioxide, ozone)
 - diffuse sky irradiance - scattering effects
 - path radiance - scattering effects

Relative Radiometric Correction

- Involves:
- normalization of bands using histogram adjustment
 - normalization of multitemporal imagery using regression and pseudo-invariant surfaces

2. - **Problem: Topographic attenuation**

- **Solutions:**
 - use corrections for geometric effects
 - use corrections based around a digital elevation model

GEOMETRIC ERRORS

- **Sources of Error**

- Systematic distortions
 - scan skew
 - mirror-scan velocity
 - panoramic distortion
 - platform velocity
 - earth rotation
 - perspective
- Nonsystematic distortions
 - altitude
 - attitude

- **Image-to-Map Rectification**

- Spatial interpolation:
 - relate input pixels to map coordinates (ground control points - GCPs)
 - polynomial equations are fitted to the GCPs using least-squares criteria
 - Intensity interpolation:
 - determines brightness values of new pixels
- Uses
- **nearest neighbour** (closest pixel)
 - **bilinear interpolation** (average of 4 pixels)
 - **cubic convolution** (average of 16 pixels)

- **Image-to-Image Registration**

Uses the same principles

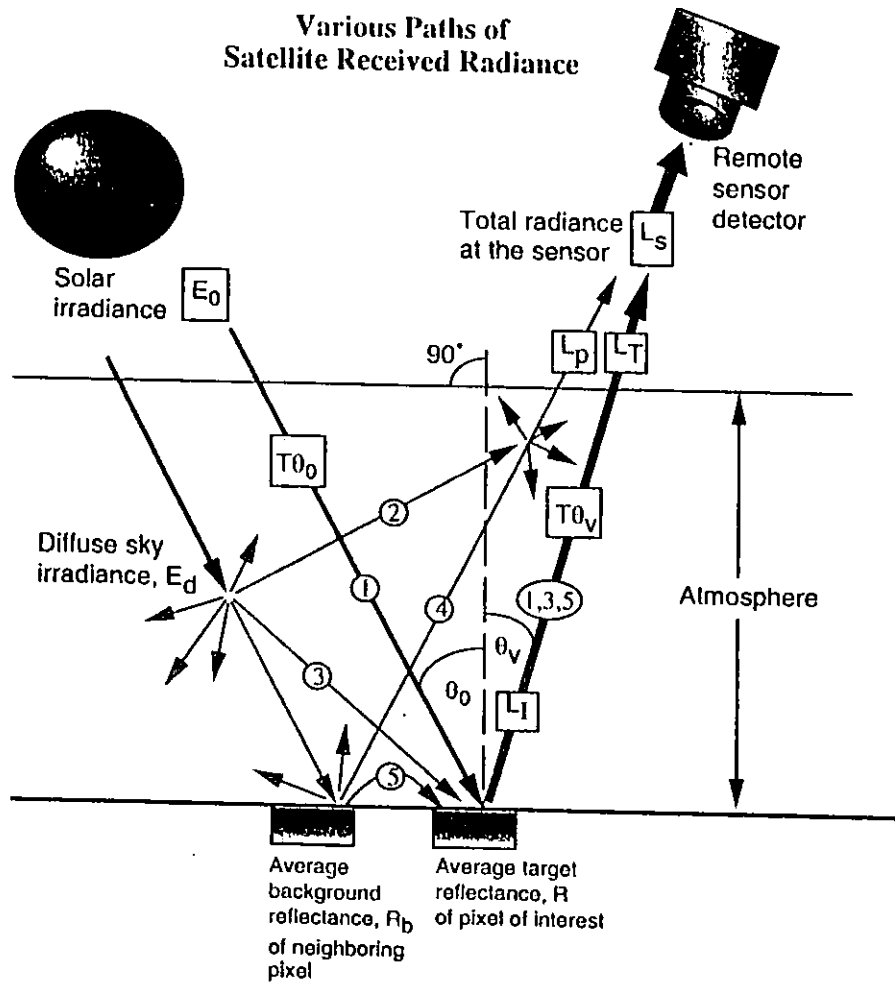


Figure 6-1 Various paths of radiance received by the satellite remote sensing system.

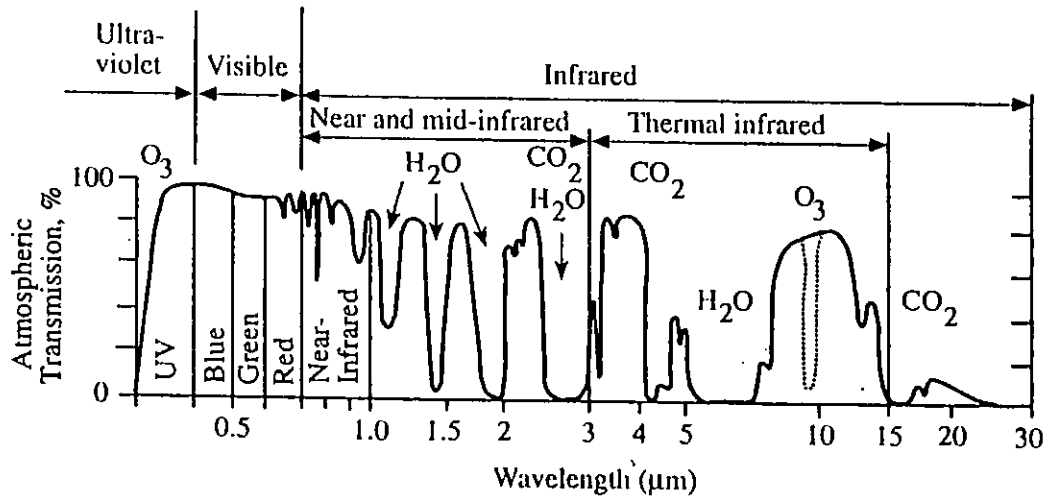


Figure 6-3 Atmospheric absorption bands in the visible, near-infrared, and thermal-infrared portions of the electromagnetic spectrum.

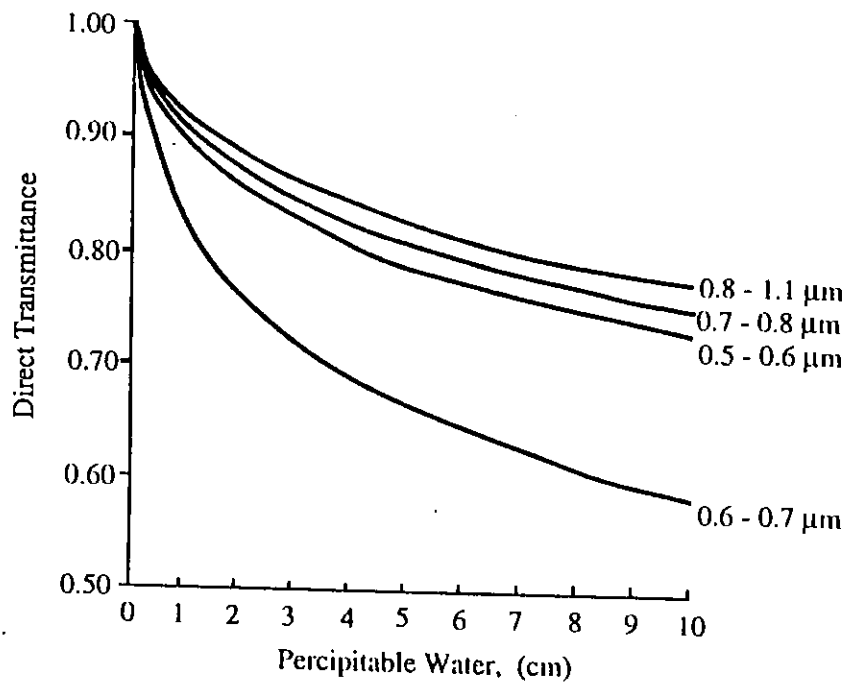


Figure 6-4 Effects of atmospheric water vapor absorption on radiation transmitted to Earth's surface.

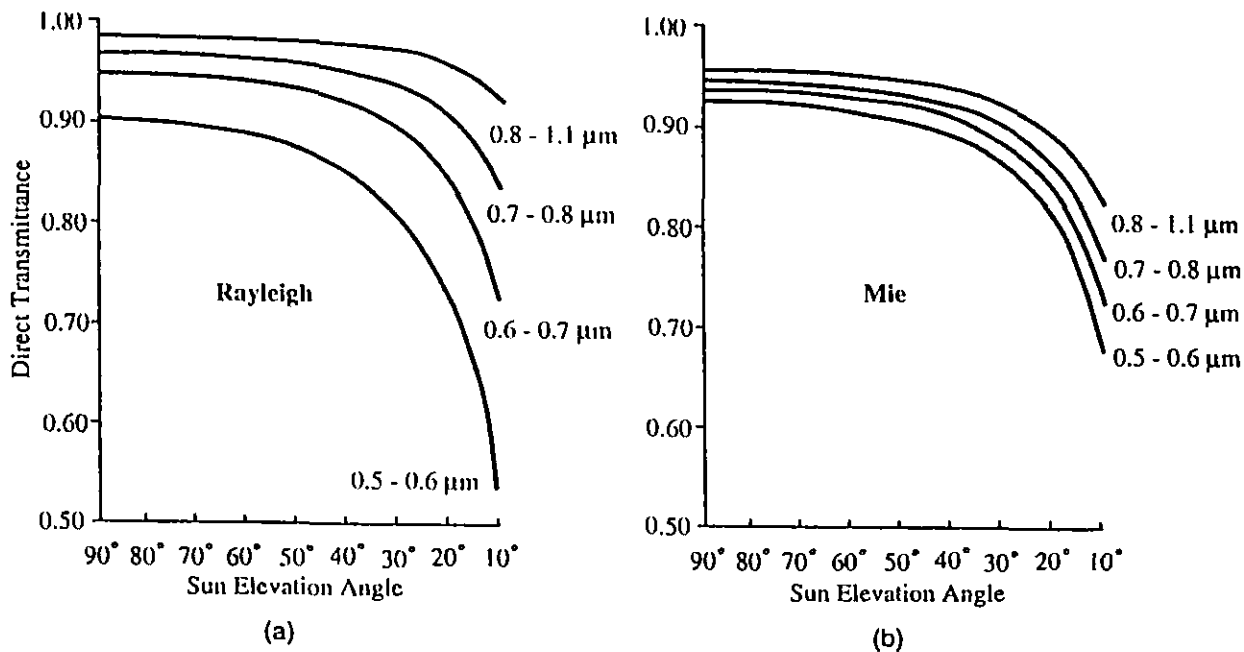


Figure 6-2 (a) Effects of molecular (Rayleigh) scattering and sun angle on incident radiation transmitted to Earth's surface; (b) Effects of aerosol (Mie) scattering and sun angle on radiation transmitted to Earth's surface.

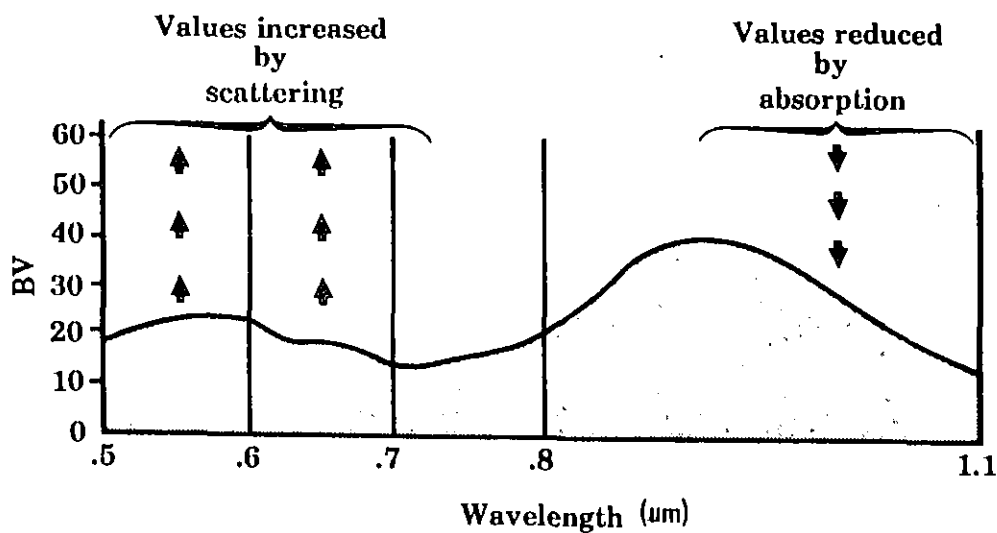


Figure 6-3 Combined effects of scattering and absorption on the brightness values (BV) eventually produced by the Landsat MSS sensor system. (From Tarantik, 1978.)

Original Data

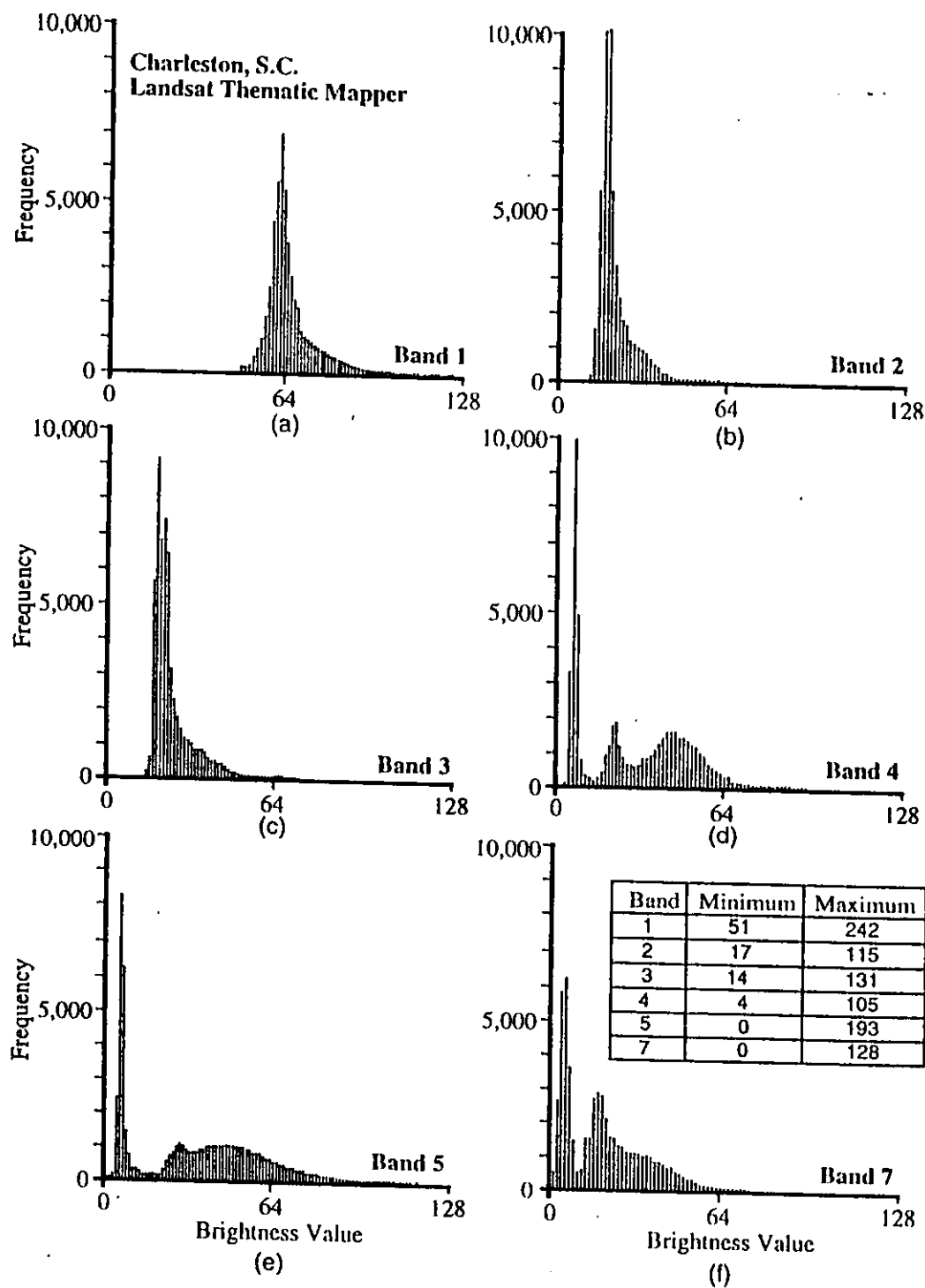


Figure 6-6 Original histograms of six bands of the Charleston, S.C. Thematic Mapper scene. Atmospheric scattering in the visible regions has increased the minimum brightness values in bands 1, 2, and 3. Generally, the shorter the wavelengths sensed by each band, the greater the offset from a brightness value of zero.

Adjusted

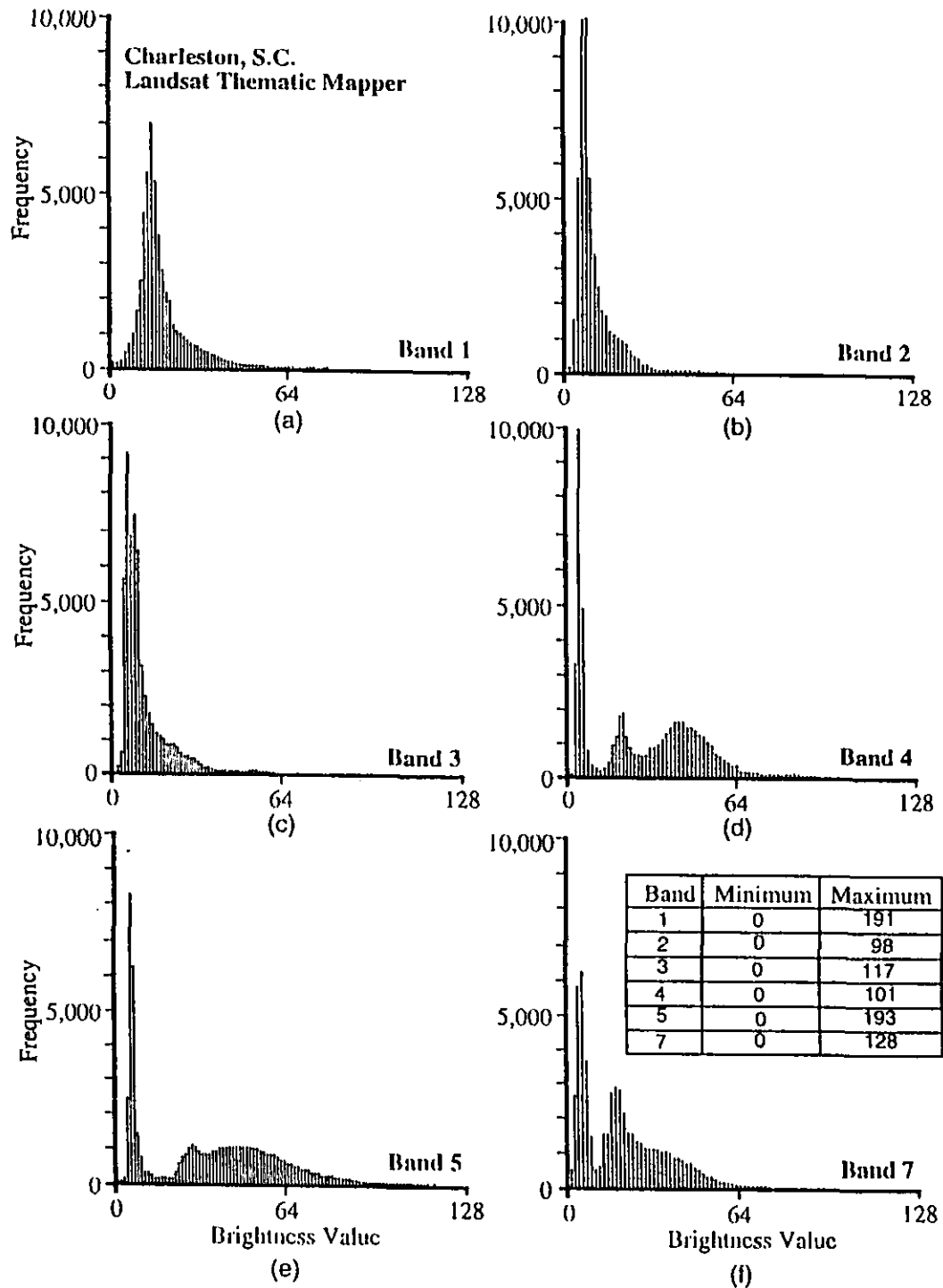


Figure 6-7 Result of applying a simple histogram adjustment atmospheric scattering correction to the data shown in Figure 6-6. Only the first four Thematic Mapper bands required the adjustment. This method does not correct for atmospheric absorption.

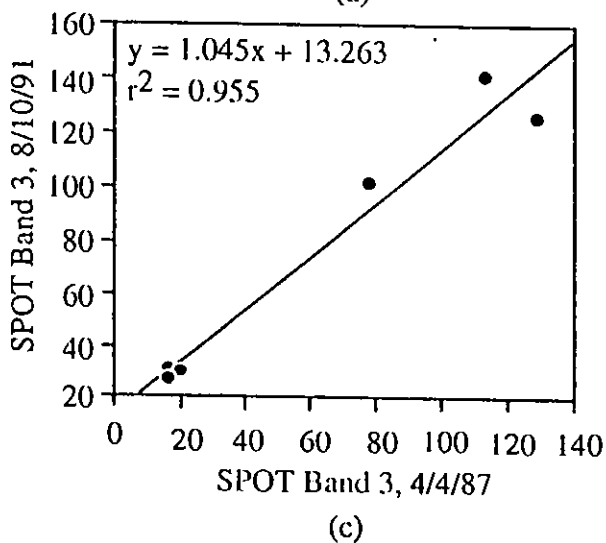
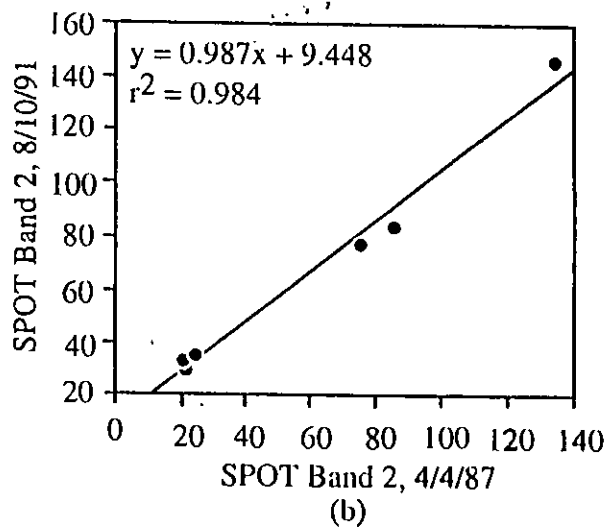
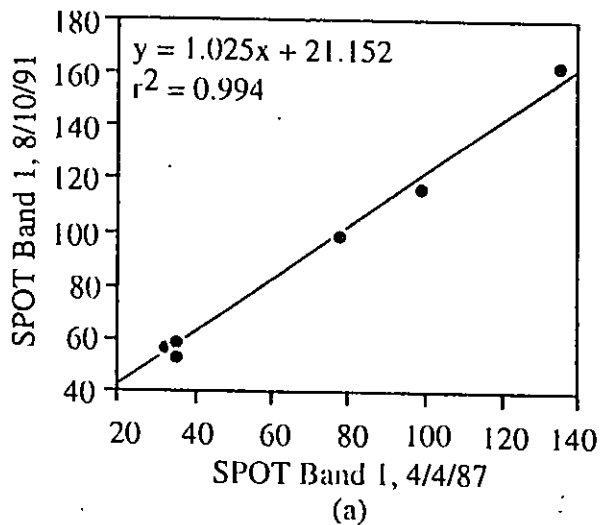
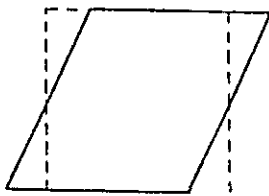


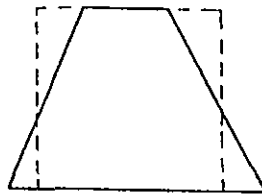
Figure 6-9 (a) Relationship between the same wet and dry regions found in both the 4/4/87 and 8/10/91 SPOT band 1 (green) dataset. The equation was used to normalize the 4/4/87 data to the 8/10/91 SPOT data as per methods described in Eckhardt et al. (1990). (b) Relationship between wet and dry regions found in both the 4/4/87 and 8/10/91 SPOT band 2 (red) dataset. (c) Relationship between wet and dry regions found in both the 4/4/87 and 8/10/91 SPOT band 3 (near-infrared) dataset (Jensen et al., 1995).

DISTORTION EVALUATED FROM TRACKING DATA

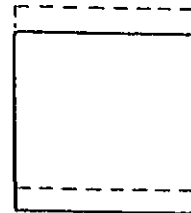
DISTORTION EVALUATED FROM GROUND CONTROL



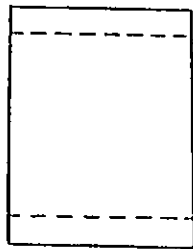
EARTH ROTATION



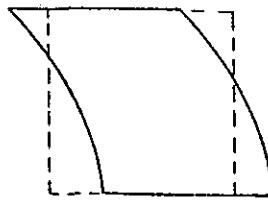
ALTITUDE VARIATION



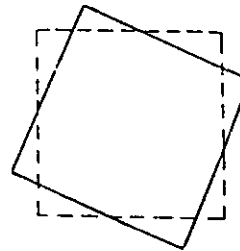
PITCH VARIATION



SPACECRAFT VELOCITY

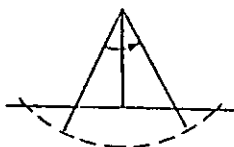


ROLL VARIATION

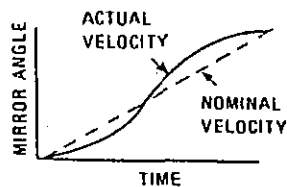


YAW VARIATION

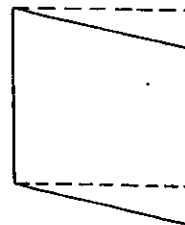
A. NON-SYSTEMATIC DISTORTIONS.



SCANNER DISTORTION



MIRROR VELOCITY VARIATIONS



SCAN SKEW

B. SYSTEMATIC DISTORTIONS.

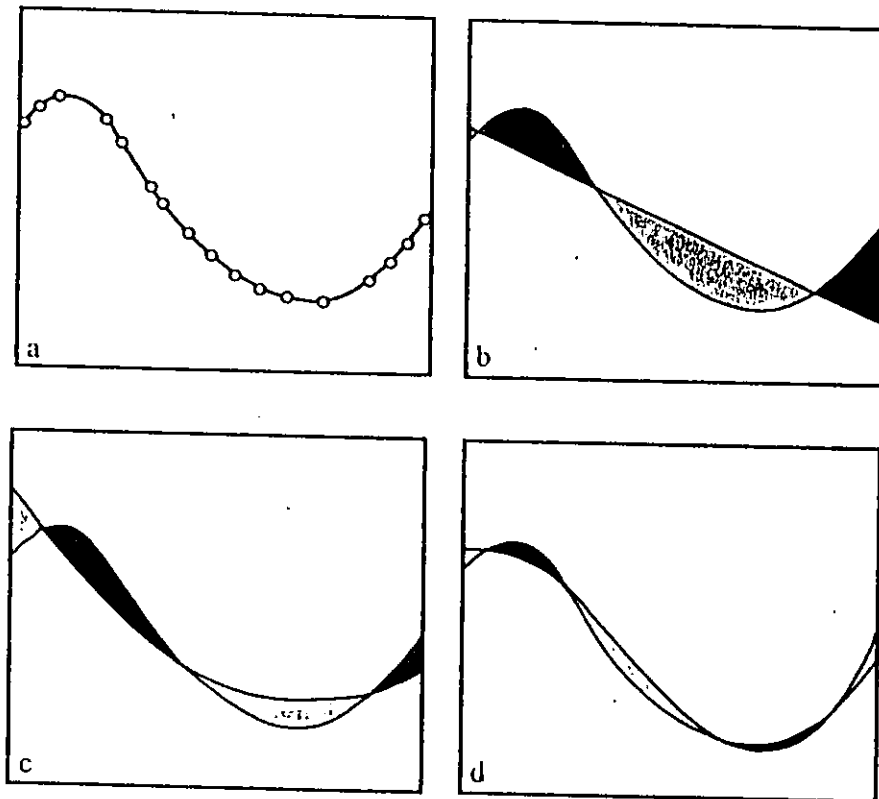


Figure 6-14 Concept of how different-order affine transformations fit a hypothetical surface illustrated in cross section. (a) Original surface. (b) A first-order linear transformation fits a plane to the data. (c) Second-order quadratic fit. (d) Third-order cubic fit (Jensen et al., 1988).

GEOMETRIC CORRECTION OF REMOTE SENSOR DATA

GEOMETRIC DISTORTION

1. Systematic (Predictable)

- Cross-Track Scanner Distortion
- Mirror Velocity Variations
- Scan Skew
- Panoramic Distortions
- Platform Velocity
- Earth Rotation
- Perspective

2. Nonsystematic Distortions (Random)

- Altitude
- Attitude (roll, pitch and yaw)

GEOMETRIC CORRECTION

1. *Sensor Characteristics (internal distortions) and Platform Ephemeris (Tracking) Data*

- predictable distortions are modelled mathematically

2a. *Spatial Interpolation*

- A . Image to Image (georeferencing, geometric registration)
- B . Image to Map (geocoding, geometric rectification)

Ground Control Points (GCPs)

- features that can be identified accurately on both the image and the reference coordinate system (e.g., road intersections, shoreline features)
- image coordinates (lines, pixels) from the distorted image are compared to their reference coordinates (e.g., image, UTM, lat./long.)

Distortion Modelling

- least-squares regression (e.g., linear, quadratic, cubic, ...) (1st, 2nd, 3rd, 4th, 5th order polynomials)
- differences between actual GCP locations and their positions in the image are used to determine the geometric transformations required to restore the image
- two coordinate transformation equations are required to interrelate the geometrically correct coordinates to the distorted image coordinates

$$x' = f_1(x, y)$$

$$y' = f_2(x, y)$$

(x', y') = distorted image coordinates (pixel, line)

(x, y) = corrected (reference) coordinates

f_1, f_2 = transformation functions

- GCPs well distributed throughout the image
- number of GCPs suited to the polynomial (for modelling the distortion)

Example: First Order Polynomial / Linear Transformation

- translation in x and y
- scale changes in x and y
- skew and rotation

$$x' = a_0 + a_1x + a_2y$$

$$y' = b_0 + b_1x + b_2y$$

Suitability of the Spatial Interpolation (Regression) Model

- calculate how well the spatial interpolation models the distortion in the original image:

Root Means Square Error (RMSError)

$$\text{RMS}_{\text{error}} = [(x' - x_{\text{orig}})^2 + (y' - y_{\text{orig}})^2]^{1/2}$$

- low RMS indicates that the geometric distortions within the original image are being modelled correctly (i.e., +/- 0.5 pixels)

2b. Intensity Interpolation (Resampling)

1. coordinates of each element in the reference matrix are transformed to determine their corresponding location in the original image matrix
2. cells in the output matrix will not directly overlay a pixel in the original image matrix (a procedure is required to determine the new brightness value)

- (i) Nearest Neighbour
- (ii) Bilinear Interpolation
- (iii) Cubic Convolution

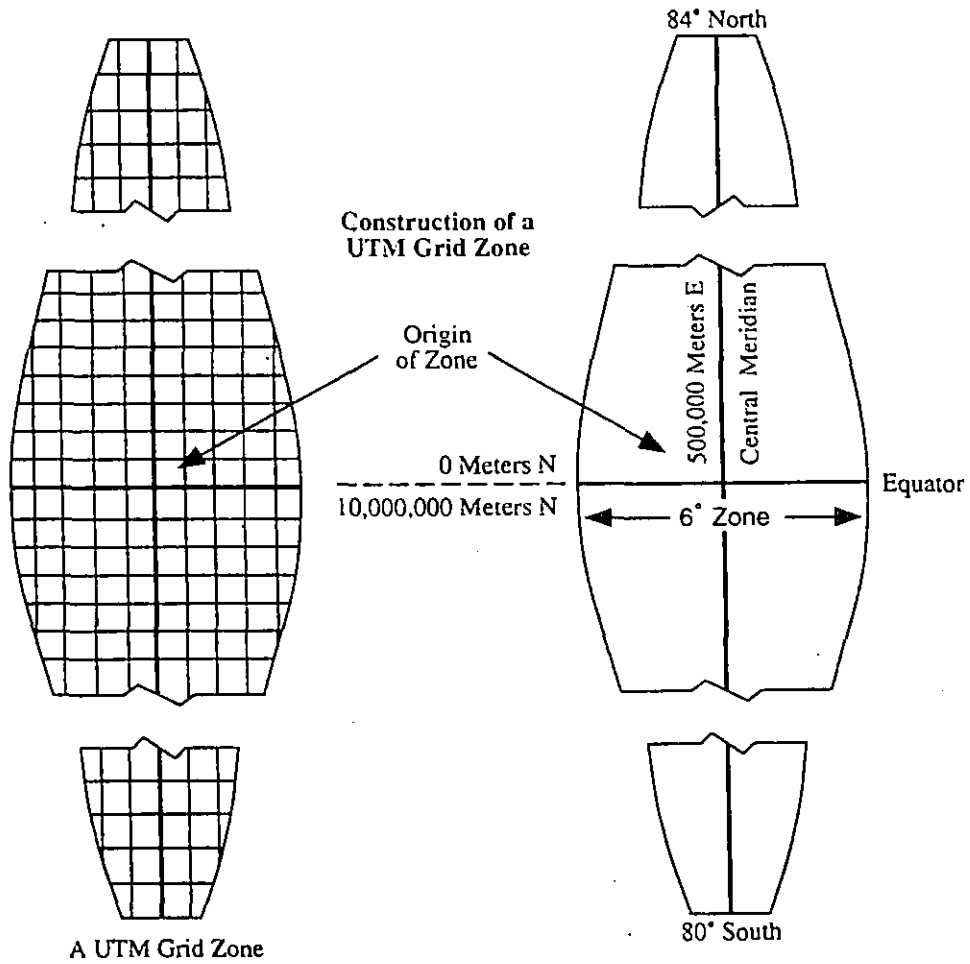


Figure 6-15 Universal transverse mercator (UTM) grid zone with associated parameters. This projection is often used when rectifying remote sensor data to a base map. It is found on U. S. Geological Survey 7.5- and 15-minute quadrangles.

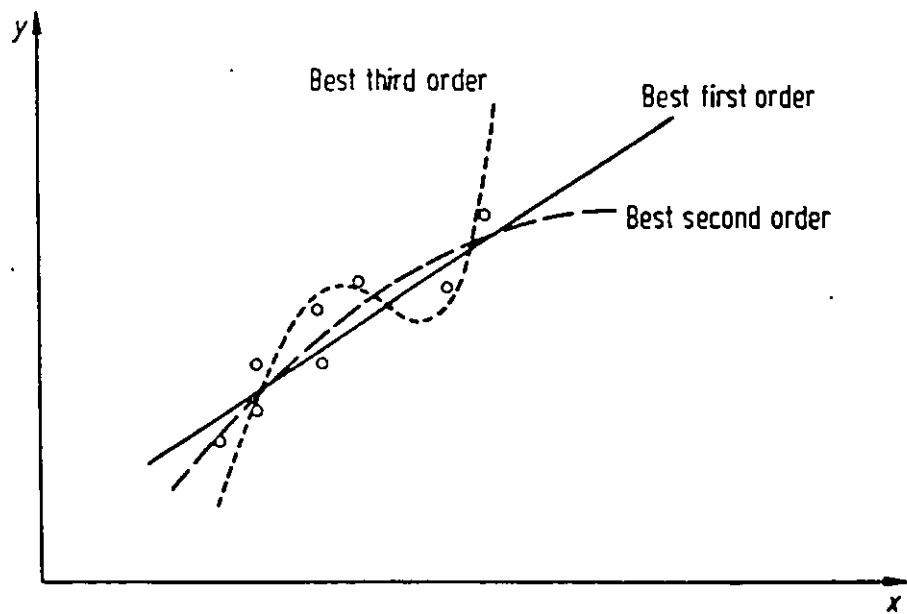


Fig. 2.15. Illustration from curve fitting to reinforce the potentially poor behaviour of high order mathematical functions when used to extrapolate

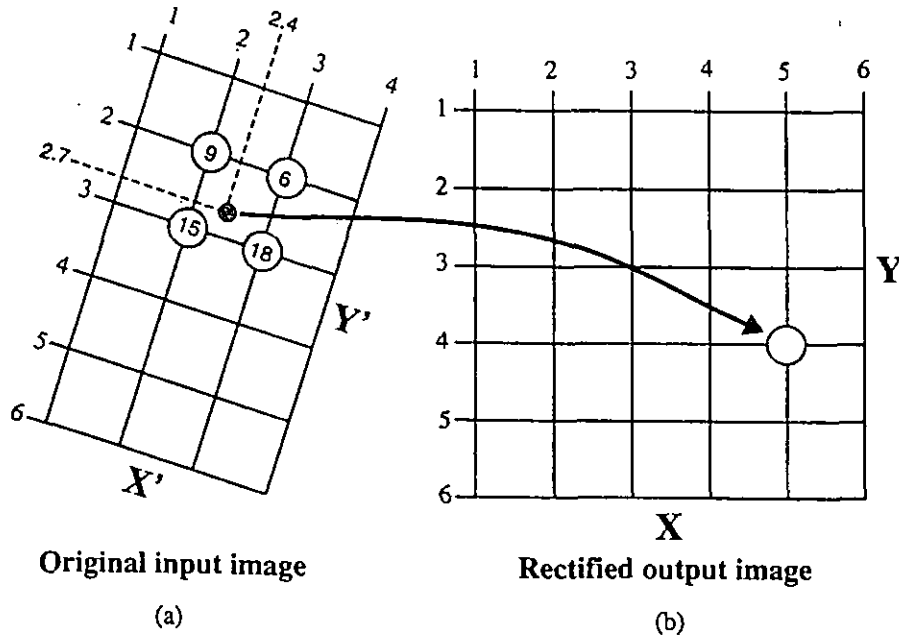
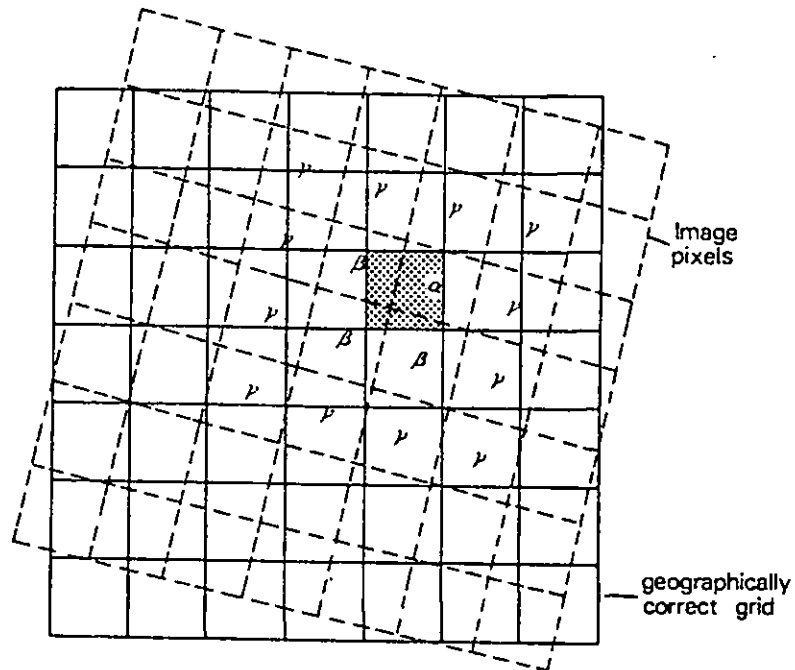



Figure 6-13 This diagram illustrates how the rectified output grid (X, Y) is filled with brightness values from the geometrically distorted input grid (X', Y'). In particular, we are trying to fill pixel 5, 4 in the output grid with a value from the appropriate location in the input grid. The appropriate location is computed using Equation 6-18 with the six necessary coefficients and a value of 5 for the X value and a value of 4 for the Y value in the output image. The equation then computes the X', Y' coordinates of the location in the original image to obtain the appropriate brightness value. The location in this example is 2.4, 2.7. Because these coordinates are not integers, it is necessary to use an intensity interpolation technique to compute the exact brightness value to be placed in X, Y location 5, 4 of the rectified image.

Fig. 6.16
Resampling procedure used to geometrically correct an image.
(Modified from Lillesand and Kiefer 1979)



 Cell in geographically correct grid to which pixel DN is to be allotted

<i>Method</i>	<i>Technique</i>	<i>Example pixels to be transferred in Figure 6.16</i>	<i>Relative computing time</i>	<i>Advantages</i>	<i>Disadvantages</i>
Nearest Neighbour	Transfer DN of nearest pixel	α	1	Simple to compute. DN unaltered.	Image disjointed. Pixels offset by up to half a pixel.
Bilinear Interpolation	Transfer proximity weighted average of nearest 4 pixels	α and β	10	Smooth image. Geometrically accurate.	DN altered
Cubic Convolution	Transfer evaluated weight of nearest 16 pixels	α , β and γ	20	Very smooth image	Complex to compute. DN altered

Table 6.2
A comparison between three methods of resampling remotely sensed images.

Sources: Bernstein 1976; Lillesand and Kiefer 1979; Moik 1980; Short 1982.

Table 6-6. Characteristics of Twenty Ground Control Points Used to Rectify the Charleston, South Carolina Landsat Thematic Mapper Scene

Point Number	Order of Points Deleted ^a	Easting on Map, X_1	Northing on Map, X_2	X' Pixel	Y' Pixel	Total RMS _{error} after This Point Deleted
1	12	597,120	3,627,050	150	185	0.501
2	9	597,680	3,627,800	166	165	0.663
3	Kept	598,285	3,627,280	191	180	—
4	Kept	595,650	3,627,730	98	179	—
5	2	596,750	3,625,600	123	252	6.569
6	13	597,830	3,624,820	192	294	0.435
7	Kept	596,250	3,624,380	137	293	—
8	Kept	602,200	3,628,530	318	115	—
9	Kept	600,350	3,629,730	248	83	—
10	5	600,680	3,629,340	259	93	1.291
11	Kept	600,440	3,628,860	255	113	—
12	10	599,150	3,626,990	221	186	0.601
13	8	600,300	3,626,030	266	211	0.742
14	6	598,840	3,626,460	211	205	1.113
15	3	598,940	3,623,430	214	295	4.773
16	Kept	600,540	3,626,450	272	196	—
17	4	596,985	3,629,350	134	123	1.950
18	7	596,035	3,627,880	109	174	0.881
19	11	600,995	3,630,000	269	71	0.566
20	1	601,700	3,632,580	283	12	8.542
Total RMS _{error} with all 20 GCPs used:						11.016

^a For example, GCP 20 was the first point deleted. After it was deleted, the total RMS_{error} dropped from 11.016 to 8.542. Point 5 was the second point deleted. After it was deleted, the Total RMS_{error} dropped from 8.542 to 6.569.

DIGITAL IMAGE ENHANCEMENTS

OBJECTIVE:

- to improve the visual interpretability of an image by increasing the apparent distinction between features in the scene

A) POINT OPERATIONS

- modify the brightness value of each pixel in an image independently.

Contrast Stretch

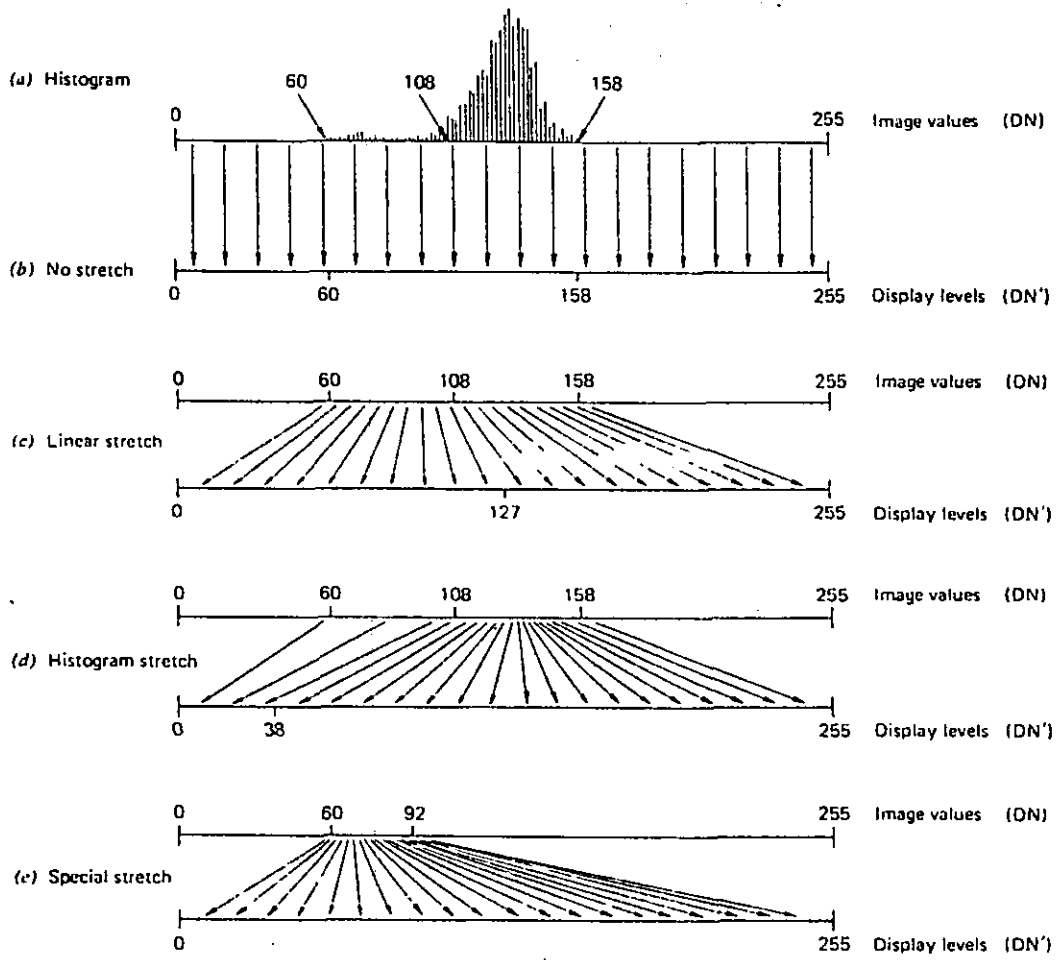
- to expand the range of brightness values in an input image over a wider range of gray values.

Linear Stretch

- a uniform expansion of the range of digital values. (insensitive to frequency)

Histogram Equalization

- output image values are assigned on the basis of DN frequency in the original data (i.e., more display levels are assigned to the frequently occurring DN's)



Principle of contrast stretch enhancement.

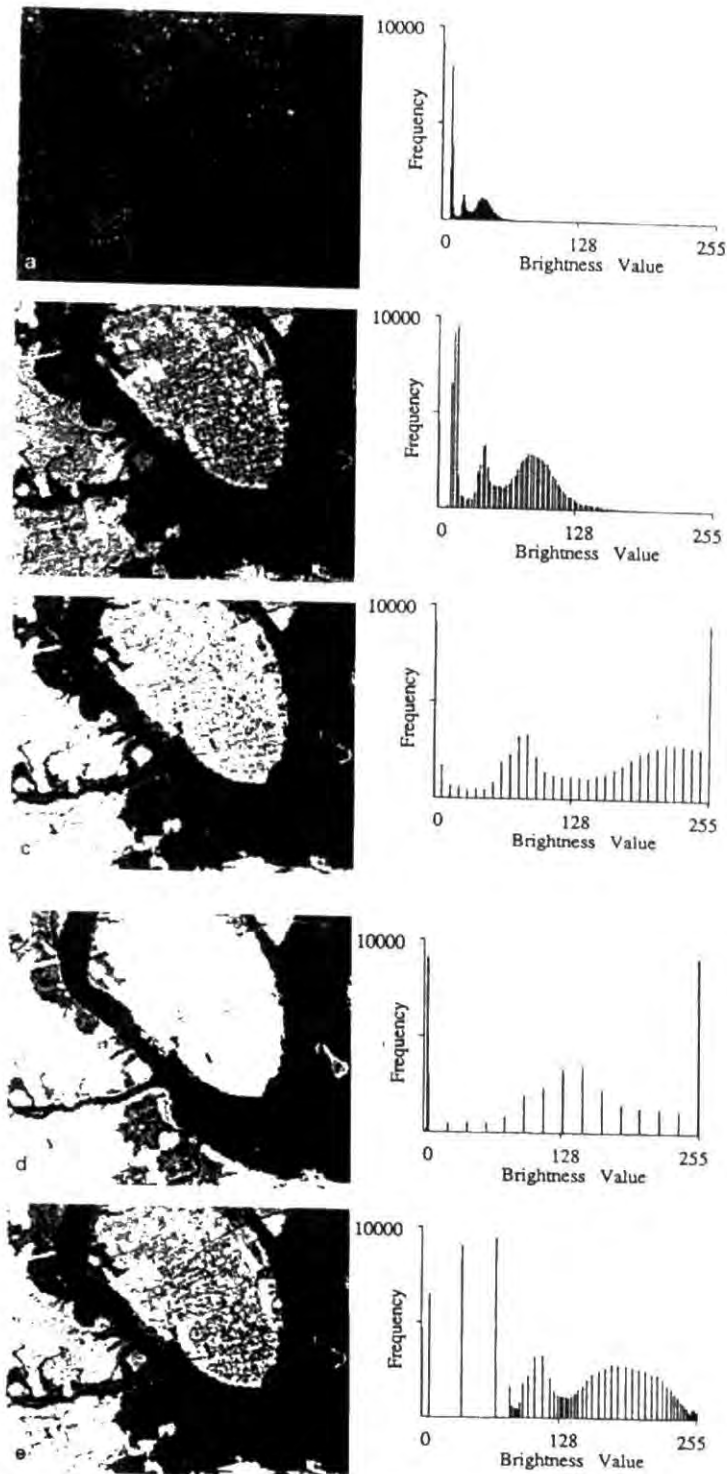


Figure 7-8 (a) Original Thematic Mapper band 4 data of Charleston, S.C., not contrast stretched, and its histogram. (b) Minimum-maximum contrast stretch applied to the data and the resultant histogram. (c) One standard deviation ($\pm 1\sigma$) percentage linear contrast stretch applied to the data and resultant histogram. (d) Specific percentage linear contrast stretch designed to highlight wetland and the resultant histogram. (e) Application of histogram equalization and resultant histogram.

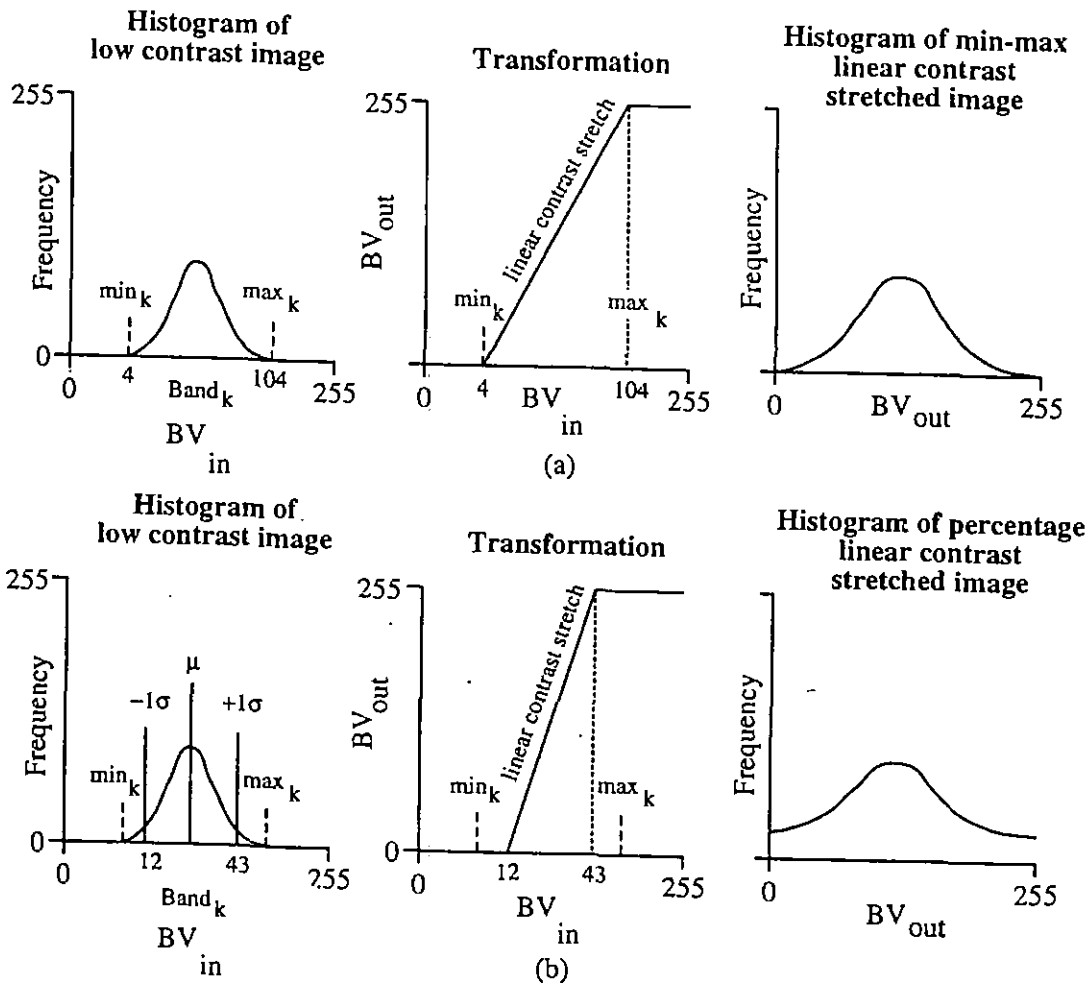


Figure 7-9 (a) Theoretical result of applying a *minimum-maximum* contrast stretch to normally distributed remotely sensed data. The histograms before and after the transformation are shown. The minimum and maximum brightness values encountered in band k are min_k and max_k , respectively. (b) Theoretical result of applying a ± 1 standard deviation *percentage linear contrast stretch*. This moves the min_k and max_k values $\pm 34\%$ from the mean into the tails of the distribution.

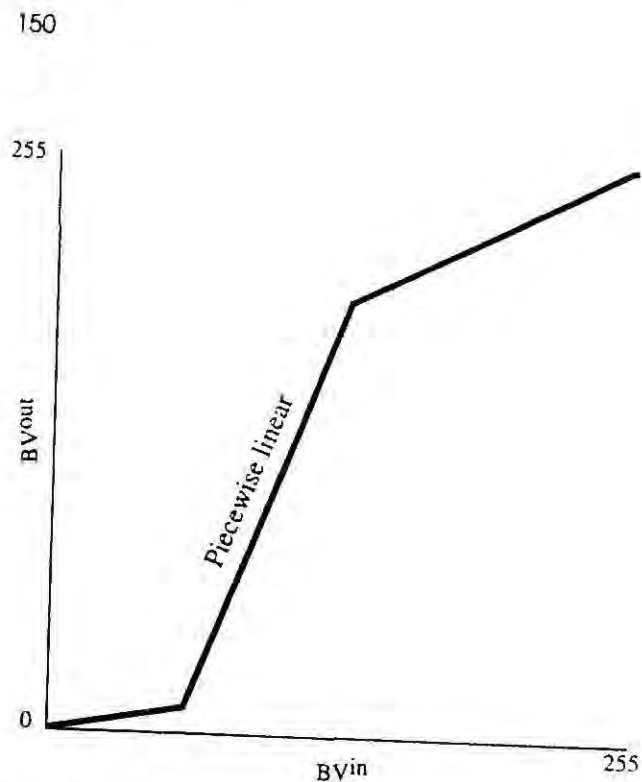


Table 7-2. Statistics for a 64×64 Hypothetical Image with Brightness Values from 0 to 7^a

Brightness Value, BV_i	L_i	Frequency $f(BV_i)$	Probability ^b $p_i = f(BV_i)/n$
BV_0	$0/7 = 0.00$	790	0.19
BV_1	$1/7 = 0.14$	1023	0.25
BV_2	$2/7 = 0.28$	850	0.21
BV_3	$3/7 = 0.42$	656	0.16
BV_4	$4/7 = 0.57$	329	0.08
BV_5	$5/7 = 0.71$	245	0.06
BV_6	$6/7 = 0.85$	122	0.03
BV_7	$7/7 = 1.00$	81	0.02

^a Source: modified from Gonzalez and Wintz, 1977.
^b $n = 4096$ pixels.

Figure 7-11 Logic of a piecewise linear contrast stretch for which selective pieces of the histogram are linearly contrast stretched. Notice that the slope of the linear contrast enhancement changes.

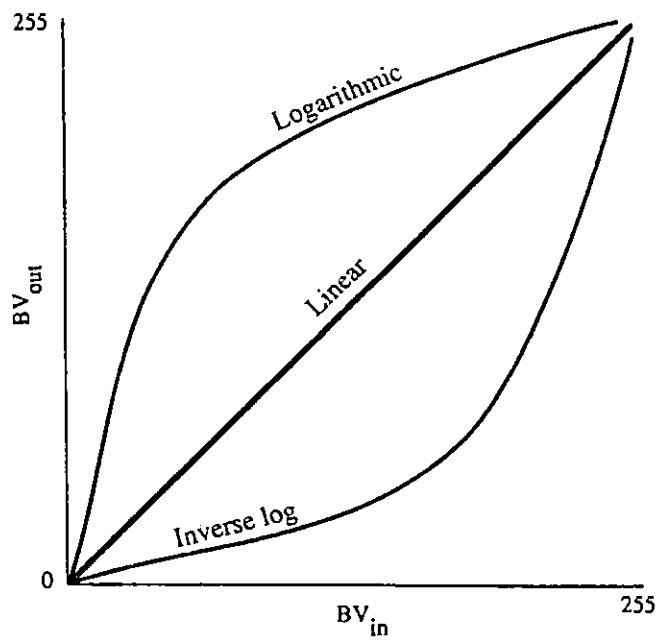


Figure 7-13 Logic of a nonlinear, logarithmic, and inverse log contrast stretch.

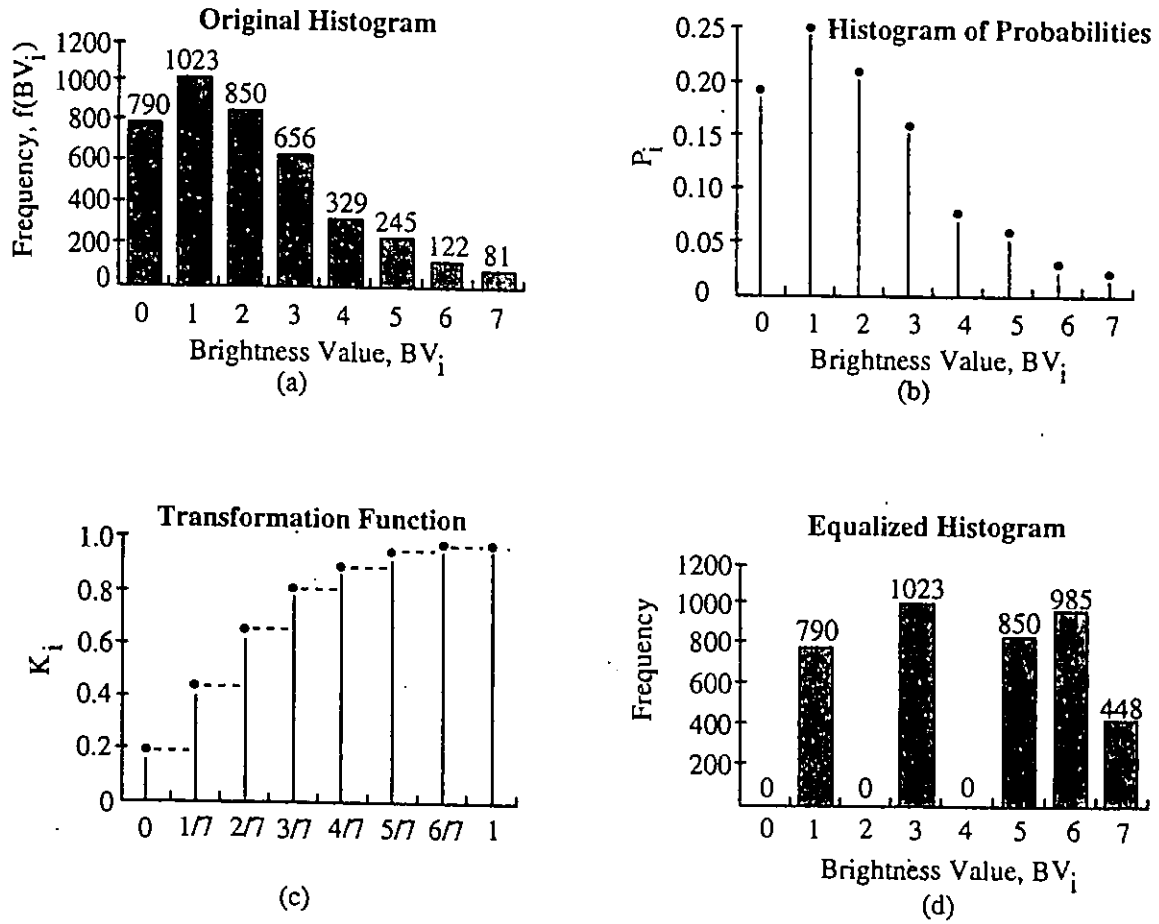
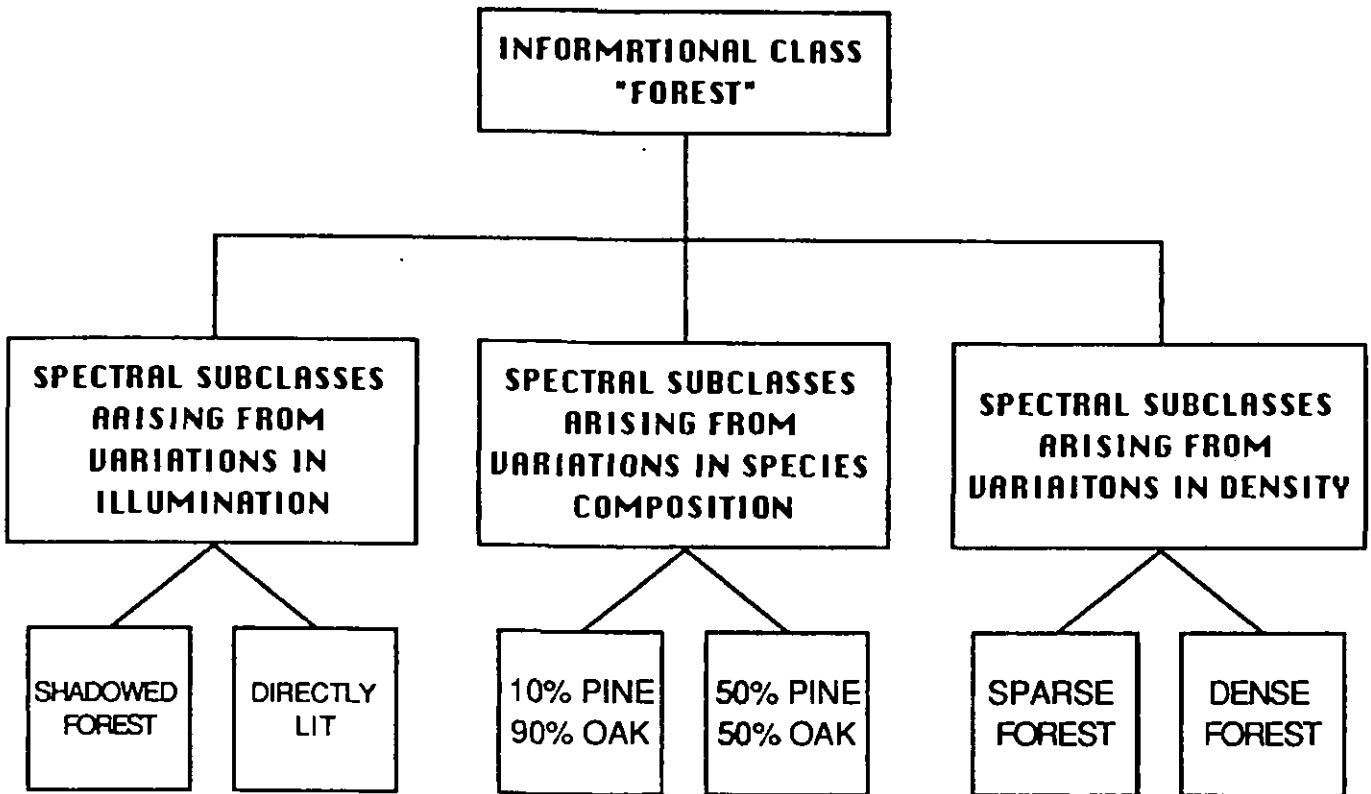


Figure 7-12 Histogram equalization process applied to hypothetical data (adapted from Gonzalez and Wintz, 1977). (a) Original histogram showing the frequency of pixels in each brightness value. (b) Original histogram expressed in probabilities. (c) The transformation function. (d) The equalized histogram showing the frequency of pixels in each brightness value.

Table 7-3. Example of How a Hypothetical 64×64 Image with Brightness Values from 0 to 7 is Histogram Equalized

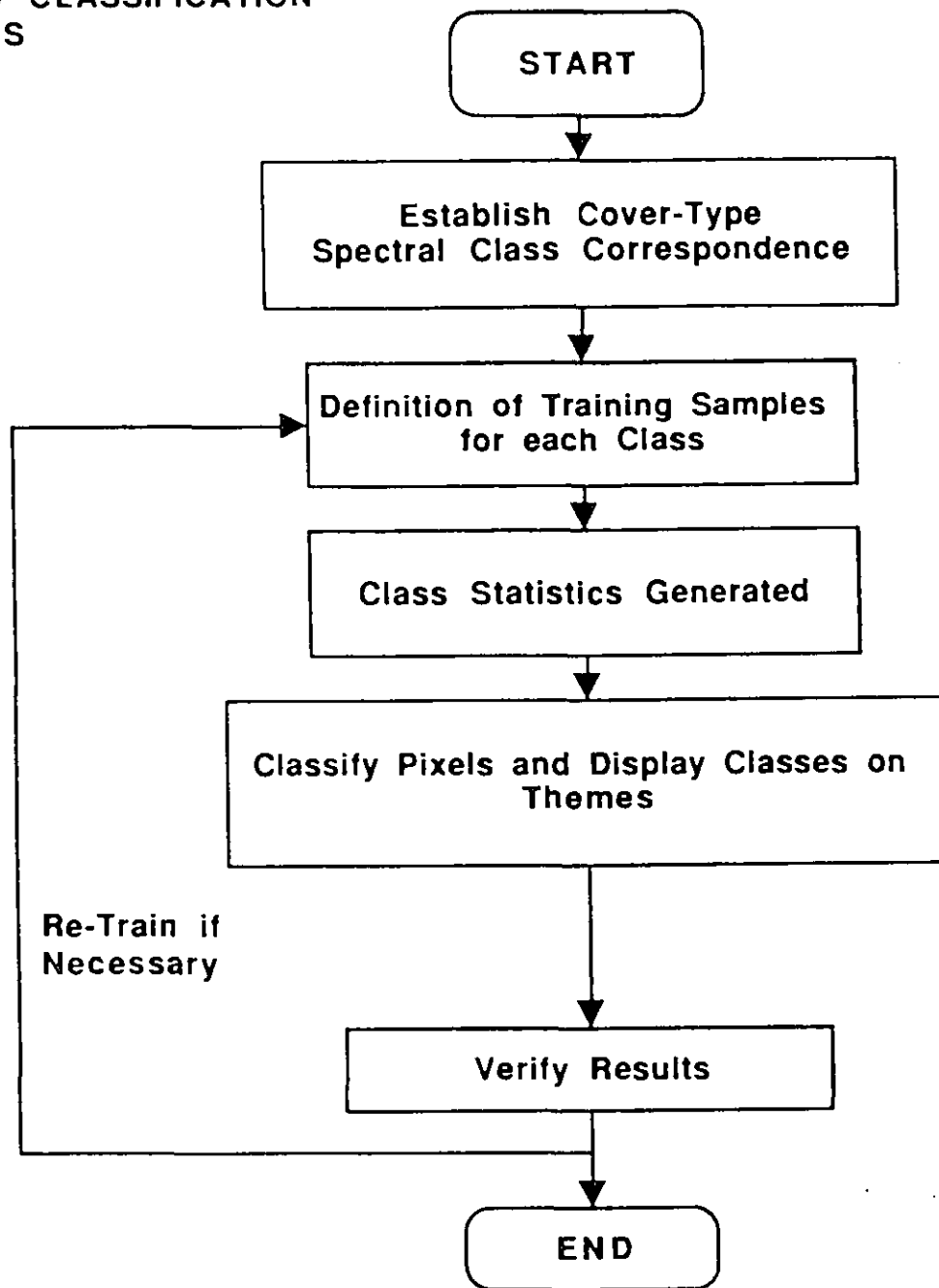
Frequency, $f(BV_i)$	790	1023	850	656	329	245	122	81
Original brightness value, BV_i	0	1	2	3	4	5	6	7
$L_i = \frac{\text{brightness value}}{n}$	0	0.14	0.28	0.42	0.57	0.71	0.85	1.0
Cumulative frequency transformation:	$\frac{790}{4096}$	$\frac{1813}{4096}$	$\frac{2663}{4096}$	$\frac{3319}{4096}$	$\frac{3648}{4096}$	$\frac{3893}{4096}$	$\frac{4015}{4096}$	$\frac{4096}{4096}$
$k_i = \sum_{i=0}^{\text{quant}_i} \frac{f(BV_i)}{n}$	=0.19	=0.44	=0.65	=0.81	=0.89	=0.95	=0.98	=1.0
Assign original BV_i class to the new class it is closest to in value	1	3	5	6	6	7	7	7

SPECTRAL SUBCLASSES



CAMPBELL (1987)

**SUPERVISED CLASSIFICATION
TECHNIQUES**



SUPERVISED IMAGE CLASSIFICATION

Objective

To automatically categorize all pixels in an image into information classes.

1. requires an analysis of the spectral properties of surface features in a multi-band image; and
2. a systematic sorting, based on mathematical decision rules, of the spectral data into spectral/textural categories.

Assumption

- different surface features manifest different combinations of digital values based on their spectral reflectance/emittance properties.

Introduction

- the image analyst “supervises” the pixel categorization process by specifying for a computer algorithm, numerical descriptors of various land cover types in a scene.
- image analyst guides the classification by identifying areas on an image that are known to belong to given categories - pixels of known identify (i.e., those assigned to informational classes) are used to determine mathematical decision rules so unknown pixels can be categorized
- pixels of known identify (i.e., of known land cover types) are located within training areas and are often referred to as calibration pixels

Information Classes

- categorizes of interest to the user
- not recorded directly, but are derived from the spectral data
- includes spectral variations due to natural variations in the class (spectral subclasses)

Spectral classes

- groups of pixels that are uniform with respect to the brightness displayed in several spectral channels

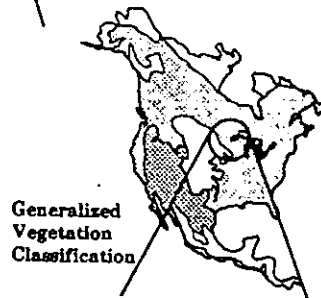
Stages to Supervised Classification

1. Definition of Information Classes
2. Training/Calibration Site Selection
 - delineate areas of known identify on the digital image
3. Generation of Statistical Parameters
 - define the unique spectral characteristics (signatures) of each of the cover classes
4. Classification
 - assignment of “unknown” pixels to the appropriate information class
5. Accuracy Assessment
 - training/calibration versus test/validation data for accuracy assessment
6. Output Stage
 - the results of the classification are presented as (i) thematic maps; (ii) tables of statistics for the land cover/use classes; and/or(iii) digital data files compatible with GIS

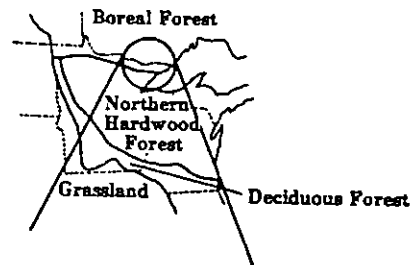
LEVEL I : Global
 AVHRR
 resolution: 1.1 km



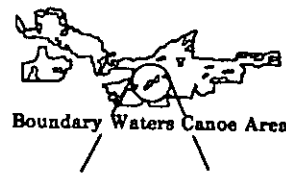
LEVEL II : Continental
 AVHRR
 Landsat Multispectral Scanner
 resolution: 1.1 km - 80 m



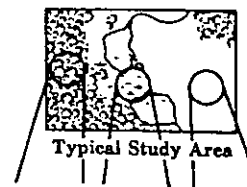
LEVEL III : Biome
 Landsat Multispectral Scanner
 Thematic Mapper
 Synthetic Aperture Radars
 resolution : 80 m - 30 m



LEVEL IV : Region
 Thematic Mapper
 High Altitude Aircraft
 Large Format Camera
 SPOT
 resolution : 30 m - 3 m +



LEVEL V : Plot
 High and Low Altitude Aircraft
 resolution : 3 m + - 1 m +



LEVEL VI : In Situ Sample Site
 Surface Measurements
 and Observations

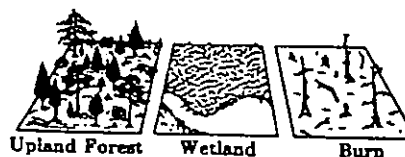


Figure 8-6 Relationship between the level of detail required and the spatial resolution of various remote sensing systems for vegetation inventories (Botkin, et al., 1984).

The Training Stage

Objective

To assemble a set of statistics that describe the spectral response pattern for each information class.

Requires:

1. close interaction between the analyst and the image data; and 2. reference data

For an accurate classification, training data must be:

1. Representative
 - to adequately sample the spectral variation for the information class
 - sample numerous small areas scattered throughout the image
2. Complete
 - a sufficient sample size is required to ensure accurate statistical descriptors
 - (e.g., 100 pixels; 10N to 100N pixels)

Classification Schemes

- systems developed in order to ensure that image data on land cover characteristics and discernible human activities (i.e., land use) are objectively and consistently classified
- the classification system is used in a process of segmenting the image into a mosaic of parcels, with each parcel assigned to a land-cover or land-use class

Land Use: the use of land by humans usually with an emphasis on the functional role of the land in economic activities

Land Cover: the natural and cultivated vegetation on the earth's surface. In general, may also include visible evidence of land use, including both vegetative and non-vegetative features (i.e., plowed land, paved parking lots, forest).

Hierarchical Classification Schemes

- those schemes that employ multiple levels (classes) to typify and group land-use and land-cover data
- generally proceed from an initial level (e.g., Level I) of data of general spatial resolution through to a final level (i.e., Level IV) of data of some higher spatial resolution

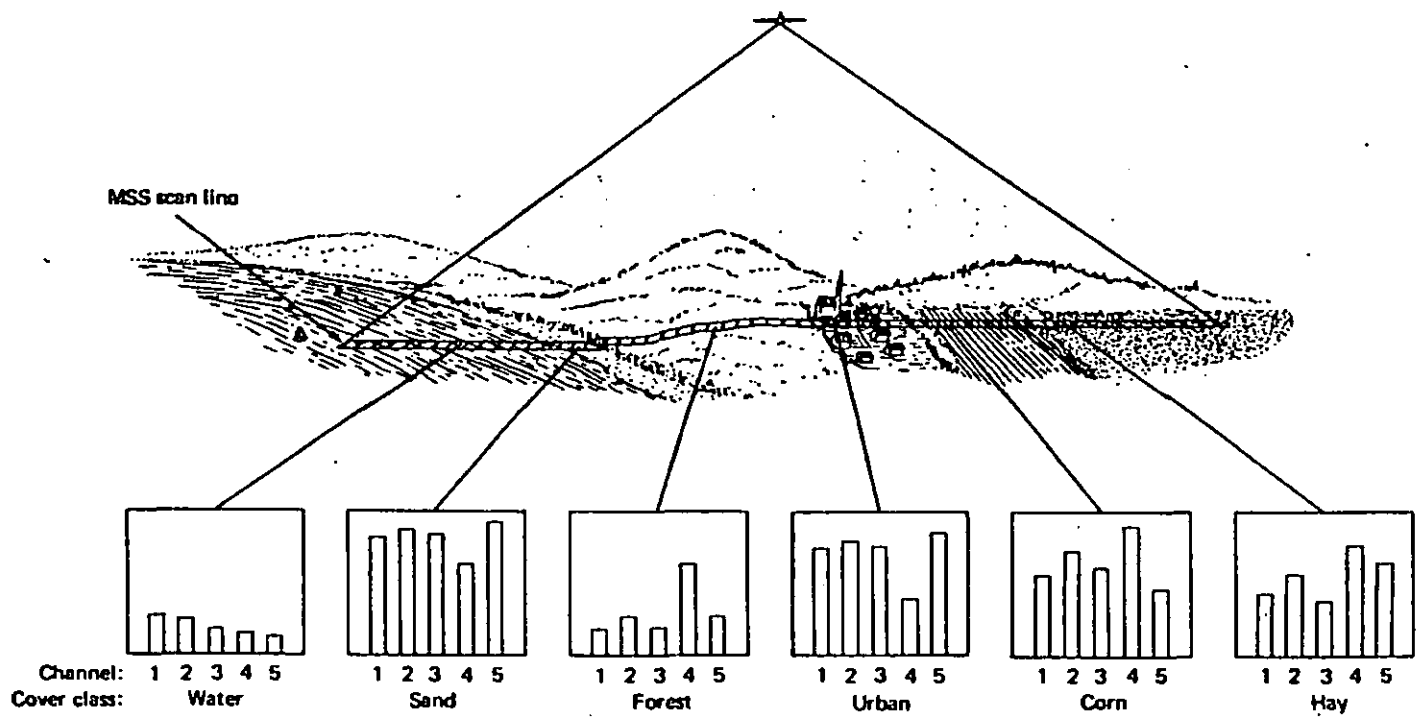


Figure 7.36 Selected MSS measurements made along one scan line. Channels cover the following spectral bands: 1, blue; 2, green; 3, red; 4, near infrared; 5, thermal infrared.

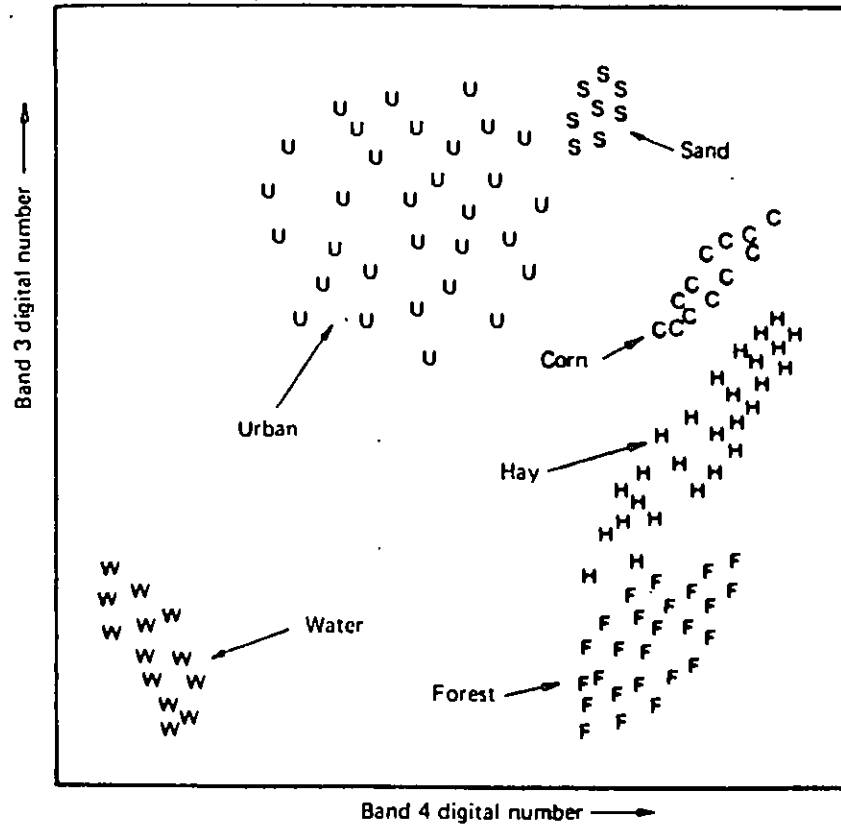


Figure 7.38 Pixel observations from selected training sites plotted on scatter diagram.

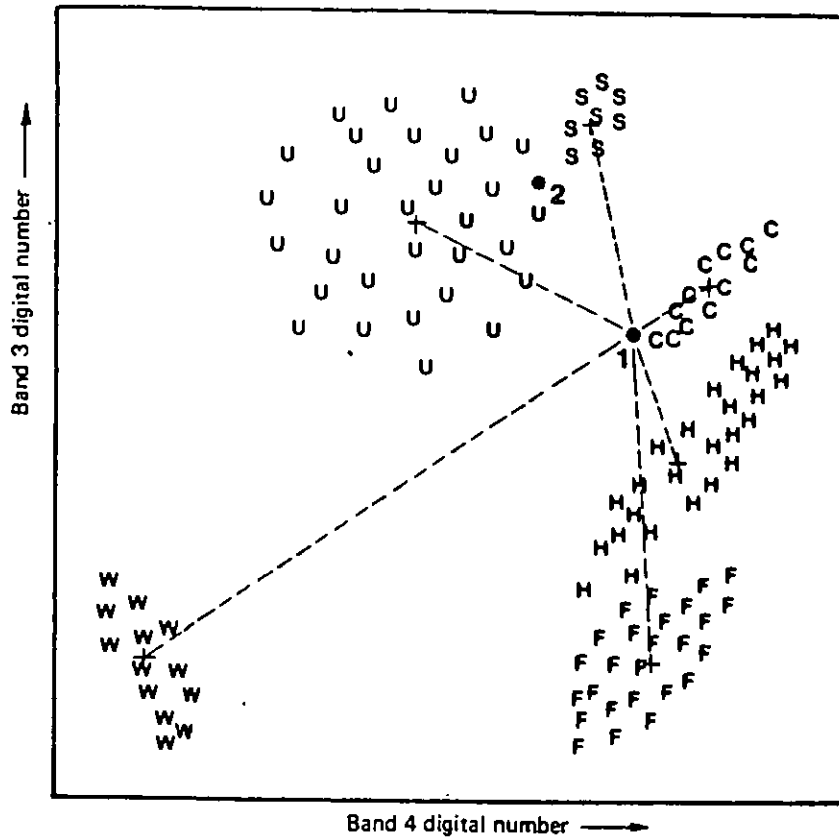
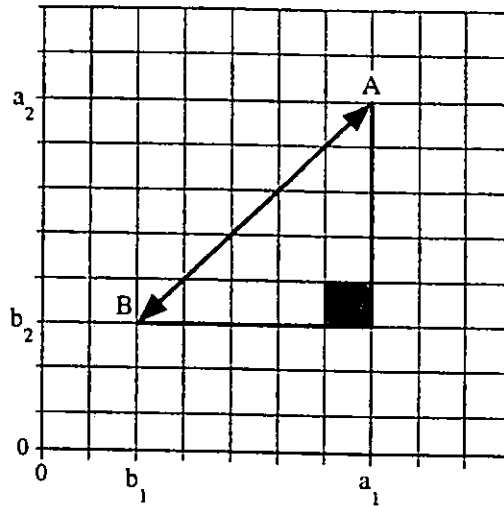


Figure 7.39 Minimum distance to means classification strategy.



Euclidean distance

"Round the block" distance

$$D_{AB} = \sqrt{\sum_{i=1}^n (a_i - b_i)^2}$$

$$D_{AB} = \sum_{i=1}^n |(a_i - b_i)|$$

Figure 8-15 The distance used in a *minimum distance to means* classification algorithm can take two forms: the Euclidean distance based on the Pythagorean theorem and the round-the-block distance. The Euclidean distance is more computationally intensive.

Table 8-7. Example of Minimum Distance to Means Classification Logic for Pixels *a* and *b* in Figure 8-14.

Class	Distance from pixel <i>a</i> (40, 40) to the mean of each class	Distance from pixel <i>b</i> (10, 40) to the mean of each class
1. Residential	$\sqrt{(40 - 36.7)^2 + (40 - 55.7)^2} = 16.04$	$\sqrt{(10 - 36.7)^2 + (40 - 55.7)^2} = 30.97$
2. Commercial	$\sqrt{(40 - 54.8)^2 + (40 - 77.4)^2} = 40.22$	$\sqrt{(10 - 54.8)^2 + (40 - 77.4)^2} = 58.35$
3. Wetland	$\sqrt{(40 - 20.2)^2 + (40 - 28.2)^2} = 23.04$	$\sqrt{(10 - 20.2)^2 + (40 - 28.2)^2} = 15.75$ Assign pixel <i>b</i> to this class; it has the minimum distance
4. Forest	$\sqrt{(40 - 39.1)^2 + (40 - 35.5)^2} = 4.59$ Assign pixel <i>a</i> to this class; it has the minimum distance	$\sqrt{(10 - 39.1)^2 + (40 - 35.5)^2} = 29.45$
5. Water	$\sqrt{(40 - 9.3)^2 + (40 - 5.2)^2} = 46.4$	$\sqrt{(10 - 9.3)^2 + (40 - 5.2)^2} = 34.8$

Table 8-8. Total Number of Pixels Classified into Each of the Five Charleston Land-cover Classes Shown in Figure 8-17

Class	Total Number of Pixels
1. Residential	14,398
2. Commercial	4,088
3. Wetland	10,772
4. Forest	11,673
5. Water	20,509

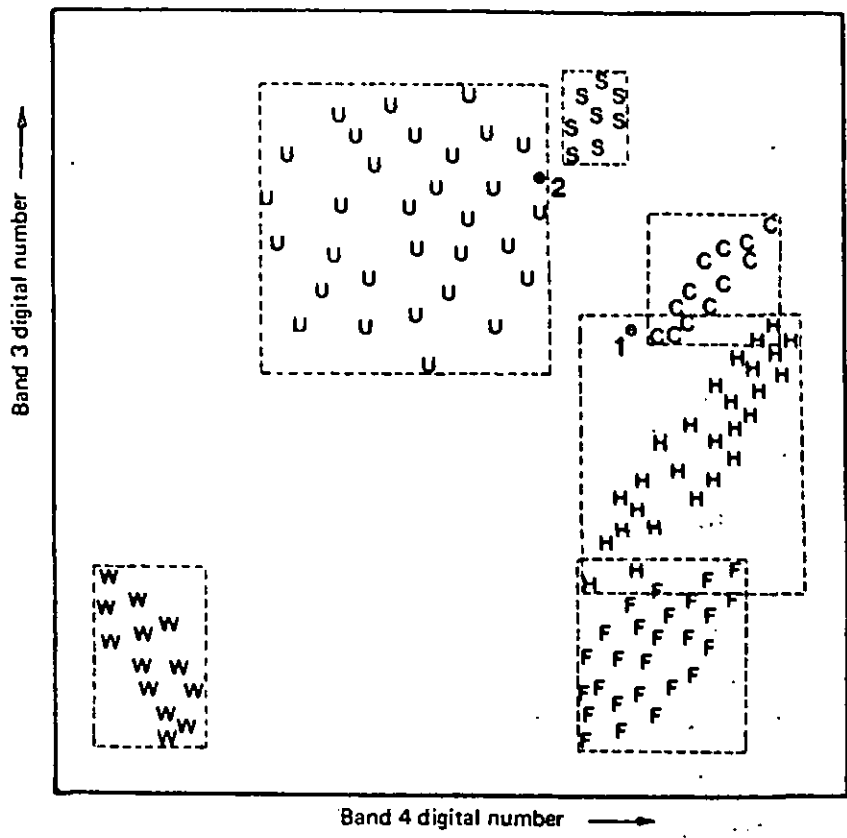


Figure 7.40 Parallelepiped classification strategy.

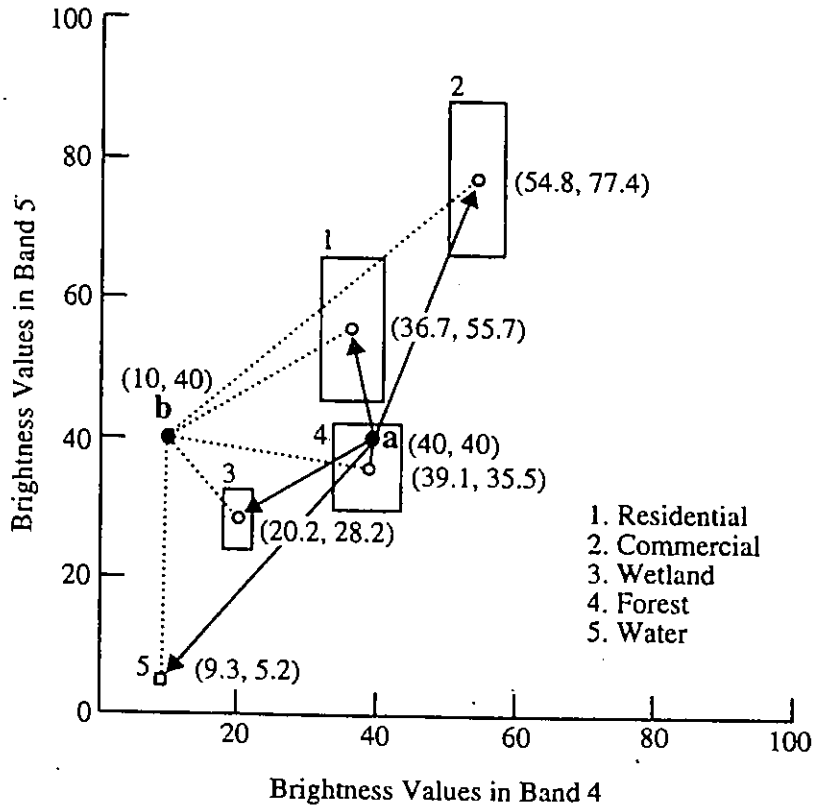


Figure 8-14 Points *a* and *b* are pixels in the image to be classified. Pixel *a* has a brightness value of 40 in band 4 and 40 in band 5. Pixel *b* has a brightness value of 10 in band 4 and 40 in band 5. The boxes represent the *parallelepiped* decision rule associated with a ± 1 standard deviation classification. The vectors (arrows) represent the distance from *a* and *b* to the mean of all classes in a *minimum distance to means* classification algorithm. Refer to Tables 8-8 and 8-9 for the results of classifying points *a* and *b* using both classification techniques.

Table 8-6. Example of Parallelepiped Classification Logic for Pixels *a* and *b* in Figure 8-14.

Class	Lower Threshold, L_{ck}	Upper Threshold, H_{ck}	Does pixel <i>a</i> (40, 40) satisfy criteria for this class in this band? $L_{ck} \leq a \leq H_{ck}$	Does pixel <i>b</i> (10, 40) satisfy criteria for this class in this band? $L_{ck} \leq b \leq H_{ck}$
1. Residential				
Band 4	$36.7 - 4.53 = 31.27$	$36.7 + 4.53 = 41.23$	Yes	No
Band 5	$55.7 - 10.72 = 44.98$	$55.7 + 10.72 = 66.42$	No	No
2. Commercial				
Band 4	$54.8 - 3.88 = 50.92$	$54.8 + 3.88 = 58.68$	No	No
Band 5	$77.4 - 11.16 = 66.24$	$77.4 + 11.16 = 88.56$	No	No
3. Wetland				
Band 4	$20.2 - 1.88 = 18.32$	$20.2 + 1.88 = 22.08$	No	No
Band 5	$28.2 - 4.31 = 23.89$	$28.2 + 4.31 = 32.51$	No	No
4. Forest				
Band 4	$39.1 - 5.11 = 33.99$	$39.1 + 5.11 = 44.21$	Yes	No
Band 5	$35.5 - 6.41 = 29.09$	$35.5 + 6.41 = 41.91$	Yes, assign pixel to class 4, forest. STOP.	No
5. Water				
Band 4	$9.3 - 0.56 = 8.74$	$9.3 + 0.56 = 9.86$	—	No
Band 5	$5.2 - 0.71 = 4.49$	$5.2 + 0.71 = 5.91$	—	No, assign pixel to unclassified category. STOP.

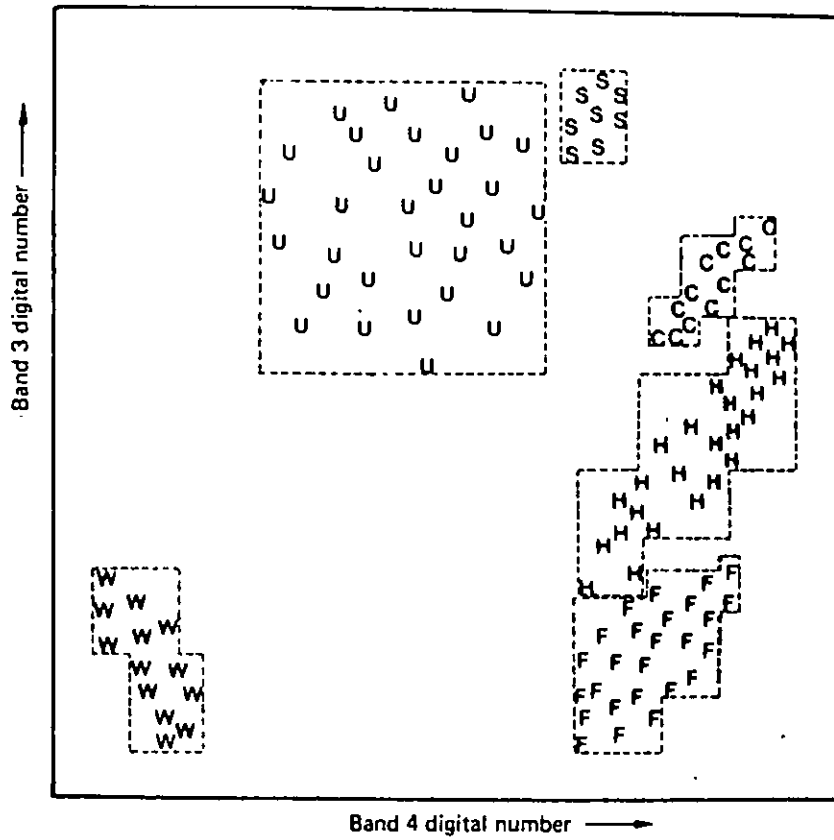


Figure 7.41 Parallelepiped classification strategy employing stepped decision region boundaries.

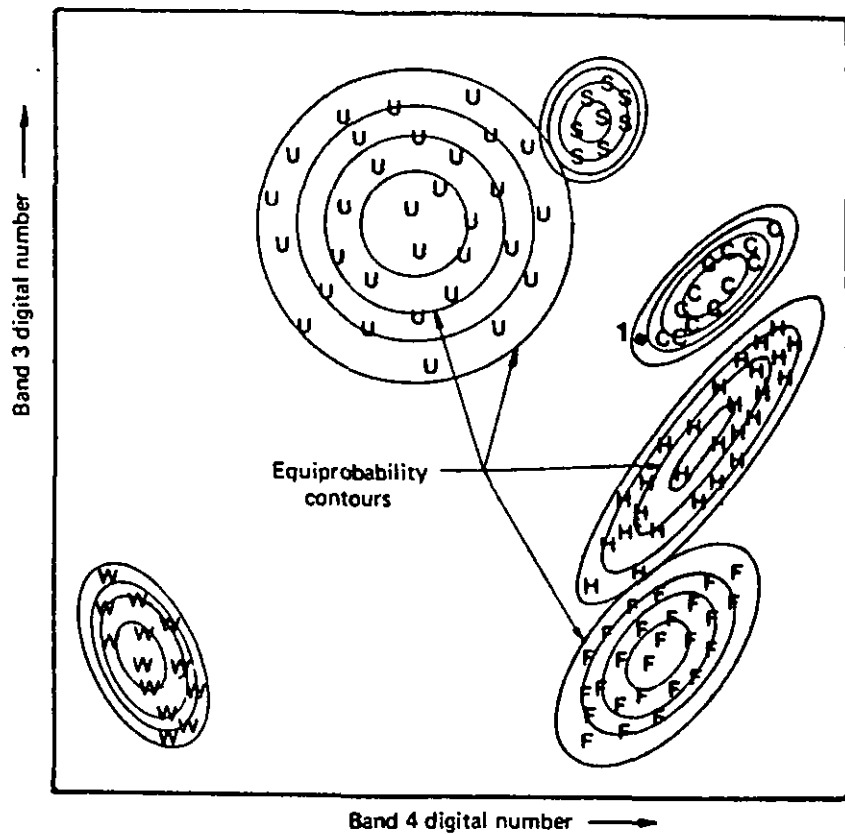


Figure 7.43 Equiprobability contours defined by a maximum likelihood classifier.

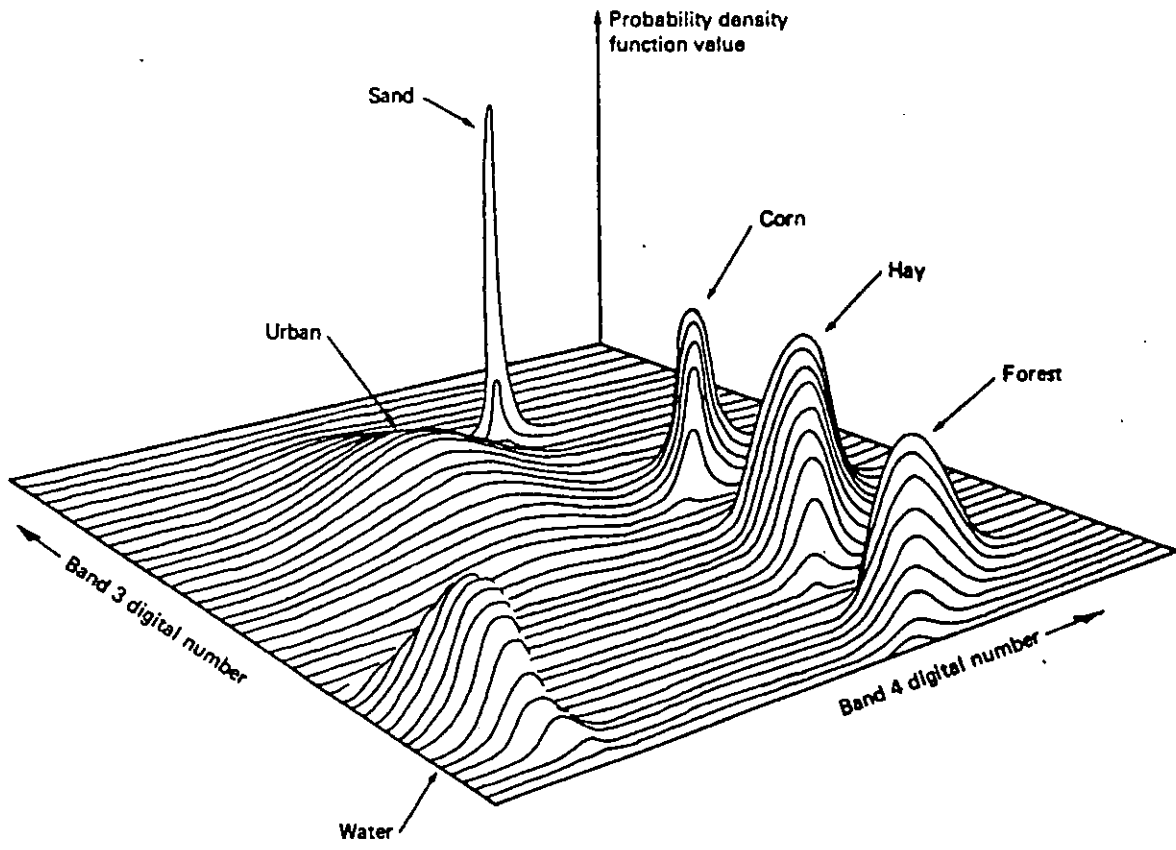


Figure 7.42 Probability density functions defined by a maximum likelihood classifier.

Table 8-4. Univariate and Multivariate Training Statistics for the Five Land-cover Classes Using Six Bands of Landsat Thematic Mapper Data Obtained over Charleston, South Carolina

a. Statistics for Residential

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Univariate statistics						
Mean	70.6	28.8	29.8	36.7	55.7	28.2
Std. dev.	6.90	3.96	5.65	4.53	10.72	6.70
Variance	47.6	15.7	31.9	20.6	114.9	44.9
Minimum	59	22	19	26	32	16
Maximum	91	41	45	52	84	48
Variance-covariance matrix						
1	47.65					
2	24.76	15.70				
3	35.71	20.34	31.91			
4	12.45	8.27	12.01	20.56		
5	34.71	23.79	38.81	22.30	114.89	
7	30.46	18.70	30.86	12.99	60.63	44.92
Correlation matrix						
1	1.00					
2	0.91	1.00				
3	0.92	0.91	1.00			
4	0.40	0.46	0.47	1.00		
5	0.47	0.56	0.64	0.46	1.00	
7	0.66	0.70	0.82	0.43	0.84	1.00

b. Statistics for Commercial

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Univariate statistics						
Mean	112.4	53.3	63.5	54.8	77.4	45.6
Std. dev.	5.77	4.55	3.95	3.88	11.16	7.56
Variance	33.3	20.7	15.6	15.0	124.6	57.2
Minimum	103	43	56	47	57	32
Maximum	124	59	72	62	98	57

b. Statistics for Commercial (Continued)

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Variance-covariance matrix						
1	33.29					
2	11.76	20.71				
3	19.13	11.42	15.61			
4	19.60	12.77	14.26	15.03		
5	-16.62	15.84	2.39	0.94	124.63	
7	-4.58	17.15	6.94	5.76	68.81	57.16
Correlation matrix						
1	1.00					
2	0.45	1.00				
3	0.84	0.64	1.00			
4	0.88	0.72	0.93	1.00		
5	-0.26	0.31	0.05	0.02	1.00	
7	-0.10	0.50	0.23	0.20	0.82	1.00

c. Statistics for Wetland

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Univariate statistics						
Mean	59.0	21.6	19.7	20.2	28.2	12.2
Std. dev.	1.61	0.71	0.80	1.88	4.31	1.60
Variance	2.6	0.5	0.6	3.5	18.6	2.6
Minimum	54	20	18	17	20	9
Maximum	63	25	21	25	35	16
Variance-covariance matrix						
1	2.59					
2	0.14	0.50				
3	0.22	0.15	0.63			
4	-0.64	0.17	0.60	3.54		
5	-1.20	0.28	0.93	5.93	18.61	
7	-0.32	0.17	0.40	1.72	4.53	2.55

c. Statistics for Wetland (Continued)

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Correlation matrix						
1	1.00					
2	0.12	1.00				
3	0.17	0.26	1.00			
4	-0.21	0.12	0.40	1.00		
5	-0.17	0.09	0.27	0.73	1.00	
7	-0.13	0.15	0.32	0.57	0.66	1.00

d. Statistics for Forest

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Univariate statistics						
Mean	57.5	21.7	19.0	39.1	35.5	12.5
Std. dev.	2.21	1.39	1.40	5.11	6.41	2.97
Variance	4.9	1.9	1.9	26.1	41.1	8.8
Minimum	53	20	17	25	22	8
Maximum	63	28	24	48	54	22
Variance-covariance matrix						
1	4.89					
2	1.91	1.93				
3	2.05	1.54	1.95			
4	5.29	3.95	4.06	26.08		
5	9.89	5.30	5.66	13.80	41.13	
7	4.63	2.34	2.22	3.22	16.59	8.84
Correlation matrix						
1	1.00					
2	0.62	1.00				
3	0.66	0.80	1.00			
4	0.47	0.56	0.57	1.00		
5	0.70	0.59	0.63	0.42	1.00	
7	0.70	0.57	0.53	0.21	0.87	1.00

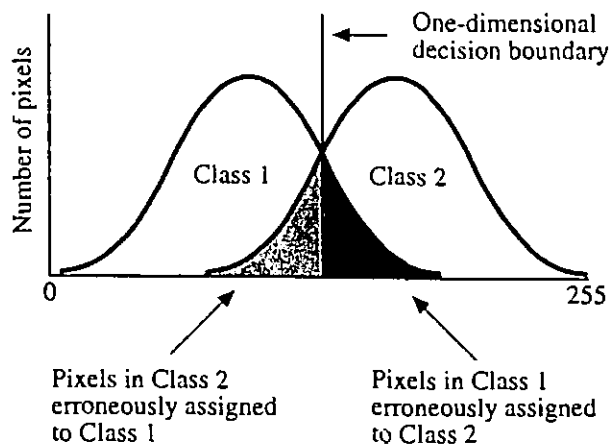
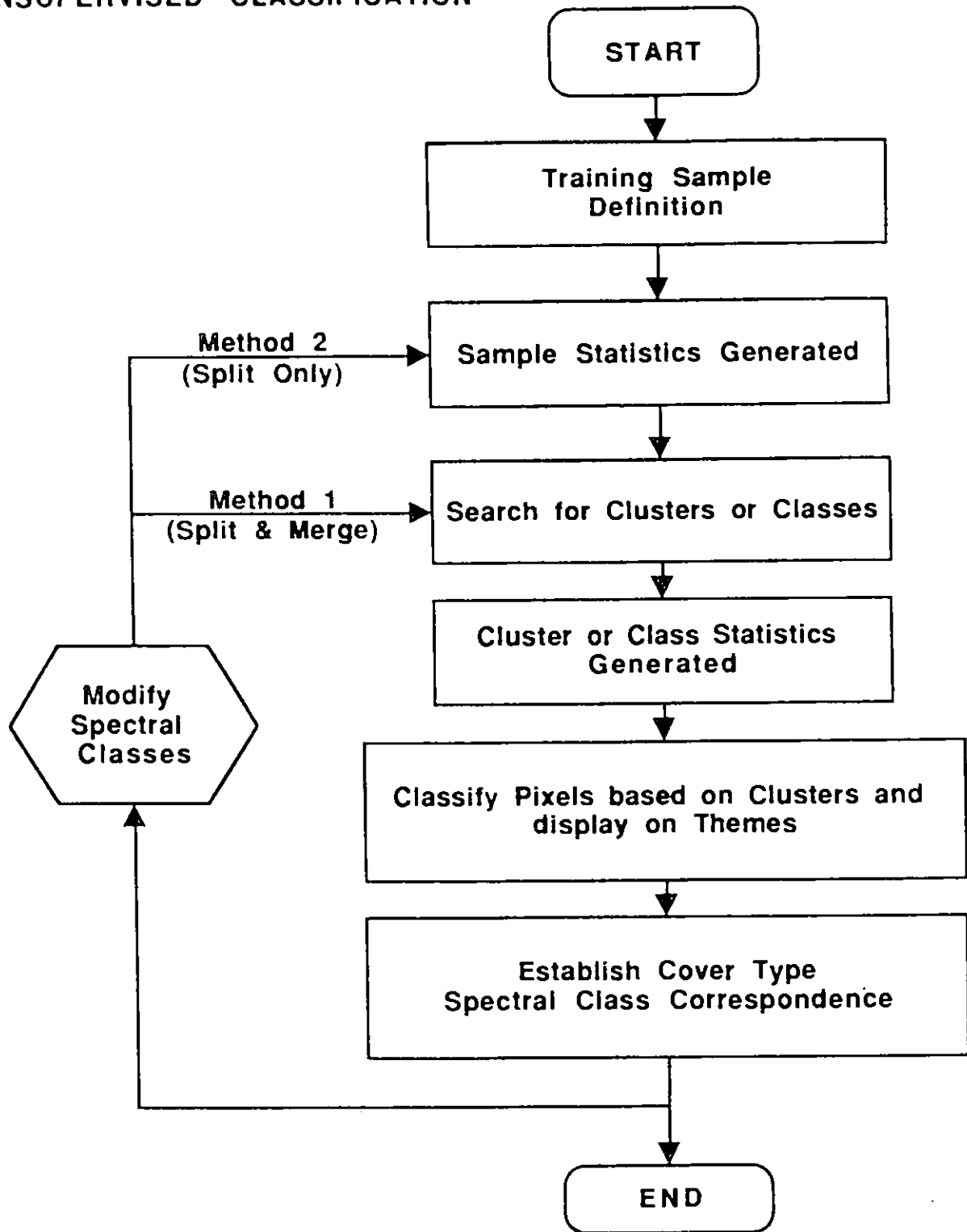


Figure 8-13 The basic problem in remote sensing pattern recognition classification is, given a spectral distribution of data in n bands (here just 1 band), to find an n -dimensional decision boundary that will allow the separation of the major classes (just 2 in this example) with a minimum of error and a minimum number of bands being evaluated. The dark areas of both distributions identify potential classification error.

UNSUPERVISED CLASSIFICATION



UNSUPERVISED IMAGE CLASSIFICATION (UC)

Definition: identification of natural groups, or structures within multispectral data

- does **NOT** use training data for individual information classes as the basis for classification
- image pixels are examined and aggregated into a number of spectral classes based on natural clustering in multi-dimensional space
- UC is the definition, identification, labelling and mapping of natural spectral classes

Assumption

- natural spectral groupings exist within a scene (inherently uniform in respect to brightness in several spectral channels)
- spectral classes within a given cover class should "**cluster**" close together whereas data in different classes should be well separated

Supervised: define information categories and then examine their spectral separability verses

Unsupervised: determine spectrally separable classes and then define their informational usefulness

Advantages (relative to supervised classification)

1. no extensive/detailed *a priori* knowledge of the region is required (nature of the knowledge required for UC differs from that required for supervised classification)
2. minimize human errors/biases (fewer decisions by analyst)
3. produces more **uniform** classes
4. spectrally distinct classes present in the data may not have initially been apparent to the analyst

Disadvantages (relative to supervised classification)

1. spectral grouping may not correspond to information classes of interest to the analyst
2. limited control over the "menu" of classes
3. spectral properties of specific classes will change over time (relationships between information classes and spectral classes are not constant)
4. computationally intensive

Stages to Unsupervised Classification

1. Definition of minimum and maximum number of categories to be generated by the particular classification algorithm (based on an analyst's knowledge or user requirements).
2. Random selection of pixels to form cluster centre's.
3. algorithm then finds distances between pixels and forms initial estimates of cluster centers as permitted by user defined criteria.
4. As pixels are added to the initial estimates, new class means are calculated. This is an iterative process until the mean does not change significantly from one iteration to the next (a kind of wearing down of the classification problem by repetitive application assignment and reassignment of pixels to groups).

Key component of unsupervised classification:

1. effective methods of measuring distances in data/feature space;
2. identifying class centroids; and
3. testing distinctiveness of classes.

Chain Method:

Information provided by the analyst (not truly objective process):

1. R, a radius distance in spectral space used to determine when a new cluster should be formed (e.g., DN=15).
2. C, a spectral space distance parameter used when merging clusters (e.g., DN=30) when N is reached.
3. N, the number of pixels to be evaluated between each major merging of the clusters (e.g., 2000 pixels).
4. C_{max} , the maximum number of clusters to be identified by the algorithm (e.g., 20 clusters).

ISODATA (Interactive Self-Organizing Data Analysis Technique)Method

Information provided by the analyst (not truly objective process):

1. C_{max} : the maximum number of classes to be identified (e.g., 20 clusters);
2. T: the maximum percentage of pixels whose class values are allowed to be unchanged between iterations;
3. M; the maximum number of times ISODATA is to classify pixels and recalculate cluster mean vectors;
4. Minimum members in a cluster (%);
5. Maximum Standard Deviation;
6. Split Separation Values; and
7. Minimum distance between cluster means.

Post-classification Smoothing

- to remove salt-and -pepper appearance due to spectral variability encountered with per-pixel classifiers
- e.g., several pixels in a corn field classified as soybean and vice-versa (smooth the classification to show only the dominant (presumably correct) class
- majority filter (not a low-pass filter)

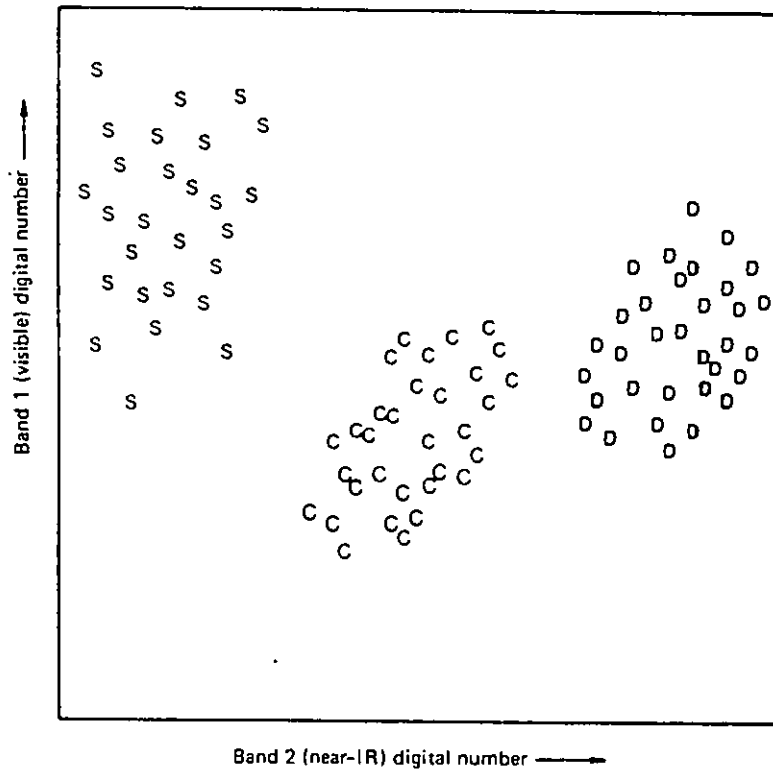


Figure 7.47 Spectral classes in two-channel image data.

TABLE 7.2 Spectral Classes Resulting from Clustering a Forested Scene

Spectral Class	Identity of Spectral Class	Corresponding Desired Information Category
<i>Possible Outcome 1</i>		
1	Water	Water
2	Coniferous trees	Coniferous trees
3	Deciduous trees	Deciduous trees
4	Brushland	Brushland
<i>Possible Outcome 2</i>		
1	Turbid water	Water
2	Clear water	
3	Sunlit conifers	Coniferous trees
4	Shaded hillside conifers	
5	Upland deciduous	Deciduous trees
6	Lowland deciduous	
7	Brushland	Brushland
<i>Possible Outcome 3</i>		
1	Turbid water	Water
2	Clear water	
3	Coniferous trees	Coniferous trees
4	Mixed coniferous/deciduous	Deciduous trees
5	Deciduous trees	
6	Deciduous/brushland	Brushland

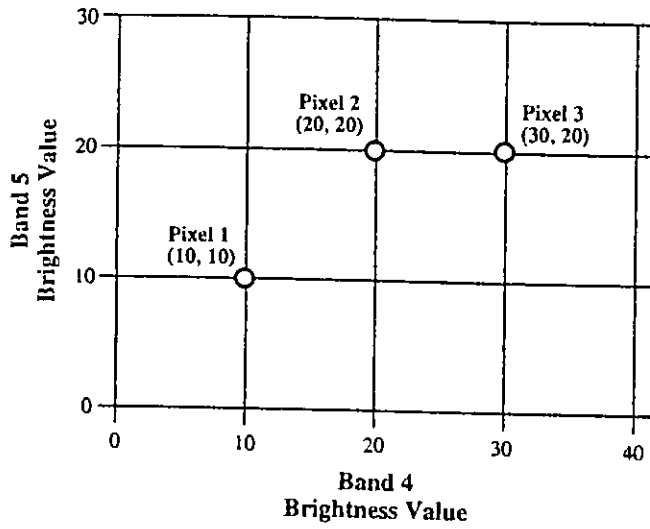


Figure 8-18 Original values of pixels 1, 2, and 3 as measured in bands 4 and 5 of the hypothetical remotely sensed data.

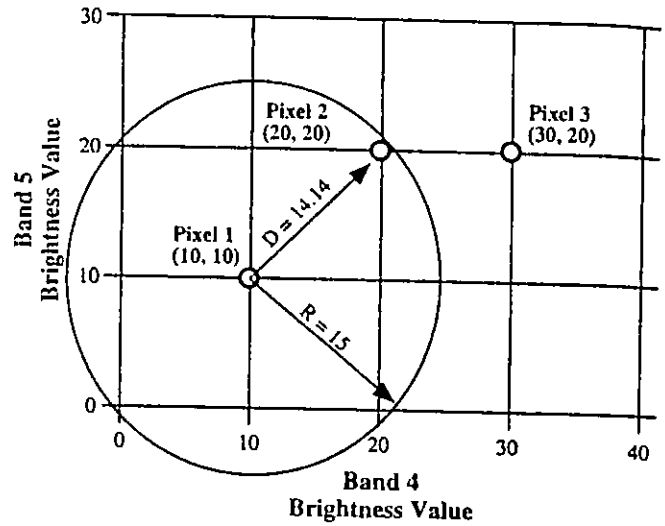


Figure 8-19 The distance (D) in two-dimensional spectral space between pixel 1 (cluster 1) and pixel 2 (cluster 2) in the first iteration is computed and tested against the value of R , the minimum acceptable radius. In this case, D does not exceed R ; therefore, we merge clusters 1 and 2 as shown in the next illustration.

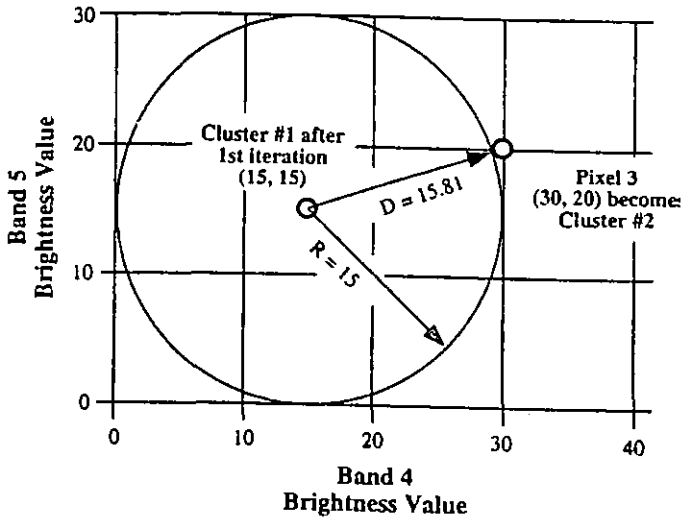


Figure 8-20 Pixels 1 and 2 now represent cluster 1. Note that the location of cluster 1 has migrated from 10, 10 to 15, 15 after the first iteration. Now, pixel 3 distance (D) is computed to see if it is greater than the minimum threshold, R . It is, so pixel location 3 becomes cluster 2. This process continues until all 20 clusters are identified. Then the 20 clusters are evaluated using a distance measure, C (not shown), to merge the clusters that are closest to one another.

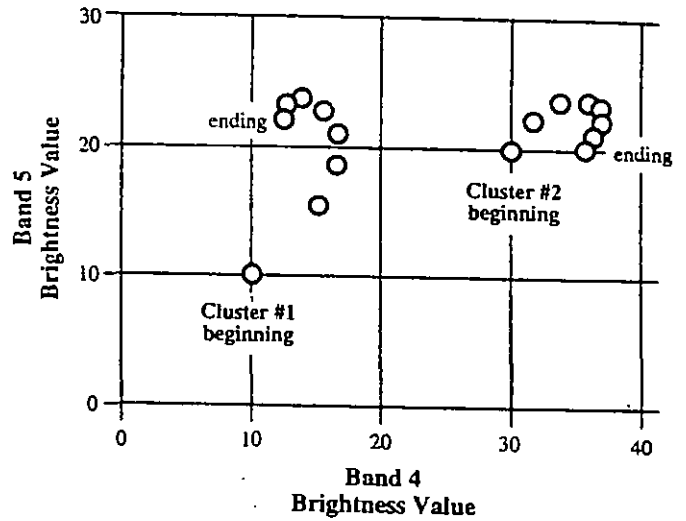


Figure 8-21 How clusters migrate during the several iterations of a clustering algorithm. The final ending point represents the mean vector that would be used in phase 2 of the clustering process when the minimum distance classification is performed.

Table 8-9. Results of Clustering on Thematic Mapper Bands 2, 3, and 4 of the Charleston, South Carolina TM Scene

Cluster	Percent of scene	Mean vector			Class description	Color assignment
		Band 2	Band 3	Band 4		
1	24.15	23.14	18.75	9.35	Water	Dark blue
2	7.14	21.89	18.99	44.85	Forest 1	Dark green
3	7.00	22.13	19.72	38.17	Forest 2	Dark green
4	11.61	21.79	19.87	19.46	Wetland 1	Bright green
5	5.83	22.16	20.51	23.90	Wetland 2	Green
6	2.18	28.35	28.48	40.67	Residential 1	Bright yellow
7	3.34	36.30	25.58	35.00	Residential 2	Bright yellow
8	2.60	29.44	29.87	49.49	Parks, golf	Gray
9	1.72	32.69	34.70	41.38	Residential 3	Yellow
10	1.85	26.92	26.31	28.18	Commercial 1	Dark red
11	1.27	36.62	39.83	41.76	Commercial 2	Bright red
12	0.53	44.20	49.68	46.28	Commercial 3	Bright red
13	1.03	33.00	34.55	28.21	Commercial 4	Red
14	1.92	30.42	31.36	36.81	Residential 4	Yellow
15	1.00	40.55	44.30	39.99	Commercial 5	Bright red
16	2.13	35.84	38.80	35.09	Commercial 6	Red
17	4.83	25.54	24.14	43.25	Residential 5	Bright yellow
18	1.86	31.03	32.57	32.62	Residential 6	Yellow
19	3.26	22.36	20.22	31.21	Commercial 7	Dark red
20	0.02	34.00	43.00	48.00	Commercial 8	Bright red

Cluster Means for TM Bands 3 and 4

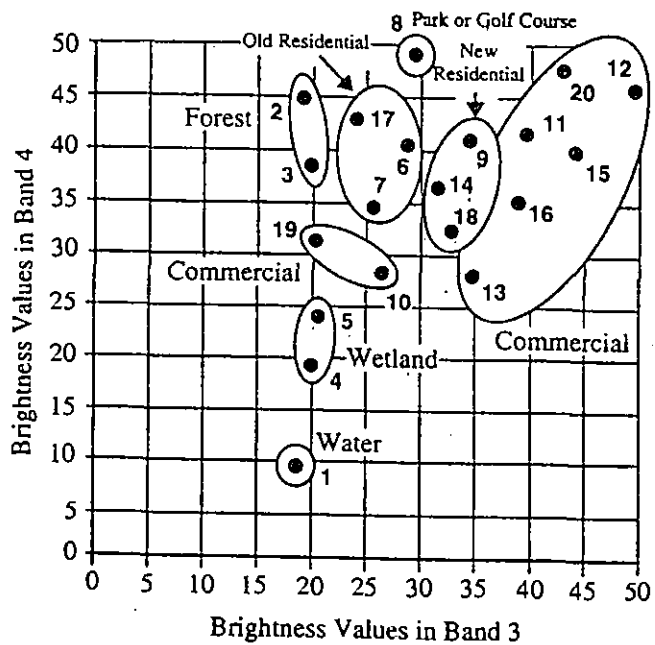


Figure 8-25 Grouping (relabeling) of the original 20 spectral clusters into information classes. The relabeling was performed by analyzing the mean vector locations in bands 3 and 4.

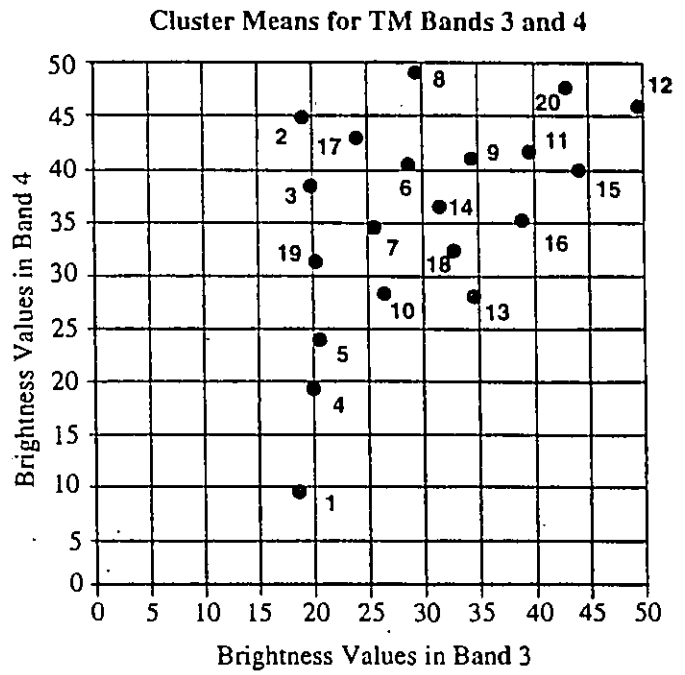
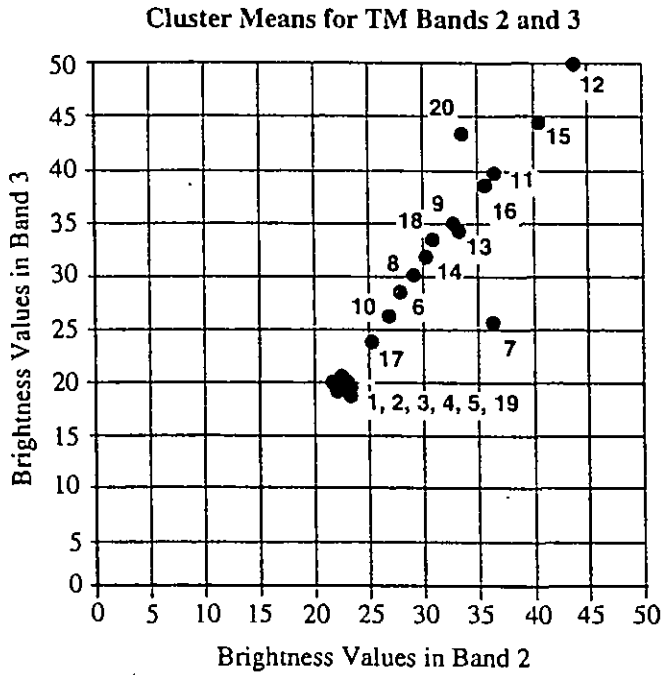


Figure 8-23 The mean vectors of the 20 clusters displayed in Figure 8-22 are shown here using only bands 2 and 3. The mean vector values are summarized in Table 8-9. Notice the substantial amount of overlap among clusters 1 through 5 and 19.

Figure 8-24 The mean vectors of the 20 clusters displayed in Figure 8-22 are shown here using only band 3 and 4 data. The mean vectors values are summarized in Table 8-9. Compare the spatial distribution of these 20 clusters in the red and near-infrared feature space with what is expected in a typical perpendicular vegetation index as discussed in Chapter 7 and Figure 7-41.

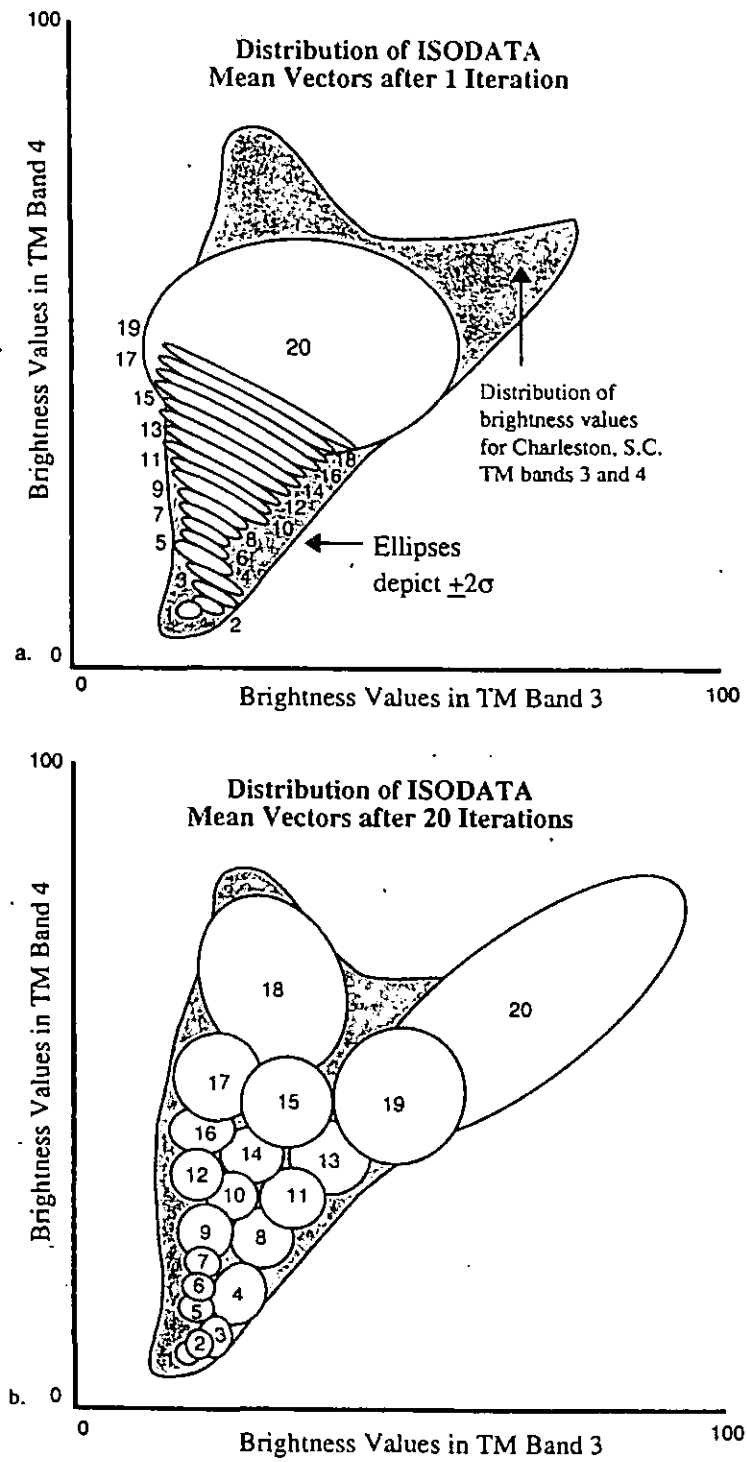


Figure 8-27 (a) Distribution of 20 ISODATA mean vectors after just one iteration using Landsat TM band 3 and 4 data of Charleston, S.C. Notice how the initial mean vectors are distributed along a diagonal in two-dimensional feature space according to the $\pm 2\sigma$ standard deviation logic discussed. (b) Distribution of 20 ISODATA mean vectors after 20 iterations. The bulk of the important feature space (the gray background) is partitioned rather well after just 20 iterations.

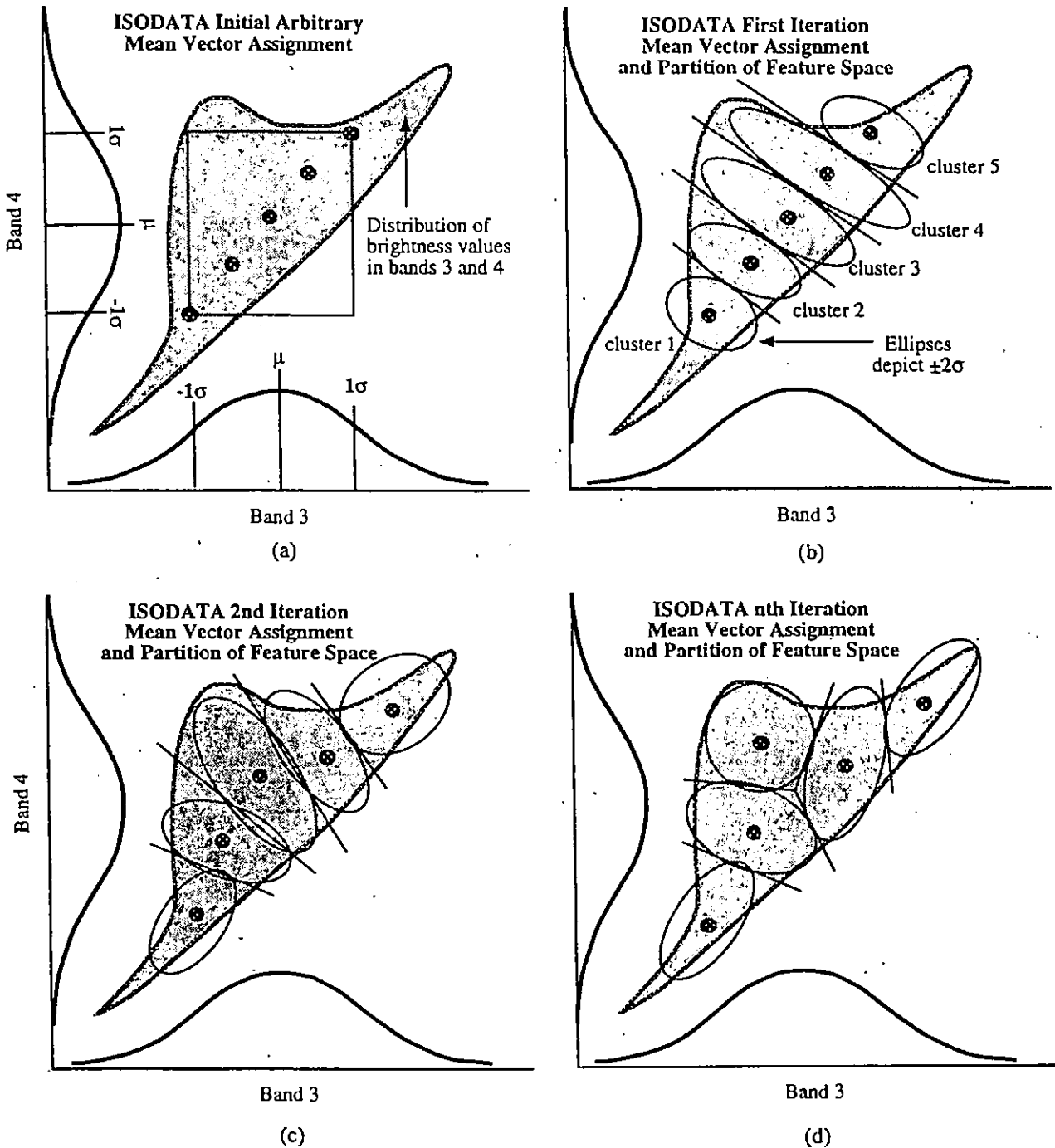


Figure 8-26 (a) ISODATA initial distribution of five hypothetical mean vectors using $\pm 1\sigma$ standard deviations in both bands as beginning and ending points. (b) In the first iteration, each candidate pixel is compared to each cluster mean and assigned to the cluster whose mean is closest in Euclidean distance. (c) During the second iteration, a new mean is calculated for each cluster based on the actual spectral locations of the pixels assigned to each cluster, instead of the initial arbitrary calculation. This involves analysis of several parameters to merge or split clusters. After the new cluster mean vectors are selected, every pixel in the scene is once again assigned to one of the new clusters. (d) This split-merge-assign process continues until there is little change in class assignment between iterations (the T threshold is reached) or the maximum number of iterations is reached (M).

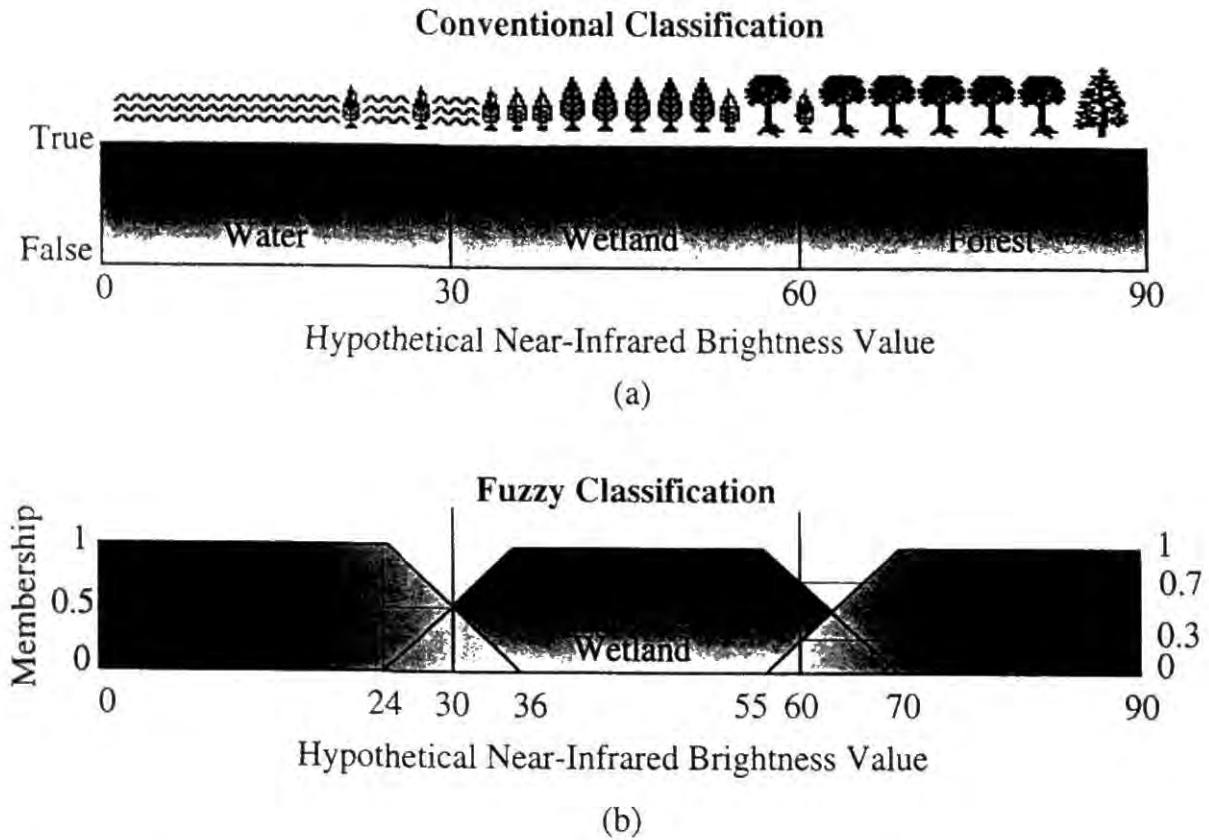


Figure 8-28 (a) Conventional hard classification rules applied to discriminate among three land-cover classes. The terrain icons suggest that there is a gradual transition in near-infrared brightness value as one progresses from water to forested wetland to upland forest. A remote sensing system would be expected to record radiant flux from mixed pixels at the interface between the major land-cover types. Mixed pixels may also be encountered within a land-cover type due to differences in species, age, or functional health of vegetation. Despite these fuzzy conditions, a hard classification would simply assign a pixel to one and only one class. (b) The logic of a fuzzy classification. In this hypothetical example, a pixel having a near-infrared brightness value of <24 would have a *membership grade* value of 1.0 in water and 0 in both forested wetland and upland forest. Similarly, a brightness value of 60 would have a graded value of 0.70 for forested wetland, 0.30 for upland forest, and 0 for water. The membership grade values provide information on mixed pixels and may be used to classify the image using various types of logic.

Classification of Remotely Sensed Data Based on Hard Versus Fuzzy Logic

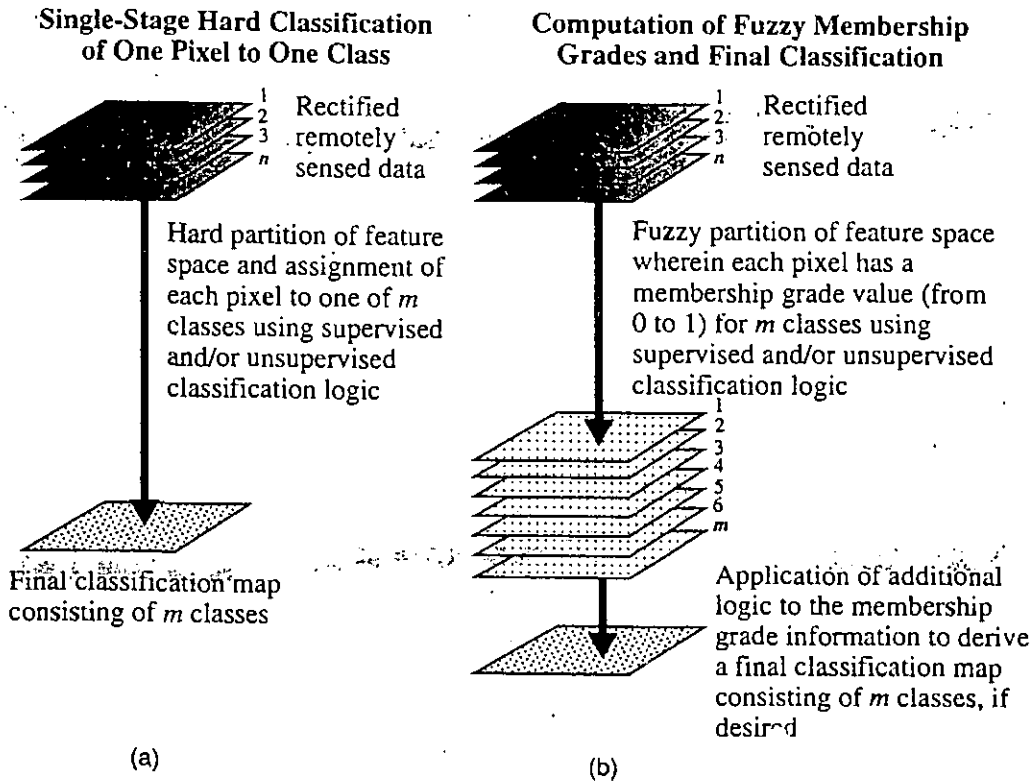


Figure 8-2 Difference between a traditional single-stage hard classification using supervised or unsupervised classification logic and classification using fuzzy logic.

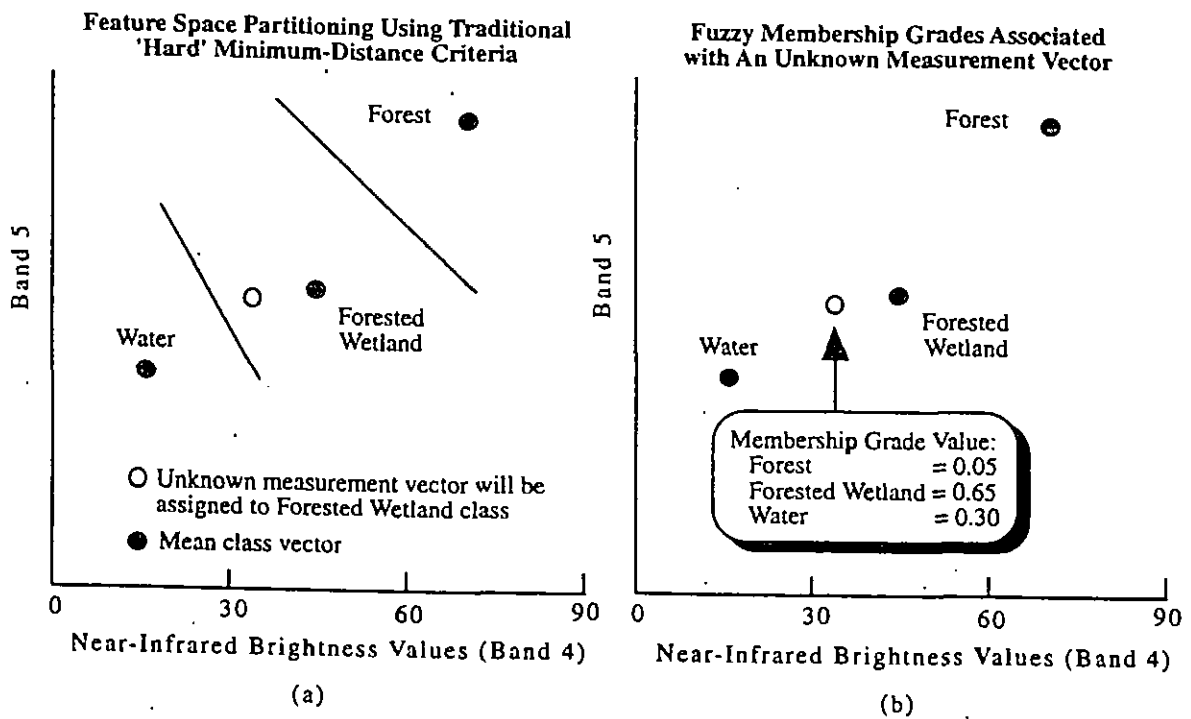


Figure 8-29 (a) Hypothetical hard partition of feature space based on classical set theory and a minimum-distance decision rule. (b) Each unknown measurement vector (pixel) has membership grade values describing how close the pixel is to the m training class mean vectors. In this example, we are most likely working with a mixed pixel predominantly composed of forested wetland (0.65) and water (0.30) based on the membership grade values. This membership grade information may be used to classify the image using various types of logic.

Image Interpretation

Accuracy Assessment and Sampling

References

- Jensen, J.E., 1996. *Introductory Digital Image Processing*, pp. 247-252.
 Campbell, J.B., 1987. *Introduction to Remote Sensing*, Chapter 12
 Congalton, R.G., 1991. A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data, *Remote Sensing of Environment*, 37:35-46.
 Janssen, L.F., and van der Wel, F.J.M., 1994. Accuracy Assessment of Satellite Derived Land-Cover Data: A Review, *Photogrammetric Engineering and Remote Sensing*, 60(4):419-426.

1. Introduction

- little attention was paid to the question of the accuracy of thematic maps before the advent of digital remote sensing
- accuracy should be reported based on location, not just summary of land use / land cover area
- accuracy versus precision
 - accuracy defines "correctness". It measures the agreement between a 'standard' and an image classification of unknown quality.
 - precision defines "detail". Increasing detail (e.g., forest - coniferous - pine - red pine) leads to increasing opportunity for error.
- accuracy assessment is important to provide an indication of the validity of a map. It can also be important from a legal point of view.
- compare remote-sensing-derived classification map with reference test information (error matrix).
- accuracy level strived for is usually quoted as 85%.

2. Sources of Error

- error will occur in any classification. The most common causes of error are:
 - image registration and resampling
 - similar spectral responses for different informational classes (e.g., bare fields vs. pavement)
 - mixed pixels occur on boundaries and can easily be misclassified
- the nature of the landscape being analysed can influence the accuracy obtained - a simple landscape will be more accurate than a complex environment (e.g., an agricultural landscape & an urban landscape)
- although high spatial resolution imagery displays greater precision, accuracies are likely to be lower than with low spatial resolution images
- errors that occur in classifications are usually not random. They tend to be systematic and grouped

3. Measurement of Map Accuracy

- important to differentiate between geometric error and thematic error
- the map to be evaluated is compared with a "reference" map

a) Types of Accuracy

- non site-specific accuracy
 - comparison of total areas of classes on the two maps
- site-specific accuracy
 - based upon a pixel-by-pixel comparison
 - classifications of pixels used for training samples can be used, but are biased
 - more appropriate to use test area data which were not used in generating the classification

b) Sampling

- is important when undertaking ground data collection
- an appropriate sample scheme is required for accuracy assessment
- timing - in some cases ground data must be acquired at the time of imaging
- sample size - the larger the number of samples, the greater the confidence in the results
 - statistical methods of determining sample size
 - general rule 50-100 samples for each land-cover class in the error matrix
 - can also be based on importance or variability of class

c) Sampling Schemes

- appropriate sampling schemes must be selected
- purposive sampling
 - traverses
 - site locations
- random sampling (without replacement)
 - provides adequate estimates of population parameters, given a large enough sample size
 - may undersample classes of small extent
 - **stratified random sampling** (minimum number of samples are selected from each strata)
 - some combination of random and stratified sampling provides the best balance between statistical validity and practical application

b) Numerical Assessment of Accuracy

- error can be measured using a confusion matrix (contingency table or error matrix)
- rows represent the classification generated from the remotely sensed data;
columns provide the reference data

Descriptive Statistical Measures**Overall Classification Accuracy**

- divide the total correctly classified pixels (sum of the diagonal) by the total number of pixels in the error matrix

Producer's Accuracy (a measure of omission error - errors of exclusion)

- total number of correct pixels in a category divided by the total number of pixels of that category as derived from the reference data (i.e., column total)
- probability of a reference pixel being correctly classified

User's Accuracy (a measure of commission error - errors of inclusion)

- total correct pixels in a category divided by the total number of pixels that were actually classified into that category (i.e., row total)
- the probability that a pixel classified on the map actually represents that category on the ground

Discrete Multivariate Analytical Techniques (applied to the error matrix)

- Kappa coefficient (K_{hat})

$$K_{hat} = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \cdot x_{+i})}$$

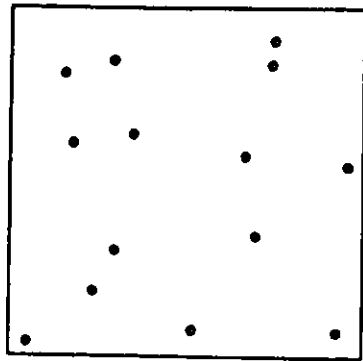
where: r = # of rows in the error matrix

x_{ii} = # of observations in row i and column i (diagonal entries)

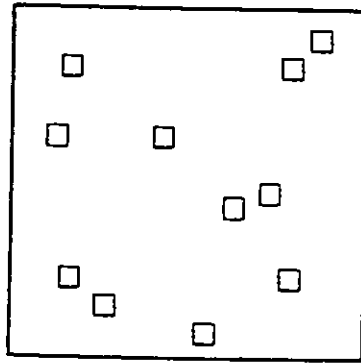
x_{i+} and x_{+i} = marginal totals of row i and column i respectively

N = total number of observations

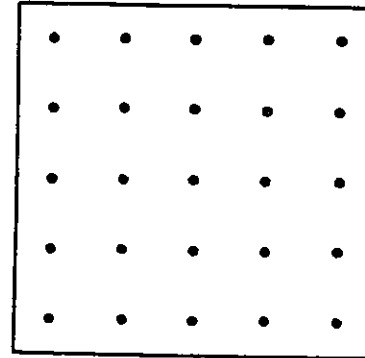
- strength of the Kappa statistic is that it incorporates the off-diagonal elements as a product of the row and column marginals
- can be used for hypothesis testing (comparison of error matrices)



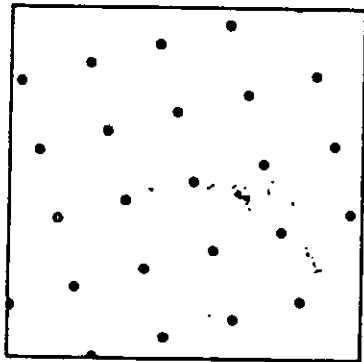
(a) Random point sample



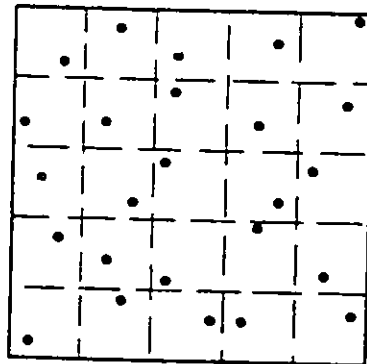
(b) Random areal sample



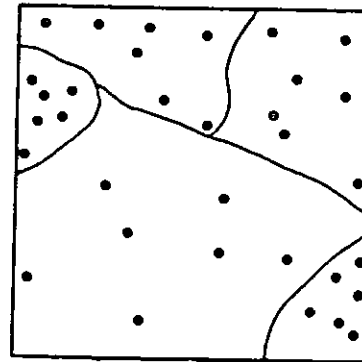
(c) Systematic sample



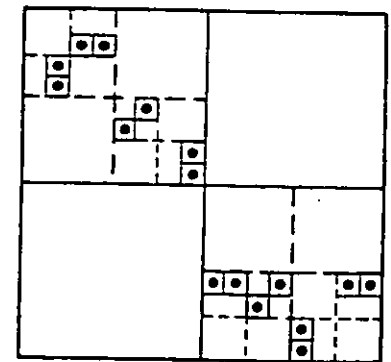
(d) Randomly aligned systematic sample



(e) Unaligned systematic random sample



(f) Stratified random sample



(g) Random nested sample

TABLE 8-8 Evaluation of the Charleston, S.C., Thematic Mapper Test Data

a. Error Matrix

Actual land-use class	Interpreted land use						Omission error (%)	Commission error (%)	Accuracy* (%)
	1	2	3	4	5	Total			
1. Residential	70	5	0	13	0	88	20.5	4.5	79.5
2. Commercial	3	55	0	0	0	58	5.2	8.6	94.8
3. Wetland	0	0	99	0	0	99	0.0	4.0	100.0
4. Forest	1	0	4	37	0	42	11.9	30.9	88.0
5. Water	0	0	0	0	121	121	0.0	0.0	100.0
Total	74	60	103	50	121	408			

b. Derivation of Omission and Commission Errors

Land-use class	Omission errors		Commission errors		Correct	
	Total	%	Total	%	Total	%
1. Residential	18/88	20.5	4/88	4.5	70/88	79.5
2. Commercial	3/58	5.2	5/58	8.6	55/58	94.8
3. Wetland	0/99	0.0	4/99	4.0	99/99	100.0
4. Forest	5/42	11.9	13/42	30.9	37/42	88.0
5. Water	0/121	0.0	0/121	0.0	121/121	100.0

* Overall accuracy = 382/408 pixels = 93.6%.

Table 12.1. Example of Error Matrix

	Image to be evaluated						Totals
	Urban	Crop	Range	Water	Forest	Barren	
Urban	150	21	0	7	17	30	225
Crop	0	730	93	14	115	21	973
Range	33	121	320	23	54	43	594
Water	3	18	11	83	8	3	126
Forest	23	81	12	4	350	13	483
Barren	39	8	15	3	11	115	191
Totals	248	979	451	134	555	225	1,748

Note. Percentage correct = Sum of diagonal entries/Total observations = 1,748/2,592 = 67.4%.

Table 12.5. Worked Example Illustrating Calculation of κ

Part 1. Calculation of "observed correct"					
		Image to be evaluated			
Reference image	35	14	11	1	
	4	11	3	0	
	12	9	38	4	
	2	5	12	2	
	
Grand total = 163					
Total correct = 86					
"Observed correct" = $86/163 = 0.528$					
(Percentage correct = 53%)					
Part 2. Calculation of "expected correct"					
Marginals					
				61	
				18	
				63	
				21	
53	39	64	7		
Products of row and column marginals					
3,233	2,379	3,904	427		
954	702	1,152	126		
3,339	2,457	4,032	441		
1,113	819	1,344	147		
Expected agreement by chance = $\frac{\text{Sum of diagonal entries}}{\text{Grand total}} = \frac{8,114}{26,569} = 0.305$					
Part 3. Calculation of κ using data from Parts 1 and 2					
$\kappa = \frac{\text{Observed} - \text{expected}}{1 - \text{expected}} = \frac{0.528 - 0.305}{1 - 0.305} = \frac{0.223}{0.695} = 0.321$					

Classification Schemes

- systems developed in order to ensure that image data on land cover characteristics and discernible human activities (i.e., land use) are objectively and consistently classified
- the classification system is used in a process of segmenting the image into a mosaic of parcels, with each parcel assigned to a land-cover or land-use class

Land Use: the use of land by humans usually with an emphasis on the functional role of the land in economic activities

Land Cover: the natural and cultivated vegetation on the earth's surface. In general, may also include visible evidence of land use, including both vegetative and non-vegetative features (i.e., plowed land, paved parking lots, forest).

Hierarchical Classification Schemes

- those schemes that employ multiple levels (classes) to typify and group land-use and land-cover data
- generally proceed from an initial level (e.g., Level I) of data of general spatial resolution through to a final level (i.e., Level IV) of data of some higher spatial resolution

USGS Classification Scheme

- hierarchical-type scheme developed by J.R. Anderson of the USGS in early 70's
- developed to standardize data classification among federal agencies that would accommodate data from remote sensors on high-altitude aircraft as well as from conventional sources (e.g., topographical maps, ground surveys)

Some of the general criteria for USGS and other classification systems:

- the minimum level of interpretation accuracy in identifying land -use and land-cover categories from remote sensor data should be approximately 85%
- the accuracy of interpretation for all categories should be about equal
- repeatable or repetitive results should be obtainable from one interpreter to another and from one time of sensing to another
- the classification should be applicable over extensive areas
- the classification should be suitable for use with remote sensor data obtained at different times of the year

TABLE 8-2 The Four Levels of the U.S. Geological Survey Land Use/Land Cover Classification System and the Type of Remotely Sensed Data Typically Used to Provide the Information

Classification level	Typical data characteristics
I	Landsat (formerly ERTS) type of data
II	High-altitude data acquired at 40,000 ft (12,400 m) or above; results in imagery that is less than 1:80,000 scale
III	Medium-altitude data acquired between 10,000 and 40,000 ft (3100 and 12,400 m); results in imagery that is between 1:20,000 and 1:80,000 scale
IV	Low-altitude data acquired below 10,000 ft (3100 m); results in imagery that is larger than 1:20,000 scale

Source: Anderson et al. (1976) and Jensen et al. (1983). © American Society of Photogrammetry and Remote Sensing. Used with permission.

TABLE 8-1 U.S. Geological Survey Land Use/Land Cover Classification System for Use with Remote Sensor Data

Level I	Level II
1 Urban or built-up land	11 Residential
	12 Commercial and services
	13 Industrial
	14 Transportation, communications, and services
	15 Industrial and commercial complexes
	16 Mixed urban or built-up land
	17 Other urban or built-up land
2 Agricultural land	21 Cropland and pasture
	22 Orchards, groves, vineyards, nurseries, and ornamental horticultural areas
	23 Confined feeding operations
	24 Other agricultural land
3 Rangeland	31 Herbaceous rangeland
	32 Shrub and brush rangeland
	33 Mixed rangeland
4 Forest land	41 Deciduous forest land
	42 Evergreen forest land
	43 Mixed forest land
5 Water	51 Streams and canals
	52 Lakes
	53 Reservoirs
	54 Bays and estuaries
6 Wetland	61 Forested wetland
	62 Nonforested wetland
7 Barren land	71 Dry salt flats
	72 Beaches
	73 Sandy areas other than beaches
	74 Bare exposed rocks
	75 Strip mines, quarries, and gravel pits
	76 Transitional areas
	77 Mixed barren land
	81 Shrub and brush tundra
82 Herbaceous tundra	
8 Tundra	83 Bare ground
	84 Mixed tundra
	91 Perennial snowfields
	92 Glaciers
9 Perennial snow and ice	

Source: Anderson et al. (1976).

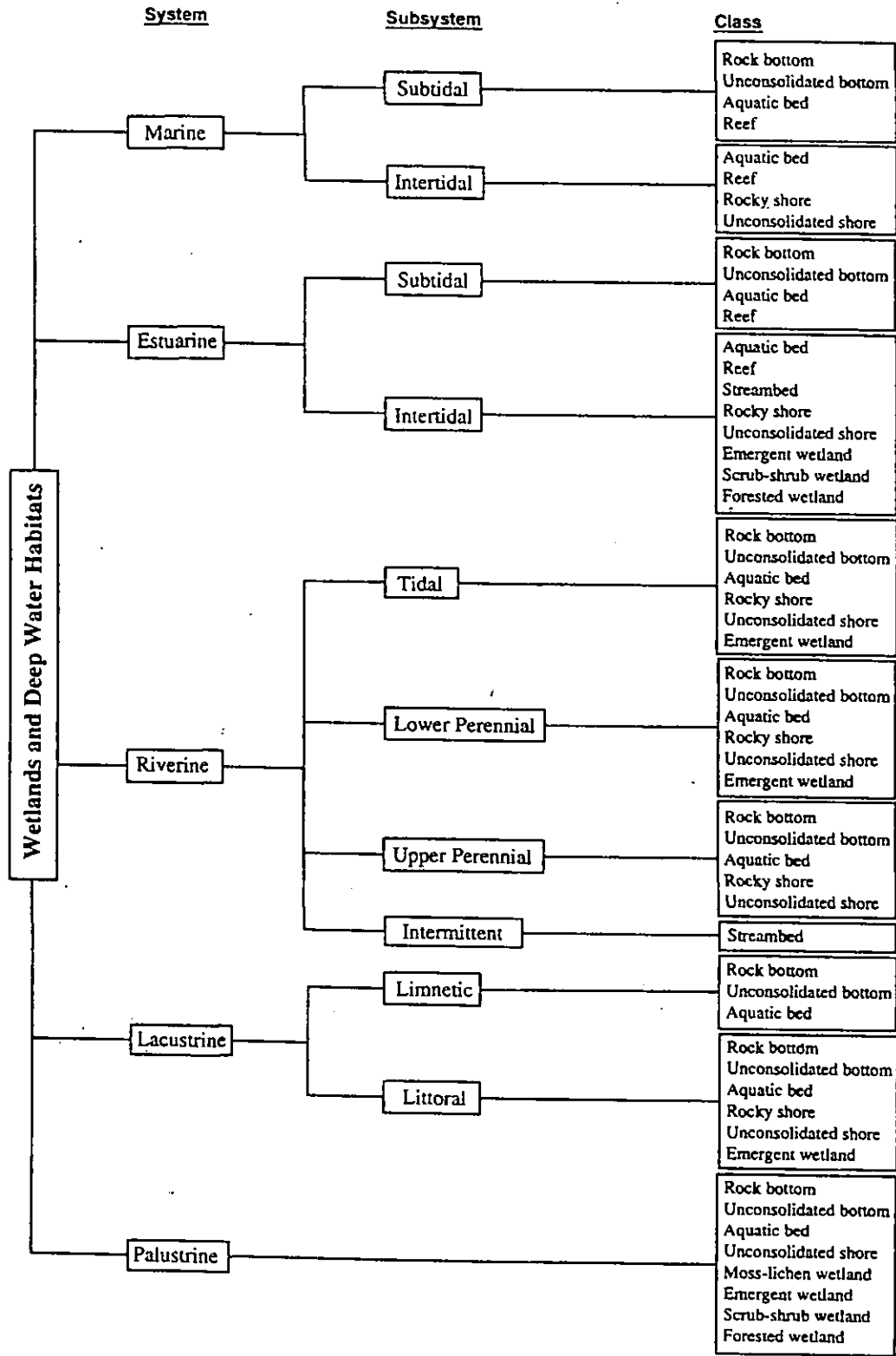


Figure 8-3 The U.S. Fish and Wildlife Service classification hierarchy of wetlands and deepwater habitats showing systems, subsystems, and classes (Cowardin et al., 1979). The palustrine system does not include deepwater habitats.

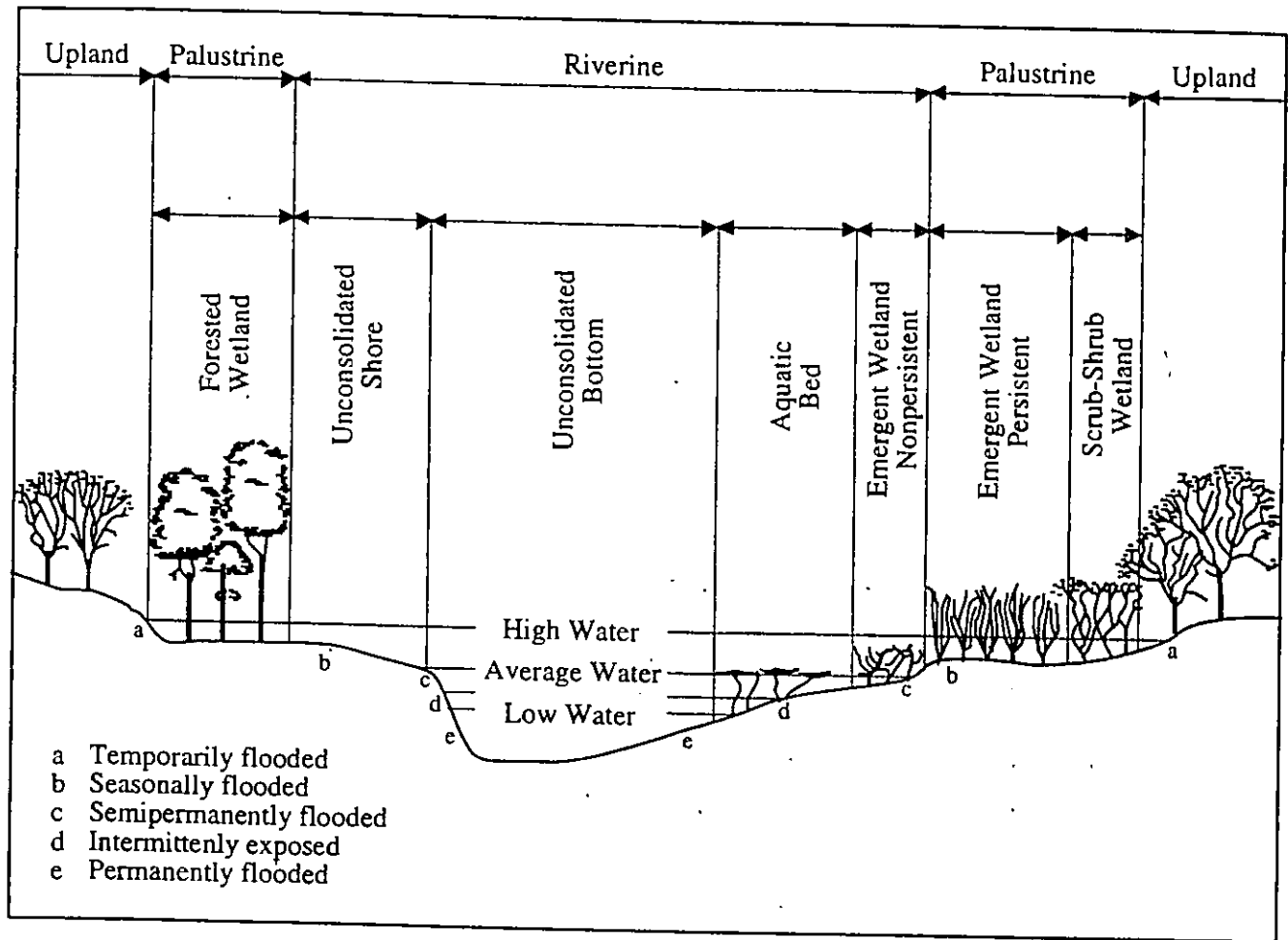


Figure 8-4 Distinguishing features and examples of habitats in the riverine system. (Cowardin et al., 1979).

Table 8-3. C-CAP Coastal Land Cover Classification System

1.0 Upland**1.1 Developed Land**

- 1.11 High Intensity
- 1.12 Low Intensity

1.2 Cultivated Land

- 1.21 Orchards/Groves/Nurseries
- 1.22 Vines/Bushes
- 1.23 Cropland

1.3 Grassland

- 1.31 Unmanaged
- 1.32 Managed

1.4 Woody Land (Scrub-Shrub/Forested)

- 1.41 Deciduous
- 1.42 Evergreen
- 1.43 Mixed

1.5 Bare Land**1.6 Tundra****1.7 Snow/Ice**

- 1.71 Perennial Snow/Ice
- 1.72 Glaciers

2.0 Wetland (Excludes Bottoms, Reefs, Nonpersistent Emergent Wetlands, and Aquatic Beds, all of which are covered under 3.0. Water and Submerged Land)**2.1 Marine/Estuarine Rocky Shore**

- 2.11 Bedrock
- 2.12 Rubble

2.2 Marine/Estuarine Unconsolidated Shore (Beach, Flat, Bar)

- 2.21 Cobble-gravel
- 2.22 Sand
- 2.23 Mud/Organic

2.3 Estuarine Emergent Wetland

- 2.31 Haline (Salt Marsh)
- 2.32 Mixohaline (Brackish Marsh)

2.4 Estuarine Woody Wetland (Scrub-Shrub/Forested)

- 2.41 Deciduous
- 2.42 Evergreen
- 2.43 Mixed

2.5 Riverine Unconsolidated Shore (Beach, Flat, Bar)

- 2.51 Cobble-gravel
- 2.52 Sand
- 2.53 Mud/Organic

2.6 Lacustrine Unconsolidated Shore (Beach, Flat, Bar)

- 2.61 Cobble-gravel
- 2.62 Sand
- 2.63 Mud/Organic

Table 8-3. C-CAP Coastal Land Cover Classification System

2.7 Palustrine Unconsolidated Shore (Beach, Flat, Bar)

- 2.71 Cobble-gravel
- 2.72 Sand
- 2.73 Mud/Organic

2.8 Palustrine Emergent Wetland (Persistent)**2.9 Palustrine Woody Wetland (Scrub-Shrub/Forested)**

- 2.91 Deciduous
- 2.92 Evergreen
- 2.93 Mixed

3.0 Water and Submerged Land (Includes deepwater habitats and those wetlands with surface water but lacking trees, shrubs, and persistent emergents)**3.1 Water (Bottoms and undetectable reefs, aquatic beds or nonpersistent emergent wetlands)**

- 3.11 Marine/Estuarine
- 3.12 Riverine
- 3.13 Lacustrine (Basin ≥ 20 acres)
- 3.14 Palustrine (Basin < 20 acres)

3.2 Marine/Estuarine Reef**3.3 Marine/Estuarine Aquatic Bed**

- 3.31 Algal (e.g., kelp)
- 3.32 Rooted Vascular (e.g., seagrass)
 - 3.321 (High Salinity (≥ 5 ppt; Mesosaline, Polysaline, Eusaline, Hypersaline))
 - 3.322 Low Salinity (< 5 ppt; Oligosaline, Fresh)

3.4 Riverine Aquatic Bed

- 3.41 Rooted Vascular/Algal/Aquatic Moss
- 3.42 Floating Vascular

3.5 Lacustrine Aquatic Bed (Basin ≥ 20 acres)

- 3.51 Rooted Vascular/Algal/Aquatic Moss
- 3.52 Floating Vascular

3.6 Palustrine Aquatic Bed (Basin < 20 acres)

- 3.61 Rooted Vascular/Algal/Aquatic Moss
- 3.62 Floating Vascular

**INTRODUCTION TO DIGITAL
IMAGES AND DIGITAL
ANALYSIS TECHNIQUES:
A Basic Course for the
Appreciation of Digital
Analysis of Remotely Sensed
Multispectral Data**

T. T. Alföldi
Applications Division

Technical Note 78-1
March 1978

**Canada Centre for Remote Sensing
Energy, Mines and Resources, Ottawa**

1. INTRODUCTION

A simulation of "hands-on" processing of digital images has been designed to give the new user some familiarity with the manipulation of digital data. Although the original intent of this exercise was to provide a self-teaching mechanism for potential users of the IMAGE-100 at the Canada Centre for Remote Sensing (CCRS), the concepts contained herein are sufficiently general as to be applicable to most digital image processing systems. If an instructor is available, the practical exercise should be preceded by a brief description of the basic characteristics of digital, multispectral remotely-sensed images: spatial, temporal, spectral and radiometric.

NOTE:

To permit hand simulation with only paper and pencil, the following simplifications have been made:

- a) The "picture" to be processed by the reader is reduced in size to 49 picture elements (pixels), compared to the several millions typical of digital images.
- b) A multispectral image often contains from 4 to 24 spectral channels or bands. For hand simulation purposes, the "pseudo" images have been designed with only two spectral bands (or dimensions in feature space).
- c) The number of intensity levels which may be recorded by a sensor is typically 64 to 256. This is impractical to manipulate by hand, so the reader's image has merely 10 levels.

The manual techniques to be described are very similar to the tasks performed by computer. However, the computer's great speed permits it to handle much larger images with more channels and greater radiometric range.

2. DATA ARRANGEMENT AND PRESENTATION

Figure 1 shows the data from two bands of a small segment of a satellite scene, with brightness information quantified into ten levels (from 0 to 9) for each band. One band (A) is red-sensitive and the other band (B) covers a portion of the reflective infrared. The format of the data in this figure is similar to that provided by CCRS on "line-interleaved" computer compatible tapes (CCTs). For the 7 x 7 image represented on this tape, the first seven numbers correspond to the pixel intensities in the first line of band A, from left to right in the picture. The next seven numbers are for the same first line but of band B data. This is followed by the next seven numbers which are for line No. 2, band A, and so on. For the 7 x 7 picture area, there are 7 lines x 7 pixels x 2 bands = 98 numbers. It is useful to arrange the numbers in a geometrically convenient form.

INSTRUCTION No. 1:

Beginning at the "start", mark off every seven numbers from left to right, and label the first seven for band A, the second seven for band B, the third seven for band A, and so on.

Figure No. 2 prepares the format of the digital image. Band A and band B represent the same area on the earth's surface, but are coded separately because they represent different portions of the electromagnetic spectrum (or colours of light).

INSTRUCTION No. 2:


Insert the numbers from the tape into their appropriate geometrical position thus: The first seven numbers of band A from the tape, are positioned as pixels 1-7 of line No. 1 of the band A matrix in Figure No. 2. The next seven numbers from the tape are for pixels 1-7 of line No. 1 of band B in Figure No. 2. Continue in this manner until the two matrices of Figure No. 2 are filled.

The digital or numerical maps constructed in Figure 2 may now be converted into another format which will permit a visual appreciation of the image. A "grey map" is produced to synthesize a visual image from the numbers at hand.

The computer-produced grey maps usually present a problem, in that the number of intensity levels (64 to 256) greatly exceed the number of available grey "shades" (10 to 20) which the printing device can generate. Each pixel in the 7 x 7 image is coded at a particular intensity level from 0-9 (10 levels). It is appropriate in this example then, to use 3 shades of grey, in an attempt to represent the 10-level image.

INSTRUCTION No. 3:

For each of the band "A" and "B" digital images (Figure 2), transform the numerical values of each pixel into a "shade" of grey according to the following conversion:

NUMERICAL VALUE:	0	1	2	3	4	5	6	7	8	9
GREY LEVEL:										

and sketch these "transformed" pixels into Figure 3. Note that the smallest intensities are represented as the "darkest".

Note that in the completed Figure 3, there are some similar and some dissimilar patterns appearing when bands A & B are compared. Although some environmental spatial patterns are beginning to appear, it is obvious that the grey maps represent much less information than is inherent in the digital maps.

Following are a number of techniques which are intended to give a better understanding of the data.

An "intensity profile" gives a one dimensional view of a single cross-section of the data. It is a popular technique in photographic analysis as well, where a "density profile" is constructed.

INSTRUCTION No. 4:

An intensity profile will be constructed for line number 6 of each of the band A and band B images. Use the graph outlines prepared in Figure No. 4. For band A, line No. 6, determine the intensity level for each pixel using the digital map, and plot a point to correspond to that pixel number and intensity level. When all seven points are plotted, join the points, progressing from pixel number 1 to number 7. Repeat the same procedure for band B.

The completed Figure 4 now represents the intensities of reflected light as found on the ground track which corresponds to line No. 6 of the image. These intensity profiles may be produced for any line drawn across the image (at any angle). The inherent limitations of this technique reduce its usefulness. A more informative data arrangement is described below.

A one-dimensional histogram offers a graphical representation of the data distribution for a single band. The plot (see Figure 5) shows the number of pixels which have a particular intensity level. This is an abstract, but important concept. Alternately, one may ask: "What area of the image corresponds to a particular intensity level?"

INSTRUCTION No. 5:

For band A, count the number of pixels which have an intensity of zero. Use the digital image in Figure 2. Enter this number in the space provided below the left graph of Figure No. 5. Now count the number of times that the intensity level 1 occurs and similarly record it on Figure No. 5. Continue for all levels. Check that the sum of these values is 49 (= 7 x 7). Now plot these values on the graph and join the plotted points with straight lines, progressing from left-to-right. Similarly construct the histogram for band B.

There are several observations to be made regarding the appearance of these two histograms. First, the fact that the two histograms are significantly different means that there is different information (and perhaps useful information,) available from the two bands concerning the same pixel (or ground area). Second, note the various peaks of the histograms. Each peak separated from neighbouring peaks by valleys is called a "mode" of the histogram. Often it is found that a mode corresponds to a particular feature on the ground. The presence of several of these modes (a multi-modal histogram) leads to the conclusion that several (different) environmental features have been imaged.

Next, consider the band B histogram. There are two major modes in this histogram, separated by the valley at intensity level 2. Since band B is a reflective infrared band, knowledge of the infrared reflection characteristics of land & water can help identify these 2 modes. Water strongly absorbs infrared, resulting in low reflectivity. The typically vegetation-covered land surfaces will have high reflection during the summer months. Thus the assumption is made that the left peak or mode designates water while the large mode on the right is of the land surfaces.

The "spectral signature" of any one pixel is the combination of its intensity levels in the two bands. This characteristic may be plotted in a two-dimensional (2-D) histogram. In a 2-D histogram, the two axes depict the intensity levels for the two bands (see Figure No. 6). What is to be plotted is the frequency of occurrence of any one combination of band A and band B intensities. Stated in another manner, a 2-D histogram indicates the number of pixels which have a particular combination of intensities in the two bands. As an example, refer to pixel number 6 of line 2 (using Figure No. 2). In band "A" it has an intensity value of 4, and in band "B" a value of 6. Thus in Figure No. 6 it would be plotted at the coordinates 4,6 for the band A and band B axes respectively. What the completed histogram will show, is the data distribution of both bands simultaneously.

INSTRUCTION No. 6:

Plot the intensity coordinates for each pixel on Figure No. 6. Use the digital maps of Figure No. 2. When the intensity coordinates for a pixel are found in Figure No. 6, place a tick mark in the appropriate square. These tick marks will be summed later to find the total in any one square. Only the pixels in first three lines of Figure 2 should be plotted, since the last four lines are already plotted as may be seen in Figure 6.

INSTRUCTION No. 7:

Transfer the data of Figure No. 6 into Figure No. 7 by summing the tick marks in each square and placing the numerical value in the corresponding square of Figure 7.

Each "square" or location in the completed 2-D histogram is called a "cell" or sometimes a "vector". The number in any one cell of Figure No. 7 depicts the frequency of occurrence of that particular set of intensity coordinates to be found in the original 7 x 7 image. This 2-D histogram plot is also the spectral signature domain. Cells which are close to each other in this plot have near-similar spectral characteristics. A much more sophisticated analysis is possible using the 2 spectral axes simultaneously (2-D histogram) than separately (1-D histograms), as shown in the examples below.

3. CLASSIFICATION USING ONE BAND

Figure No. 8 represents a ground verification map for a particular environmental feature: "forest". Three sites have been positively identified on the ground as being forested terrain, and the experts who collected this data are further assured that the combination of these three sites is representative of all forest types to be found in the area covered by the remotely sensed image. The ground verification map has been geometrically registered to the image, so that the same point on the map and the image may now be referenced by "line" and "pixel" coordinates. By using the spectral signature of these verified "forest" areas, one may find all other "forest" pixels. This can be done by searching all pixels in the scene for similar spectral signatures. The first task is then, to define the spectral characteristics of the given training sites.

INSTRUCTION No. 8:

Find the intensities corresponding to each of the three test sites for band "A". Use Figure No. 8 to obtain the geometric locations, and extract the intensity levels from the corresponding locations of Figure No. 2. Enter these values below Figure 8. The category or class: "forest" may then be assumed to be characterized by the range of intensities found in band "A". The range is defined by the minimum and maximum value from these three samples. Enter these also below Figure No. 8. Repeat the process for band "B".

The actual classification process now involves searching for all pixels which have an intensity level falling within the range of intensities found in the test sites. This is done separately for each band.

INSTRUCTION No. 9:

Using the band "A" digital image of Figure No. 2, scan all of the pixels in the image for intensities falling in the range defined for band "A" in the previous instruction. For any pixel with a band "A" intensity falling in this range (inclusive of the minimum and maximum intensities), darken the corresponding pixel in Figure No. 9A. Repeat the process using the band "B" digital image of Figure No. 2, the band "B" intensity range defined in the previous instruction, and map onto Figure No. 9B.

The two forest theme maps in Figure 9A and 9B represent the same environmental feature (= forest), yet are different because each map was generated using information from one band only. The procedure used to produce these theme maps is akin to a rudimentary form of intensity "slicing". One specific range of intensities was sliced from the total available range. A more valid or "correct" classification may be produced if the intensities in both bands were to be considered simultaneously.

4. MULTISPECTRAL CLASSIFICATION (RECTANGULAR)

In order to classify an image in a multi-spectral (or multi-band) mode, the intensities in all bands must be considered simultaneously. In Figure No. 10A, the range of intensities in band "A" representing "forest", is represented by the shaded area from band "A" intensity 2 to 5 inclusive. Similarly for band "B", "forest" is represented by the shaded area of intensities 3 to 7 inclusive. The overlap of these two individual intensity ranges in this two-dimensional diagram is a cross-hatched area representing the multispectral (rectangularly-defined) spectral signature of "forest". In order to produce a multispectral classification of "forest", it is necessary to find all pixels of the image, whose spectral coordinates fall inside the cross-hatched rectangular area.

INSTRUCTION No. 10:

Using the digital images of Figure No. 2, scan all pixels for band "A" intensities of 2, 3, 4, or 5. When a pixel has one of these band "A" intensities, check if its band "B" intensity is 3, 4, 5, 6 or 7. If a pixel agrees with both of these criteria, then shade in the corresponding pixel in Figure No. 10B. Only the last four lines of the image need to be considered, since the first three lines are already mapped in this manner.

As a check on this classification, note that a total of 21 pixels should have been identified as "forest". Further, it may be noted that the forest map of Figure No. 10B is the logical overlap between forest maps 9A and 9B.

In review, a rectangular classification, as has been performed above, requires "representative samples" of the environmental feature to be mapped. The intensities of these sample pixels are collected in each band. The range of intensities which correspond to the feature of interest is plotted as spectral band versus spectral band (feature space). The rectangle thus defined in 2-dimensional feature space is the spectral signature of the environmental feature. When more than 2-dimensions are utilized (4 bands on LANDSAT-1 and 2; 12, 24 and even 256 (!) bands on airborne multispectral sensors), then N-bands can produce an N-dimensional "rectangular parallelepiped" spectral signature, which is analogous to the (2-dimensional) rectangle produced above.

In IMAGE-100 terminology, the above procedure is termed "1-D training", to signify that only one band is considered at a time in defining the 4-dimensional spectral signature.

5. MULTISPECTRAL CLASSIFICATION (VECTOR)

A further refinement of the spectral signature, as defined by rectangular multispectral classification, is possible. To illustrate this, it is appropriate to demonstrate the most basic limitation of the rectangular classification technique.

INSTRUCTION No. 11:

The forest map of Figure No. 10B now has been verified on the ground by visual inspection, and homogeneous stands of coniferous and deciduous forest identified. Figure No. 11A shows the spatial distribution of these two forest types. The task is to delineate the portions of spectral feature space which correspond to each of the two forest types. For each pixel identified in the ground

verification map of Figure No. 11A, find the corresponding band "A" and band "B" intensities in Figure No. 2. Plot each such spectral coordinate in Figure No. 11B using symbols "C" (coniferous) and "D" (deciduous). Draw a rectangle to define the spectral signature of "coniferous forest". The two vertical sides of this rectangle are the lower and upper limits of the range of intensities for band "A". The top and bottom lines of the rectangle are the upper and lower limits of the range of intensities for band "B". Draw a similar rectangle for the spectral signature of "deciduous forest". Note that the two rectangles will partially overlap.

It is this overlapping of spectral signatures in feature space which is a major limiting factor to the usefulness of the rectangular classification method. If a particular pixel has spectral coordinates which fall into the overlap region, then one is at a loss whether to label this pixel as "coniferous" or "deciduous".

The multispectral vector classifier looks inside any feature space rectangle to identify each spectral coordinate (also known as "cell" or "vector") and the number of pixels which are associated with each coordinate. This defines the data density distribution in feature space.

The next task is to use a multispectral vector classification scheme to map coniferous and deciduous forests in another scene. The first scene has been used in Figure No. 11A and No. 11B to "train" the classifier. In other words the first scene contains the test sites from which the spectral signatures of the two forest types have been defined. One may extrapolate these spectral signatures to another area (scene No. 2) to look for similar environmental features. Here, we must recognize the fact, that similar spectral signatures are the only themes which a machine or an algorithm will produce. It is the investigator who must make the assumption that similar spectral signatures indicate similar environmental phenomena.

INSTRUCTION No. 12:

Figures No. 12A and No. 12B contain the digital images of band "A" and band "B" of the new scene (No. 2). Figure No. 12C is the feature space representation of the spectral signatures of coniferous (C) and deciduous (D) forests, as previously constructed. Scan the new scene pixel by pixel for the first four lines (the last three lines have been mapped already). In order to classify any one pixel as one of the two forest types, it must agree in band "A" and band "B" intensities with one of the cells in Figure No. 12C which is marked "C" or "D". It is NOT sufficient for the spectral coordinates to merely fall within the rectangular limits. It is mandatory that the spectral coordinates being considered coincide with a cell marked by "C" or "D". Only in this manner will ambiguities related to the overlap region, be avoided. Those pixels thus identified in Figure No. 12C should be marked appropriately as "C" or "D" on the theme map of Figure No. 12D.

In the terminology used on the IMAGE-100 system, the above procedure is called: "N-D training", to refer to the fact that more than one band intensities are considered simultaneously. This type of training and classification scheme is also known as "non-parametric" in that the absolute location of spectral coordinates in feature space is the criterion for defining an environmental feature, and NOT statistical parameters such as mean and standard deviation.

6. INTERPRETATIONS (FROM SPECTRAL SIGNATURES)

Although ground verification is essential in assigning environmentally valid names to features found on an image, it is however, apropos to make deductions concerning an unverified feature, from its spatial and spectral characteristics.

INSTRUCTION No. 13:

As has been previously described, a one-dimensional histogram of the infrared band ("B") will display a marked difference between a low intensity mode corresponding to water, and a high intensity mode corresponding to land features. This may be observed on the one-dimensional histogram of band "B" of scene No. 2, plotted in Figure No. 13A. The left mode of the histogram comprising band "B" intensities less than 2 will relate to water pixels to a high degree of certainty. (The major conflicting phenomenon would be shadow areas due to clouds or mountains which would also result in low intensities.) Find those pixels in Figure No. 12B which have intensities less than 2 and mark the corresponding pixels in Figure No. 12D as: "W".

Figure No. 13B shows the data density of spectral feature space for scene No. 2. Note the cluster of three low-intensity cells which correspond to "water". Sum the number of pixels corresponding to these three cells and check that the number of pixels marked "W" in Figure No. 12D agrees with this sum.

The portions of feature space which were previously defined as representing coniferous and deciduous forest are indicated in Figure No. 13B. It is reasonable to assume that the portion of feature space which lies between two specific spectral signatures, may represent a mixed environmental target. Thus, the cells lying between the areas shown as "coniferous" and "deciduous" may be the spectral representation of the mixture of these two forest types, namely: mixedwood. Identify the pixels which are represented by these (three) cells, and mark them on Figure No. 12D as "M". Verify that the correct number of pixels have been identified as mixedwood by summing the densities of the three cells in Figure No. 13B.

7. UNSUPERVISED CLASSIFICATION

The previous classification schemes utilized a training area in the image, from which a spectral signature was defined, and for which the investigator had some prior knowledge. This spectral signature was then extrapolated throughout the image, or to another image, in search of other spectrally similar areas. This is known as a variation of "supervised classification". An investigator may prefer to reverse the procedure. It is often useful to delineate spectrally dissimilar areas of an image, even when nothing is known about the environmental character of the resulting subdivisions or classes. These classes are then mapped and the map taken into the field to identify the classes. This procedure is known as "unsupervised classification" since no training sites are involved. The main advantage of using an unsupervised classification technique is that the classes are subdivided based on their statistical characteristics usually covering large geographical areas, rather than depending on a "training sample" which may be quite un-representative of the class variability over the whole scene to be mapped.

There are a large number of mathematical algorithms which use various schemes to locate and separate the statistically "cohesive" clusters in feature space, which are likely to have environmental significance. Most of these algorithms rely on finding areas of high pixel density (in feature space) which are separated by regions of low density. The following task serves to illustrate this by a less sophisticated algorithm than is actually used in practice.

INSTRUCTION No. 14:

The feature space representation of scene No. 2 is reproduced in Figure No. 14A. Into Figure No. 14B, copy those cells from Figure No. 14A, which have a count of (density) 3 or more.

To be observed now in Figure No. 14B are three clusters of high density cells. These groupings of high density cells are each only the nucleus of a cluster. The next step is to define the boundaries of each whole cluster. For reference, the cluster with a nucleus of two cells will be called cluster "A" in feature space and class "A" when it is finally mapped geographically (by line and pixel). Identify each cell which touches the nucleus cells of cluster "A", by marking such cell with the letter "A". There should be 10 such cells marked, counting even those cells which touch with a corner only.

Repeat the process for cluster "B" (with 3 nucleus cells) using the letter "B" for the neighbouring cells, and also for cluster "C" (with 1 nucleus cell) and using the letter "C". There will be a point of ambiguity where two clusters overlap and a cell is identified as belonging to the neighbourhood of two clusters. A decision must be forced, so identify this conflict cell as belonging to the cluster with the larger nucleus.

Draw the boundary for each cluster, enclosing its complete neighbourhood, in Figure No. 14B. There should be 11 cells inside the boundary for cluster "A", 15 cells in cluster "B", and 6 cells in cluster "C". Transfer just the boundaries back to the original feature space in Figure No. 14A.

For the final representation of feature space as divided into clusters, transfer those cells in Figure No. 14A, which fall inside the boundary for cluster "A" and which display a count or density of 1 or greater, into Figure No. 14C, and identify those cells by the letter "A". Similarly, repeat the procedure for clusters "B" and "C" using the appropriate designation.

Now that feature space has been (pseudo-) statistically subdivided into cohesive clusters, it remains to map these clusters into their geographical locations. This will require that for each pixel of Figure No. 14D which is to be classified, its spectral coordinates must be obtained from the digital maps of Figures No. 12A and No. 12B, these coordinates located in Figure No. 14C, and the representative symbol (A, B, or C) allocated to the pixel in Figure No. 14D. Only the last three lines of pixels need to be considered, since the first four lines have been mapped.

The unsupervised classification shown in Figure No. 14D now requires that the individual classes (A, B, C) be identified environmentally. This may be done by a variety of techniques, notably airphoto interpretation, or actually visiting the site, if practical. But it is not necessary to completely cover the scene in question. It is another advantage of the unsupervised classification scheme, that it can direct fieldwork or other forms of ground verification, to convenient, small and representative locations, where environmentally valid names may be assigned to the classes. For instance, the location marked by an asterisk in Figure No. 14D would be a suitable location to identify classes "A", "B", and "C" because of their proximity to each other. Just a few such locations need to be investigated for a large scene, in order to be able to name the classes with confidence. Sometimes this field investigation procedure is utilized to establish classification accuracy figures.

Also during a ground verification exercise, it may be opportune to identify those areas which are "unclassified" (such as pixel No. 4, line No. 6 on Figure No. 14D). Whereas these unclassified areas may be due to imperfections in the processing technique or a "noisy" image, if the areas seem large and cohesive, they may be identified as a particular environmental feature.

8. FURTHER STUDY

A few examples are shown of documents which deal with similar topics and are instructional in format. They vary, however, in complexity, approach and emphasis.

Grabau, W.E., "Pixel Problems", Miscellaneous Paper M-76-9 Mobility and Environmental Systems Laboratory, U.S. Army Engineering Waterways Experiment Station, P.O. Box 631, Vicksburg, Miss. 39180. May, 1976.

Landgrebe, D.A., "Machine Processing for Remotely Acquired Data", LARS Information Note 031573, Purdue University, West Lafayette, Indiana. 1973.

Lindenlaub, J. and J. Russell, "An Introduction to Quantitative Remote Sensing", LARS Information Note 110474, Purdue University, West Lafayette, Indiana, 1974.

Orhaug, T. and I. Akersten, "A Workshop Introduction to Digital Image Processing, FOA Report D-30053-E1. Research Institute of Sweden National Defense, S-104 50 Stockholm 80, Sweden. September 1976.

Smith, J.A., L.D. Miller, and T. Ells, "Pattern Recognition Routines for Graduate Training in the Automatic Analysis of Remote Sensing Imagery -- RECOG", Science Series No. 3A, Colorado State University, Fort Collins, Colorado. February, 1972.

Readers interested in a further, more detailed examination of the concepts described and their mathematical implementation, are invited to continue their study of digital pattern recognition techniques. The documents listed below are a suitable but very small initial sample of the large number of papers, books and articles dealing with this extensive topic.

Goldberg, M., D. Goodenough and S. Shlien, "Classification Methods and Error Estimation for Multispectral Scanner Data", 3d Canadian Symposium on Remote Sensing, Edmonton, Alberta. September, 1975.

Goldberg, M., and S. Shlien, "A Four Dimensional Histogram Approach to the Clustering of LANDSAT Data", Canadian Journal of Remote Sensing, Vol. 2, No. 1. April 1976.

Goldberg, M., and P.M. Narendra, "An Efficient Algorithm for Classification of LANDSAT Data", 4th Canadian Symposium on Remote Sensing, Quebec City, Quebec. May, 1977.

Goldberg, M. and S. Shlien, "A Clustering Scheme for Multispectral Images", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-8, No. 2. February, 1978.

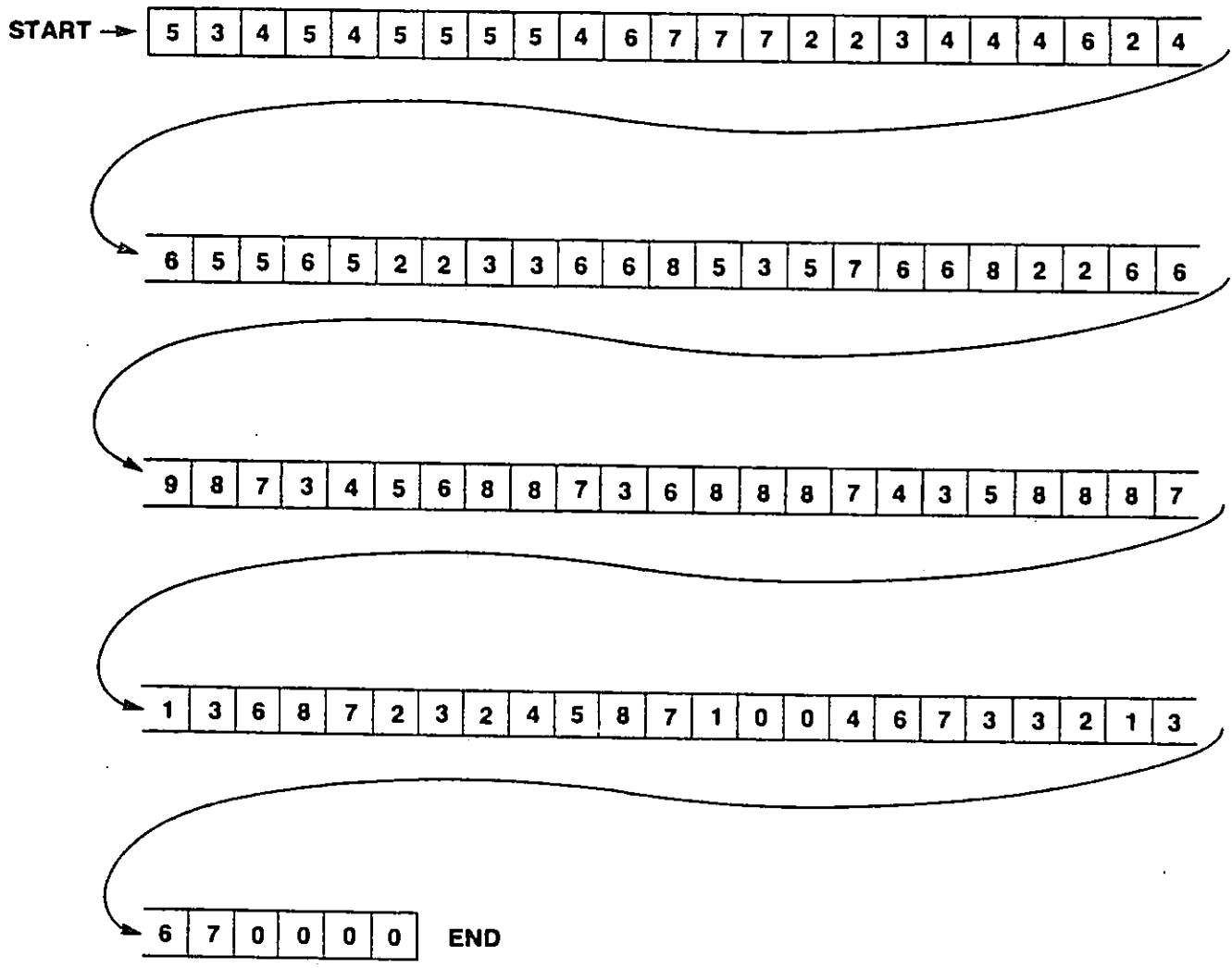
Goodenough, D., "Image-100 Classification Methods for ERTS Scanner Data", Canadian Journal of Remote Sensing, Vol. 2, No. 1. April, 1976.

Goodenough, D., "The Canada Centre for Remote Sensing's Image Analysis System (CIAS)", 4th Canadian Symposium on Remote Sensing, Quebec City, Quebec. May, 1977.

Reeves, G. (ed.) Manual of Remote Sensing, Vol. 1, Ch. 12, American Society of Photogrammetry, 1975.

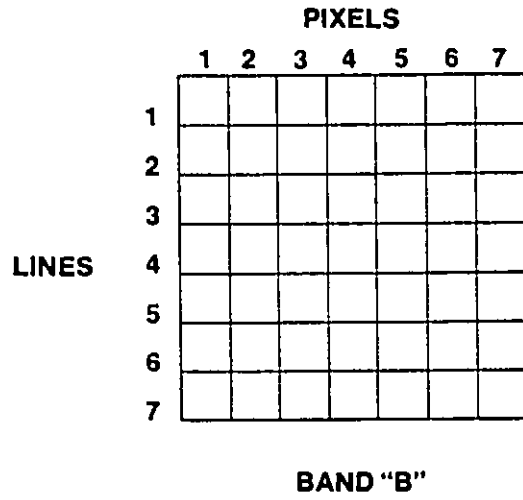
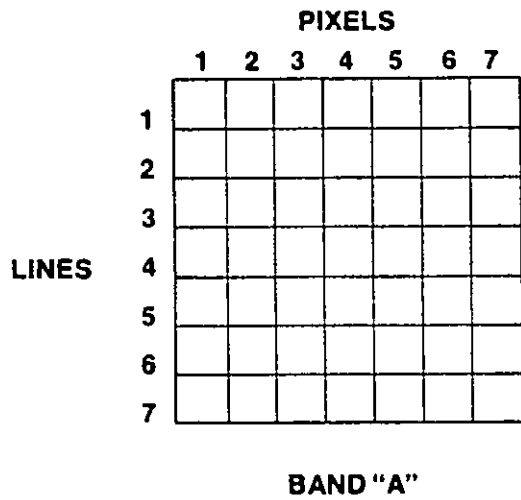
Shlien, S., and A. Smith, "A Rapid Method to Generate Spectral Theme Classification of LANDSAT Imagery", Remote Sensing of Environment, No. 4. 1975.

FIGURE 1



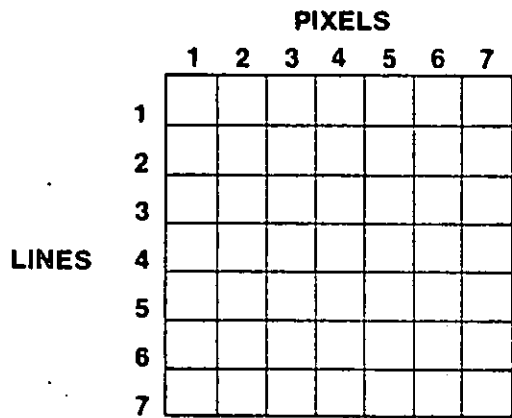
A digitized image, 2 bands, 7 x 7 area, line interleaved.

FIGURE 2

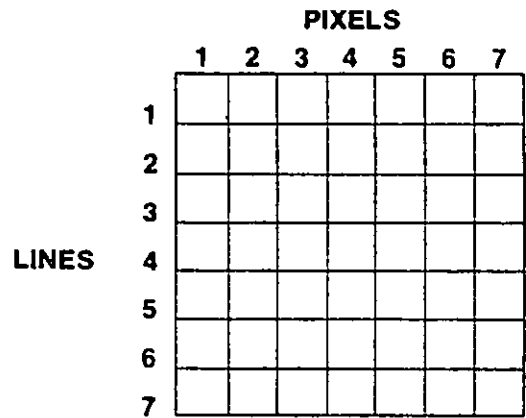


Digital images arranged in proper geometry.

FIGURE 3



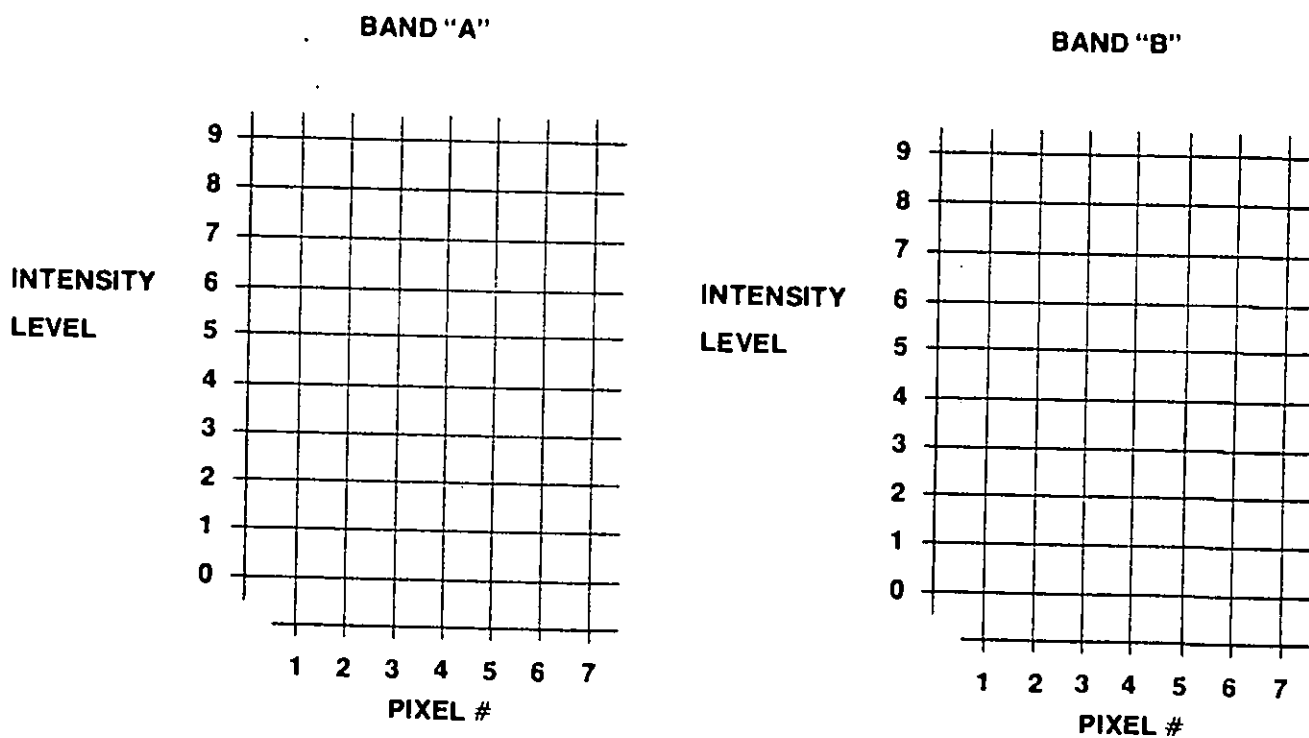
BAND "A"



BAND "B"

Grey maps.

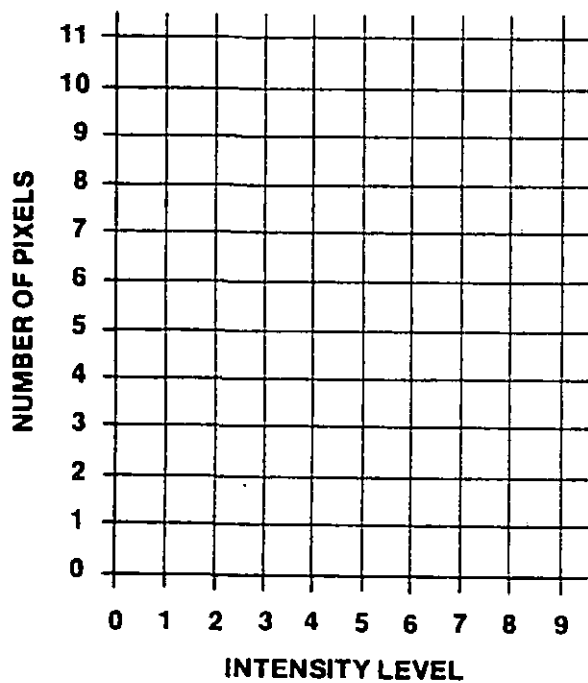
FIGURE 4



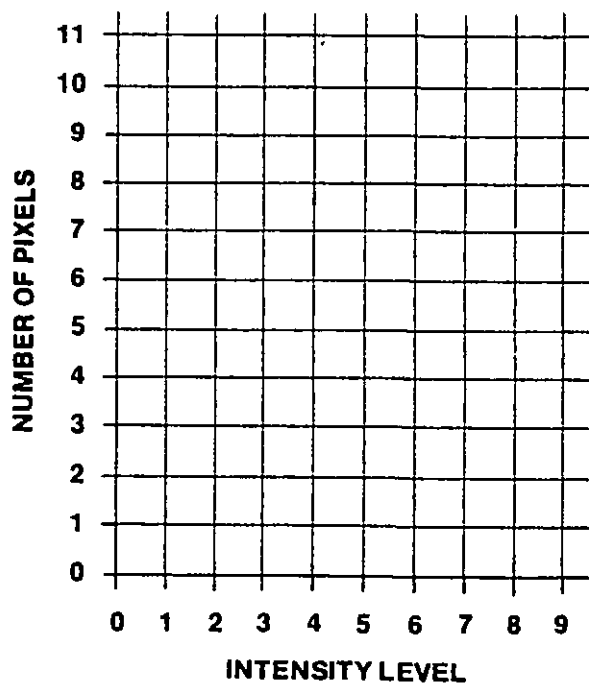
Intensity Profiles

FIGURE 5

BAND "A"



BAND "B"



NUMBER OF PIXELS: _____

SUM = _____

NUMBER OF PIXELS: _____

SUM = _____

FIGURE 6

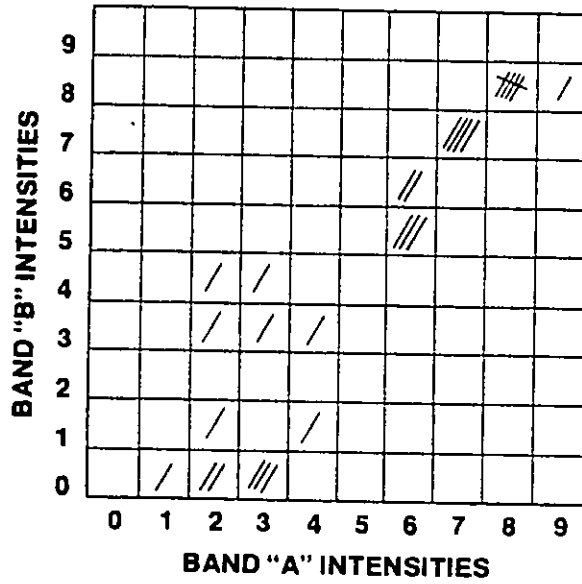
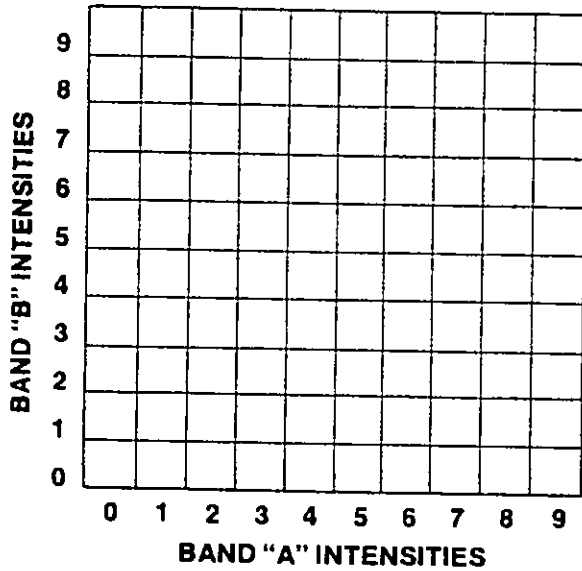


FIGURE 7



**TWO-DIMENSIONAL
HISTOGRAM**

FIGURE 8

PIXELS

	1	2	3	4	5	6	7
1						F	
2					F		
3							
4	F						
5							
6							
7							

LINES

GROUND VERIFICATION MAP: "FOREST"

BAND "A" INTENSITY VALUES: _____, _____, _____

BAND "A" INTENSITY RANGE:

MINIMUM =

MAXIMUM =

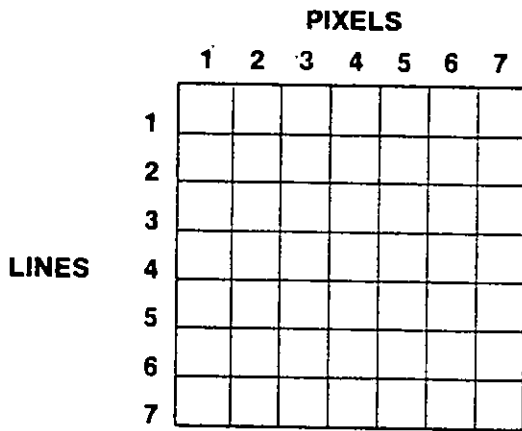
BAND "B" INTENSITY VALUES: _____, _____, _____

BAND "B" INTENSITY RANGE:

MINIMUM =

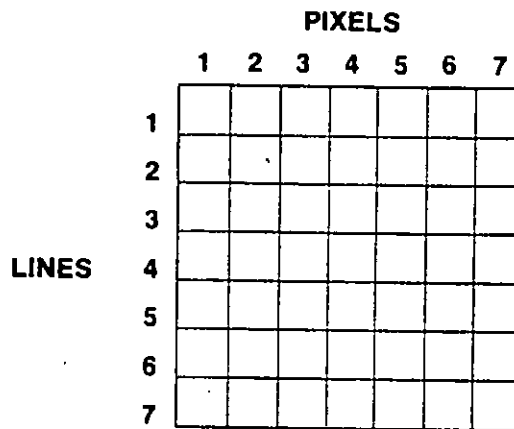
MAXIMUM =

FIGURE 9A



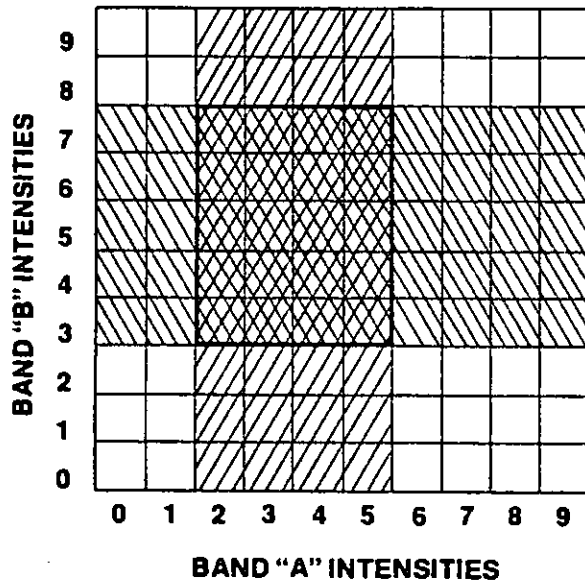
**FOREST MAP
FROM BAND "A"**

FIGURE 9B



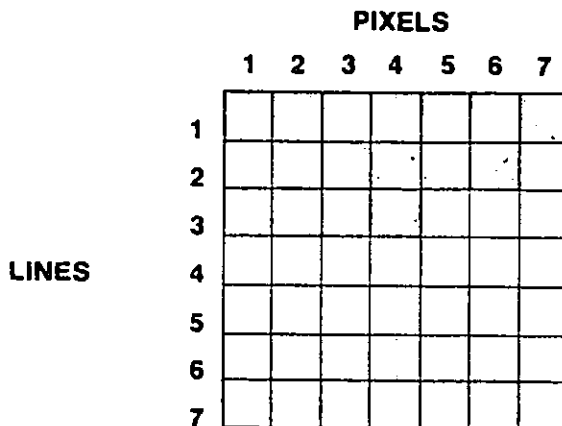
**FOREST MAP
FROM BAND "B"**

FIGURE 10A



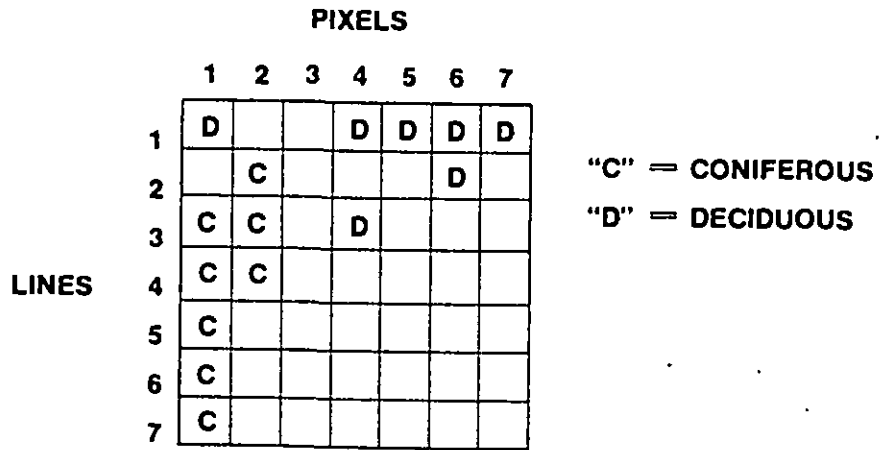
**FEATURE SPACE PORTION
REPRESENTING "FOREST"**

FIGURE 10b



**"FOREST" THEME FROM
BANDS "A" AND "B"**

FIGURE 11A



GROUND VERIFICATION MAP: FOREST TYPES

FIGURE 11B

**FOREST TYPE DESIGNATION
IN FEATURE SPACE**

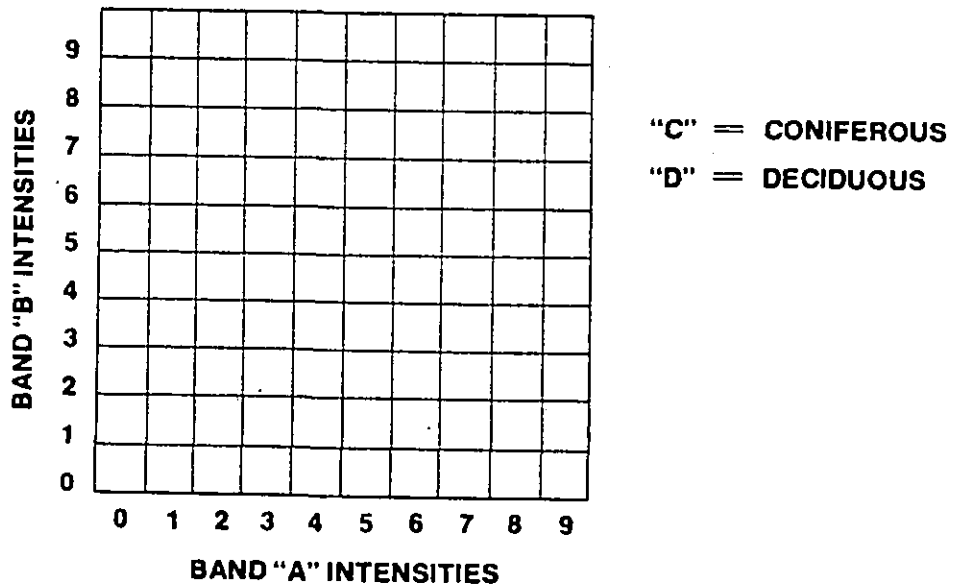


FIGURE 12A

		PIXEL						
		1	2	3	4	5	6	7
LINE	1	3	4	1	1	2	2	2
	2	4	4	4	2	1	2	2
	3	3	3	5	2	2	2	2
	4	5	5	2	2	2	2	2
	5	4	5	5	2	2	2	2
	6	4	3	3	4	4	5	5
	7	5	5	3	4	4	5	4

BAND "A"

FIGURE 12B

		PIXEL						
		1	2	3	4	5	6	7
LINE	1	7	7	0	0	0	3	3
	2	7	7	6	0	0	3	4
	3	4	4	7	1	1	3	4
	4	7	7	4	4	3	4	4
	5	6	7	7	4	5	5	5
	6	7	5	5	5	7	7	6
	7	7	6	6	7	7	7	7

BAND "B"

SCENE #2

FIGURE 12c

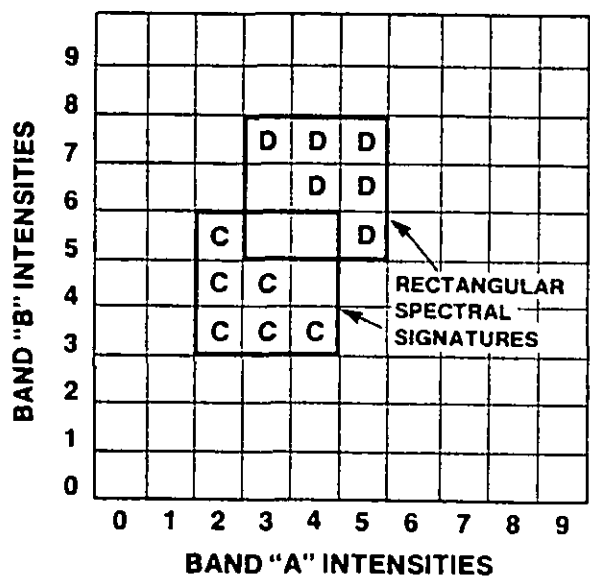


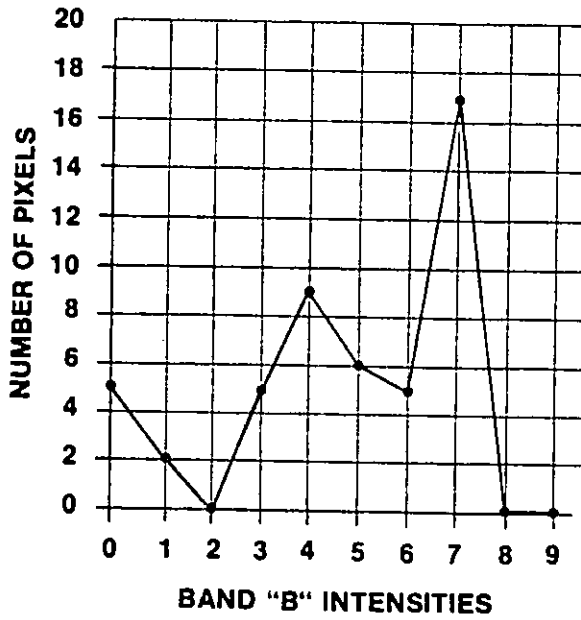
FIGURE 12D

		PIXEL						
		1	2	3	4	5	6	7
LINE	1							
	2							
	3							
	4							
	5	D	D	D	C	C	C	C
	6	D				D	D	D
	7	D	D		D	D	D	D

THEME MAP

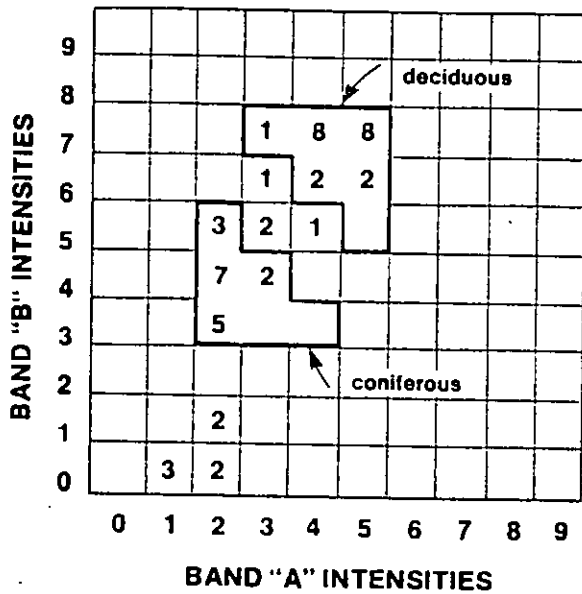
"C" = CONIFEROUS FOREST
 "D" = DECIDUOUS FOREST

FIGURE 13A



**ONE-DIMENSIONAL HISTOGRAM
SCENE #2, BAND "B"**

FIGURE 13B



**TWO-DIMENSIONAL
HISTOGRAM, SCENE #2**

Digital Image Analysis - Other Analysis Techniques

SPATIAL FILTERING

Spatial Frequency - the number of changes in brightness values per unit distance for any particular part of an image

Local Enhancement - spatial approach that incorporates information from neighboring pixels

Filters - suppress certain frequencies and pass others

Low Pass Filter

High Pass Filter

e.g., new BV_{ij} = weighted average of a neighbourhood of pixels around old BV_{ij} (2D - convolution)

Low Frequency Filtering (Low-Pass Filtering)

- suppress high spatial frequency detail (noise)

$$\text{Filter Mask} = \begin{matrix} c_1 & c_2 & c_3 \\ c_4 & c_5 & c_6 \\ c_7 & c_8 & c_9 \end{matrix}$$

$$\text{Example Mask A} = \begin{matrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{matrix}$$

- the pixel to be altered at any given time is at the centre of the mask

For Mask A

$$BV_{5,OUT} = \text{Int} \left(\frac{\sum_{i=1}^{n=9} c_i \cdot BV_i}{n} \right)$$

$$BV_{5,OUT} = \text{Int} \left(\frac{\sum_{i=1}^{n=9} BV_i}{9} \right)$$

$$BV_{5,OUT} = \text{Int} \left(\frac{BV_1 + BV_2 + BV_3 \dots BV_9}{9} \right)$$

CHAPTER 7 Image Enhancement

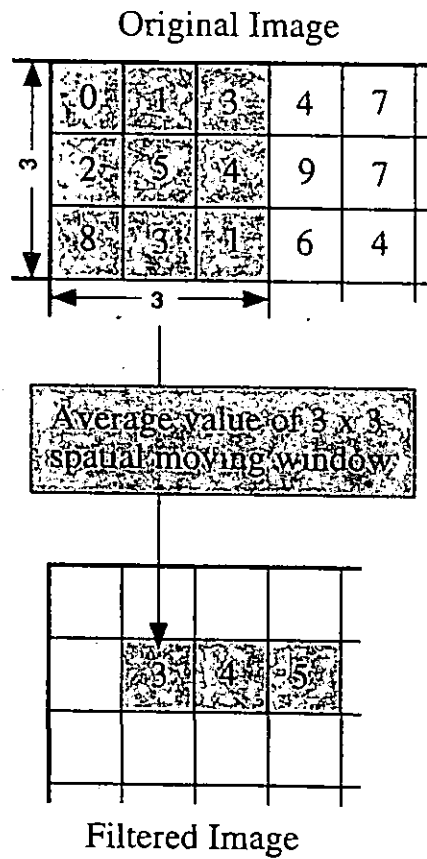


Figure 7-16 Result of applying low frequency convolution mask A to hypothetical data. The nine coefficients of the 3×3 mask are all equal to 1 in this example.

HIGH FREQUENCY FILTERING (HIGH-PASS FILTERING)

- enhances high spatial frequency detail
(accentuates edges and linear features)
- enhances noise

Example

$$\text{Mask } B = \begin{bmatrix} 1 & -2 & 1 \\ -2 & 5 & -2 \\ 1 & -2 & 1 \end{bmatrix}$$

25	29	52	66	67
25	25	47	68	67
25	25	47	64	69

16 47 81

Sample High Pass Filters

$$\frac{1}{9} \begin{bmatrix} -1 & -2 & -1 \\ -2 & 19 & -2 \\ -1 & -2 & -1 \end{bmatrix}$$

$$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$$

$$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 9 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

Filter Design

1. Window Size e.g., 3x3, 5x5, 7x7, (smoothing effect increases as filter size increases)

2. Weighted Filters - to reduce blurring at edges

$$\text{e.g., } \begin{array}{ccc} 0.25 & 0.50 & 0.25 \\ 0.50 & 1.00 & 0.50 \\ 0.25 & 0.50 & 0.25 \end{array} \quad (/4)$$

or

$$\begin{array}{ccc} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{array} \quad (/16)$$

Edge EnhancementGradient Masks

$$\text{e.g. } \begin{array}{ccc} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{array}$$

- detect edges in horizontal plane (changes from left to right)
- gradient masks have zero weighting (no output for regions of constant brightness)

Laplacian Masks

$$\text{e.g. } \begin{array}{ccc} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{array}$$

- not dependent on edge direction (edges/boundaries/lines)
- susceptible to noise
- emulates human vision by emphasizing peaks/valleys

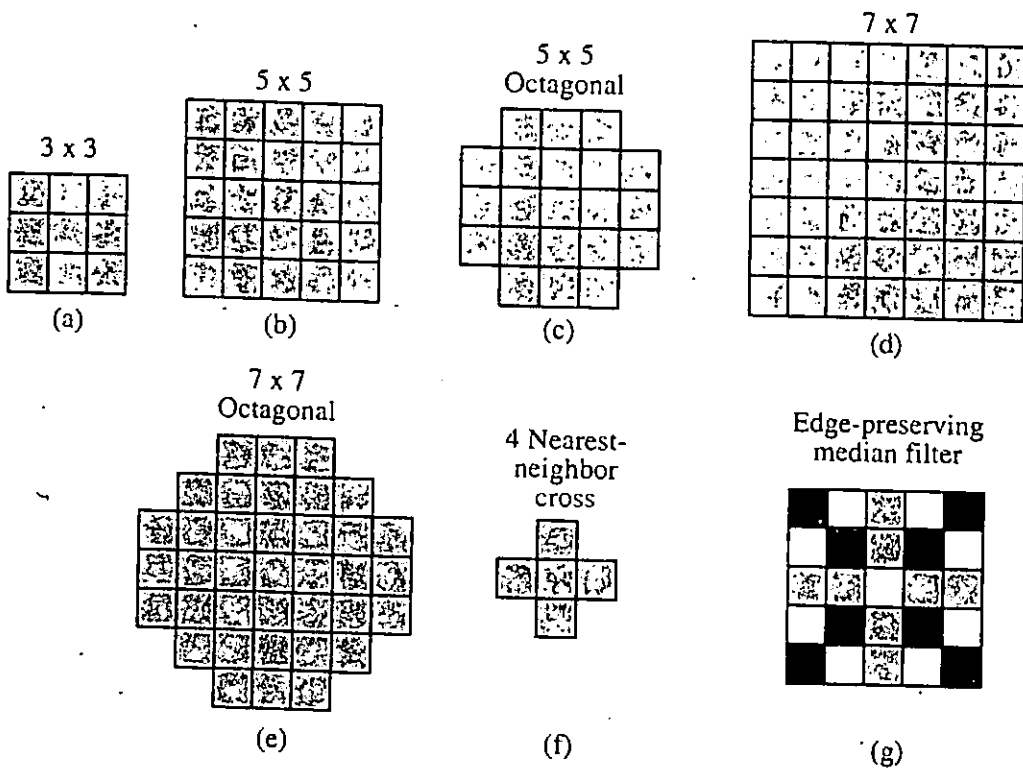


Figure 7-15 Examples of various convolution masks.

MULTI-IMAGE-PROCESSING: PRINCIPLES AND APPLICATIONS**1. Band Ratioing (Jensen, 1996 p. 152-154)**

- result from the division of DN vales in one spectral band by the corresponding values in another band
- can be used to counteract the effects of differential illumination
- may enhance subtle spectral reflectance or colour differences between surface materials
 - can produce similarities that do not occur in nature

e.g. $\frac{30}{15} = \frac{60}{30} = 2$

2. Vegetation Indexes (Jensen, 1996 p. 179-187)

- a variety of enhancements can be used to emphasize vegetation amount and condition (single number describing productivity, biomass, LAI)
- between-band ratioing of AVHRR, MSS, TM and SPOT brightness values has been used to estimate and monitor green biomass
- the red to near-infrared ratio is typically quite high for healthy vegetation

Normalized Difference Vegetation Index (NDVI)

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

$$NDVI_{TM} = \frac{TM4 - TM3}{TM4 + TM3}$$

- the brighter the pixel, the greater the amount of photosynthesizing vegetation present

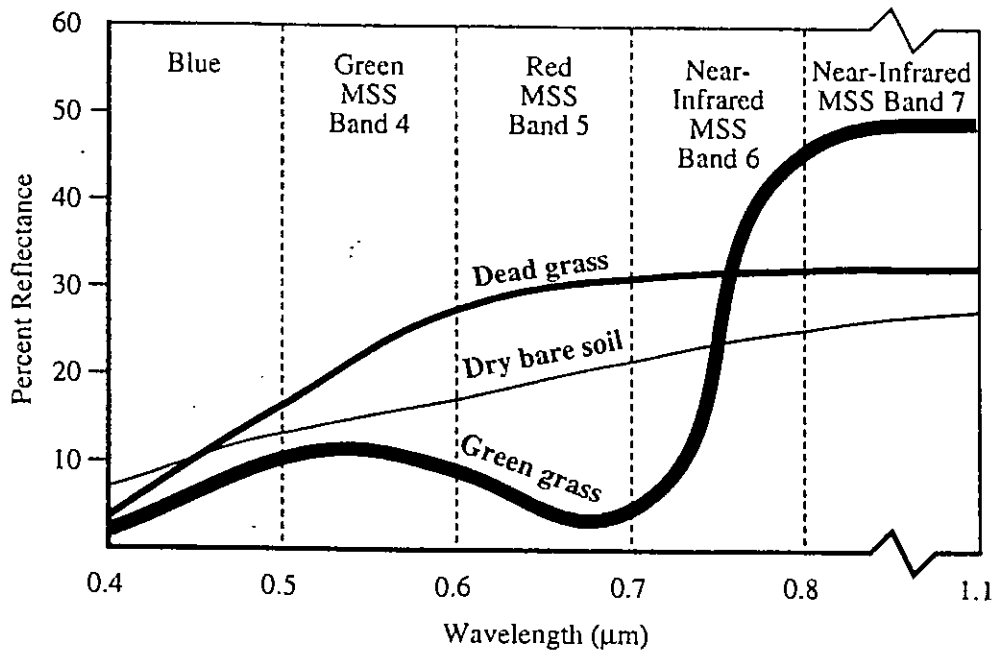


Figure 7-33 Typical spectral reflectance characteristics for healthy green grass, dead or senescing grass, and bare dry soil for the wavelength interval from 0.4 to 1.1 μm.

TASSEL CAP TRANSFORMATION

Soil Brightness Index (SBI)

Green Vegetation Index (GVI)

Yellow Stuff Index (YVI)

Non-such Index (NSI) (associated with atmospheric effects)

- in general the SVI and GVI contain approx. 95-98% of the scene information
- nearly all the variance in bare soil spectra from several different soil types is explained by the SBI
- bare soils would lie in a straight line parallel to the brightness axis
- greenness is an orthogonal deviation from the mean soil line and is used to measure vegetation amount (distance from the soil line > vegetation amount)

Tassel Cap Transformation for TM Data

Soil Brightness Index (**Brightness**)Green Vegetation Index (**Greenness**)Wetness Index (**Wetness**) (derived from middle-infrared)

In PCI the Tassel Cap Transformation (brightness, greenness, wetness) for TM Data is calculated as follows:

$$A1 * (TM1) + A2 * (TM2) + A3 * (TM3) + A4 * (TM4) + A5 * (TM5) + A7 * (TM7)$$

	A1	A2	A3	A4	A5	A6
Brightness	0.3037	0.2793	0.4743	0.5585	0.5082	0.1863
Greenness	-0.2848	-0.2435	-0.5436	0.7243	0.0840	-0.1800
Wetness	0.1509	0.1973	0.3279	0.3406	-0.7112	-0.4572

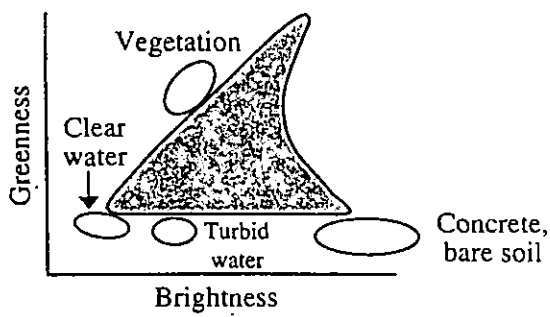


Figure 7-36 Location of various types of land cover when plotted in the brightness–greenness spectral space. Brightness is highly correlated with bare soil, while greenness is highly correlated with leaf area index, percent canopy closure, and/or biomass (Crist, 1983).

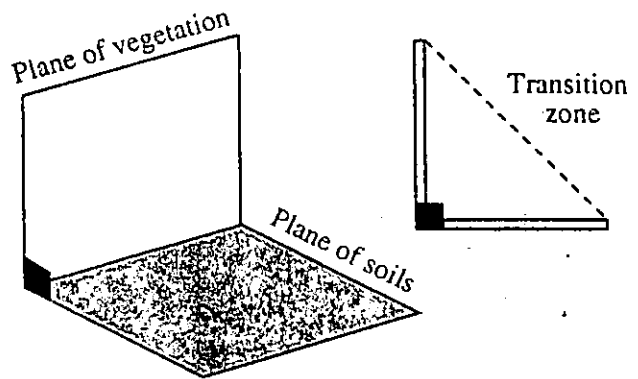


Figure 7-38 Dispersion of six-band Thematic Mapper data based on the use of the Kauth–Thomas transformation (Crist and Cicone, 1984).

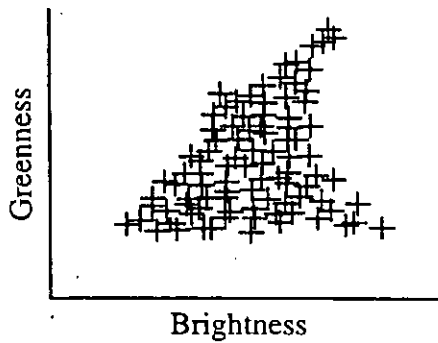


Figure 7-37 Actual plot of brightness and greenness values for an agricultural area. Note that the shape of the distribution looks like a cap (Crist, 1983).

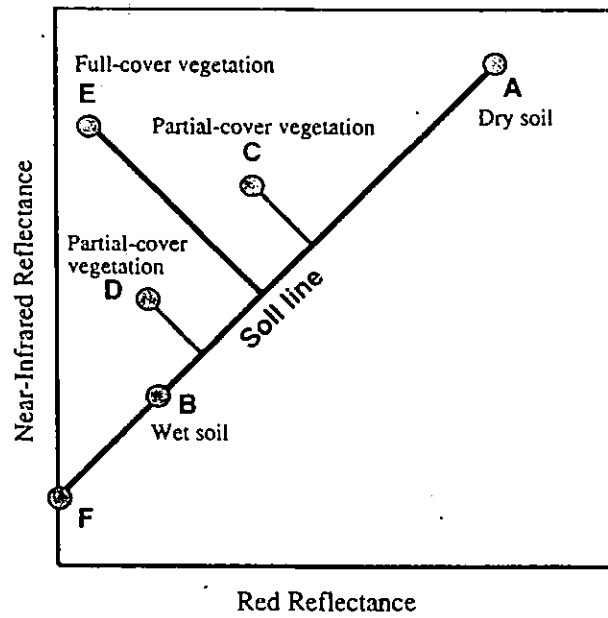


Figure 7-41 Relationship of vegetation to soil background using a perpendicular vegetation index (after Richardson and Wiegand, 1977).

Examples of Ratio-based Indices for Biophysical Studies
(adapted from Cohen, 1991; Major *et al.*, 1990)

Index	Landsat TM Equivalent	Description	Origin
Near-IR / Red Reflectance Ratio	TM4/TM3	responds to changes in amount of green biomass, chlorophyll content and leaf-water stress	Birth and McVey, 1968; Tucker, 1979
Normalized Difference Vegetation Index (NDVI)	$(TM4-TM3)/(TM4+TM3)$	responds to changes in amount of green biomass, chlorophyll content and leaf-water stress	Rouse <i>et al.</i> , 1974; Tucker 1979
Infrared Index	$(TM4-TM5)/(TM4+TM5)$	infrared index more closely tracks changes in plant biomass and water stress than NDVI	Hardisky <i>et al.</i> , 1983
Moisture Stress Index	TM5/TM4	tracks changes in plant water stress	Rock <i>et al.</i> , 1985
Leaf Water Content Index	$-\log[1-(TM4-TM5)]$ $-\log[1-(TM4_{ft}-TM5_{ft})]$ ft represents reflectance in the specified bands when leaves are at their max. relative water content	responds to changes in water stress	Hunt <i>et al.</i> , 1987
Mid-IR Index	TM5/TM7	shows a strong correlation with soil moisture	Musick and Pelletier, 1988
Vegetation Condition Index (VCI)	$\frac{100(NDVI_j - NDVI_{min_j})}{NDVI_{max_j} - NDVI_{min_j}}$	portrays weather dynamics more effectively than NDVI for non-homogeneous areas by removing the influences of geographic resources such as climate, soil, vegetation type and topography	Kogan, 1990
Perpendicular Vegetation Index (PVI)	$[-A1-A2(TM3)+A3(TM4)]^2 + (A4 + A5(TM3)-A6(TM4))^2]^{1/2}$	attempts to eliminate differences in soil background and is most effective under conditions of low LAI (arid and semi-arid environments)	Richardson and Wiegand, 1977
Soil Adjusted Vegetation Index (SAVI)	$(TM4 + L1)/(TM3 + L2)$	incorporates parameters (L1, L2) to minimize soil-brightness induced variations	Huete, 1988
Transformed Soil Adjusted Vegetation Index (TSAVI)	$(TM4)/(TM3 + \emptyset)$ (\emptyset must be empirically defined)	modifications of Huete (1988) SAVI to compensate for soil variability due to changes in solar elevation, leaf-angle distribution and LAI	Major <i>et al.</i> , 1990 Richardson and Wiegand, 1990

PRINCIPAL COMPONENTS ANALYSIS (PCA)

Purpose: to remove or diminish the redundancy of information between spectral bands

Objective: to compress all of the information within an 'n-channel' data set into fewer than 'n' new channels or components

PCA may be applied:

1. as an enhancement for visual interpretation
(provide more interpretable information than the original data)
2. as a preprocessing procedure prior to digital classification
(compress information of original data into fewer component images)

Eigenvalues / Components (λ_j) variances of the p th principal components
($p=1$ to n components)

$$R_{kp} = \frac{a_{kp} \cdot \sqrt{\lambda_p}}{\sqrt{\text{var}_k}}$$

$$R_{1,1} = \frac{0.090 \cdot \sqrt{1255.19}}{\sqrt{55.20}}$$

$$R_{1,1} = \frac{3.19}{7.43}$$

$$R_{1,1} = 0.429$$

$$R_{1,2} = \frac{0.400 \cdot \sqrt{219.41}}{\sqrt{55.20}}$$

$$R_{1,2} = \frac{5.92}{7.43}$$

$$R_{1,2} = 0.797$$

Table 7-5. Charleston, South Carolina Thematic Mapper Scene Statistics Used in the Principal Components Analysis

Band Number:	1	2	3	4	5	7	6
μm :	0.45-0.52	0.52-0.60	0.63-0.69	0.76-0.90	1.55-1.75	2.08-2.35	10.4-12.5
Univariate Statistics							
Mean	64.80	25.60	23.70	27.30	32.40	15.00	110.60
Standard Deviation	10.05	5.84	8.30	15.76	23.85	12.45	4.21
Variance	100.93	34.14	68.83	248.40	568.84	154.92	17.78
Minimum	51	17	14	4	0	0	90
Maximum	242	115	131	105	193	128	130
Variance-Covariance Matrix							
1	100.93						
2	56.60	34.14					
3	79.43	46.71	68.83				
4	61.49	40.68	69.59	248.40			
5	134.27	85.22	141.04	330.71	568.84		
7	90.13	55.14	86.91	148.50	280.97	154.92	
6	23.72	14.33	22.92	43.62	78.91	42.65	17.78
Correlation Matrix							
1	1.00						
2	0.96	1.00					
3	0.95	0.96	1.00				
4	0.39	0.44	0.53	1.00			
5	0.56	0.61	0.71	0.88	1.00		
7	0.72	0.76	0.84	0.76	0.95	1.00	
6	0.56	0.58	0.66	0.66	0.78	0.81	1.00

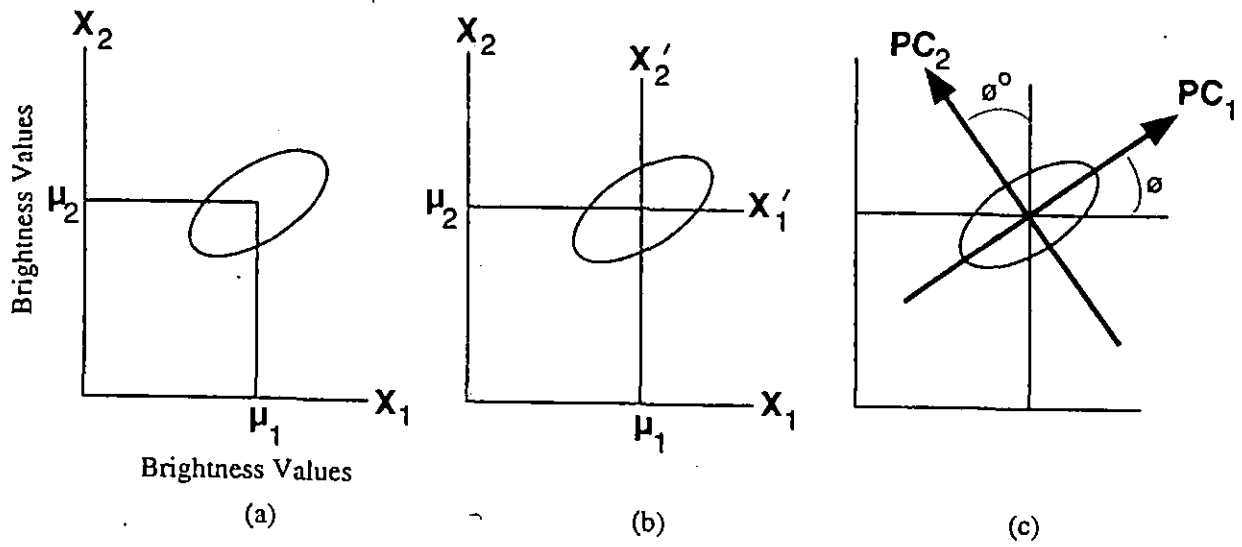


Figure 7-31 Diagrammatic representation of the spatial relationship between the first two principal components: (a) Scatterplot of data points collected from two remotely bands labeled X_1 and X_2 with the means of the distribution labeled μ_1 and μ_2 . (b) A new coordinate system is created by shifting the axes to an X' system. The values for the new data points are found by the relationship $X'_1 = X_1 - \mu_1$ and $X'_2 = X_2 - \mu_2$. (c) The X' axis system is then rotated about its origin (μ_1, μ_2) so that PC_1 is projected through the semimajor axis of the distribution of points and the variance of PC_1 is a maximum. PC_2 must be perpendicular to PC_1 . The PC axes are the principal components of this two-dimensional data space. Component 1 usually accounts for approximately 90% of the variance, with component 2 accounting for approximately 5%.

Table 7-6. Eigenvalues Computed for the Covariance Matrix

	Component <i>p</i>						
	1	2	3	4	5	6	7
Eigenvalues, λ_p	1010.92	131.20	37.60	6.73	3.95	2.17	1.24
Difference	879.72	93.59	30.88	2.77	1.77	.93	--
Total Variance = 1193.81							

Percent of total variance in the data explained by each component:

$$\text{Computed as } \%_p = \frac{\text{eigenvalue } \lambda_p \times 100}{\sum_{p=1}^7 \text{eigenvalue } \lambda_p}$$

For example,

$$\sum_{p=1}^7 \lambda_p = 1010.92 + 131.20 + 37.60 + 6.73 + 3.95 + 2.17 + 1.24 = 1193.81$$

$$\text{Percentage of variance explained by first component} = \frac{1010.92 \times 100}{1193.81} = 84.68$$

Percentage:	84.68	10.99	3.15	0.56	0.33	0.18	0.10
Cumulative:	84.68	95.67	98.82	99.38	99.71	99.89	99.99

Table 7-7. Eigenvectors (a_{kp}) (Factor Scores) Computed for the Covariance Matrix found in Table 7-4

	Component <i>p</i>						
	1	2	3	4	5	6	7
band 1	0.205	0.637	0.327	-0.054	0.249	-0.611	-0.079
2	0.127	0.342	0.169	-0.077	0.012	0.396	0.821
3	0.204	0.428	0.159	-0.076	-0.075	0.649	-0.562
4	0.443	-0.471	0.739	0.107	-0.153	-0.019	-0.004
5	0.742	-0.177	-0.437	-0.300	0.370	0.007	0.011
7	0.376	0.197	-0.309	-0.312	-0.769	-0.181	0.051
6	0.106	0.033	-0.080	0.887	0.424	0.122	0.005

Table 7-8. Degree of Correlation, R_{kp} , between Each Band k and Each Principal Component p

$$\text{Computed as: } R_{kp} = \frac{a_{kp} \times \sqrt{\lambda_p}}{\sqrt{\text{Var}_k}}$$

For example:

$$R_{1,1} = \frac{0.205 \times \sqrt{1010.92}}{\sqrt{100.93}} = \frac{0.205 \times 31.795}{10.046} = 0.649$$

$$R_{5,1} = \frac{0.742 \times \sqrt{1010.92}}{\sqrt{568.84}} = \frac{0.742 \times 31.795}{23.85} = 0.989$$

$$R_{2,2} = \frac{0.342 \times \sqrt{131.20}}{\sqrt{34.14}} = \frac{0.342 \times 11.45}{5.842} = 0.670$$

Band, k	Component p						
	1	2	3	4	5	6	7
1	0.649	0.726	-0.199	-0.014	0.049	-0.089	-0.008
2	0.694	0.670	0.178	-0.034	0.004	0.099	0.157
3	0.785	0.592	0.118	-0.023	-0.018	0.115	-0.075
4	0.894	-0.342	0.287	0.017	-0.019	-0.002	-0.000
5	0.989	-0.084	-0.112	-0.032	0.030	0.000	0.000
7	0.961	0.181	-0.152	0.065	-0.122	-0.021	0.004
6	0.799	0.089	-0.116	0.545	0.200	0.042	0.001

PCA \ Principal Component Analysis V6.0 EASI/PACE 09:08 07-Oct-96

/gisdata1/faculty/treitz/Tiger_Cats.pix [S 22BIC 512P 512L] 07-Oct-96

Input Channels: 1 2 3 4 5 6 7
 Output Channels: 8 9 10 11 12 13 14
 Eigenchannels : 1 2 3 4 5 6 7

Sampling Window: 0 0 512 512
 Sample size : 32768

Channel	Mean	Deviation
1	80.6112	7.4044
2	32.6788	4.9110
3	30.2317	8.2441
4	47.2402	22.5392
5	47.6859	26.0414
6	140.8421	9.6392
7	21.7582	12.8020

Covariance matrix for input channels:

	1	2	3	4	5	6	7
1	54.825						
2	32.990	24.117					
3	54.401	39.219	67.965				
4	11.282	38.030	58.508	508.015			
5	76.378	81.422	137.660	503.635	678.154		
6	36.200	28.146	51.650	101.213	157.994	92.915	
7	61.343	50.419	87.996	162.394	288.609	84.608	163.890

Eigenchannel	Eigenvalue	Deviation	%Variance
1	1282.7013	35.8148	80.68%
2	214.7299	14.6537	13.51%
3	46.1200	6.7912	2.90%
4	31.2909	5.5938	1.97%
5	10.3872	3.2229	0.65%
6	3.9111	1.9776	0.25%
7	0.7406	0.8606	0.05%

Eigenvectors of covariance matrix (arranged by rows):

0.07900	0.08640	0.14470	0.57045	0.71975	0.17627	0.30140
-0.40339	-0.21988	-0.39742	0.61861	-0.10325	-0.24985	-0.41860
0.06031	0.00826	0.04937	0.24498	-0.34913	0.88141	-0.18728
-0.55223	-0.33002	-0.40135	-0.39580	0.31926	0.34583	0.21649
-0.18650	-0.04249	-0.01866	0.27124	-0.49736	-0.08897	0.79638
0.67554	-0.18975	-0.69932	0.02336	0.01025	0.02043	0.13241
-0.17695	0.89297	-0.41013	-0.03354	0.00467	0.04119	0.01554

Now that we understand what information each component contributes, it is useful to see what the images of these components look like. To do this it is necessary to first identify the brightness values ($BV_{i,j,k}$) associated with a given pixel. In this case we will evaluate the first pixel in a hypothetical image at row 1, column 1 for each of seven bands. We will represent this as the vector X , such that

$$X = \begin{bmatrix} BV_{1,1,1} = 20 \\ BV_{1,1,2} = 30 \\ BV_{1,1,3} = 22 \\ BV_{1,1,4} = 60 \\ BV_{1,1,5} = 70 \\ BV_{1,1,7} = 62 \\ BV_{1,1,6} = 50 \end{bmatrix} \quad (7-65)$$

We will now apply the appropriate transformation to this data such that it is projected onto the first principal component's axes. In this way we will find out what the new brightness value (new $BV_{i,j,p}$) will be for this component, p . It is computed according to the formula

$$\text{new}BV_{i,j,p} = \sum_{k=1}^n a_{kp} BV_{i,j,k} \quad (7-66)$$

where a_{kp} = eigenvectors, BV_{ijk} = brightness value in band k for the pixel at row i , column j , and n = number of bands. In our hypothetical example, this yields

$$\begin{aligned} \text{new}BV_{1,1,1} &= a_{1,1}(BV_{1,1,1}) + a_{2,1}(BV_{1,1,2}) + a_{3,1}(BV_{1,1,3}) + a_{4,1}(BV_{1,1,4}) \\ &\quad + a_{5,1}(BV_{1,1,5}) + a_{6,1}(BV_{1,1,7}) + a_{7,1}(BV_{1,1,6}) \\ &= 0.205(20) + 0.127(30) + 0.204(22) + 0.443(60) \\ &\quad + 0.742(70) + 0.376(62) + 0.106(50) \\ &= 119.53 \end{aligned}$$

This pseudomeasurement is a linear combination of original brightness values and factor scores (eigenvectors). The new brightness value for row 1, column 1 in principal component 1 after truncation to an integer is $\text{new}BV_{1,1,1} = 119$.

DIMPLE Principal Components of "Hamilton 85.09.20 256x256"

Covariance matrix

	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7
Channel 1	55.20	34.33	54.88	24.67	88.78	45.02	63.60
Channel 2	34.33	24.69	37.83	38.80	77.61	31.13	46.55
Channel 3	54.88	37.83	61.35	47.97	116.43	51.46	74.70
Channel 4	24.67	38.80	47.97	535.43	505.33	97.04	151.41
Channel 5	88.78	77.61	116.43	505.33	647.38	158.86	259.32
Channel 6	45.02	31.13	51.46	97.04	158.86	93.28	84.70
Channel 7	63.60	46.55	74.70	151.41	259.32	84.70	140.65

PC	Eigenvalue		Eigenvector						
			Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7
1	1255.19	(80.56%)	0.09	0.09	0.13	0.60	0.71	0.18	0.28
2	219.41	(14.08%)	0.40	0.22	0.39	-0.60	0.12	0.32	0.40
3	39.20	(2.52%)	0.16	0.10	0.14	0.37	-0.46	0.73	-0.23
4	31.70	(2.03%)	-0.46	-0.34	-0.44	-0.29	0.24	0.57	0.11
5	8.81	(0.57%)	0.17	0.07	0.07	-0.23	0.46	0.08	-0.83
6	2.95	(0.19%)	-0.75	0.28	0.60	-0.03	0.01	0.01	-0.06
7	0.73	(0.05%)	-0.09	0.86	-0.50	-0.03	0.01	0.03	0.03

Factor Loadings - Hamilton

Channel	Variance	Component	Eigenvalue		C1	C2	C3	C4	C5	C6	C7
C1	55.20	PC1	1255.19	80.56%	0.090	0.090	0.130	0.600	0.710	0.180	0.280
C2	24.69	PC2	219.41	14.08%	0.400	0.220	0.390	-0.600	0.120	0.320	0.400
C3	61.35	PC3	39.20	2.52%	0.160	0.100	0.140	0.370	-0.460	0.730	-0.230
C4	535.43	PC4	31.70	2.03%	-0.460	-0.340	-0.440	-0.290	0.240	0.570	0.110
C5 *	647.38	PC5	8.81	0.57%	0.170	0.070	0.070	-0.230	0.460	0.080	-0.830
C6	93.28	PC6	2.95	0.19%	-0.750	0.280	0.600	-0.030	0.010	0.010	-0.060
C7	140.65	PC7	0.73	0.05%	-0.090	0.860	-0.500	-0.030	0.010	0.030	0.030
				PC1	0.429	0.642	0.588	0.919	0.989	0.660	0.836
				PC2	0.797	0.656	0.738	-0.384	0.070	0.491	0.500
				PC3	0.135	0.126	0.112	0.100	-0.113	0.473	-0.121
				PC4	-0.349	-0.385	-0.316	-0.071	0.053	0.332	0.052
				PC5	0.068	0.042	0.027	-0.030	0.054	0.025	-0.208
				PC6	-0.173	0.097	0.132	-0.002	0.001	0.002	-0.009
				PC7	-0.010	0.148	-0.055	-0.001	0.000	0.003	0.002

TEXTURE PROCESSING: PRINCIPLES AND APPLICATIONS

Scene Characteristics for Image Interpretation

- tonal variation or colour
- edge sharpness
- size, shape
- context (association)
- **texture**

TEXTURE PROCESSING

- whereas the context of a pixel refers to its spatial relationships with pixels in the remainder of the image, texture refers to the spatial variations within a surface which constitute the overall appearance of the image
- able to differentiate classes with similar spectral characteristics

The Statistical Approach

First Order Statistics in the Spatial Domain

Second Order Statistics in the Spatial Domain

Grey-Level Co-occurrence Matrix Method (GLCM)

Neighbouring Grey-Level Dependence Matrix (NGLDM)

- majority of classification algorithms are based on the use of pixel brightness values (tonal information)
- discrete tonal features (connected set of pixels of similar brightness values)
- texture - large variability of BV in a small local area
- creation of texture images to incorporate into digital classification

Statistical Approach

- texture is defined by the variations of tone (brightness values) across a surface
- an image is considered as a stochastic spatial distribution of brightness values
- texture information is derived using the spatial correlation of neighbouring pixels over local areas
- various descriptors of tonal variation (texture) associated with human visual perception are quantified using statistics (e.g., mean, std. dev., contrast, correlation, entropy, variance, etc.)

First Order Statistics in the Spatial Domain

- first order statistics of local areas (selected window size that moves over the entire image)
- a statistic is calculated within each window (i.e., mean, standard deviation, variance, entropy, etc.) and the value is assigned to the central pixel for the output image

Example (Woodcock *et al.*, 1980)

- classified forested areas in Landsat MSS scene
- texture image created by calculating the std. dev. within a 3x3 moving window
 - low std. dev. values indicated continuous canopy cover;
 - high std. dev. values indicate discontinuous canopy

Second Order Statistics in the Spatial Domain

- one method of measuring texture mathematically is based on statistics derived from a co-occurrence matrix (a matrix that shows the relationship between a given pixel to its specified neighbour)

Grey-Level Co-occurrence Matrix Method (GLCM)

- based on brightness value spatial dependency matrices
- a matrix of relative frequencies in which two neighbouring pixels, separated by distance (δ) and having an angular relationship (α), occur on the image, one with BV_i and the other BV_j

Original Image 5x5; $BV_r=4$

```

0 1 1 2 3
0 0 2 3 3
0 1 2 2 3
1 2 3 2 2
2 2 3 3 2

```

The spatial dependency matrix for the above 5x5 image ($\delta x=1, \delta y=0; (\alpha=0^\circ)$) is:

	j			
	0	1	2	3
0	1	2	1	0
1	0	1	3	0
2	0	0	3	5
3	0	0	2	2

- the entry in row i and column j of spatial dependency matrix (or GLCM) is the number of times brightness value i occurs to the left of brightness value j
- all texture information contained in the brightness value spatial-dependency matrices that are developed for angles of 0, 45, 90, and 135

Original 3x3 image

```
3 2 1
1 0 3
2 3 1
```

GLCM - 0, 45, 90, 135

		<i>j</i>			
		0	1	2	3
<i>i</i>	0	0	3	2	3
	1	3	0	2	4
	2	2	2	0	3
	3	3	4	3	2

Original 3x3 image

```
1 2 1
2 2 2
1 2 1
```

GLCM - 0, 45, 90, 135

		<i>j</i>			
		0	1	2	3
<i>i</i>	0	0	0	0	0
	1	0	0	1	0
	2	0	1	1	0
	3	0	0	0	0

- the texture of an image is related to the distance of the elements of the co-occurrence matrix from the diagonal of the matrix
- the greater the number found in the diagonal of the spatial dependency matrix, the more homogeneous the texture is for that part of the image being analyzed
- the amount of dispersion that the matrix elements have about the diagonal may be measured statistically through different texture measures
- various measures to extract information from the GLCM (e.g., mean, angular second moment, entropy, contrast, dissimilarity)

Neighbouring Grey-Level Dependence Matrix (NGLDM) Method

- for computing the NGLDM a grey level interval (α) and displacement distance (β) from the centre pixel are specified
- each entry in the matrix for a class (k,s) is generated by counting the number of occurrences in which the difference in grey level between each pixel in the class with grey tone k and s of its neighbours is equal to, or less than (α)
- invariant under spatial rotation (i.e., the same texture value will result even if the brightness values are rotated)

Original Image 6x6; BV_r=8

4	4	6	5	4	3
4	4	5	3	0	1
3	3	5	0	0	1
2	0	7	3	3	2
0	0	7	7	3	3
0	1	6	6	2	2

Computation of NGLDM entries (3x3 window; $\beta = 1$; $\alpha = 0$)

(4,3)	(5,2)	(3,0)	(0,2)
(3,1)	(5,1)	(0,2)	(0,2)
(0,2)	(7,2)	(3,2)	(3,3)
(0,3)	(7,2)	(7,2)	(3,3)

The NGLDM Matrix

BV	NGLDM Numbers								
	0	1	2	3	4	5	6	7	8
0	0	0	4	1	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	1	1	1	2	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0
5	0	1	1	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	3	0	0	0	0	0	0

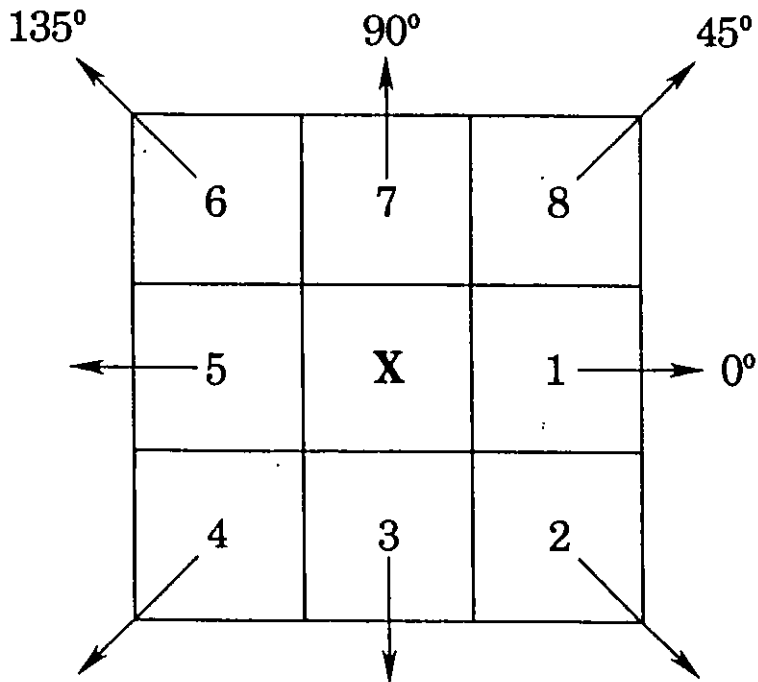


Figure 7-42 Eight nearest neighbors of pixel X according to angle ϕ used in the creation of spatial dependency matrices for the measurement of image texture. (After Haralick and Shanmugam, 1973.)

Change Detection

1. Why Change Detection with Satellites ?

- repetitive synoptic coverage
- frequent repeat coverage (3-4 days SPOT to 16 days Landsat)
- same orbit parameters - e.g., path, time, direction, scale
- only feasible way to monitor change over large areas

2. Detection of Change

a) What will be detected depends on:

- spatial resolution
- spectral bands used
- nature of the spectral change in the environment

e.g.	<u>Surface</u>	<u>Reflectance</u>	<u>Infrared</u>
	Vegetation	Dark	Light
	Bare Soil	Medium	Light
	Paved Surface	Light	Light
	Water	Med/Dark	Dark

b) Types of Change

e.g.	Vegetation	-	Bare Soil	-	Built-up	=	rural-urban fringe
	Vegetation	-	Bare Soil	-	Vegetation	=	crop land

3. Digital Change Detection

- possible to co-register and overlay bands from different dates
- use of image enhancement and image classification techniques for analysis

4. Algorithms/Procedures

a) Image Differencing

$$\Delta x_{ijk} = BV_{ijk}(T1) - BV_{ijk}(T2) + c$$

b) Image Ratio

$$\Delta r_{ijk} = (BV_{ijk}(T1)) / (BV_{ijk}(T2))$$

c) Vegetation Index Difference/Ratio

$$VI = (IR-R)/(IR+R)$$

$$\Delta v_{ijk} = VI_{ijk}(T1) - VI_{ijk}(T2) + c$$

$$\Delta v_{ijk} = (VI_{ijk}(T1)) / (VI_{ijk}(T2))$$

e) Postclassification Comparison

IMAGE DIFFERENCING
CHANGE DETECTION METHOD

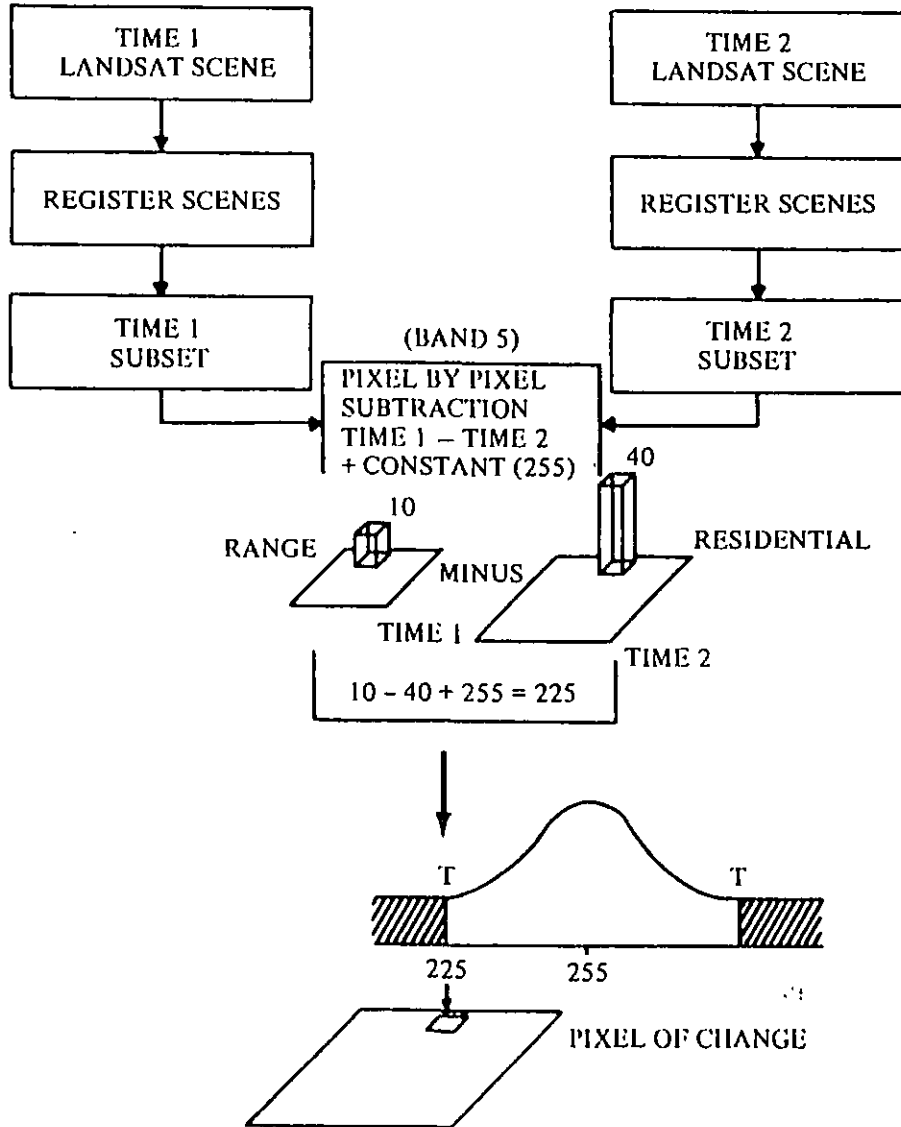


Figure 9-5 Image differencing change detection method. (From Jensen, 1981.)

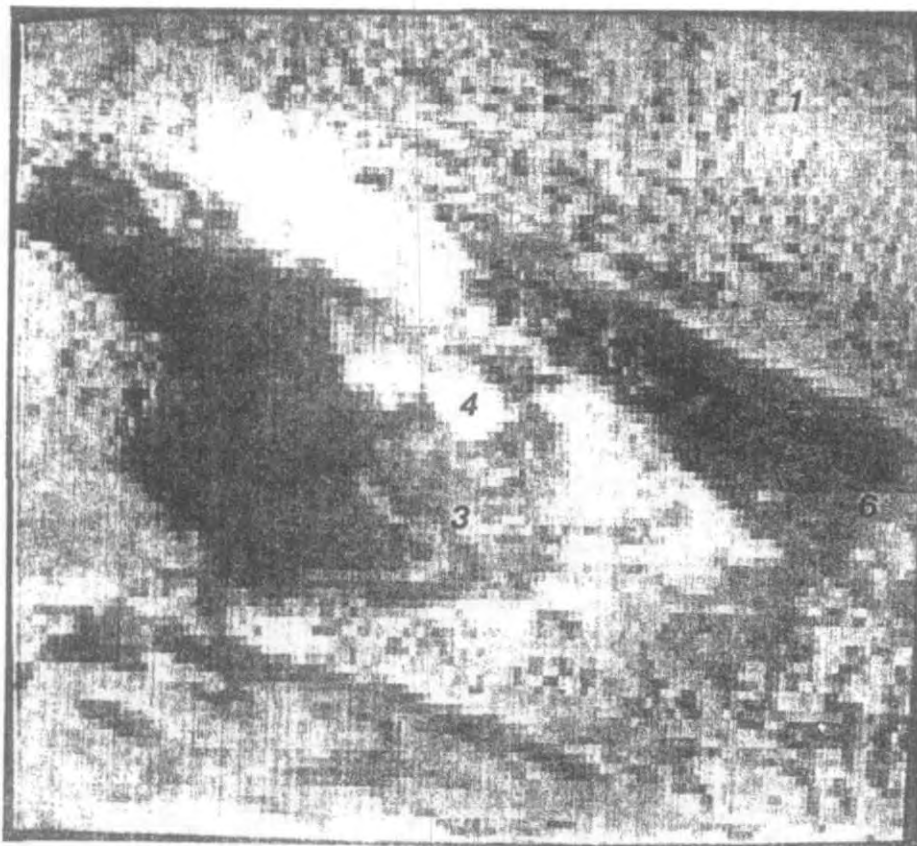
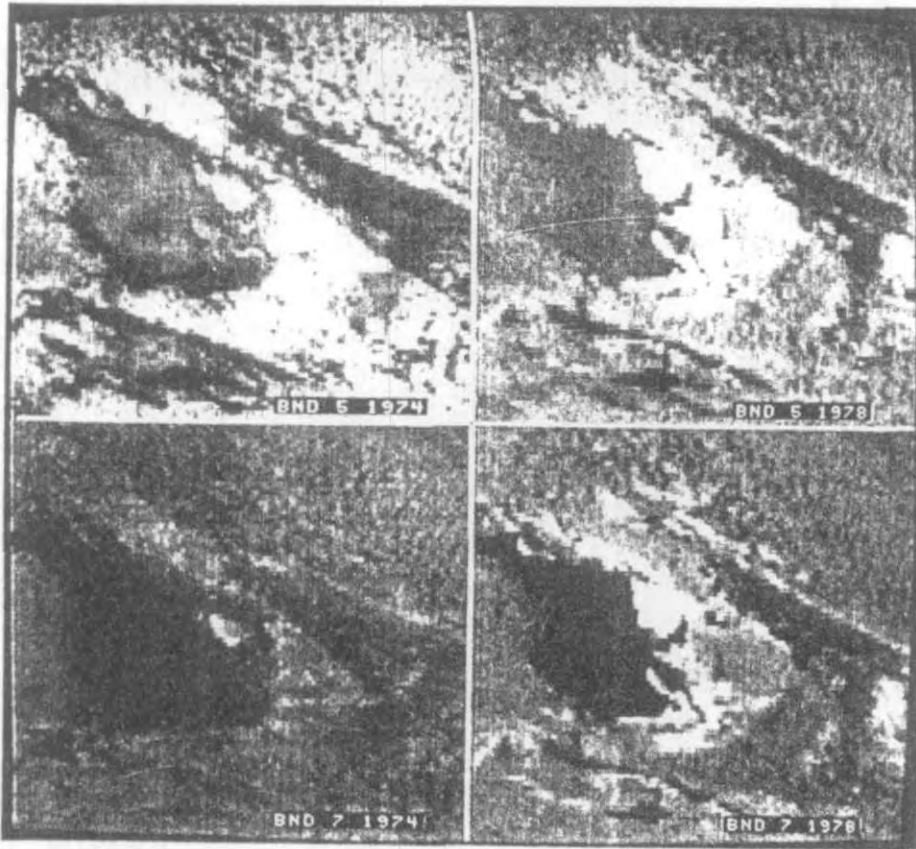


Table 1. Landscape interpretation of the Ao-bai Lake area from multirate imagery

Image colour	Digital values				Interpretation
	Band 5 (1974) Blue gun	Band 7 (1974) Green gun	Band 5 (1978) *	Band 7 (1978) Red gun	
Light blue/grey	154	124	140	131	Areas of little or no change between the two dates. (Background values)
Dark blue/black	133	39	117	22	Water on both dates. Slightly lighter areas indicate high sediment levels, interpreted from the Band 5 (1974) image.
Pink/purple	124	64	246	213	These colours fringe the lake and represent areas that were water in 1974 and bare ground with high reflectance (salt flats) in 1978.
White	197	142	170	144	Area of high reflectance in all bands represent salt flats that did not change
Green	78	125	85	106	Well vegetated area, where the vigour declined between 1974 and 1978
Orange/brown	113	103	189	180	Pixels surrounding the green area. They represent areas of poorer vegetation in 1974 which gave higher reflectance in 1978 due to die-back of vegetation and increased exposure of sand.

* Not displayed on the colour composite.

Table 2. Difference in digital values relative to the background values of no change.

Image colour	Difference in digital value				Change 1974-1978	
	Band 5 (1974)	Band 7 (1974)	Band 5 (1978)	Band 7 (1978)	Band 5	Band 7
	Blue gun	Green gun	-	Red gun		
Dark blue/ black	-21	-85	-23	-109	-2	-24
Pink/ purple	-30	-60	+106	+ 82	+136	+142
White	+43	+18	+ 30	+ 13	- 13	- 5
Green	-76	+ 1	- 55	- 25	+ 21	- 26
Orange/ brown	-41	-21	+ 49	+ 49	+ 90	+ 70

Image Interpretation

Land Use Change and Sustainable Development in the Segara Anakan Area of Java, Indonesia

Relevant Information from Remote Sensing, On-ground Survey and the ABC Method

by

Gordon Nelson
Ellsworth LeDrew
Dulbahri
Judy Harris
Caron Olive

A Joint Publication of the
Earth-Observations Laboratory
of the Institute for Space and Terrestrial Science
and the
Heritage Resources Centre of the University of Waterloo



October, 1992

IST S-EOL-TR92-004

Heritage Resources Centre
Technical Paper 7



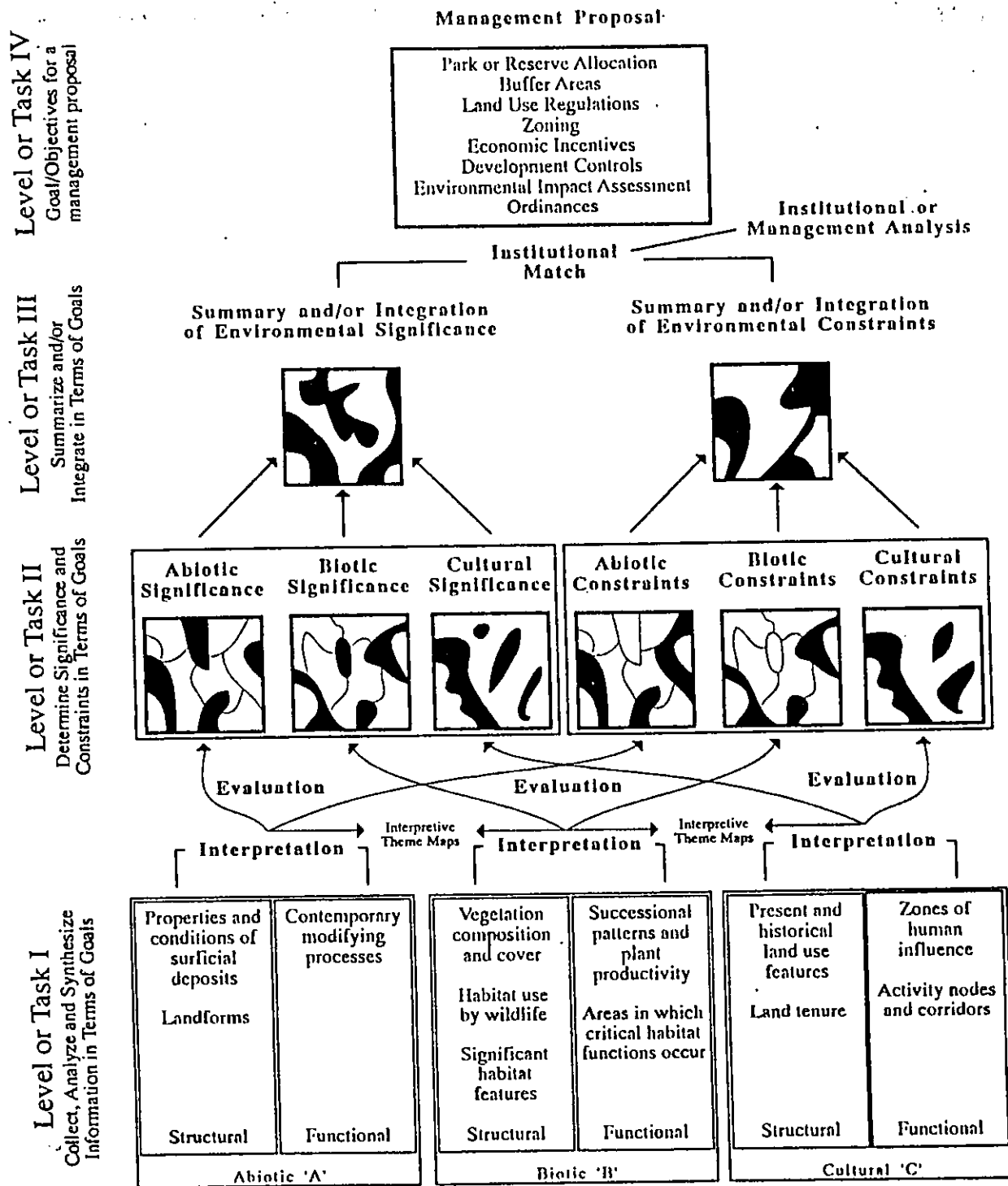


Figure 2: ABC Resource Survey and Planning Approach for Environmentally Significant Areas

Introduction to Radar Imagery

Radar Remote Sensing

1. Why use Radar Remote Sensing ?

a) Advantages:

- active remote sensing system; generates its own scene illumination
- independent of solar illumination
- penetration of cloud and rain; partial penetration of vegetation and soil
- radar produces different information from that available in the visible or infrared regions of the spectrum

b) Disadvantages:

- distortions inherent to the radar imaging geometry
- speckle or image noise makes it difficult to observe detail
- difficult to interpret
- can be expensive for information content of image

2. Special Characteristics of Radar

Radar is sensitive to:

- surface roughness
- electrical properties
- moisture
- motion

3. Imaging Radar Fundamentals

- a brief history of radar
- uses the microwave region - wavelength, frequency and polarization
- Side-Looking Airborne Radar (SLAR)
- Real-Aperture Radar (RAR) - range and azimuth resolution
- Synthetic Aperture Radar (SAR) - resolution
- radar equation

4. Radar Imaging Geometry

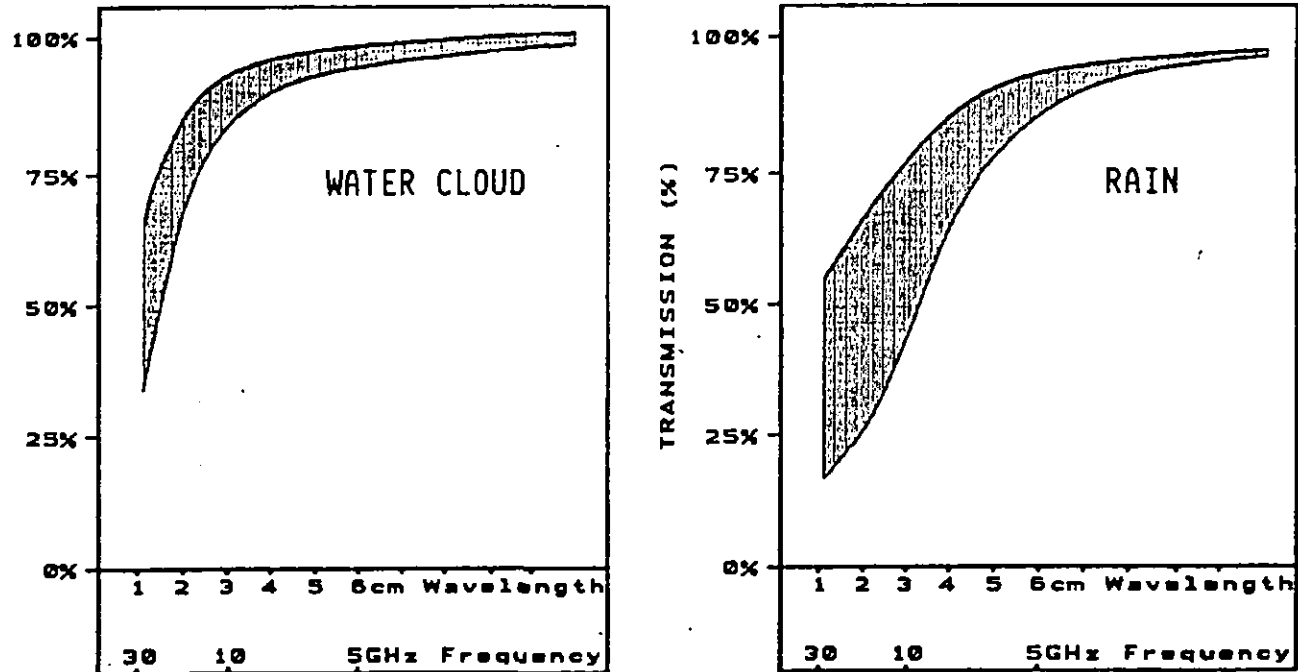
- depression angle and incidence angle
- slant range and ground range
- layover effects
- foreshortening effects
- radar shadow

5. Radar Target Parameters

- surface roughness - smooth, intermediate and rough
- dielectric constant
- surface scattering
- volume scattering
- point targets
- multiple reflections

FIGURE 1-1

EFFECT OF CLOUD AND RAIN ON MICROWAVE TRANSMISSION

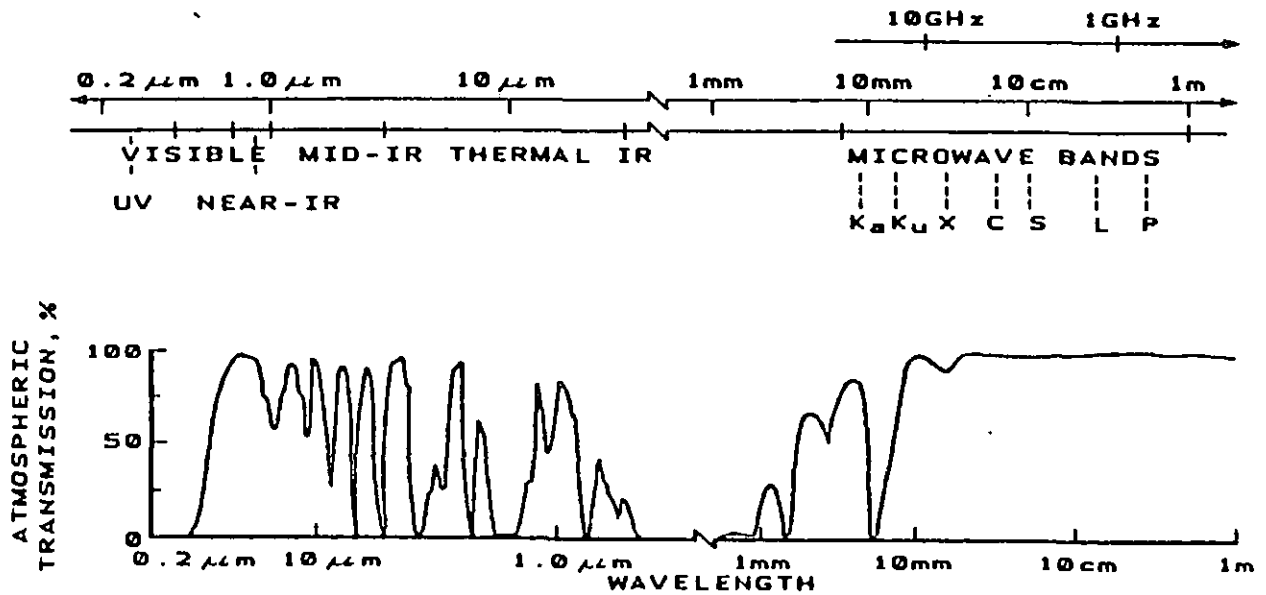


MOST IMAGING RADARS OPERATE AT WAVELENGTHS BETWEEN 3-30 cm (10-3GHz RANGE) AND ARE THEREFORE NOT SERIOUSLY AFFECTED BY CLOUD COVER OR RAIN

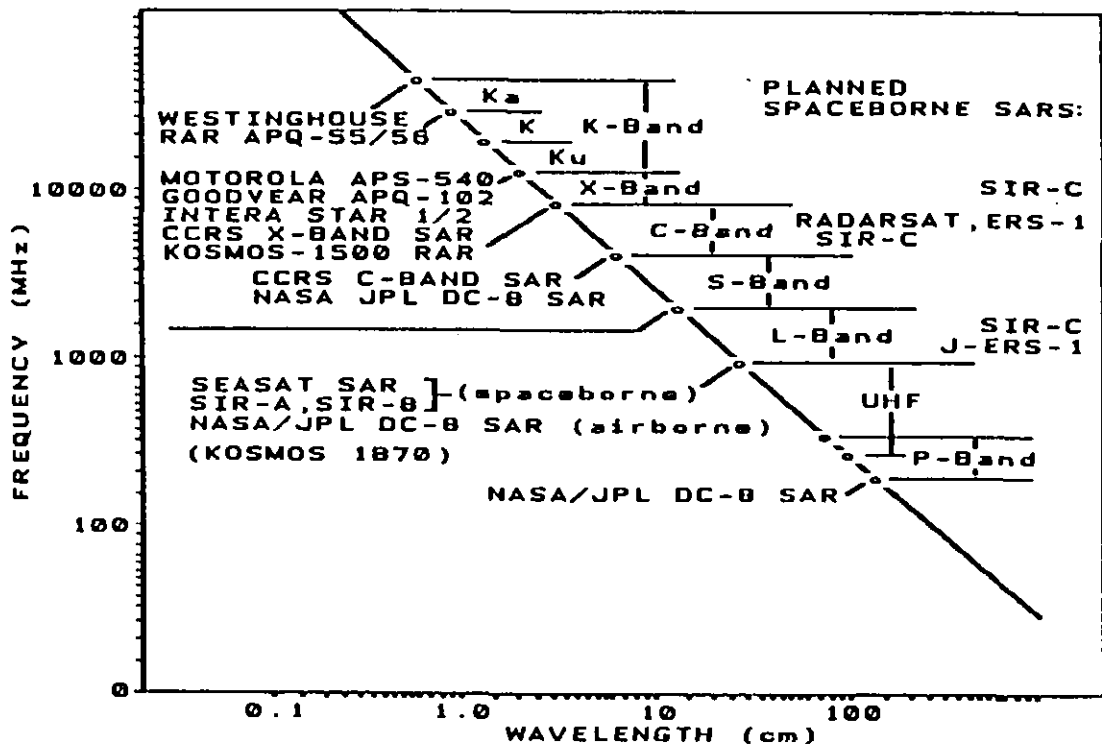
Source: after ULABY et al. (1981)

FIGURE 2-1

WAVELENGTH/FREQUENCY & EMS



ELECTROMAGNETIC SPECTRUM SHOWING ATMOSPHERIC TRANSMISSION WINDOWS, THE MICROWAVE, IR, AND VISIBLE BANDS.

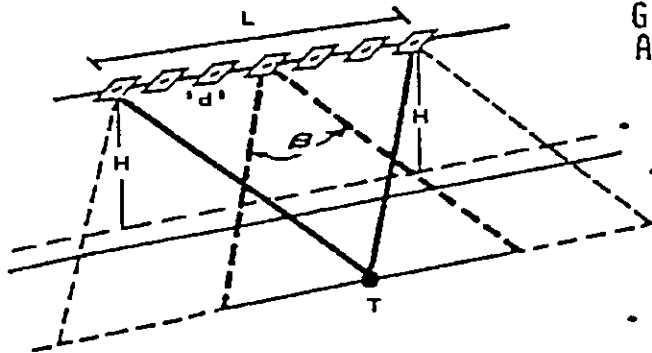


THE MICROWAVE BANDS AS ELEMENTS OF WAVELENGTH AND FREQUENCY.

Source: after TREVETT (1986)

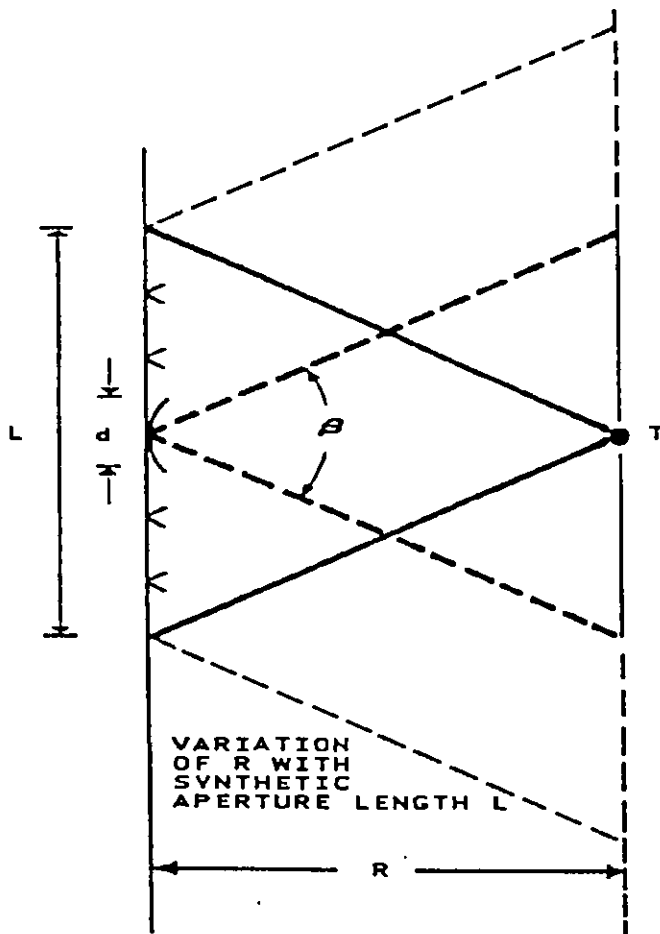
FIGURE 2-3

SYNTHETIC APERTURE RADAR



GENERATION OF A SYNTHETIC APERTURE ARRAY

- ANTENNA WITH DIMENSION d YIELDS BEAMWIDTH θ rad OF $\theta = \lambda / d$ FOR WAVELENGTH λ .
- TARGET (T) AT RANGE (R) REMAINS WITHIN THE REAL BEAMWIDTH (θ) FOR A DISTANCE $L = R \theta$ (WHICH IS THE APPROPRIATE AZIMUTH RESOLUTION OF A REAL APERTURE RADAR).



- SAR RECORDS RETURN SIGNALS FROM TARGET T AT SUCCESSIVE POSITIONS AS PLATFORM MOVES ALONG TRACK

- RECORDED SIGNALS ARE THEN PROCESSED OVER THE RESULTING EQUIVALENT SYNTHETIC ARRAY (L)

- ANGULAR RESOLUTION ACHIEVED IS

$$\theta_s = \frac{\lambda}{2L}$$

YIELDING $\theta_s = \frac{d}{2R}$

WITH A CORRESPONDING AZIMUTH RESOLUTION P AT RANGE R OF

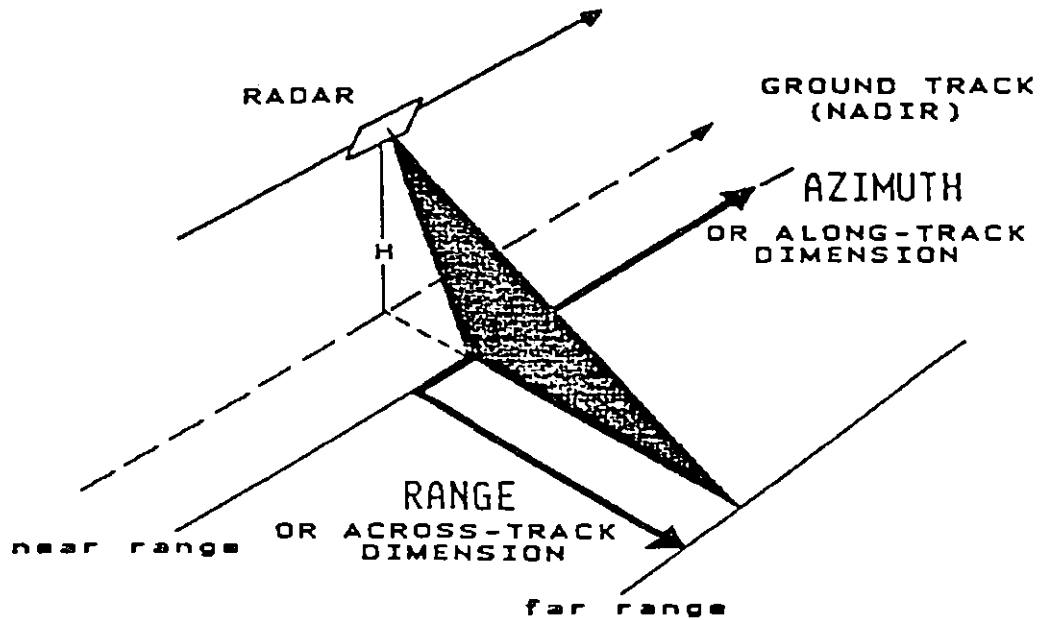
$$P = R \theta_s = \frac{d}{2}$$

VARIATION OF R WITH SYNTHETIC APERTURE LENGTH L

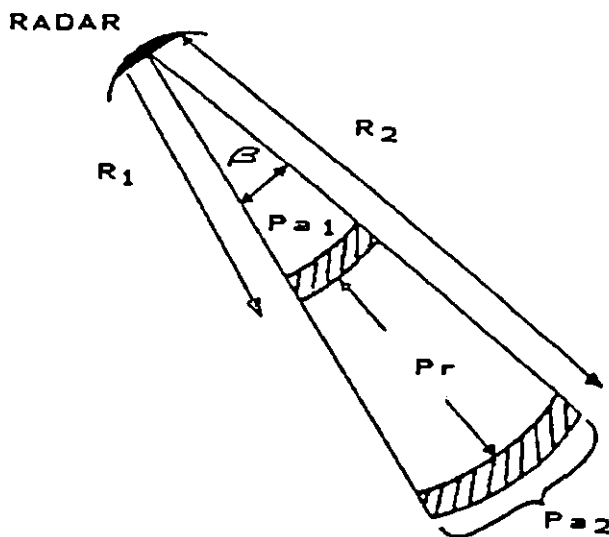
NOTE: θ_s IS NOT A FUNCTION OF λ AND BEAMWIDTH IS IMPROVED AS ANTENNA d IS MADE SMALLER (\neq RAR)

FIGURE 2-2

RANGE AND AZIMUTH



RESOLUTION (RAR)

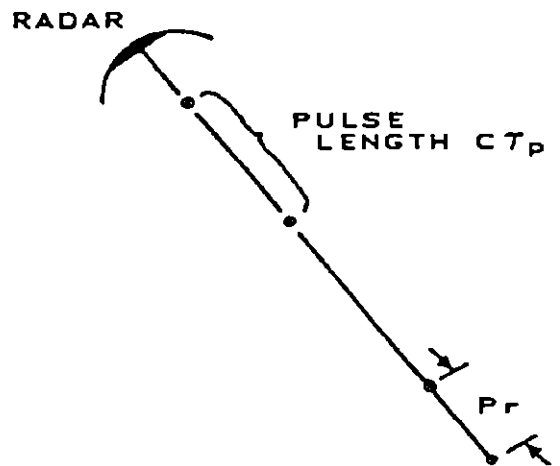


AZIMUTH RESOLUTION P_a

DEPENDS ON RANGE R
AND BEAMWIDTH β

$$P_{a1} = R_1 \beta \quad P_{a2} = R_2 \beta$$

$$P_{a1} > P_{a2}$$



RANGE RESOLUTION P_r

DEPENDS ON PULSE
DURATION/LENGTH CT_p

$$P_r = \frac{CT_p}{2}$$

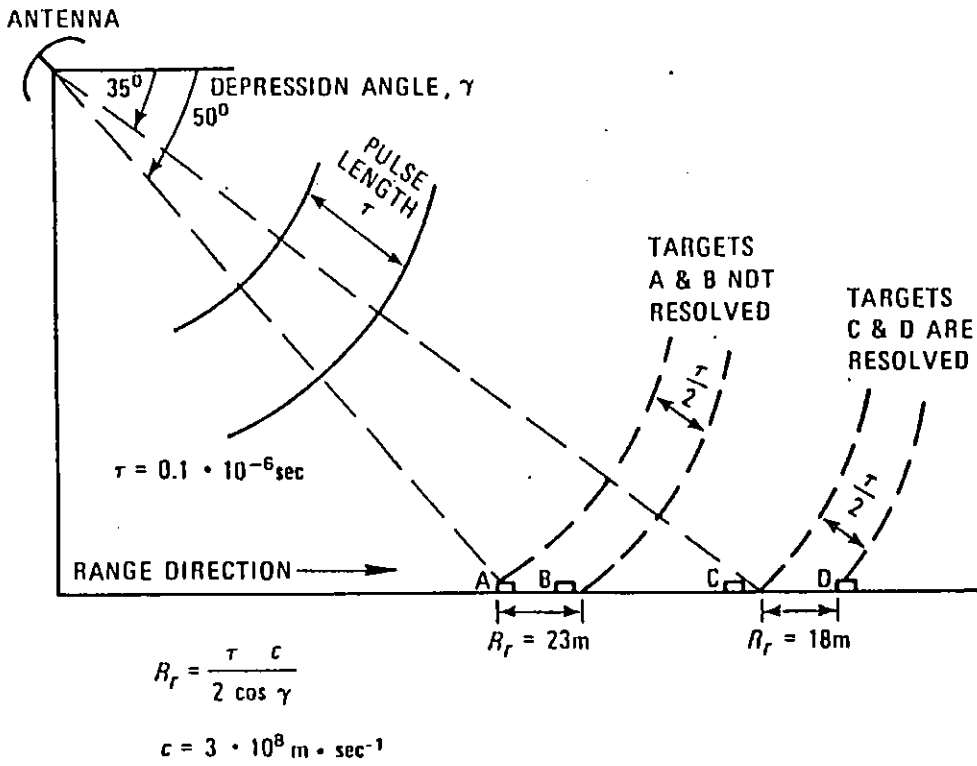


FIGURE 6.7
Radar resolution in the range direction R_r . From Barr (1969).

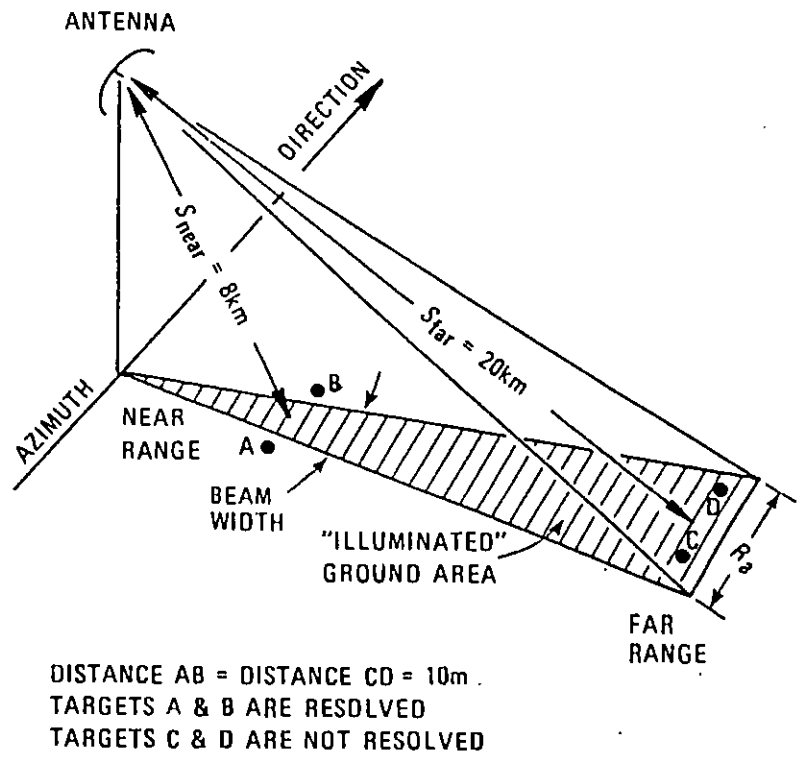


FIGURE 6.8
Radar beam width and resolution in the azimuth direction, R_a , for real-aperture SLAR system. From Barr (1969).

Sabins
(1978)

Radar Calculations

Range Resolution (R_r)

$$R_r = \frac{c \tau}{2 \cos \theta_d}$$

where c = speed of E.M radiation (3×10^8 m/sec)

τ = pulse duration

θ_d = depression angle

Example $\tau = 0.1 \mu\text{sec}$ $\theta_d = 45^\circ$ What is R_r ?

$$R_r = \frac{(3 \times 10^8 \text{ m/sec}) \cdot (0.1 \times 10^{-6} \text{ sec})}{2 \times 0.707} = 21 \text{ m}$$

Azimuth Resolution (R_a)

a) Real Aperture System (RAS)

$$R_a = \bar{GR} \cdot \beta$$

where \bar{GR} = ground range

β = beamwidth

Example $\beta = 1.8 \text{ mrad}$ What is R_a at 6 km + 12 km?

$$R_{a_{6\text{km}}} = (6 \times 10^3 \text{ m}) \cdot (1.8 \times 10^{-3}) = 10.8 \text{ m}$$

$$R_{a_{12\text{km}}} = (12 \times 10^3 \text{ m}) \cdot (1.8 \times 10^{-3}) = 21.6 \text{ m}$$

Beam Width

$$\beta = \frac{\lambda}{AL}$$

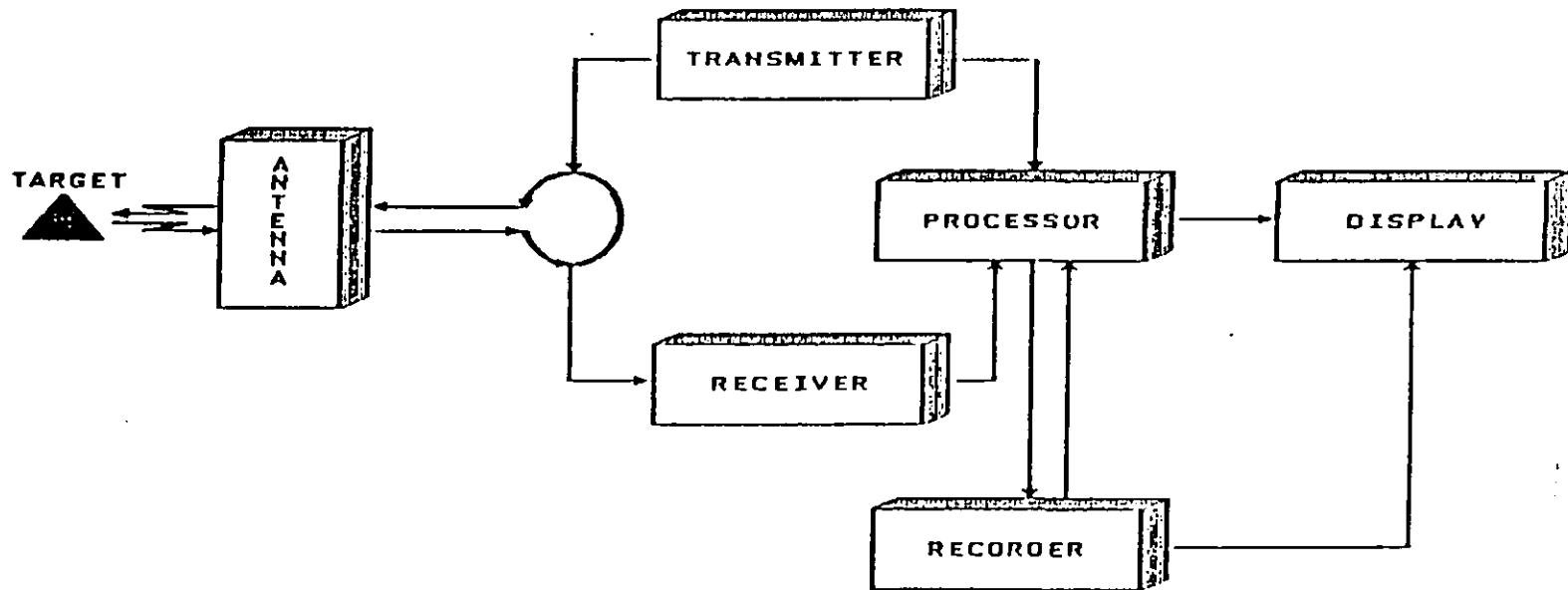
Beam width is decreased by:

• decreasing λ

• increasing antenna length AL

FIGURE 2-5

BASIC ELEMENTS OF A RADAR SYSTEM



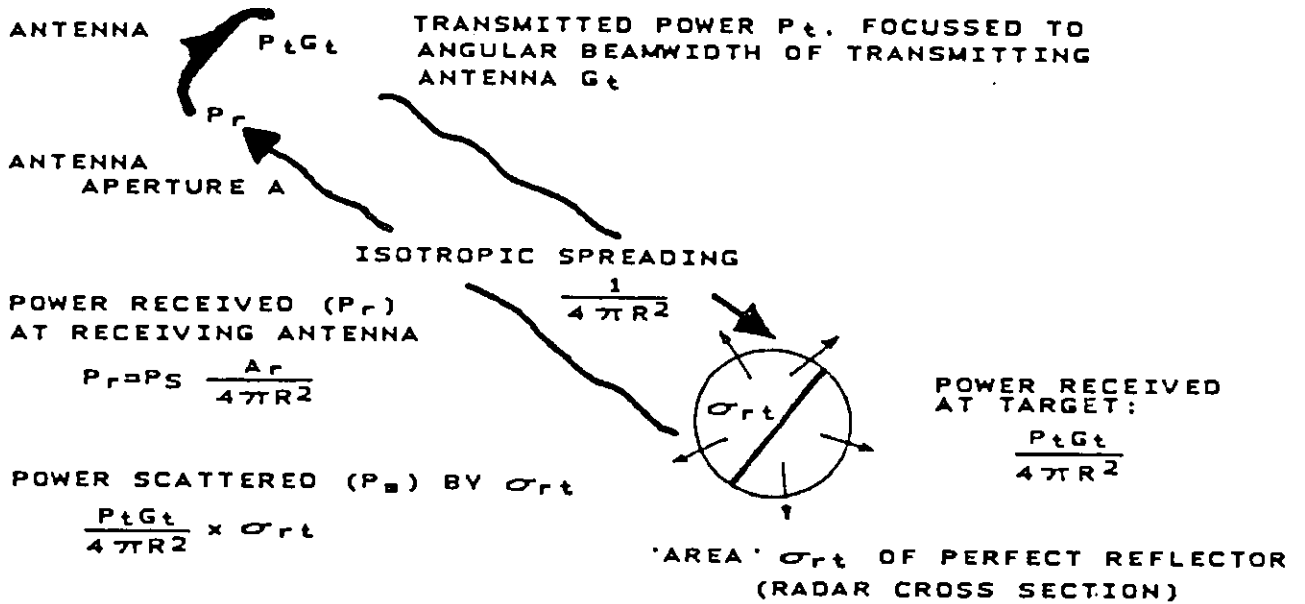
Source: after ULANDY et al. (1981), TREVETT (1986)

FIGURE 2-6

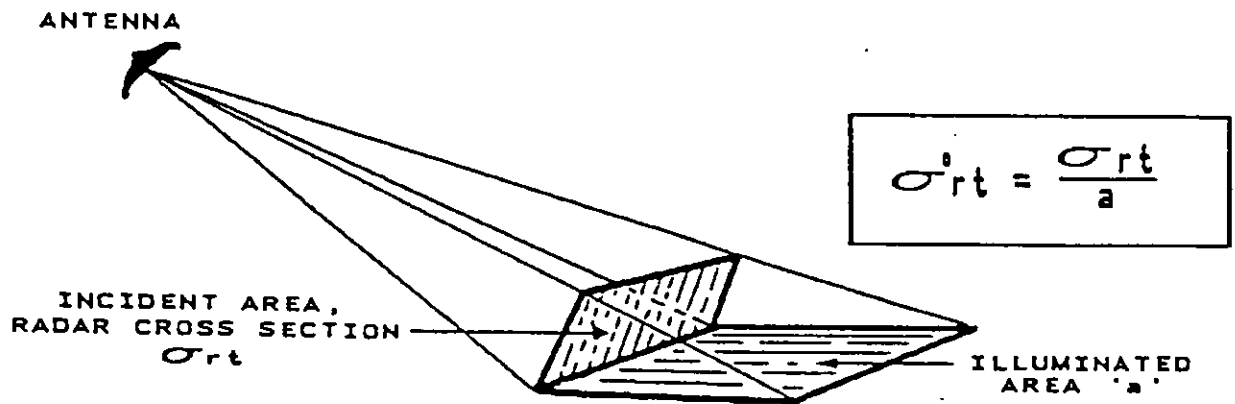
RADAR EQUATION

RELATES RECEIVED POWER (P_r) TO RADAR AND TARGET PARAMETERS

$$P_r = \frac{P_t G_t}{4\pi R^2} \sigma_{rt} \frac{A_r}{4\pi R^2}$$



RADAR BACKSCATTER COEFFICIENT



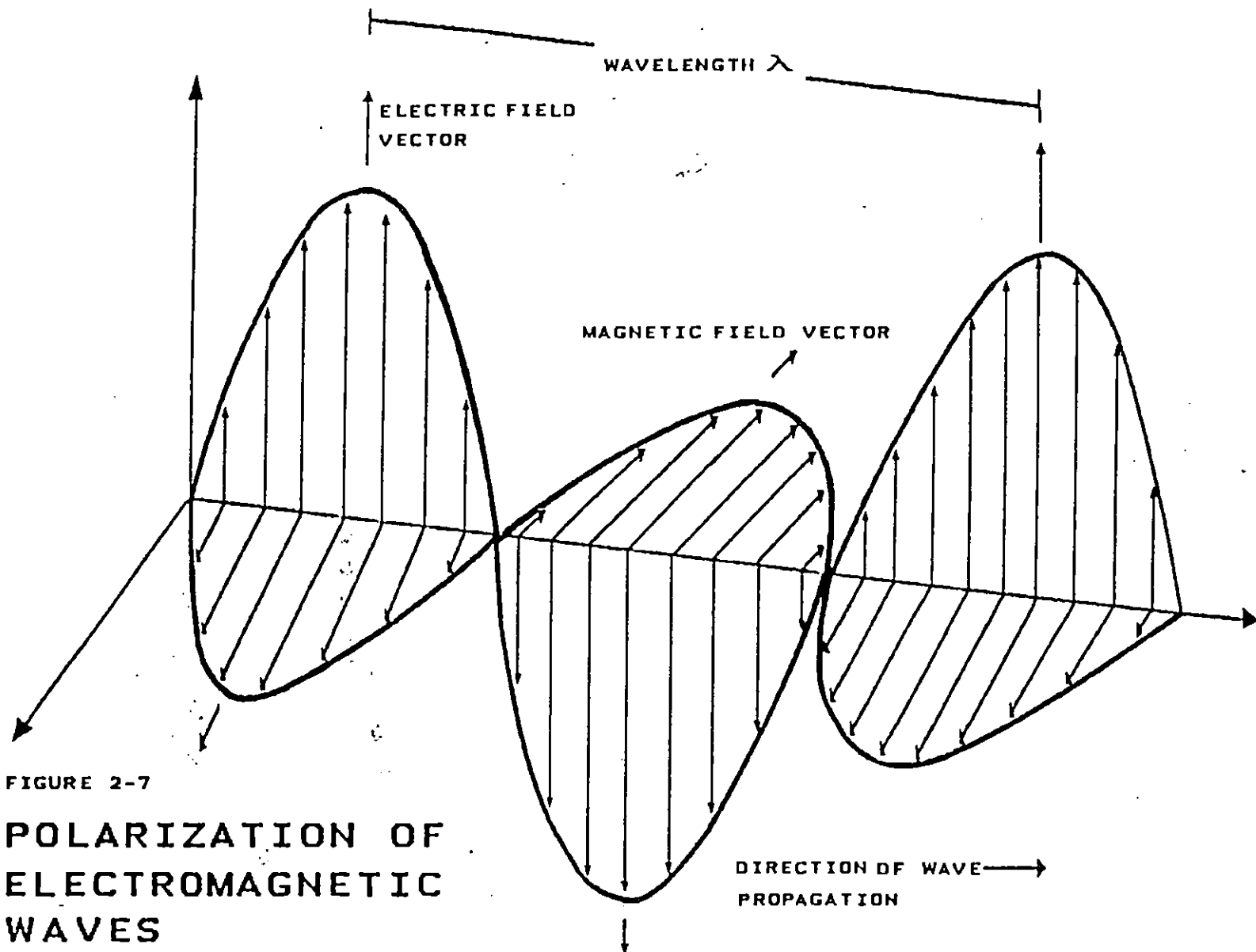


FIGURE 2-7

**POLARIZATION OF
ELECTROMAGNETIC
WAVES**

DIRECTION OF WAVE
PROPAGATION →

FIGURE 2-8

DEPRESSION ANGLE AND INCIDENCE ANGLE

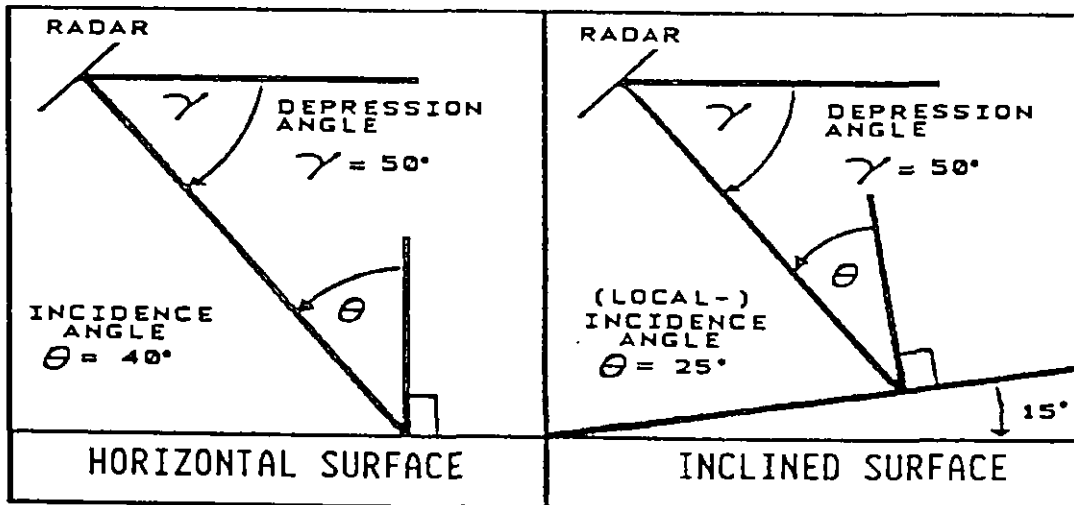
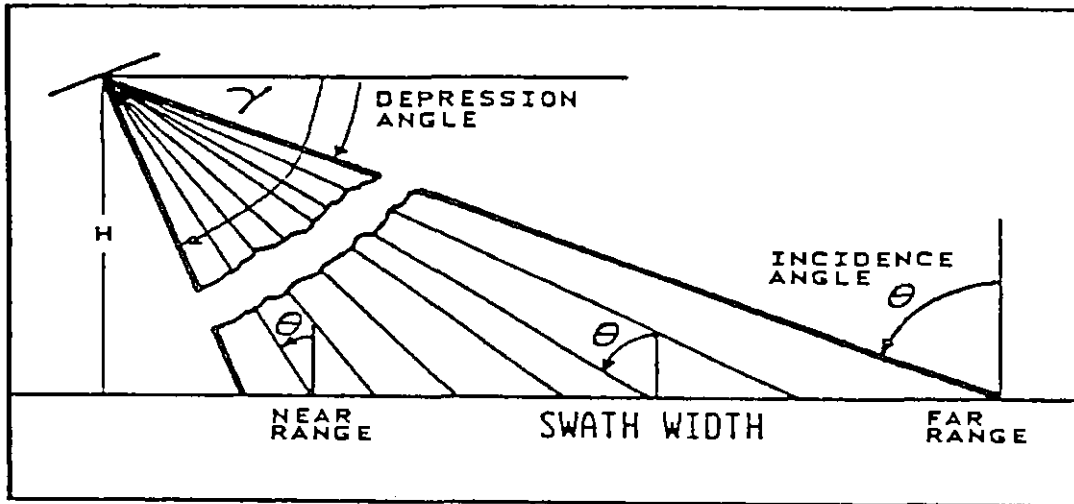


Figure 2-9

RELIEF DISPLACEMENT

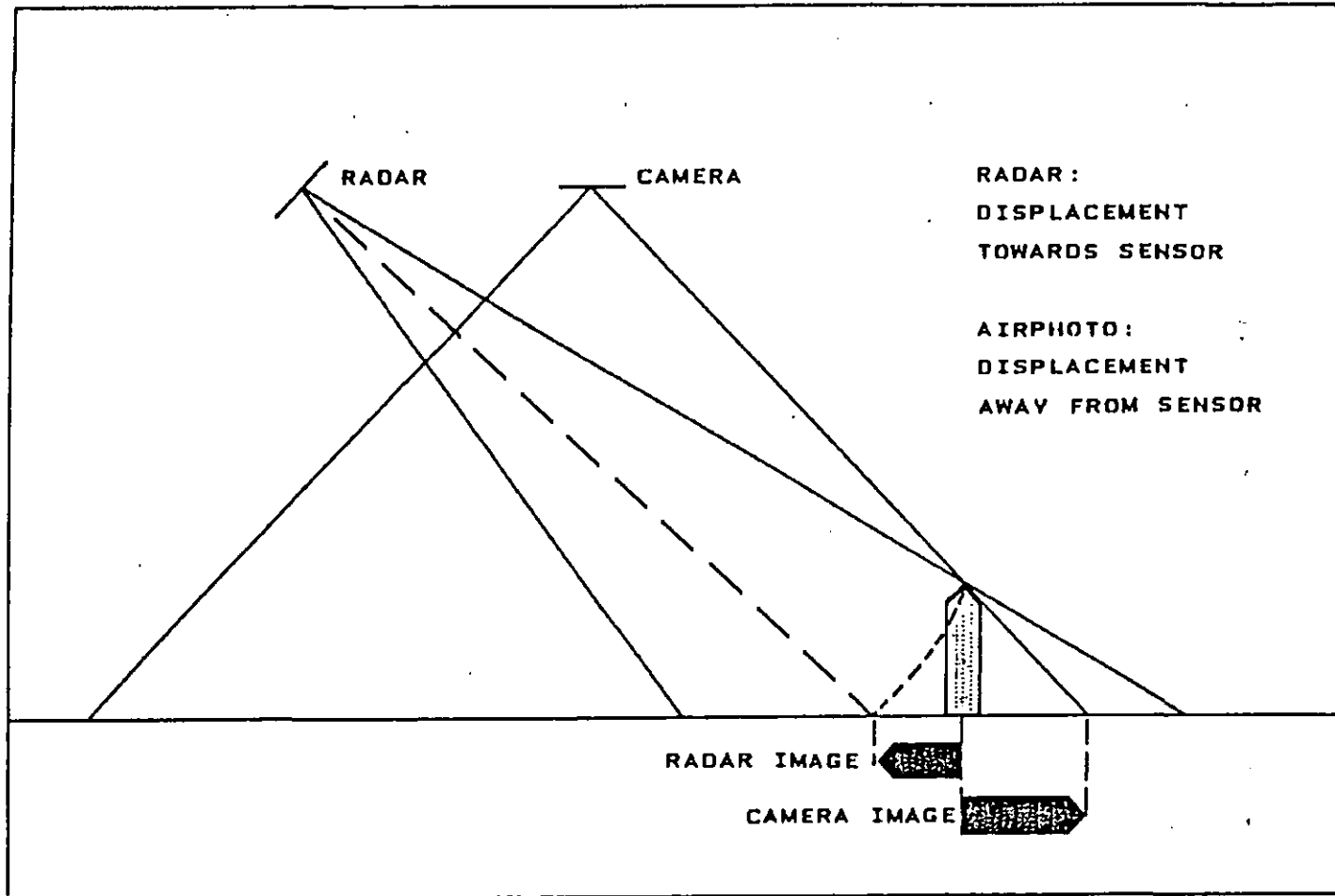


FIGURE 2-10

DISTANCE: SLANT RANGE VS. GROUND RANGE

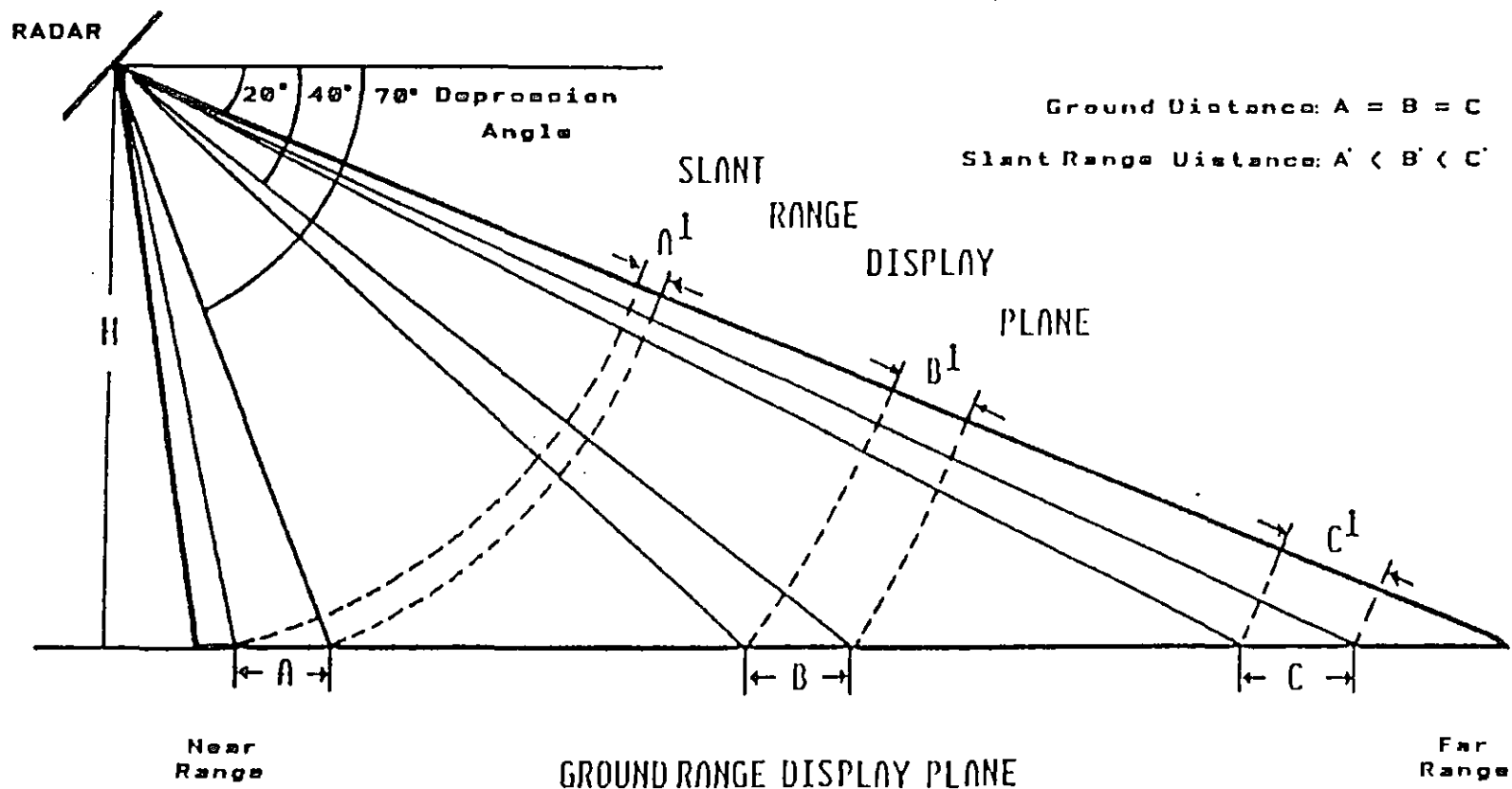


FIGURE 2-11

LAYOVER

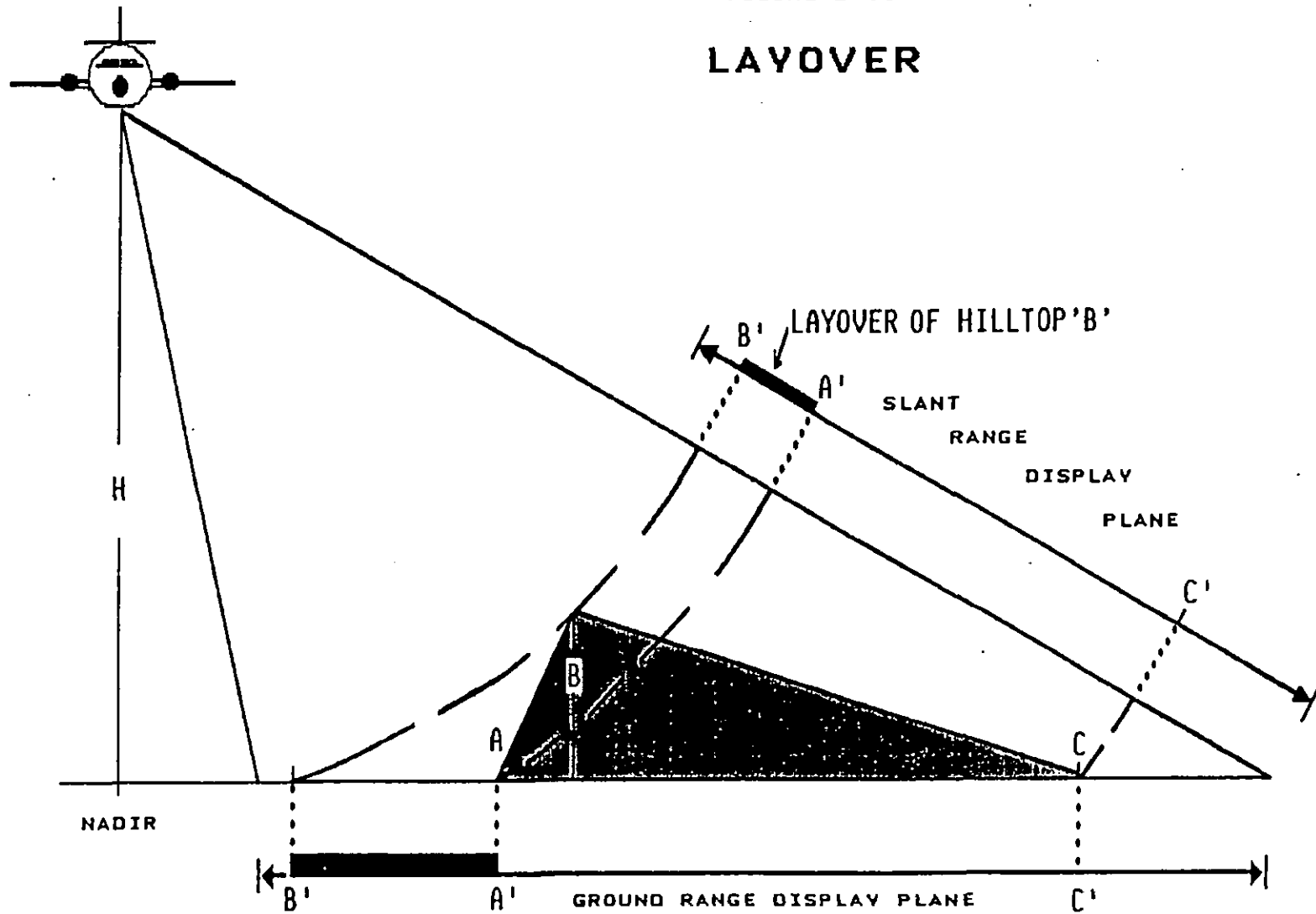


FIGURE 2-12

FORESHORTENING

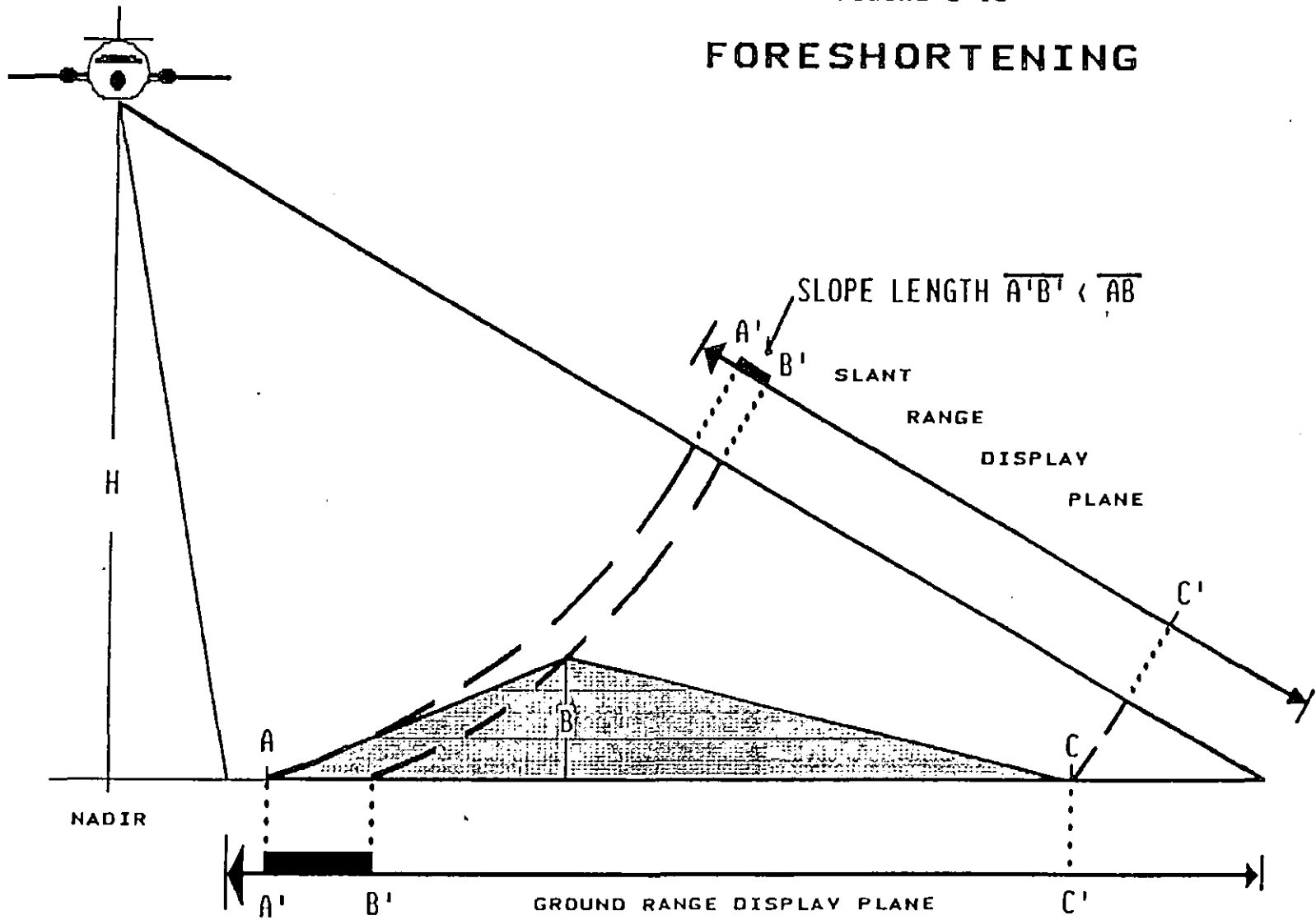
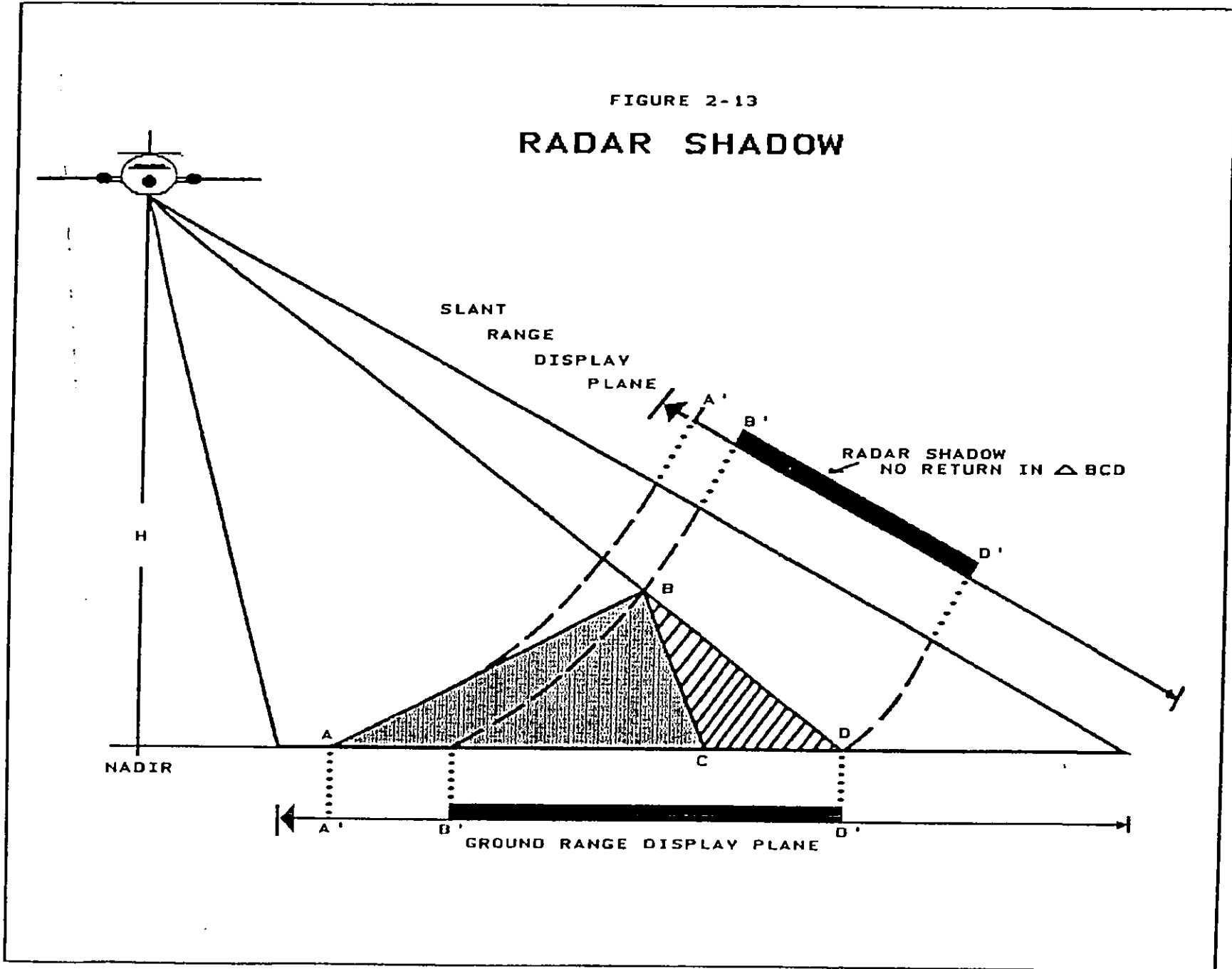


FIGURE 2-13

RADAR SHADOW



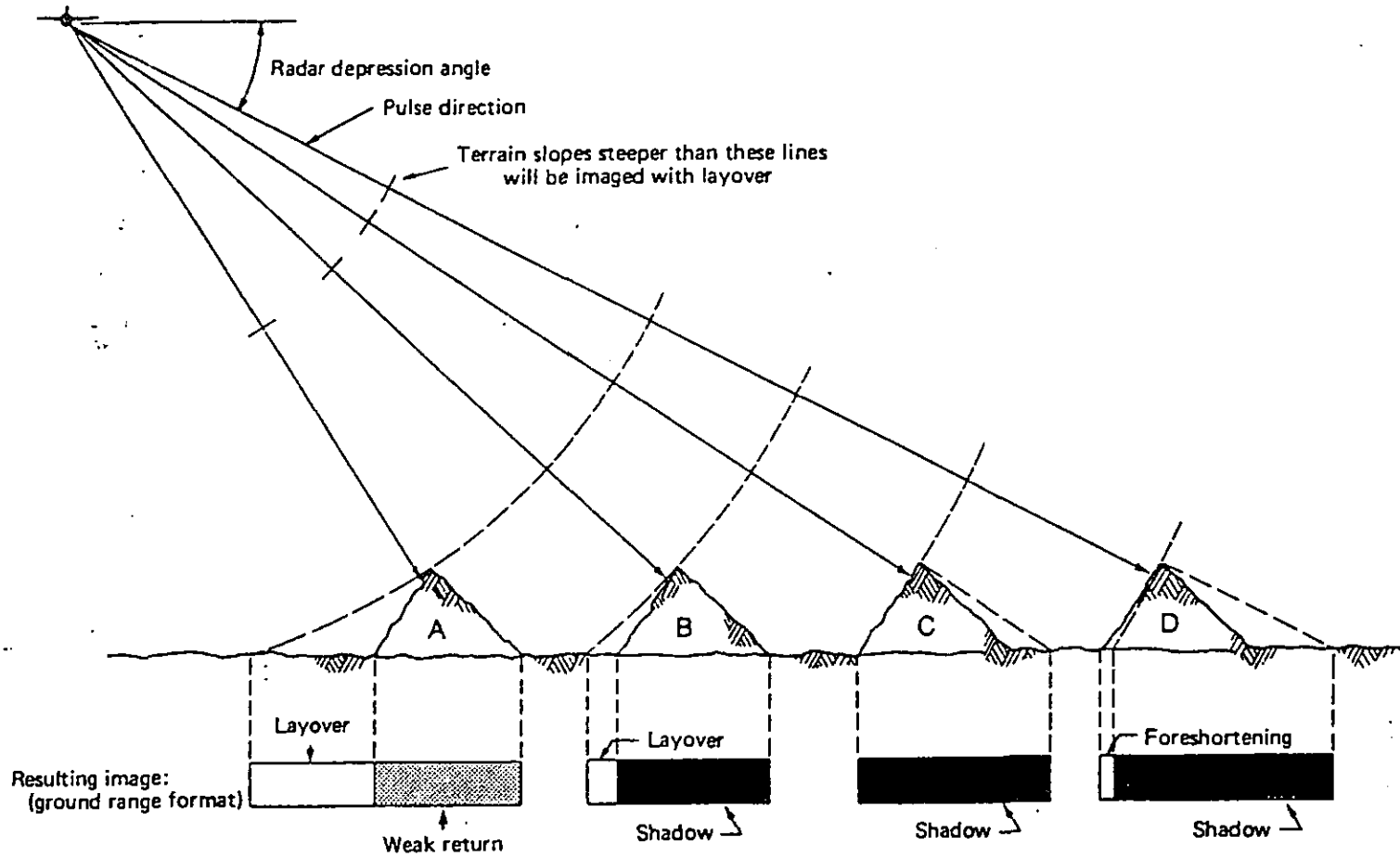


Figure 8.13 Effects of terrain relief on SLAR images. (Adapted from [66].)

Lillesand & Krier (1987)

FIGURE 2-14

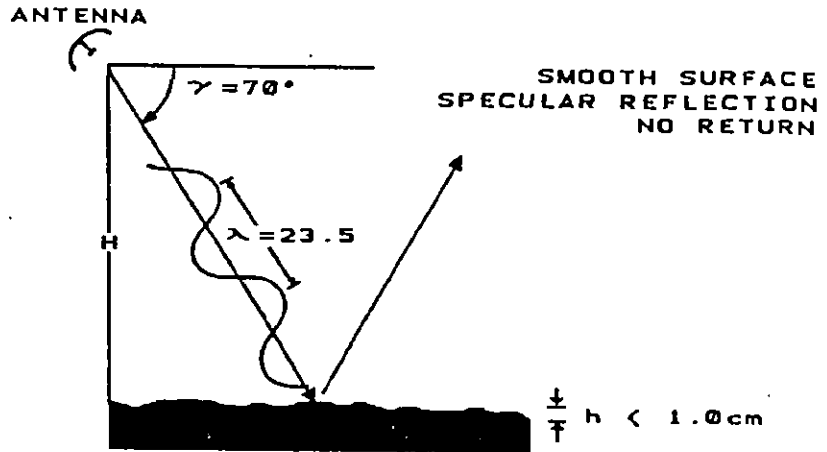
MODELS OF **SURFACE ROUGHNESS CRITERIA** AND
RADAR RETURN INTENSITY FOR THE SEASAT SAR

'SMOOTH' CRITERION:

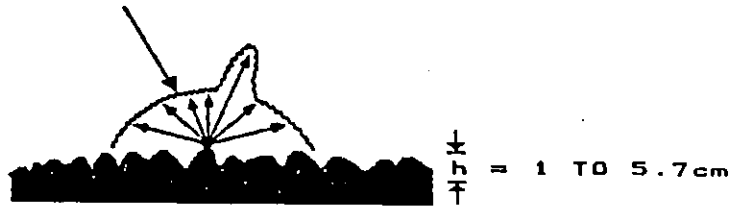
$$h < \frac{\lambda}{25 \sin \gamma}$$

$$< \frac{23.5 \text{ cm}}{25 \sin 70^\circ}$$

$$< \frac{23.5 \text{ cm}}{25 \times 0.94}$$



INTERMEDIATE ROUGHNESS
MIXED SCATTER
MODERATE RETURN

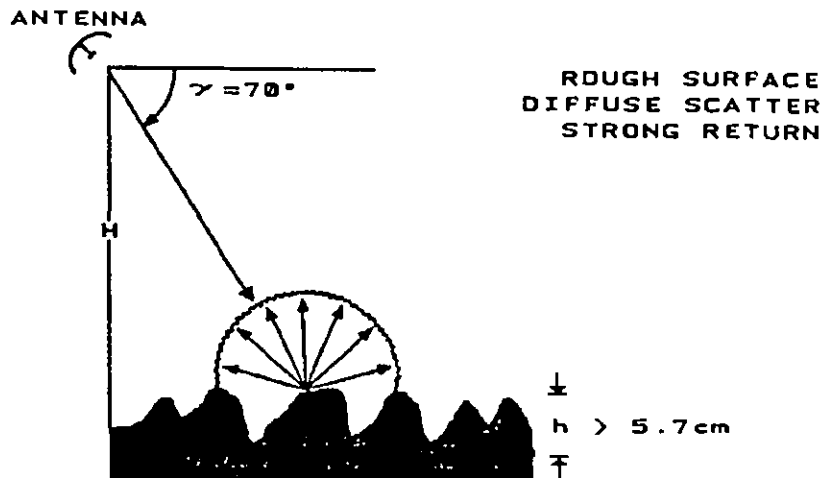


'ROUGH' CRITERION:

$$h > \frac{\lambda}{4.4 \sin \gamma}$$

$$> \frac{23.5 \text{ cm}}{4.4 \sin 70^\circ}$$

$$> \frac{23.5 \text{ cm}}{4.4 \times 0.94}$$



Source: after SABINS (1987, 2nd. edition)

15

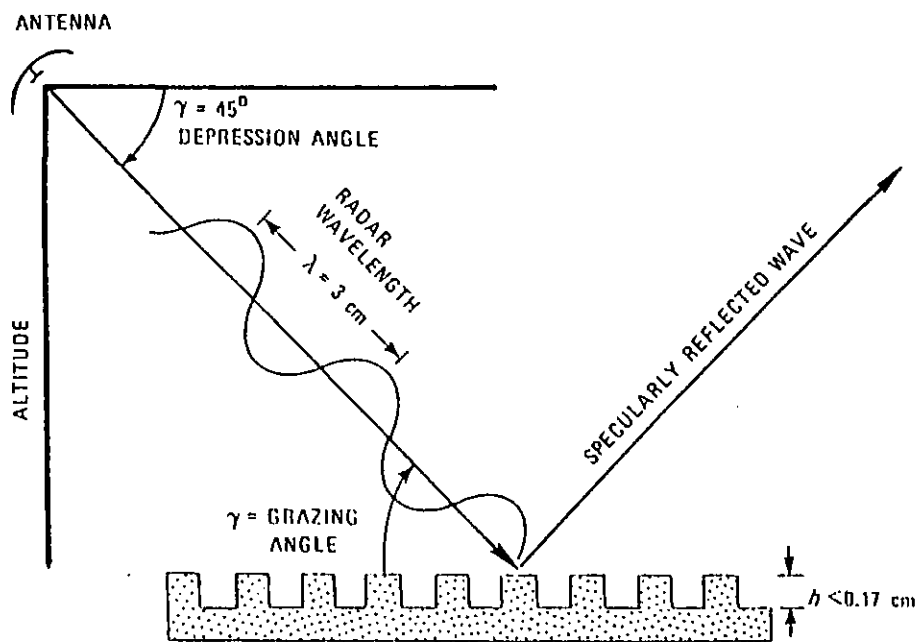
20

Figure 2-15

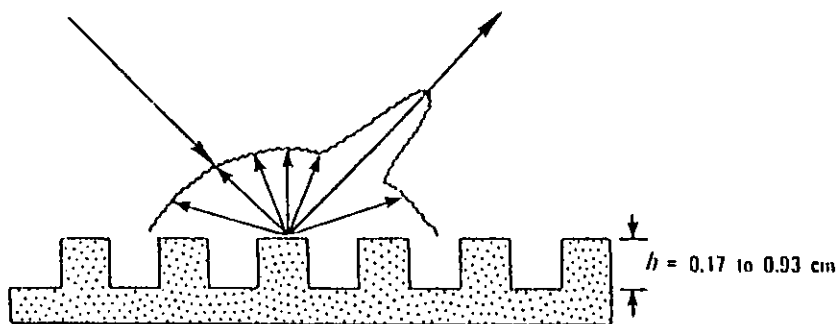
SURFACE ROUGHNESS CATEGORIES FOR TYPICAL RADAR SYSTEMS

Roughness category	Aircraft Ka-band ($\lambda = 0.86$ cm, $\gamma = 40^\circ$)	Aircraft X-band ($\lambda = 3$ cm, $\gamma = 40^\circ$)	SIR-A L-band ($\lambda = 23.5$ cm, $\gamma = 40^\circ$)	Seasat L-band ($\lambda = 23.5$ cm, $\gamma = 70^\circ$)
Smooth	$h < 0.05$ cm	$h < 0.19$ cm	$h < 1.46$ cm	$h < 1.00$ cm
Intermediate	$h = 0.05$ to 0.30 cm	$h = 0.19$ to 1.06 cm	$h = 1.46$ to 8.35 cm	$h = 1.00$ to 5.68 cm
Rough	$h > 0.30$ cm	$h > 1.06$ cm	$h > 8.35$ cm	$h > 5.68$ cm

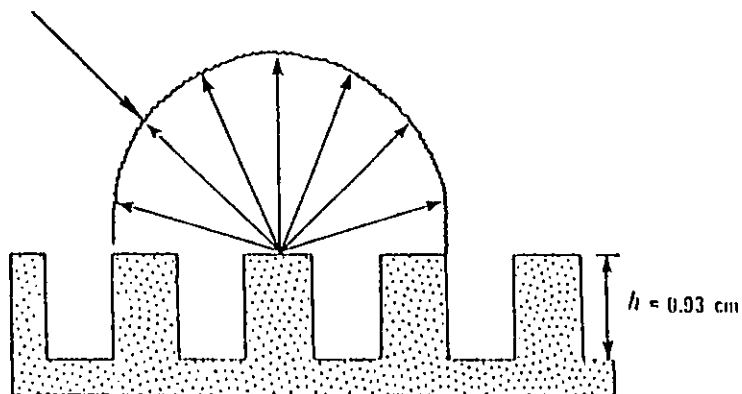
Source: after SABINS 1987, 2nd edition



A. SMOOTH SURFACE WITH SPECULAR REFLECTION; NO RETURN.



B. INTERMEDIATE SURFACE ROUGHNESS; MODERATE RETURN.



C. ROUGH SURFACE WITH DIFFUSE SCATTERING; STRONG RETURN.

FIGURE 6.11

Models of surface roughness and return intensity for X-band radar ($\lambda = 3 \text{ cm}$).

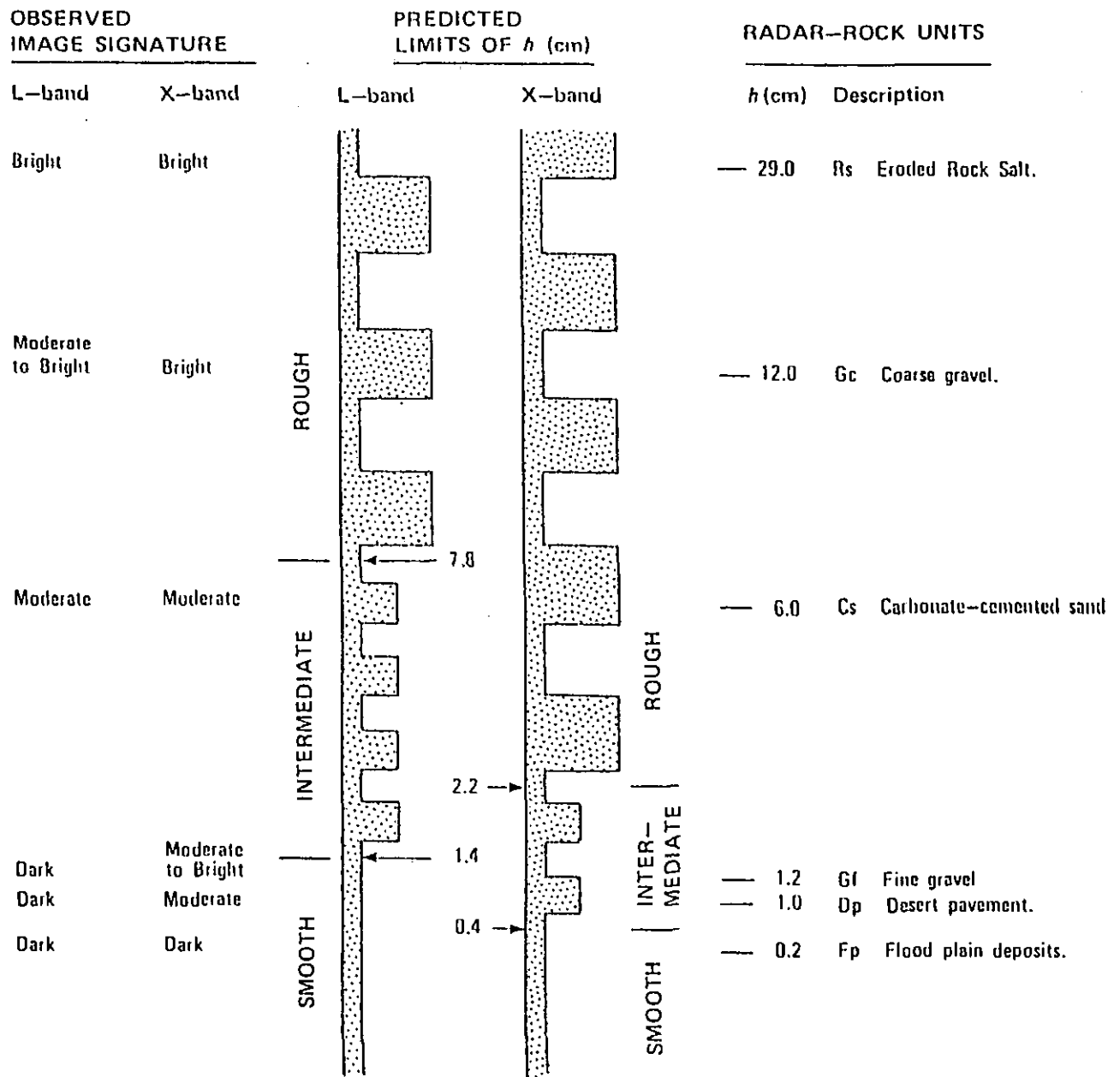


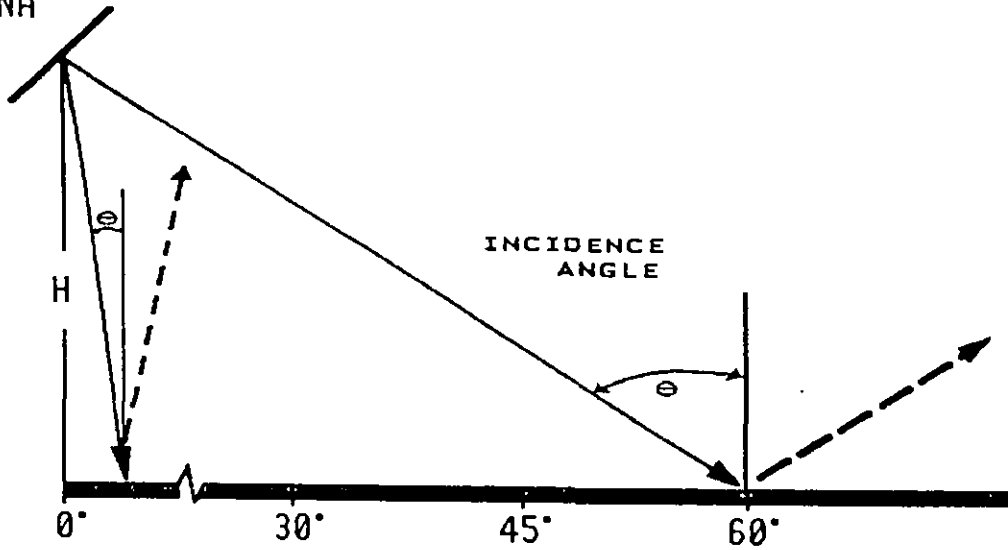
FIGURE 6.19

Comparison of predicted and observed image signatures at L-band and X-band wavelengths for radar-rock units at Tucki fan. Data from Schaber, Berlin, and Brown (1976).

FIGURE 2-16

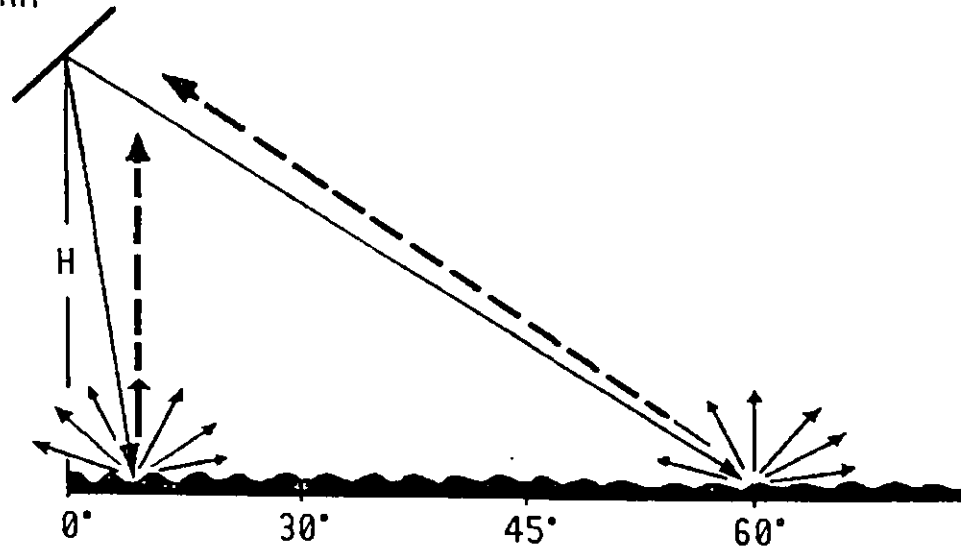
RADAR BACKSCATTER AS A FUNCTION OF INCIDENCE ANGLE

ANTENNA



SMOOTH SURFACE - SPECULAR REFLECTION,
HENCE LITTLE OR NO RADAR BACKSCATTER

ANTENNA



ROUGH SURFACE - DIFFUSE SCATTERING,
HENCE RELATIVELY HIGH RADAR BACKSCATTER

FIGURE 2-17

TYPICAL BACKSCATTERING CURVES FOR SMOOTH, MODERATELY ROUGH, AND VERY ROUGH SURFACES.

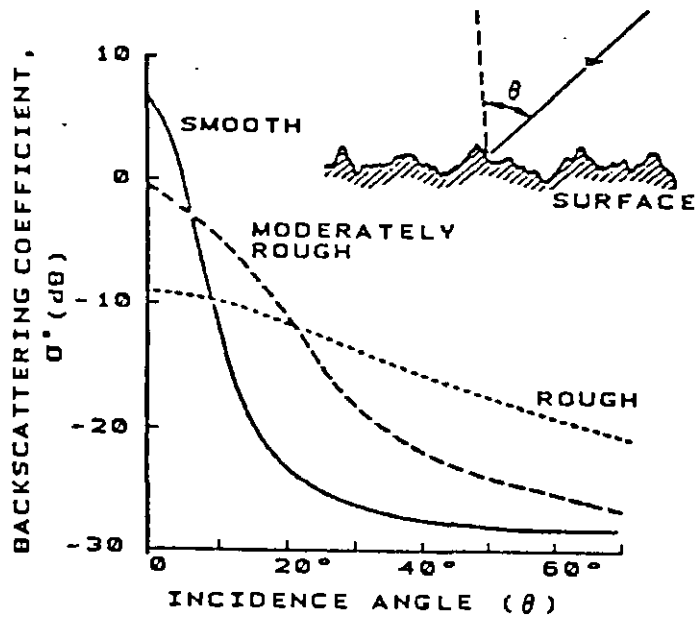
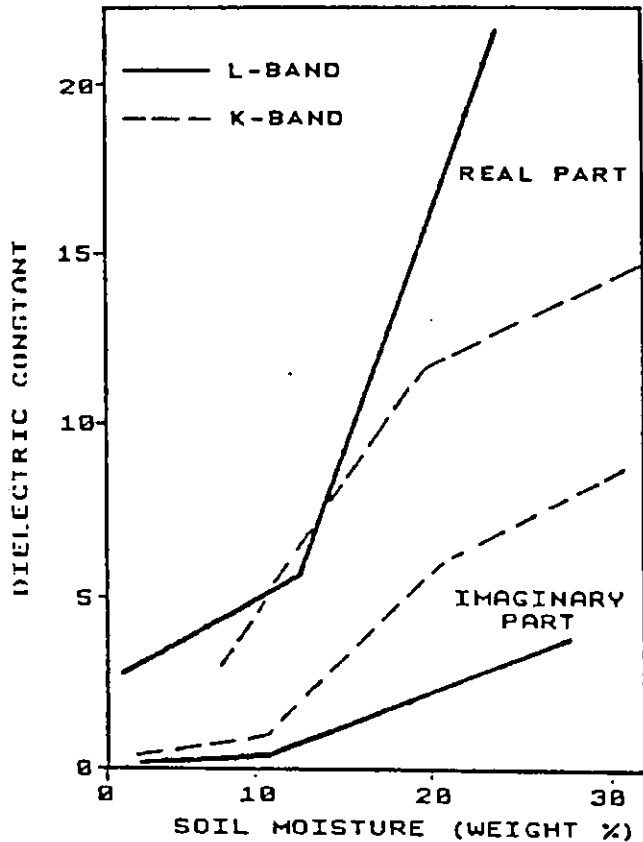


FIGURE 2-18

COMPLEX DIELECTRIC CONSTANT

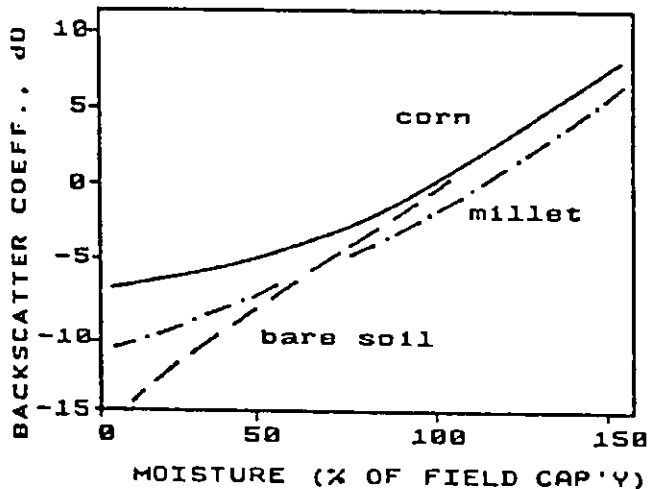
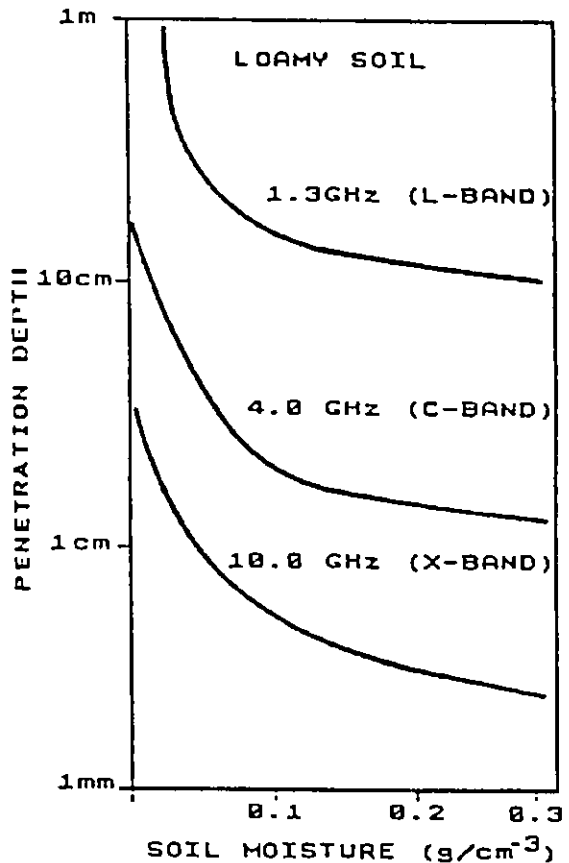
DIELECTRIC CONSTANT AS A FUNCTION OF SOIL MOISTURE AND RADAR FREQUENCY

Source: after NASA (1980)



PENETRATION DEPTH AS A FUNCTION OF SOIL MOISTURE AND DIFFERENT RADAR FREQUENCIES AND L-BAND

Source: after ULABY et al. (1981)

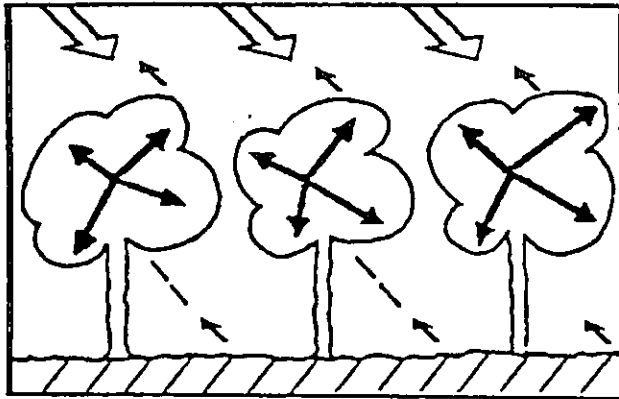


DEPENDENCE OF BACKSCATTER AT C-BAND ON MOISTURE CONTENT OF SOIL, CORN AND MILLET

Source: after ULABY et al. (1982)

FIGURE 2-19

VOLUME SCATTERING

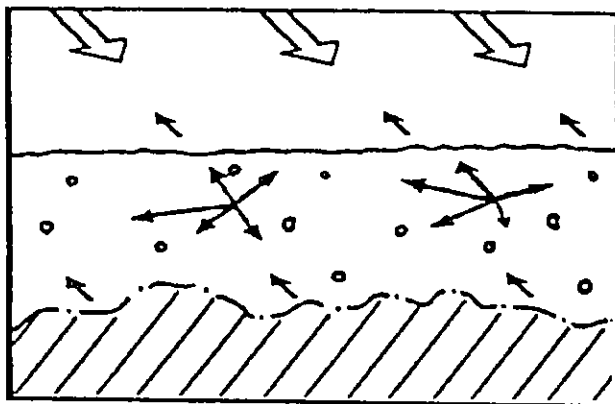


VEGETATION

SCATTERING FROM
CANOPY SURFACE

VOLUME SCATTERING
(LEAVES, BRANCHES etc.)

SURFACE SCATTERING

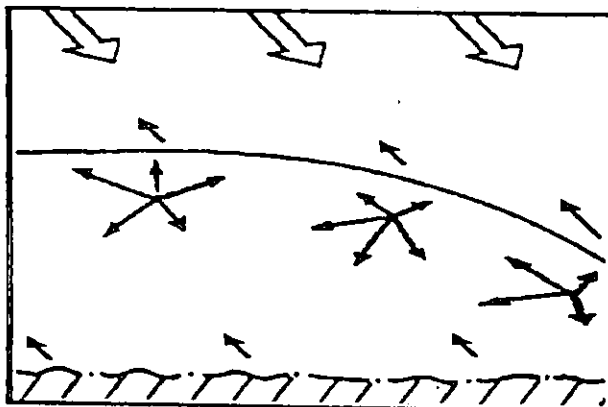


DRY ALLUVIUM

SURFACE SCATTERING

VOLUME SCATTERING
(SAND PARTICLES)

SCATTERING FROM SUBSURFACE
HORIZON
(DISCONTINUITY SURFACE)



GLACIER ICE

SURFACE SCATTERING

VOLUME SCATTERING

SCATTERING FROM SUBSURFACE
STRATA
(DISCONTINUITY SURFACE)

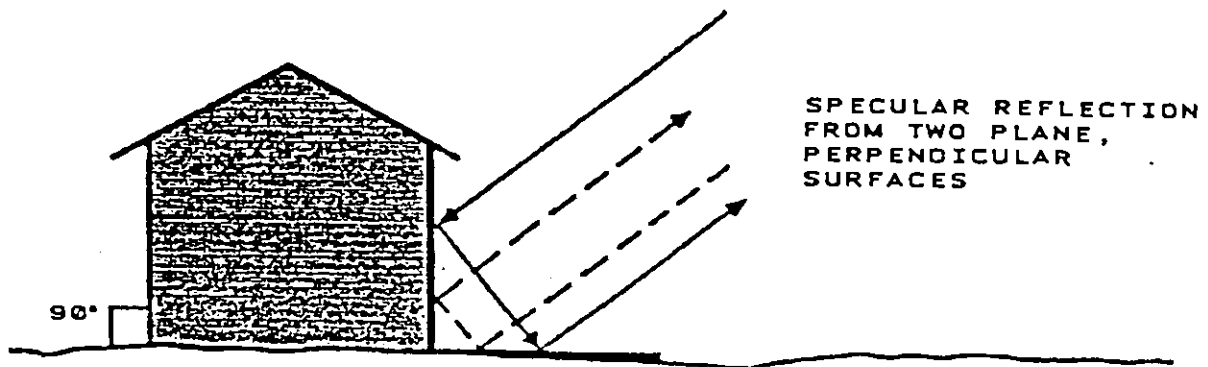
FIGURE 2-20

POINT TARGETS

DISCRETE TARGET WITH SIMPLE CONFIGURATION
STRONG RADAR RETURN DISPROPORTIONATE TO ITS SIZE

EXAMPLES: BUILDINGS, TRANSMISSION TOWERS, BRIDGES:

A: DIHEDRAL CORNER REFLECTOR



B: TRIHEDRAL CORNER REFLECTOR

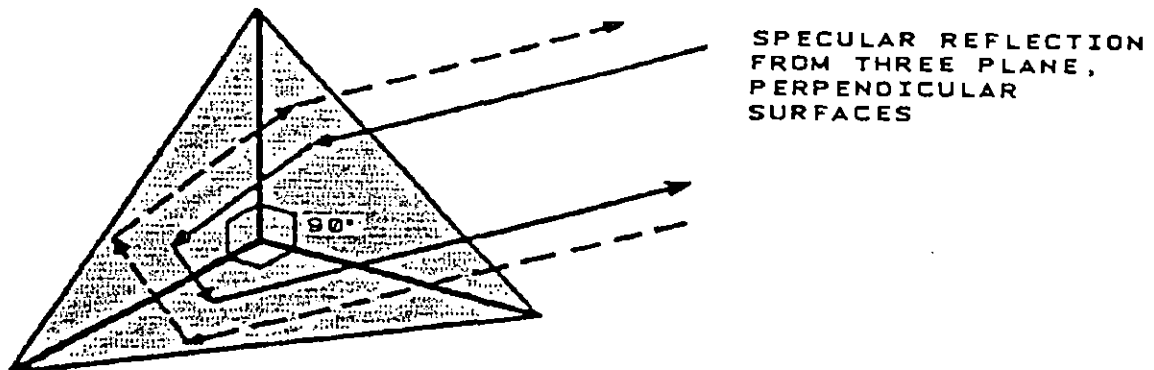
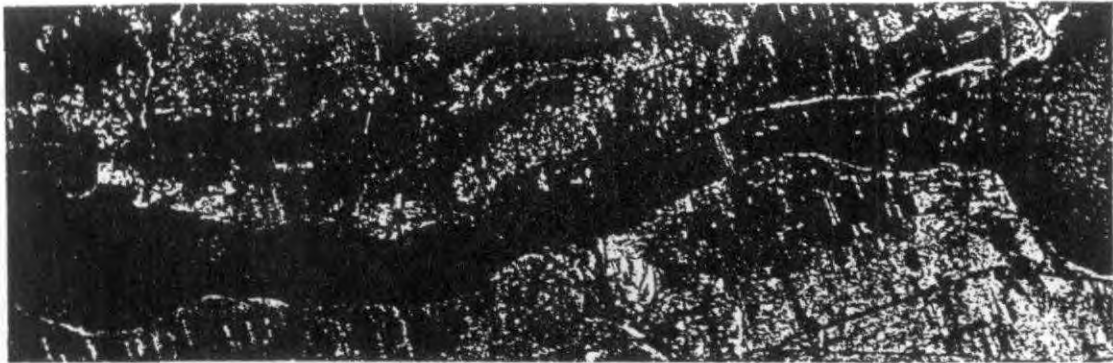
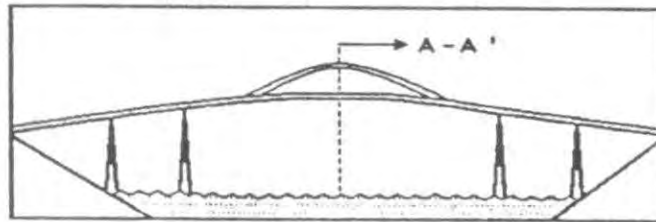


FIGURE 2-21

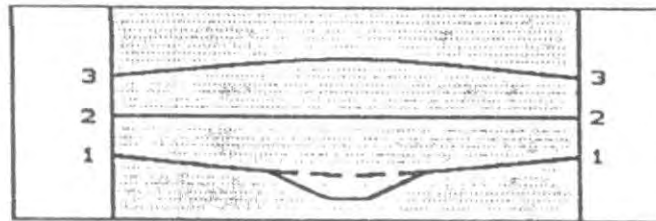
MULTIPLE REFLECTIONS



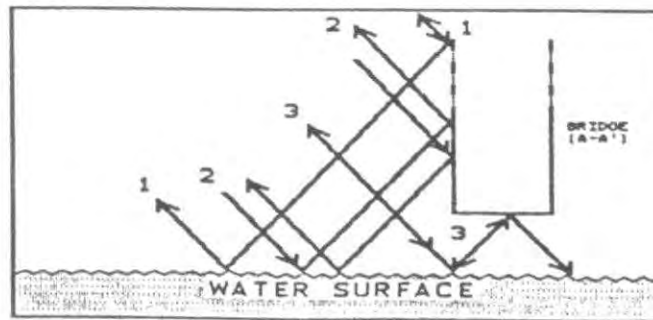
SEASAT SAR IMAGE OF THE TROIS RIVIERE BRIDGE, QUE.
(IMAGE COURTESY OF M.D.A.)



PROFILE OF TROIS RIVIERE BRIDGE (SKETCH)



REFLECTIVITY LOCI OF THE BRIDGE ON THE IMAGE



IMAGING GEOMETRY/MULTIPLE REFLECTIONS

Source: after RANEY (1983)

Radar Satellites and Sensors

Remote Sensing Workshop

Colombo, Sri Lanka

Radar Systems

1. Airborne SAR

- Convair 580

2. Shuttle Imaging Radar (SIR)

- SIR-A
- SIR-B
- SIR-C

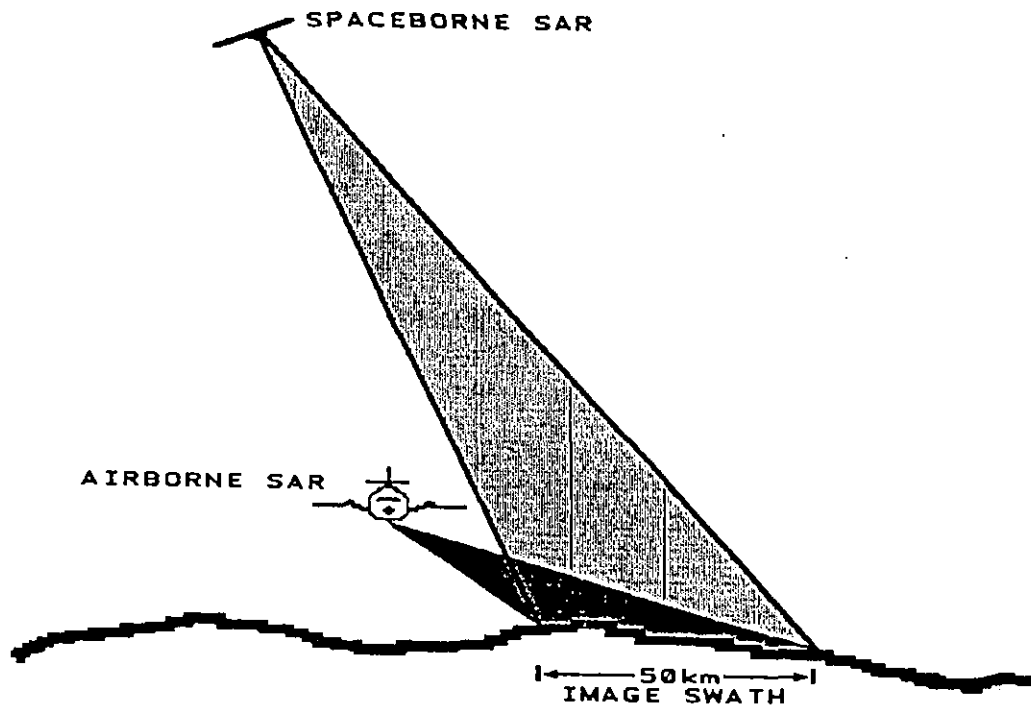
3. Spaceborne Radar

- Seasat
- ERS-1
- JERS-1
- RADARSAT

(Modified from Dendron Resource Surveys Ltd., 1988. "Radar Remote Sensing - a Training Manual")

FIGURE 2-27

COMPARISON OF IMAGING GEOMETRIES FOR SPACEBORNE AND AIRBORNE SARs



AIRBORNE SAR TYPICAL ALTITUDES 6-10 km:

- INCIDENCE ANGLES FOR WIDE SWATH COVERAGE VARY CONSIDERABLY ACROSS THE SWATH, IN THIS EXAMPLE BETWEEN 45° AND 80°.

SPACEBORNE SAR TYPICAL ALTITUDES 250-800 km:

- INCIDENCE ANGLES ACROSS THE SAME SWATH VARY ONLY SLIGHTLY (SEASAT: 6°)

FIGURE 2-28

VIEWING GEOMETRY AND IMAGING MODES OF SELECTED AIRBORNE SAR SYSTEMS

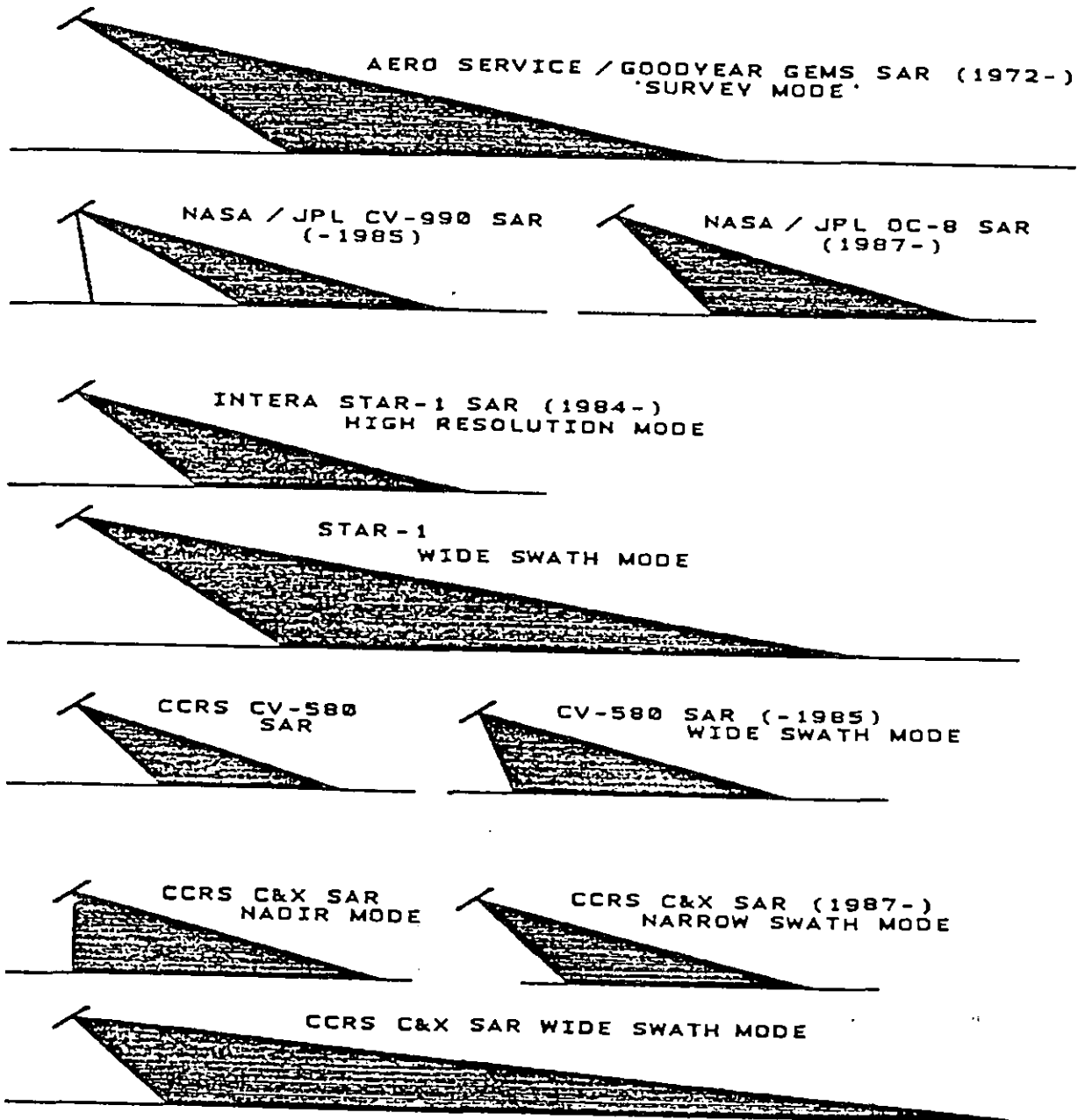
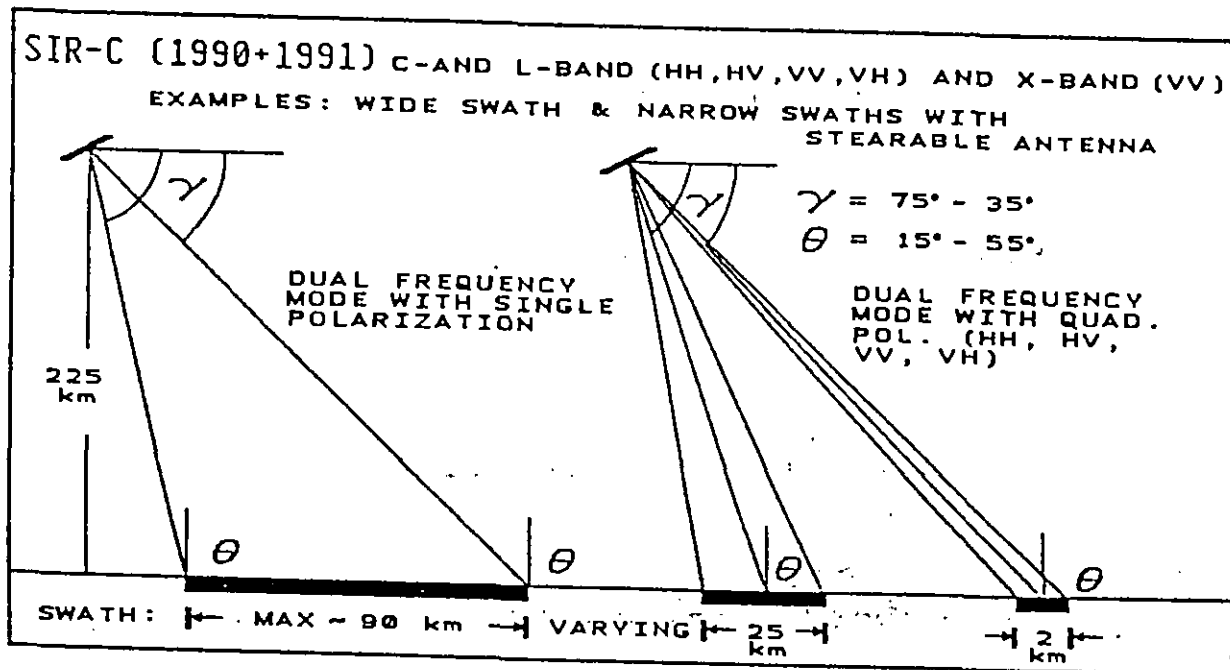
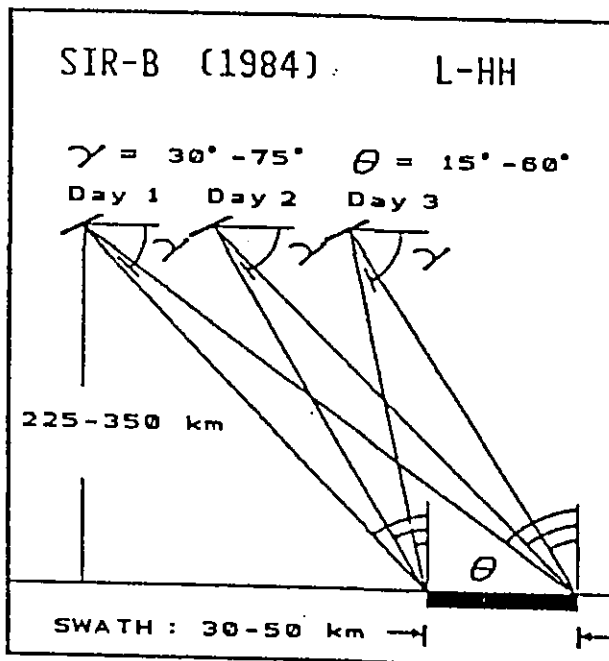
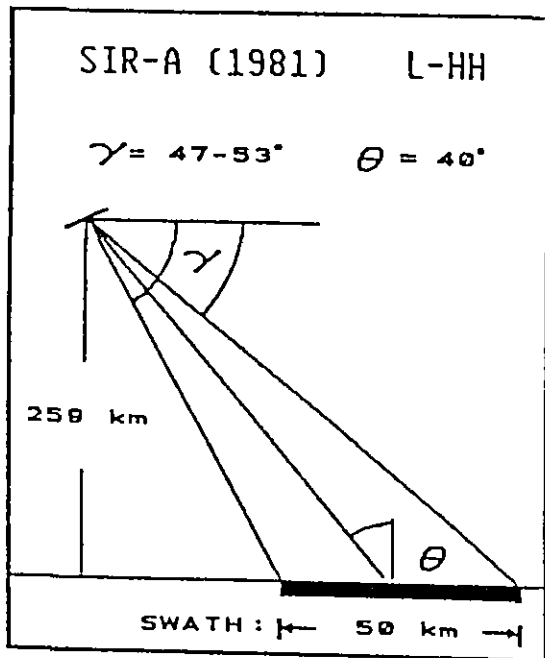


FIGURE 2-29

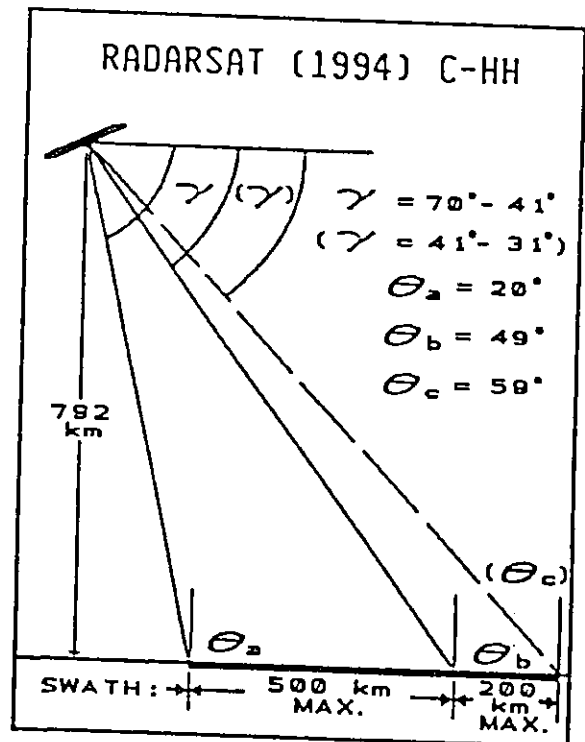
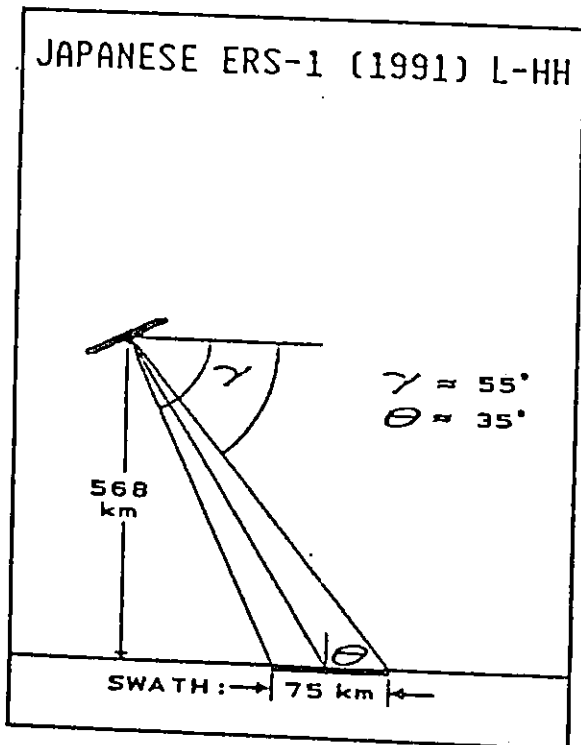
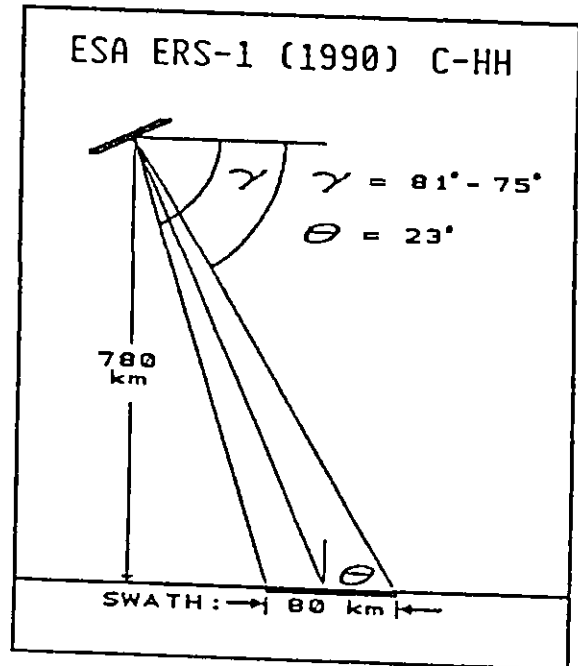
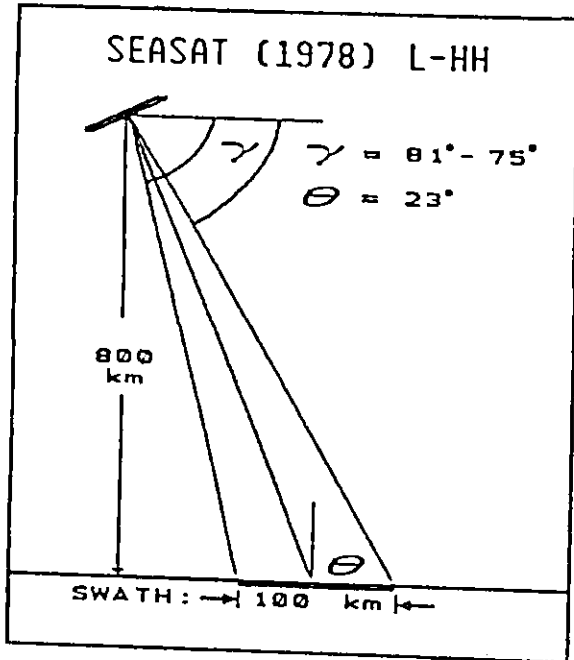
VIEWING GEOMETRY OF PREVIOUS AND PLANNED SHUTTLE IMAGING RADARS



Source: after CIMINO & ELACHI (1986), FORD et. al. NASA/JPL (1986)

FIGURE 2-30

VIEWING GEOMETRY OF PREVIOUS AND PLANNED SPACEBORNE SARs



Source: after CIMINO & ELACHI (1986),
 FORD et. al. NASA/JPL (1986)

Figure 2-31(a)

SYSTEM PARAMETERS OF SELECTED AIRBORNE SAR'S

	CV-580 SAR CCRS (-1986)	CV-990 SAR NASA/JDL (-1985)	GEMS SAR GOODYEAR
BAND	X/C/L	L	X
FREQUENCY	9.4/5.4/1.3 GHz	1.2 GHz	9.6 GHz
WAVELENGTH	3.2/5.7/23.5 cm	23.5 cm	3.2 cm
POLARIZATION	H,V	H,V	H
INCIDENCE ANGLES	0° - 90°	0° - 90°	57° - 78°
RESOLUTION, range	2 - 5 m	20 m	12 m
azimuth	1.5 - 5 m	10 m	10 m
SWATH WIDTH	5.4 - 20 km	8 - 15 km	37 km
RECORDING	OPTICAL & DIGITAL	OPTICAL & DIGITAL	OPTICAL & DIGITAL

Source: after KASISCHKE et al. (1984)

Figure 2-31(b)

SYSTEM PARAMETERS OF SELECTED AIRBORNE SAR'S

	CCRS AIRBORNE C/X SAR	DC-8 SAR NASA/JPL	STAR-1/STAR-2 INTERA
BAND	C/X	C/I/P	X
FREQUENCY	5.3/9.25 GHz	5.30/1.25/.44 GHz	9.4 GHz
WAVELENGTH	5.66/3.24 cm	5.6/24.0/67.0 cm	3.2 cm
POLARIZATION	II,V	II,V	II
INCIDENCE ANGLE	NADIR MODE: 90° - 74° NARROW SWATH: 45° - 76° WIDE SWATH: 45° - 85°	30° - 80°	HIGH RES.: 60° - 76° WIDE SWATH: 57° - 80°
RESOLUTION, range	6 - 20 m	7.5 m	6 - 12 m/8 - 18 m
azimuth	6 - 10 m	10.0 m	6 m/5 m
SWATH WIDTH	NADIR MODE: 22 km NARROW MODE: 18 km	5-15 km	HIGH RES.: 22.4/19 km WIDE SWATH: 44.7/65 km WIDE SWATH: 63 km
RECORDING	DIGITAL	DIGITAL	DIGITAL

Source: after EMR/CCRS (1988), NASA (1987), INTERA (1984)

Figure 2-32

PARAMETERS OF U.S. SPACEBORNE SAR MISSIONS

Parameters	Seasat	SIR-A	SIR-B	SIR-C
Mission date	1978	1981	1984	1990
Orbital altitude	800 km	259 km	225 km	225 km ^a
Orbital inclination	108°	38°	57°	≥57°
Frequency	1.28 GHz	1.28 GHz	1.28 GHz	1.25 GHz ^c 5.3 GHz ^c 9.6 GHz ^b
Polarization	HH	HH	HH	HH (L C) VV (L C X) ^b VH (L C) HV (L C)
Incidence angle	23°	50°	15° - 55°	15° - 55°
Swath width	100 km	50 km	20-50 km	15-90 km ^c
Azimuth resolution	25 m (4 look)	40 m (6 look)	30 m (4 look)	(30 m (4 look)) ^c
Range resolution	25 m	40 m	58-17 m	60-10 m ^c
Peak power	1 kW	1 kW	1 kW	3.8 kW (L) 2.1 kW (C) 3.3 kW (X) ^b
Bandwidth	19 MHz	6 MHz	12 MHz	10 or 20 MHz
Optical data collection	42 hours	8 hours	8 hours	N/A
Digital data collection	42 hours	N/A	8 hours	50 h/channel, 5 channels

^aApproximate

^bX.=band VV-polarized SAR to be added by DFVLR

^cBased on preliminary design parameters

Source: after NASA/JPL (1986)

Figure 2-33

SYSTEM PARAMETERS OF FUTURE SPACEBORNE SAR'S

	E-ERS-1 (ESA, 1990)	J-ERS-1 (JAPAN, 1991)	RADARSAT (CANADA, 1994)	EOS SAR (USA, proposed, 1999)
BAND	C	L	C	X/C/L
FREQUENCY	5.3 GHz	1.3 GHz	5.3 GHz	9.6/5.3/1.25 GHz
WAVELENGTH, cm	5.7 cm	23.0 cm	5.7 cm	3.1/5.6/24.0 cm
POLARIZATION	H	H	H	H,V
INCIDENCE ANGLE	20° - 35°	35°	20° - 59°	15° - 55°
RESOLUTION	30 m	18 m	10-55 m	20-500 m
SWATH WIDTH	80 km	75 km	45-500 km	30-700 km
RECORDING	DIGITAL	DIGITAL	DIGITAL	DIGITAL
ON-BOARD RECORDER	NO	YES	YES	YES

Source: after ESA (1986) ISHIWADA & NEMOTO (1986), AMIED et al. (1987), NASA (1987)

ERS 1 (European Remote Sensing Satellite)

Mission date: July 17/91

Developed by: European Space Agency

Type: Earth resources-ocean/sun-synchronous orbit

Payload:

- **AMI** (Active Microwave Instrumentation) SAR - image mode
- SAR wave mode resolution <30m, 80-100 km swath
- **ATSR** (Along Track Scanning Radiometer)
- consists of infrared imaging radiometer and microwave radiometer
- uses C-Band, 1 km x 1 km resolution, 22-500 km swath
- **PRARE** (Precise Range and Rate Equipment)
- range accuracy 5-10 cm

ERS 2

Mission date: April 20/95 (delayed)

Payload:

Same as ERS 1 with the addition of:

- **GOME** (Global Ozone Monitoring Equipment)
- uses a double spectrometer, 40 x 2 km resolution
- **AATSR** (Advanced Along Track Scanning Radiometer)
- 0.5 km resolution, 500 km swath

ERS 3

Mission date: 1990s

Earth resources/sun-synchronous orbit, same as ERS 2

JERS 2A

Mission date: 1995

Developed by: National Space Development Agency of Japan

Type: earth resources/sun-synchronous orbit

Payload:

- **SAR** (Synthetic Aperture Radar)
 - 18 m resolution, 75 km swath, L-Band (1275 MHz)

- **OPS** (Optical Sensors)
 - 18 x 24 m resolution, 75 km swath, overlapping bands for stereo-coverage

- Stereo **VNIR** (Visible Near IR Radiometer), 15m resolution

JERS 3A

Mission date: 1998 (proposed)

Same specifications as JERS 2A with the addition of **VNTIR** (Visible Near and Thermal IR Radiometer) having 15m resolution.

RADARSAT

Mission date: November 4, 1995 @ 09:22, Vandenberg Air Force Base
California

Developed by: Canadian Space Agency, EMR (CCRS), SPAR, Intera, + others

Type: special applications/near-polar orbit

Payload:

- **SAR** (Synthetic Aperture Radar)
 - operation on C-Band (5.3 GHz), 10-100 m resolution, image swath 35-500 m
 - incidence angles 20-50°
- - view any region of Canada within 3 days, complete coverage of equatorial areas every 6 days using 500 m swath
 - for each orbit data capture is possible for up to 28 minutes, with imaging of up to 1.1 million km² of the Earth's surface
 - altitude 798 km (above poles)
- Potential applications during an anticipated 5 year life span include: real-time monitoring of sea ice, snow cover & density, military, fisheries, geology, and special missions (e.g. Antarctica)

RADARSAT 2

Mission date: 2000 (proposed) - \$225 million available for development

Payload:

- same as RADARSAT

RADARSAT 3

Mission date: 2005 (proposed) - \$20 million available for development

Payload:

- same as RADARSAT, but to be designed for a 10 year life span

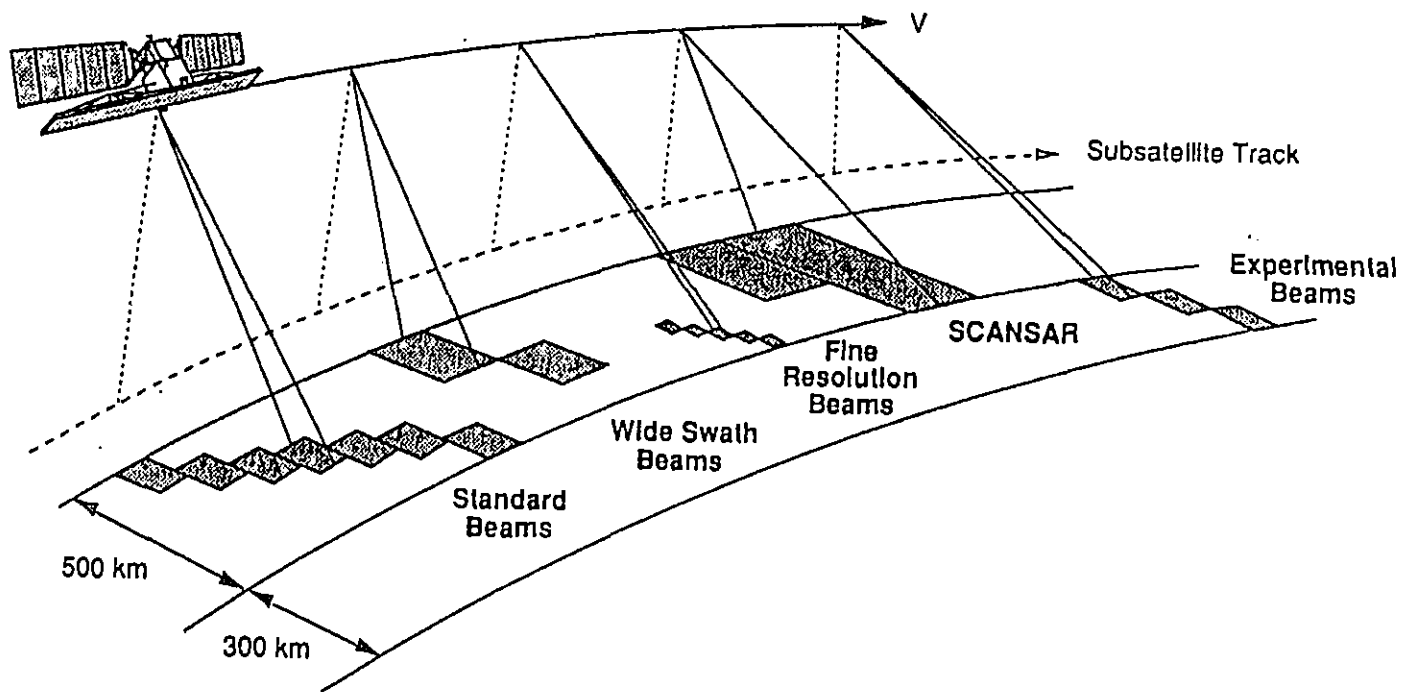
RADARSAT ORBIT CHARACTERISTICS

Geometry	Circular, sun-synchronous (dawn-dusk)
Altitude	798 km
Inclination	98.6°
Period	100.7 minutes
Repeat Cycle	24 days

RADARSAT SAR OVERVIEW

Frequency:	5.3 GHz (C-band)
Polarization:	HH
Aspect:	Right-looking SAR (north)
Tape Recorders:	2 high speed (10 minutes capacity)
SAR on-time	28 minutes per orbit

SAR Operating Modes



RADARSAT BEAM MODES AND RESOLUTION

MODE OF OPERATION	SWATH WIDTH (KM)	RESOLUTION/IRW (RANGE X AZIMUTH, M)	NUMBER OF LOOKS
STANDARD BEAMS	100	25 X 28	4
WIDE SWATH BEAMS	150	25 X 28	4
FINE RESOLUTION BEAMS	50	11 X 9	1
NARROW SCANSAR	300	50 X 50	4
WIDE SCANSAR	500	100 X 100	7
HIGH INCIDENCE BEAMS	75	25 X 28	4
(IRW = IMPULSE RESPONSE WIDTH)			

Introduction to Geographic Information Systems

THE GIS PARADIGM

A geographic information system (GIS) is a collection of information technology, data, and procedures for collecting, storing, manipulating, analyzing and presenting maps and descriptive information about features that can be represented on maps (Huxhold and Levinsohn, 1995 p. 3).

GIS - the application of information technology, data management principles, and organization theory to the geographic information needs of an organization (Huxhold and Levinsohn, 1995 p. 5).

Why GIS?

- improved operational efficiency
- improved effectiveness
- increased wealth (government)
- better service
- increased profits (private sector)

Evolution of GIS Implementation

- need to integrate GIS with other information systems
- move from project-oriented databases to continuously updated ("corporate-wide") databases
- expand GIS to decision-making and policy analysis rather than limiting its use to single-purpose support functions
- to be implemented as any other data storage and analysis software (i.e. spreadsheet software)

The Four Elements of GIS in an Organizational Context

- *Data Management Principles* - the logical structuring and management of large spatially related databases of interest to an organization.
- *Technology* - synergy of computer software and hardware to automate geographic data processing.
- *Organizational Setting* - a management environment that provides resources and enables implementation of GIS throughout the organization.
- *The GIS Paradigm* - a conceptual framework for using geographic information that provides a common reference for the above three elements.

The GIS Paradigm (broad framework for understanding reality)

- space is the operational ground by which problems are solved
- manipulation and analysis of data about features from the real world within a space-time relationship

Geographic concepts and principles define GIS and are necessary to successfully implement a GIS.

1. **Georeferencing:** process of locating features within a model of the earth's surface.
2. **Geocoding:** process of attaching a geographic reference to non-geographic data.
3. **Topology:** the branch of mathematics that defines the relationships between features.

Essentially, these components together create a model of the real world that can then be manipulated for making decisions about management and planning actions.

GIS Data Management

Conversion of the user's perception of the real world to a physical implementation (of the paradigm).

Features and events of significance to the individual or organization often differ due to management responsibility.

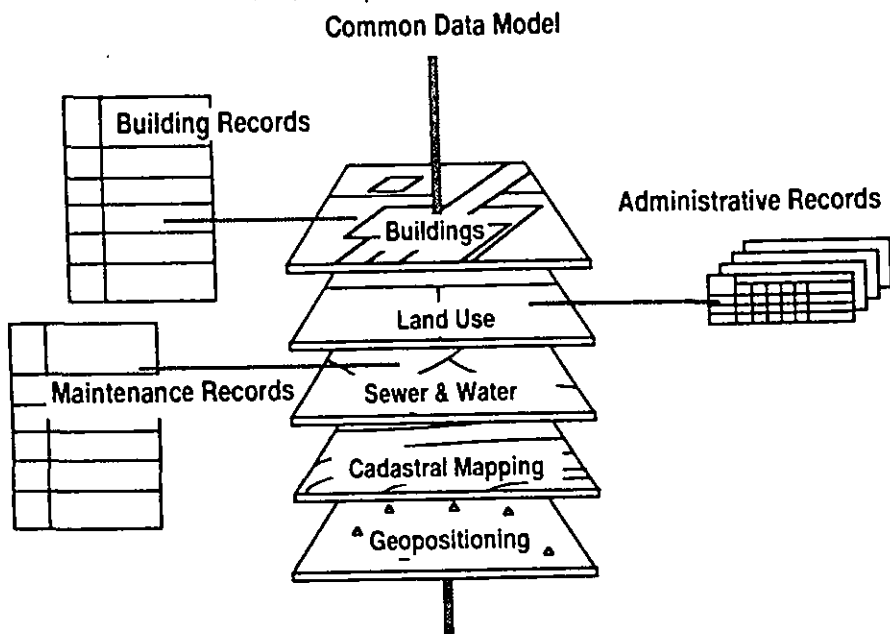
- I. *Perception structure* is organized into a conceptual or *logical data model*:
 - A. *spatial entities* - computer representations of features from the perception structure (e.g., building, woodlot, street);
 - B. *attributes* - descriptive data about the spatial entities;
 - C. relationships between spatial entities and attributes.
- II. Implementation of a data model requires adoption of standards related to how data are defined, stored and transferred between systems and applications.
- III. Once defined, the logical data model is translated into a database structure that can be implemented on a computer.
- IV. Data representing the real world is dynamic - data management strategy for maintaining spatial data.

GIS Technology (enabling portion of the GIS paradigm)

- computer assisted mapping
- database management software
- Global Positioning System technology (GPS)
- remote sensing and image processing
- word processing
- multimedia

Organizational Strategy for GIS Implementation

- incorporate technology into the working environment
- how GIS fits in to organization structure
- how GIS will help manage information about the real world as required to deliver products or services



Requirements for a common GIS data model:

- Shared geopositioning
- Standard data definitions
- Explicit entity relationships
- Planned data distribution
- Standards for data communication
- Data maintenance processes

FIGURE 1.3 Conceptual illustration of a GIS data model.

(Huxford and Levinson, 1995)

Table 2.1 IAAO GIS Principles

Principle 1: A GIS is a data-driven, data-based information system. Making maps is only one capability of GIS technology. GIS is based upon database management concepts that allow flexible access to data, integration of data from different sources, and manipulation and analysis of data in ways that are not possible with other techniques or technologies.

Principle 2: GIS data and maps must be maintained. Because the GIS is designed for use in the operating environment of the organization for specific service delivery, management, and policy-related activities, the data and, ultimately, the system will not be used if they are out of date or if they are inaccurate.

Principle 3: A GIS is most useful when geographic references are registered on a consistent, continuous coordinate system. A GIS is not merely a collection of computerized map sheets. Its use demands that an entire geographic area be accessible in order that the spatial relationships among features in different parts of the area can be identified and displayed. This requires locating each map sheet in its proper place within the entire geographic area. It is accomplished by setting coordinates for each map sheet that come from a consistent, continuous coordinate system.

Principle 4: A GIS has topology. Since a computer cannot see a map as a human can, additional definitions of the relationships among the points, lines, and areas must be established. This topology allows the GIS to perform certain spatial analysis functions including (but not limited to): network analysis and optimal path determination, polygon overlay, geocoding, and area calculations and shading.

Principle 5: A GIS has many uses and should be shared by many different functions. Since the value of information increases the more it is shared and used by others who need it, and since a GIS requires a significant amount of resources to develop, a multiuse, shared system can prevent duplication of common data and the effort to maintain them and can also reduce the cost of the system to any single user.

Principle 6: A GIS contains hardware and software that are constantly undergoing change, which improves its functionality over time. A delay in acquiring GIS hardware and software in anticipation of future price reductions or technological breakthroughs is not prudent because existing technology is fully adequate to develop GIS applications. The benefits of the system cannot be realized until the databases are built and implemented on the system, so a delay in implementation only creates a delay in realizing its benefits. Future improvements to the technology will enhance the use of the data - not restrict it.

Principle 7: A GIS grows incrementally in terms of technology, cost, and administrative support needed. Therefore, a long-term commitment is needed to assure success. The large amount of time required to build the databases and the large number of potential users and applications prevent a GIS from becoming fully functional within a short time frame. Given limited resources and an ambitious plan for GIS implementation, priorities must be established and commitments maintained over a multiyear time frame.

Principle 8: A GIS causes changes in procedures, operations, and institutional arrangements among all users. The common databases accessed by many different users eliminates the compartmentalization of data storage and individualization of data coding schemes. This will result in changes in responsibilities, procedures, security measures, standards, and even organizational structures and laws in order for the GIS to function for the benefit of all users.

Principle 9: A cadre of trained, educated, motivated, and dedicated people is crucial to a successful GIS program. Without exception, organizations that have successful systems have been able to assemble, and retain for a long time, the appropriate level of staff with technical and communication skills who have, as well, a shared understanding and vision of the potential for the technology. Technical problems can be resolved with money and time, but staff without the motivation, dedication, creativity, and willingness to accept new ideas are likely to scuttle the project. Most successful systems have had a "champion" - a high-level official who is willing to push the project forward and motivate and educate those whose support is needed. However, increasingly, successful organization-wide GIS implementation is being led by a dedicated team, rather than a single "champion." *(Huxhold and Levinson, 1995)*

SPATIAL (GEOGRAPHIC) DATA

Location, Location, Attributes..... the essence of spatial data

A. Cartographic Models/Modelling (Tomlin 1990)

- models/representations expressed in cartographic form
- envisioned as a bound collection of maps
- modelling is oriented towards process rather than product (how data are used)

Map Layer: a set of data describing the spatial variation in one characteristic of a geographic study area (minimal requirements - title, resolution, orientation, zone).

Title: written name (e.g. vegetation).

Resolution: a number describing the relationship between distance as measured on the ground and distance as measured on the map layer.

- specifies the number of units (e.g., metres) of geographic distance that are to be associated with a standard unit of spatial observation
- in this sense is analogous to a conventional cartographic scale
- however, this number does not relate to the physical size of any particular graphic image
- the smallest standard unit of space for which data are recorded

Orientation: describe the relationship between geographic and cartographic directions

Zones: the set of data pertaining to one of the variations on a map layer's theme

Labels: written name of a zone

Values: comparable to the label of a zone (numeric)

Value Precision: precision with which zonal characteristics can be represented by integer (or real) numbers

- based on the range of values that can be stored and processed by a given computing system (e.g. 0 - 65536 ==> 16 bit unsigned integer)

Null Value: zones of unknown or undefined characteristics

- ignored in calculations

Types of Measurement:

Ratio - measurements that represent quantities in terms of position relative to a fixed point on a calibrated, linear scale (transformed mathematically) (e.g., age, frequency, physical distances, monetary values, etc.).

Interval - represent quantities in terms of positions that are defined in relation to one another along a calibrated, linear scale but not in relation to any fixed point (e.g., temperature, date of origin) (useful in quantifying differences but not proportions).

Ordinal - quantifies differences by order, but not by magnitude (quantities in terms of position along an uncalibrated, linear scale) (1st, 2nd, 3rd - 1,2,3).

Nominal - represent qualities rather than quantities without any reference to a linear scale.

In general, any function that can be applied to data of a given type in the ratio-interval-ordinal-nominal sequence can also be applied to data of any preceding type in that sequence.

Locations:

- elemental unit of cartographic space for which a label and value are recorded
- similar to a cartographic point defined by an ordered pair of planar coordinates
- planar coordinates defined over a range of discrete intervals that represent finite increments of space (grid)
- all locations defined with respect to a coordinate system of equal increments along two perpendicular axes
- grid square same in terms of size, shape and orientation but differ according to position
- referred to as pixels in image processing, cells in other cartographic contexts and observations in statistics

B. Spatial Resolution and Scale

Approaches to Resolution:

1. in the geosciences, it is assumed to be based on stochastic signal reconstruction which is also the most popular view of those in remote sensing and image processing Spatial resolution is analogous to the scale of the observations;
2. in "conventional" cartography, it is more or less loosely linked to scale and observable detail, and
3. in the jargon of digital cartography ("Data Modellers") representation and model-fitting are the preferred key terms.

Scale - denoting the order of magnitude or level of generalization at which phenomena exist or are perceived to observed (scale of observation 1:1,000,000).

Resolution - the size of the smallest recording unit, akin to precision, the fineness of measurement.

C. Projections and Coordinate Systems

Size and Shape of the Earth

Earth is not a sphere, but a geoid, that is modelled (mathematically) by an ellipsoid (spheroid).

Clarke 1866 - Equatorial radius = 6,378,206.4 m; Polar radius = 6,356,538.8 m

- adopted as North American Datum of 1927 (NAD27)

Geodetic Reference System 1980 (GRS80) center of the earth used as reference point.

- brought on by the use of satellite technology
- GRS80 used as the basis for North American Datum of 1983
- differences of up to 300 metres in locations between two datums (result due to the shift in the origin or reference point)

World Geodetic System (WGS84)

- uses the GRS80 ellipsoid but slightly refined the values in 1984 (native GPS coordinate system)

Cartographically, a sphere can be used to model earth's surface at small scales (e.g., 1:1,000,000)

At larger scales (1:100,000; 1:50,000; etc.) the ellipsoid must be used.

Important that when using maps, the datum and ellipsoid are known, since at large scales there can be significant differences between datums and ellipsoids, especially in elevation

Map Scale

- the geographic property of being reduced by a representative fraction
- the ratio of distances on the map to the same distances on the ground
- distortions occur when attempting to portray a curved surface (sphere or ellipsoid) on a flat surface

Map Projections

- coordinates projected onto a flat surface
- azimuthal, cylindrical or conic surface either tangent or as secant to the globe

Conformal Projections

- preserve the property of local shape
- lines of latitude and longitude intersect at right angles
- preserve direction around any given point
- e.g., Lambert Conformal and Mercator

Equal Area or Equivalent

- preserve the property of area
- e.g., Albers equal-area and the sinusoidal projections

Equidistant

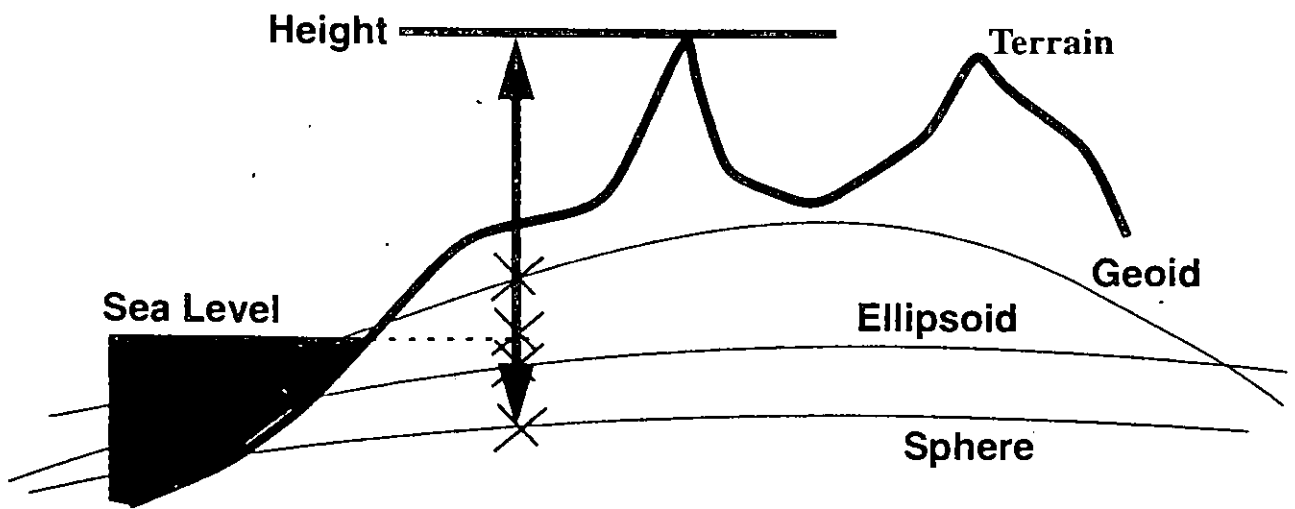


Figure 2.4 Elevations defined with reference to a sphere, ellipsoid, geoid, or local sea level will all be different. Even location as latitude and longitude will vary somewhat. When linking field data such as GPS with a GIS, the user must know what base to use.

- preserves the property of distance (although only over a single or few lines between places on the map)
 - e.g., conic and the azimuthal equidistant
1. errors become more significant for larger areas (e.g., small scales)
 2. projection used should suit the GIS application
 3. to overlay or edge mat any two map, they must be on the same projection

Coordinate Systems

Latitude and Longitude

A line of longitude is defined by the horizontal angle formed between a line drawn from a given point on the earth surface to the centre of the earth and a line drawn from the centre of the earth to the prime meridian (0° - through Greenwich Observatory in England).

- lines of longitude range from 180° W and 180° E

Lines of latitude are perpendicular to lines of longitude and are defined by the angle connecting a given point on the earth's surface and a point on the equator as measured from the earth's centre

- 0° - equator
- lines of latitude range from $0 - 90^\circ$ S and $0 - 90^\circ$ N

Precision below a degree is stored as DD.MMSS.XX or DD.XXXX

- D = degrees; M = Minutes; S = Seconds; XX = decimals

The advantage to using geographic coordinates in a GIS is that all maps can be transformed into a projection in the same way.

Universal Transverse Mercator Coordinate System

- transverse Mercator minimizes distortion in a narrow strip running from pole to pole
- widely used for large-scale mapping worldwide (in various forms)
- capitalizes on the accurate north-south strips by dividing the earth up into pole-to-pole zones, each six degrees of longitude wide
- Zone 1 - 180° West to 174° West; Zone 60 - 174° East to 180° East (date line)
- within each zone a transverse Mercator projection is centred on the middle of the zone oriented north-south e.g., Zone 1 @ 177° W
- northings are numbered from the south pole to the equator for the southern hemisphere, and from the equator to the north pole in the northern hemisphere
- for eastings, a false origin is established beyond the westerly limit of each zone
- chosen so that central meridian has an easting of 500,000 metres (eastings are positive)
- UTM Coordinate e.g., York University: Zone 17T 620000 E 4845000 N (approx.)

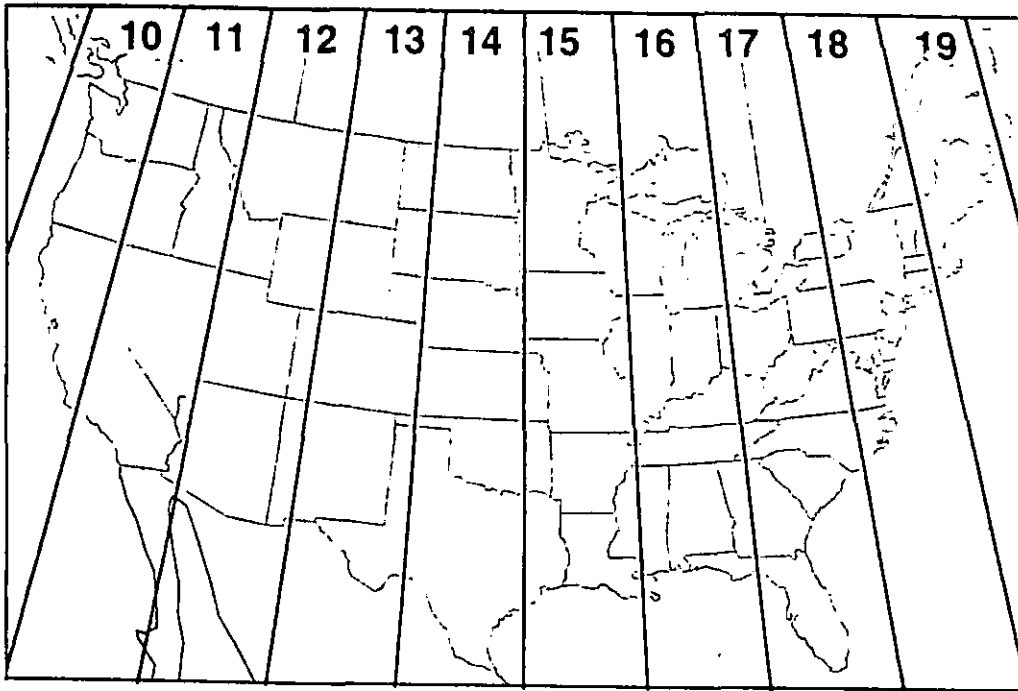


Figure 2.11 Universal transverse Mercator zones in the 48 contiguous states.

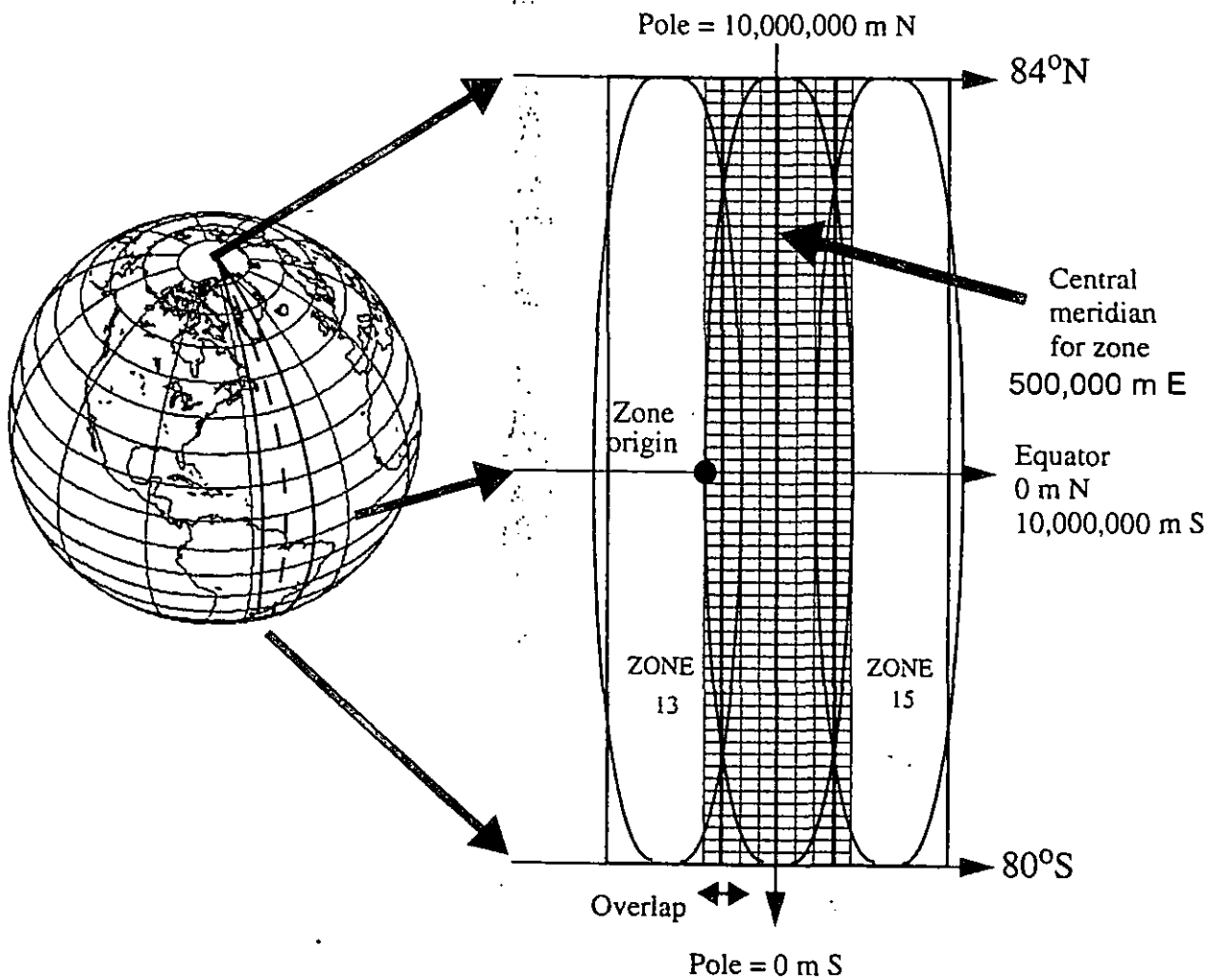


Figure 2.12 The Universal transverse Mercator coordinate system.

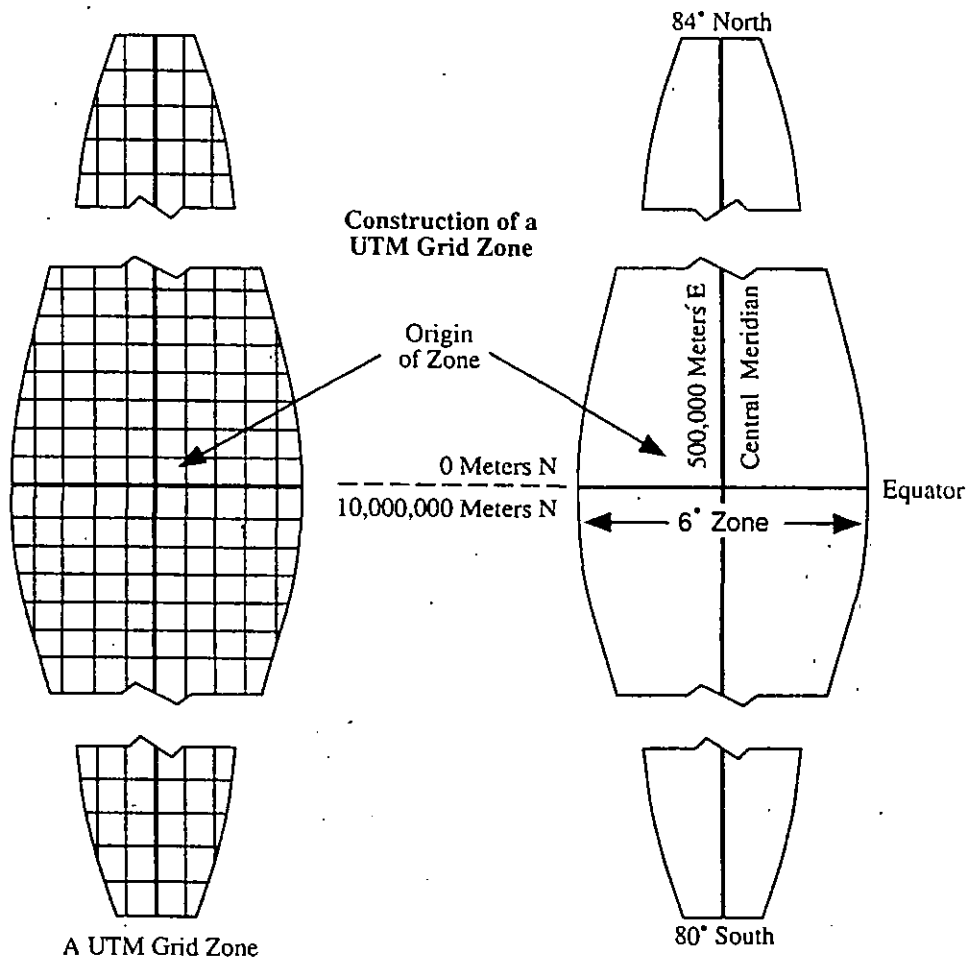


Figure 6-15 Universal transverse mercator (UTM) grid zone with associated parameters. This projection is often used when rectifying remote sensor data to a base map. It is found on U. S. Geological Survey 7.5- and 15-minute quadrangles.

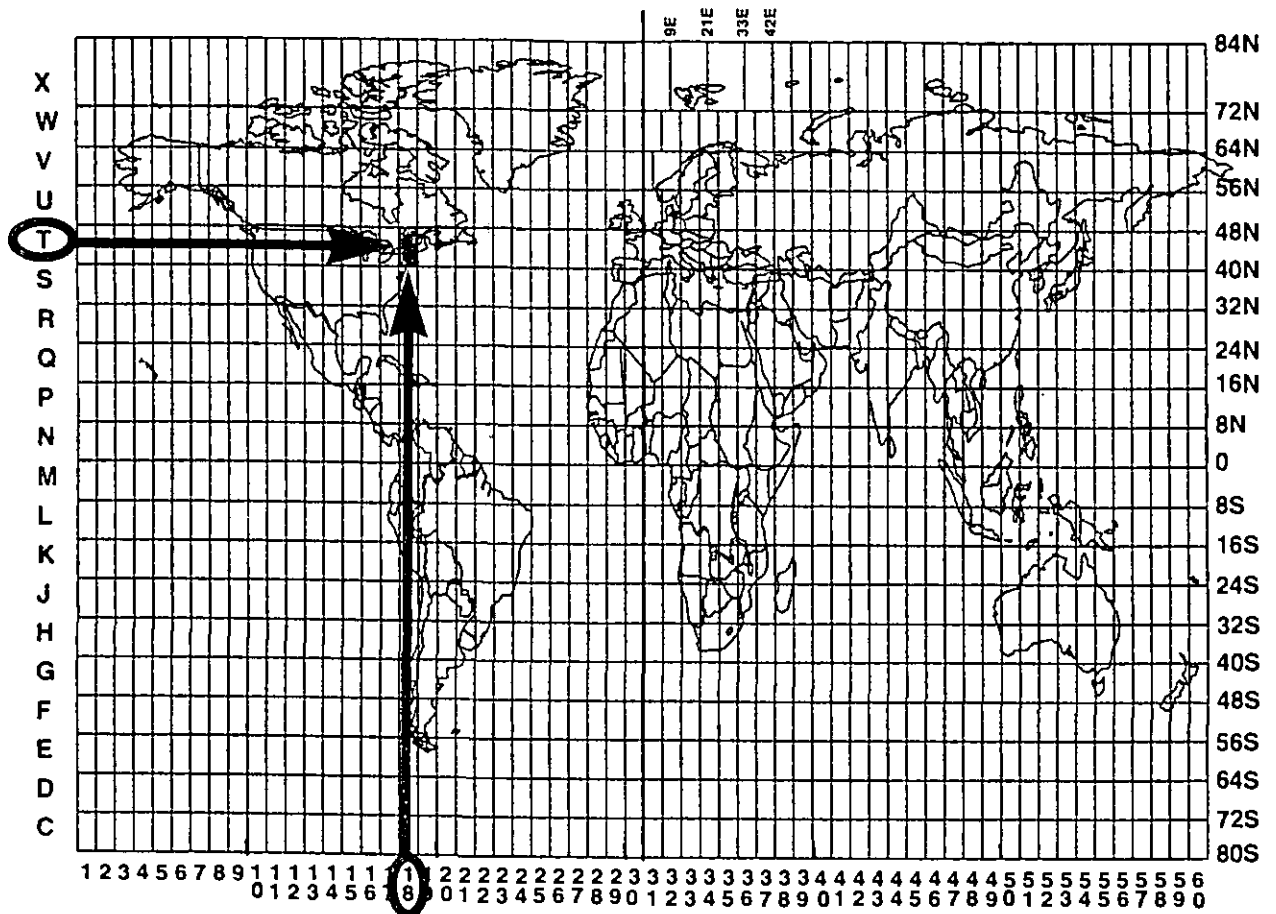


Figure 2.13 Six by eight-degree cells on the UTM military grid.

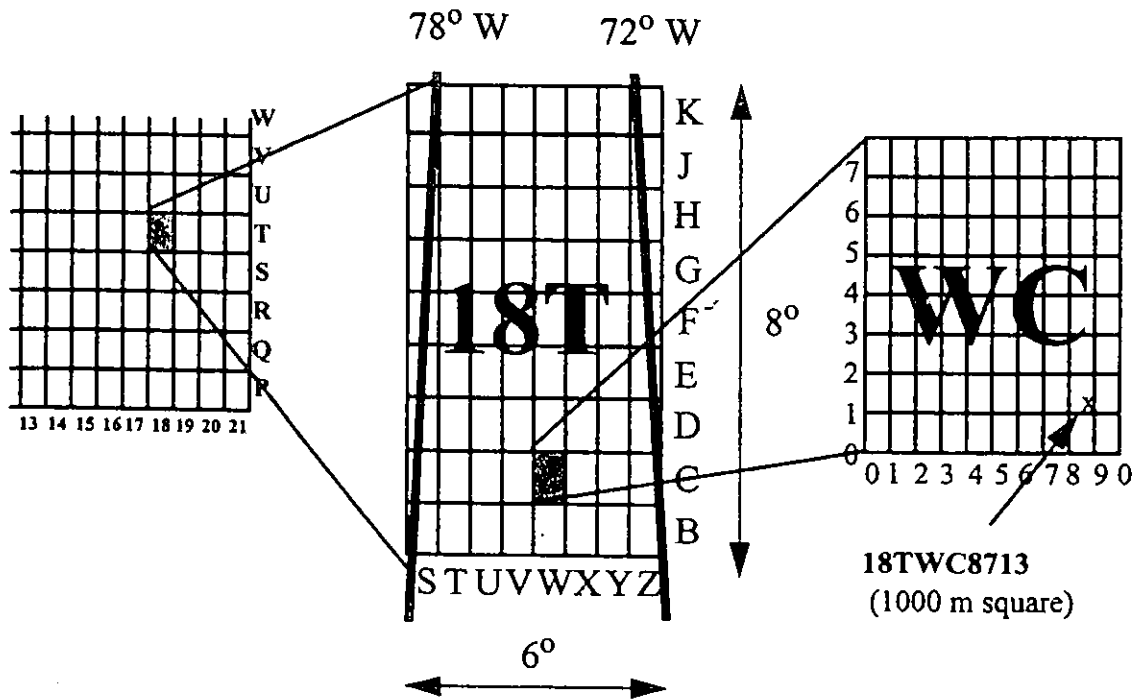


Figure 2.14 Military grid cell letters.

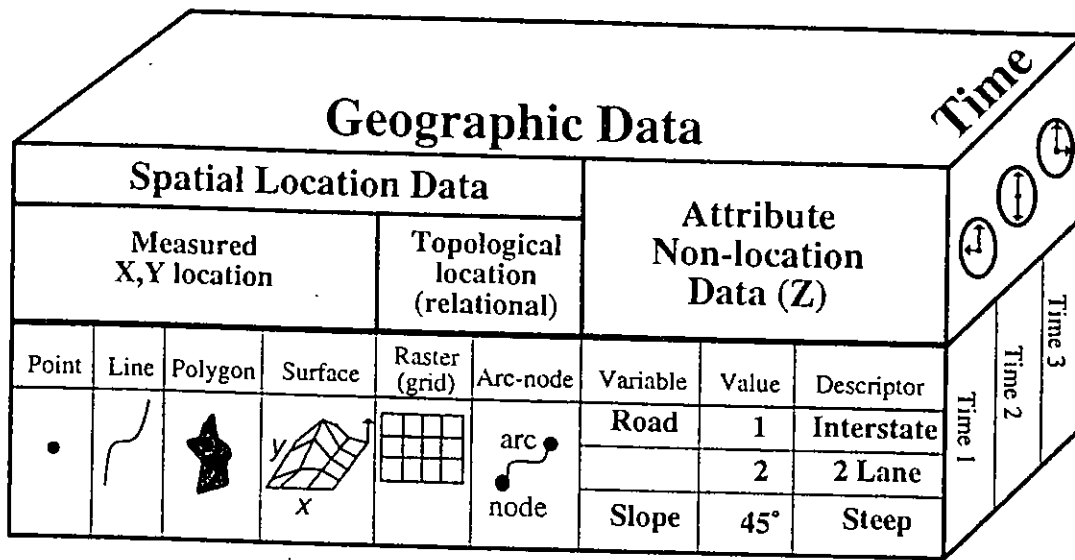
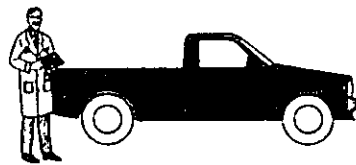


Figure 10-1 A geographic information system (GIS) stores locational (x, y) and attribute (z) information obtained at multiple times.

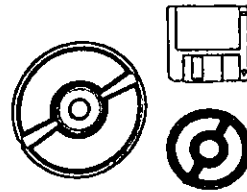
DATA ACQUISITION



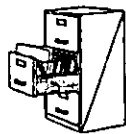
MAPS



FIELD DATA



DIGITAL PRODUCTS



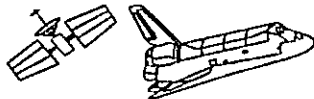
TABULAR DATA



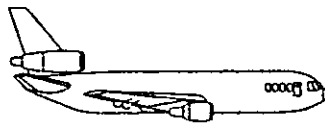
REPORTS



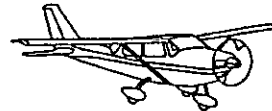
DISCUSSION



SPACE



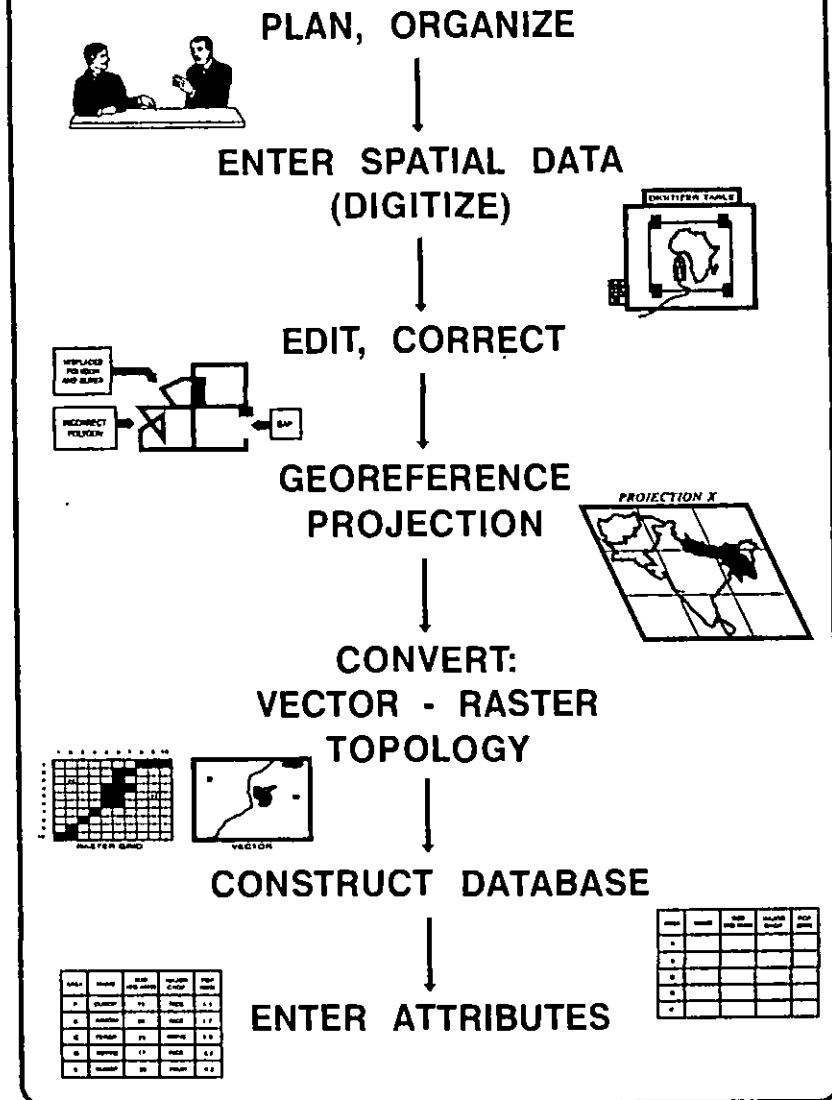
HIGH ALT.



LOW ALT.

REMOTE SENSING

DATA ENTRY PROCESS



Data Entry Process

DATA STRUCTURE FOR DIGITAL MAP DATA

A. The Raster Data Model (Aronoff (1993) pp. 164 - 172) (Burrough (1987) pp. 19 - 25)

- homogeneous units are represented by cells or pixels
- objects are located (defined) by row and column position
- the area that each cell occupies is referred to as spatial resolution
- positional accuracy defined by the spatial resolution
- cell value defines nature of the surface or object (e.g., attribute value common to the entire cell)
- rasters are easily handled by computer program since they are simply arrays/matrices of numbers
- rasters are also easily linked to display devices
- multiple attributes must be stored in multiple files
- file size based on dimension of the raster (matrix) and the nature of the attribute value
- trade-offs between spatial resolution and file size

Raster Data Compression

- if the data are highly variable from cell to cell, raster data capture that variability (ratio or continuous data)
- if the data do not vary greatly, the raster model, if at high resolution, is not efficient in storing or capturing information

Run-Length Encoding

- adjacent cells that have the same value are treated as a group (run)
- value point encoding - cells are assigned position numbers at the end of each run from left to right and top to bottom

Quadtree Data Structures

- compact raster data representation
- addresses both the resolution and redundancy issues by using a variable-size grid cell
- cells are subdivided based on complexity of the attribute/surface/variable
- higher spatial resolution required in areas of lines, points and polygon boundaries
- progressive subdivision of a variable (map) through a limited number of iterations (essentially defines a minimum cell size)
- point-in-polygon searches (neighbouring values / adjacency)
- able to generalize to various levels
- generation is CPU intensive (indexes and tables)
- best utilized when the data are relatively homogeneous and do not require frequent updating

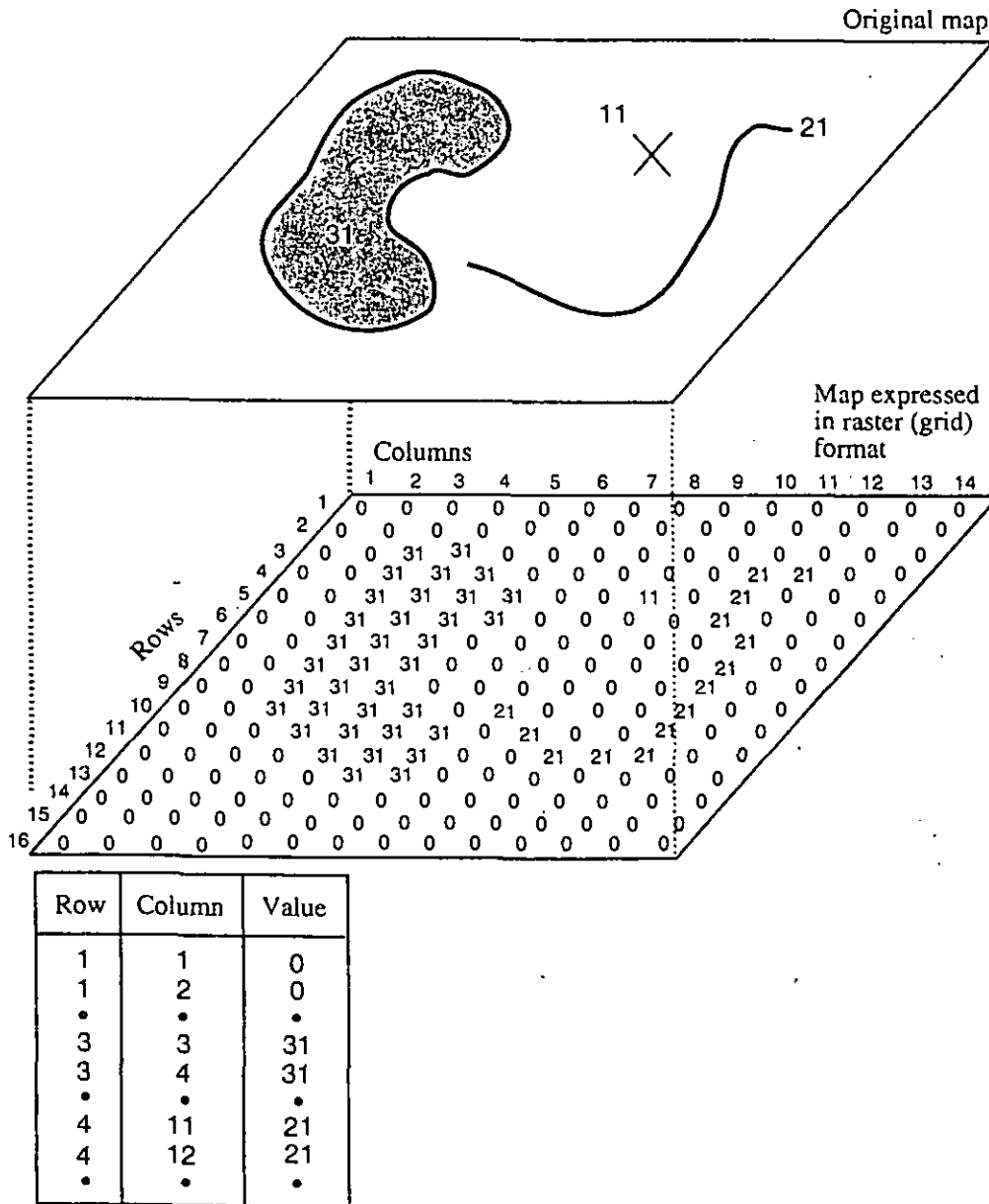
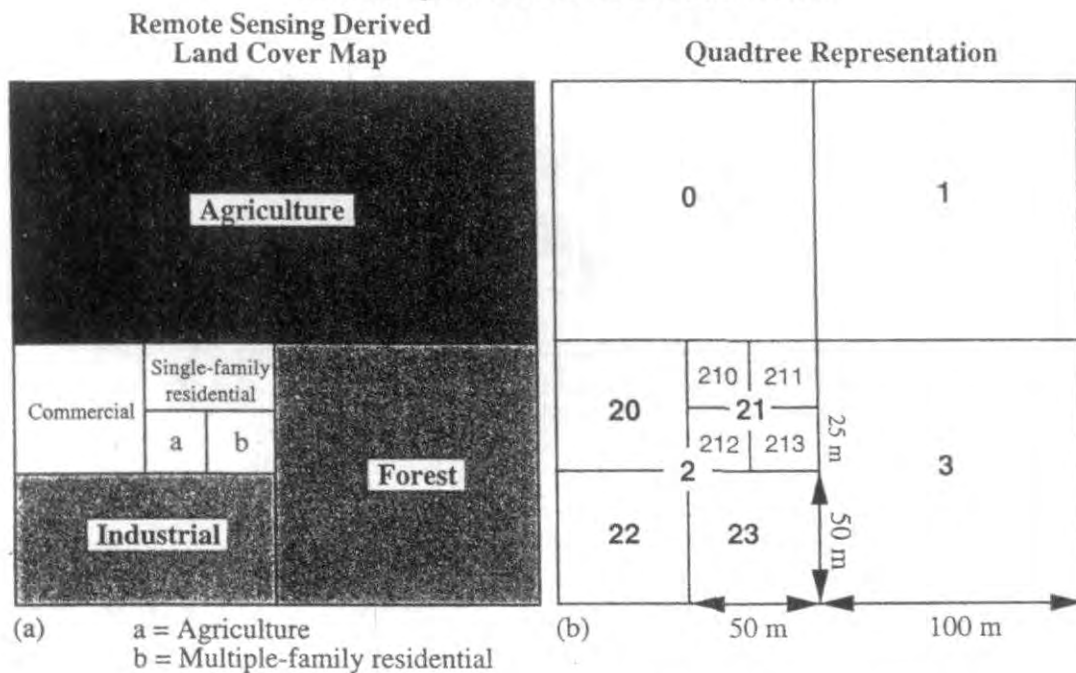


Figure 10-5 The basic structure of a grid (raster) database file.

Linear Quadtree Raster Data Model



Quadtree Attribute Table

Quadtree levels			Attributes	
1	2	3		
0			Agriculture	
1			Agriculture	
2	20		Commercial	
		21	210	Single-family residential
			211	Single-family residential
		212	Agriculture	
	213	Multiple-family residential		
	22		Industrial	
23		Industrial		
3			Forest	

Schematic Representation of the Quadtree

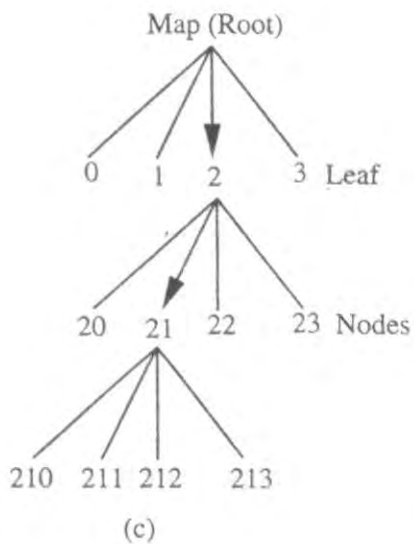
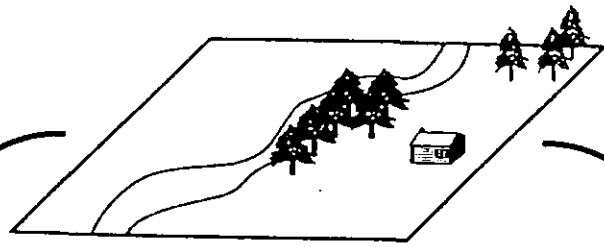


Figure 10-6 Characteristics of a linear quadtree raster data structure (modified from Aronoff, 1991).

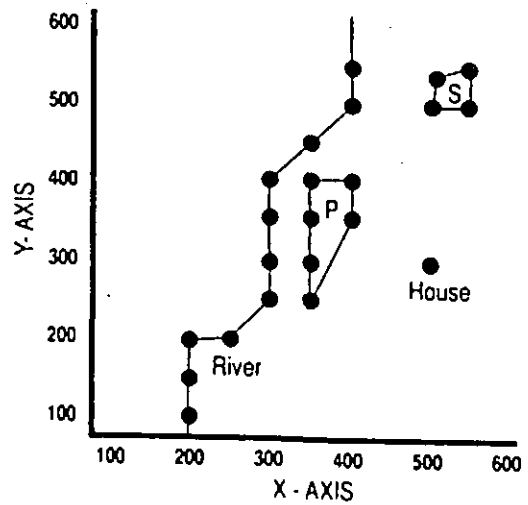
THE RASTER AND VECTOR DATA MODELS



A. REAL WORLD

	1	2	3	4	5	6	7	8	9	10
1							R			S
2							R		S	S
3						R				
4				R	P	P				
5				R	P	P				
6				R	P				H	
7				R	P					
8		R	R							
9		R								
10		R								

B. RASTER REPRESENTATION



C. VECTOR REPRESENTATION

Figure 6.10 Comparison of the Raster and Vector Models. The landscape in A is shown in a raster representation (B) and in a vector representation (C). The pine forest stand (P) and spruce forest stand (S) are area features. The river (R) is a line feature, and the house (H) is a point feature.

B. The Vector Data Model

- spatial entities in a vector model correspond to the spatial entities they represent in the real world (points, lines and polygons)
- map area is assumed to be a continuous coordinate space
- more precise positioning of features in space as opposed to raster model
- locations defined by some X-Y coordinate system

Spaghetti Data Model

- collection of coordinate strings with no inherent structure (no topology - spatial relationships between features)
- a data file of XY coordinates represents the structure of the data file (no spatial relationships between features are encoded)
- efficient method for cartographic representation (storing graphics)
- inefficient for spatial analysis since spatial relationships would have to be computed

Topological Model

- topology - the mathematical method of defining spatial relationships

Arc-Node Data Model

- the basic logical entity is the arc (a series of points that start and end at a node)
- a node is the intersection point where two or more arcs meet (or end of a dangling arc)
- isolated nodes, not associated with an arc a simply points
- a polygon is comprised of a closed chain of arcs that represent the boundaries of an area
- analyses such as contiguity (spatial relation of adjacency) and connectivity (analysis done without using the coordinate data since topology defines relationships)
- systems without topology can use simpler data structures but require sophisticated algorithms for spatial analyses

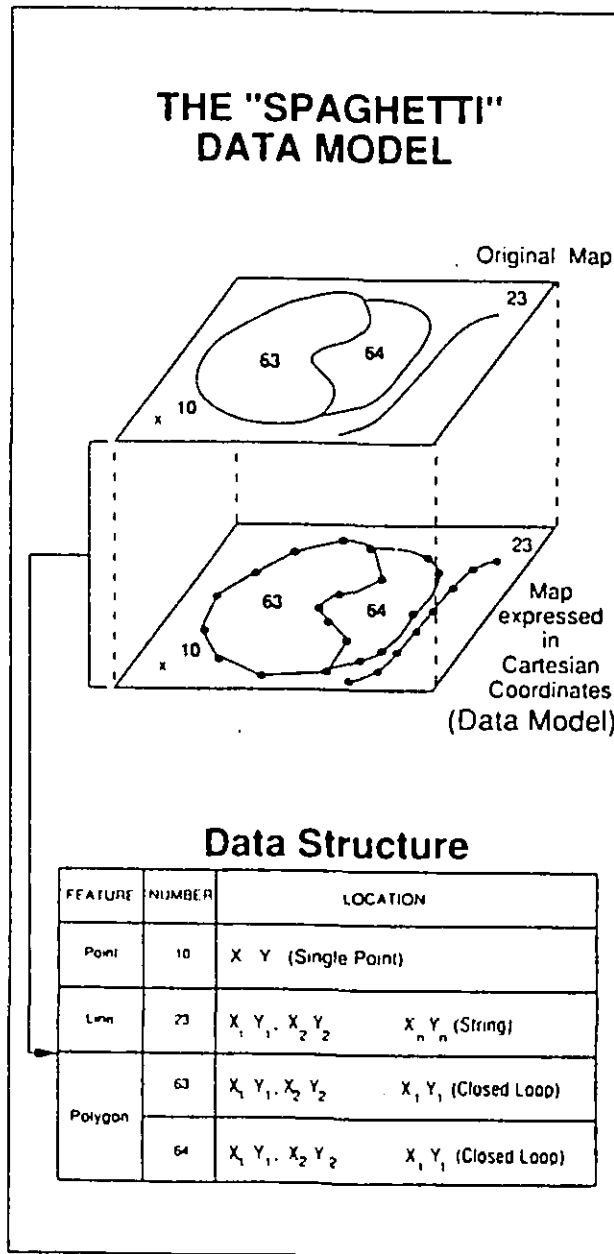


Figure 6.16 The Spaghetti Data Model. (Adapted from Dangermond 1982).

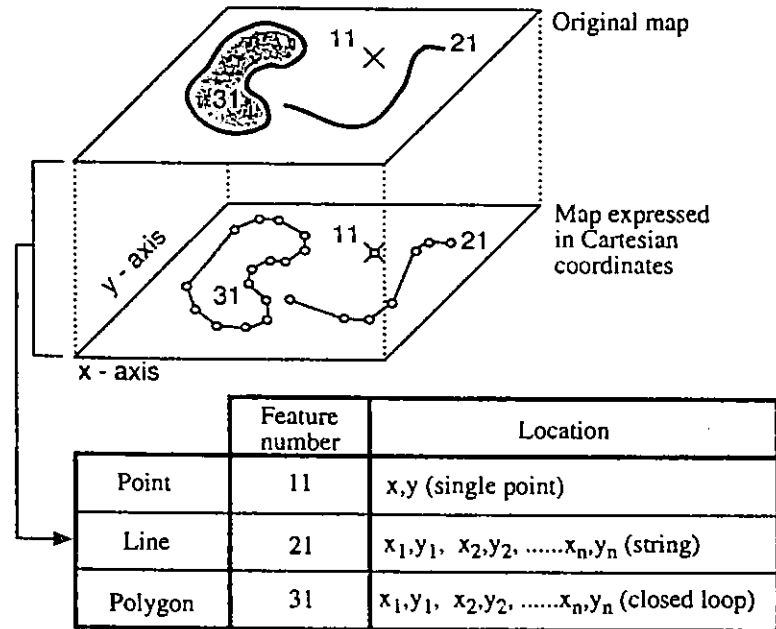


Figure 10-3 Encoding of point, line, and polygon features using traditional vector (spaghetti) Cartesian coordinate digitization techniques.

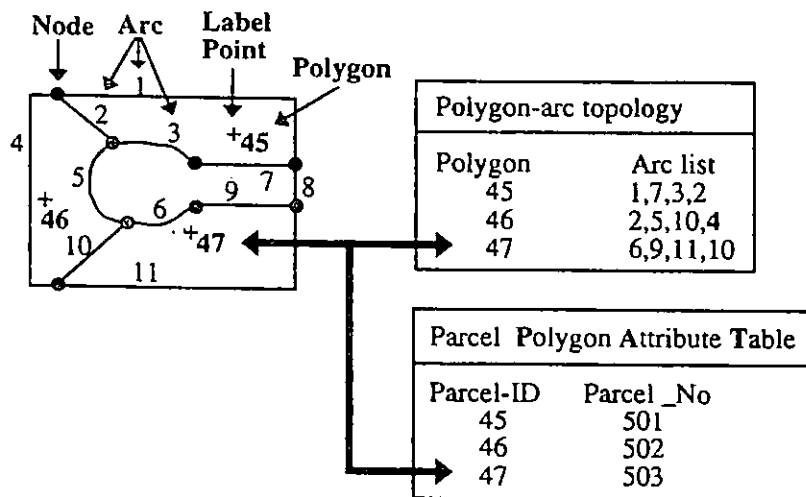
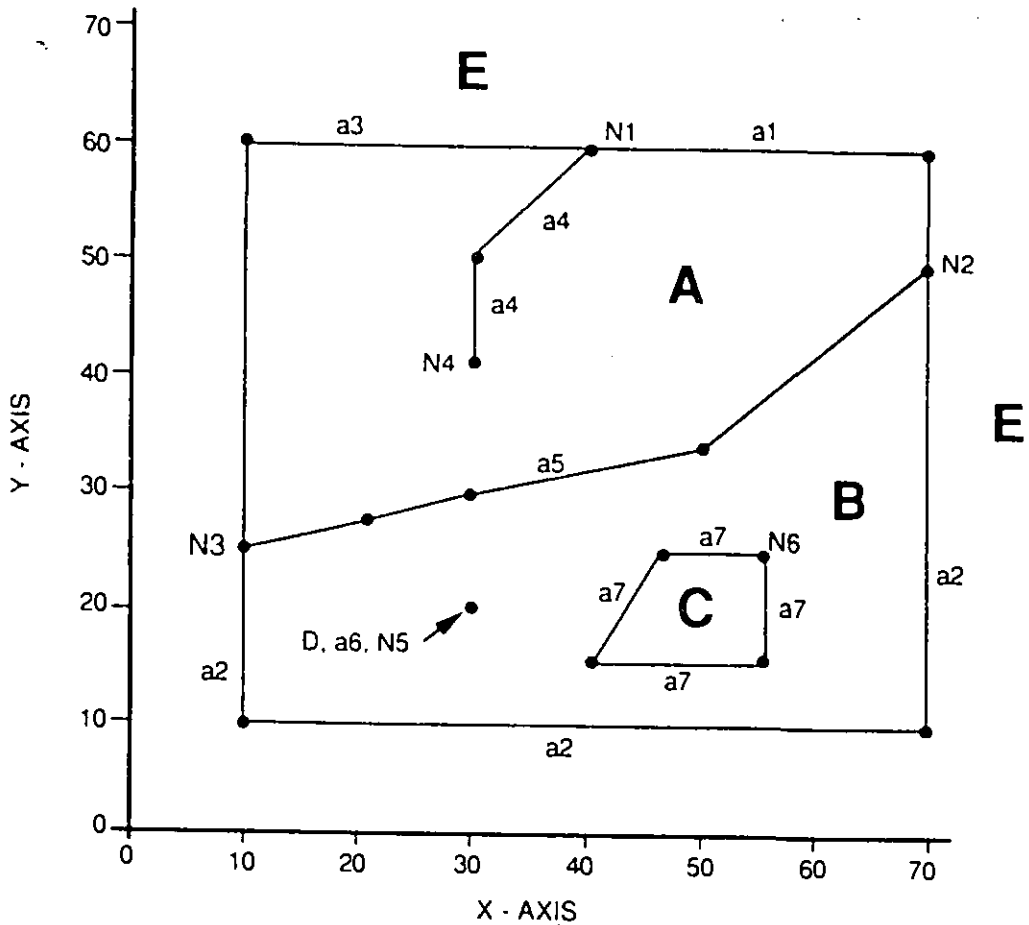


Figure 10-4 Encoding of features using a topological data structure consisting of nodes, arcs, and label points. Polygons are derived from the polygon-arc topology, and each polygon's characteristics are stored in a polygon attribute table.



SPATIAL DATA ENCODING

POLYGON TOPOLOGY	
POLYGON	ARCS
A	a1, a5, a3
B	a2, a5, a6, a7
C	a7
D	a6
E	area outside map coverage

NODE TOPOLOGY	
NODE	ARCS
N1	a1, a3, a4
N2	a1, a2, a5
N3	a2, a3, a5, a6
N4	a4, a7
N5	a6, a7
N6	a7

ARC TOPOLOGY				
ARC	START NODE	END NODE	LEFT POLYGON	RIGHT POLYGON
a1	N1	N2	E	A
a2	N2	N3	E	B
a3	N3	N1	E	A
a4	N4	N1	A	A
a5	N3	N2	A	B
a6	N5	N3	B	B
a7	N6	N5	B	C

ARC COORDINATE DATA			
ARC	START X, Y	INTERMEDIATE X, Y	END X, Y
a1	40, 60	70, 60	70, 50
a2	70, 50	70, 10; 10, 10	10, 25
a3	10, 25	10, 60	40, 60
a4	40, 60	30, 50	30, 40
a5	10, 25	20, 27; 30, 30; 50, 32	70, 50
a6	30, 20		30, 20
a7	55, 27	55, 15; 40, 15; 45, 27	55, 27

Figure 6.17 The Topological Data Model.

Table 6.1 Comparison of Raster and Vector Data Models.

RASTER MODEL	VECTOR MODEL
Advantages:	Advantages:
<ol style="list-style-type: none">1. It is a simple data structure.2. Overlay operations are easily and efficiently implemented.3. High spatial variability is efficiently represented in a raster format.4. The raster format is more or less required for efficient manipulation and enhancement of digital images.	<ol style="list-style-type: none">1. It provides a more compact data structure than the raster model.2. It provides efficient encoding of topology, and, as a result, more efficient implementation of operations that require topological information, such as network analysis.3. The vector model is better suited to supporting graphics that closely approximate hand-drawn maps.
Disadvantages:	Disadvantages:
<ol style="list-style-type: none">1. The raster data structure is less compact. Data compression techniques can often overcome this problem.2. Topological relationships are more difficult to represent.3. The output of graphics is less aesthetically pleasing because boundaries tend to have a blocky appearance rather than the smooth lines of hand-drawn maps. This can be overcome by using a very large number of cells, but may result in unacceptably large files.	<ol style="list-style-type: none">1. It is a more complex data structure than a simple raster.2. Overlay operations are more difficult to implement.3. The representation of high spatial variability is inefficient.4. Manipulation and enhancement of digital images cannot be effectively done in the vector domain.

Digital Elevation Models and Geomorphometric Processing

- digital elevation models (DEMs) often used when merely relief is represented
- digital representation of a portion of the earth's surface
- terrain allows the possibility of including landscape attributes other than topography, as a means of improving the digital representation of a section of terrain
- provide an opportunity to model, analyse and display phenomena related to topography or other surfaces
- connected surface models having unique z-values over x and y
- more generally, a DTM may be used as a digital model of any single-valued surface (e.g., air temperature, population density)

Generation and Production of DEMs/DTMs

Require:

- (i) observations of terrain elevation
- (ii) additional information on phenomena that affect shape of the surface (e.g., drainage channels, ridges)

Sources for DTM Generation:

A. Ground Survey

- survey data input directly into GIS
- survey is generally adapted to the terrain
- accurate
- time consuming - limited to small areas

B. Photogrammetric Data Capture

- stereo interpretation of aerial photographs or digital imagery
- accuracy is dependent on sampling method and imagery used
- remote sensing provides for large area coverage

C. Digitizing Contours on Topographic Maps

- contours digitized manually, semi-automated line-following, or automatic raster scanning and vectorization

Problems:

- contours are a form of terrain visualization, not as useful for numerical surface representation
- large number of points sampled along contours (oversampling) whereas no samples taken across contours (undersampling)
- errors arise due to drawing, line generalization, etc.
- original data lost in the map-making process
- contour data yield DTMs of moderate accuracy (cost effective)

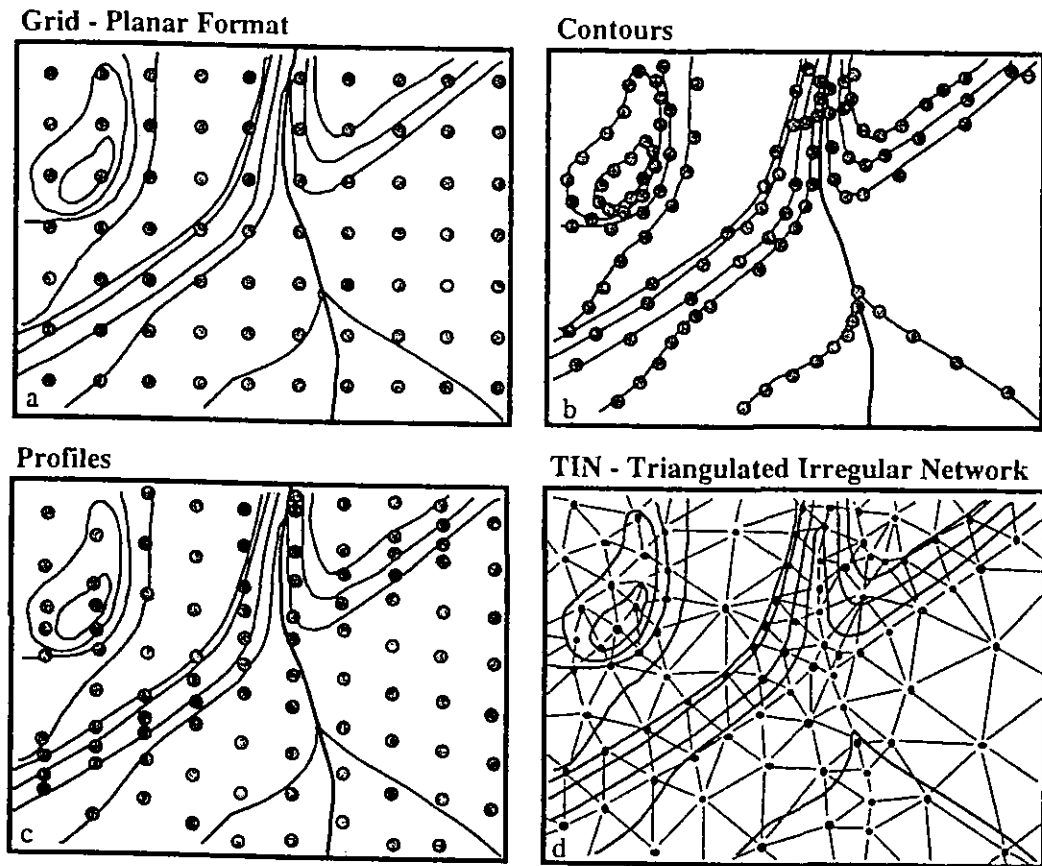


Figure 10-7 The four basic forms of capture and storage of digital elevation data. The solid lines are contours (modified from Carter, 1988).

Data Structure for DTMs

- terrain data capture generates a set of relatively unordered data elements (must apply structure to these data)

To construct a DTM:

- establish topological relations between the data elements;
- apply interpolation model to approximate the surface behaviour

Raster (rectangular grid/elevation matrix)

- topological relations between data points is implicit
- two-dimensional array of elevations (reflect storage structure of computers)
- point density of regular grids cannot be adapted to the complexity of the relief (requires excessive number of points to represent the terrain to a required level of accuracy)

Vector (Triangulated Irregular Network)

- based on triangular elements, with vertices at the sample points
- (sheet of continuous, connected triangular facets)
- structural features are easily incorporated into this structure
- reflect the variable density of data points and roughness of terrain (able to follow ridges, stream lines, etc.)
- however, topological relationships have to be computed explicitly
- TINs are more complex and difficult to handle

TIN models

- regards nodes of the network as primary entities in the database
- topological relations are built into the database by constructing pointers from each node to each of its neighbouring nodes
- neighbours are sorted clockwise around each node starting at north
- area outside the area modelled by the TIN is represented by a dummy node on the reverse side of the topological sphere (e.g., -32000)

Geomorphometric Processing (Gradient, Aspect, etc.)

Slope is defined by a plane tangent to the DTM surface at any given point, and comprises two components (gradient and aspect).

Gradient

- maximum rate of change of altitude (% or degrees)

$$\tan G = [(\delta Z/\delta X)^2 + (\delta Z/\delta Y)^2]^{1/2}$$

where Z is altitude and X and Y are the coordinate axes

Aspect (compass direction of the maximum gradient)

- although slope is defined at a point, generally assigned to a facet (i.e., triangles of a TIN or rectangular cells of gridded DTMs)

- derivatives of the hypsometric curve are usually derived locally for each cell on the DTM by computations made with a 3x3 cell window moved over the surface (regular grid)

$$\tan A = \frac{-\delta Z/\delta Y}{\delta Z/\delta X} \quad -\pi < A < \pi$$

Applications of Digital Terrain Models

Civil Engineering

road design, earthwork calculations in site planning
(emphasize volumetric calculations and design functions)

Planning and Resource Management

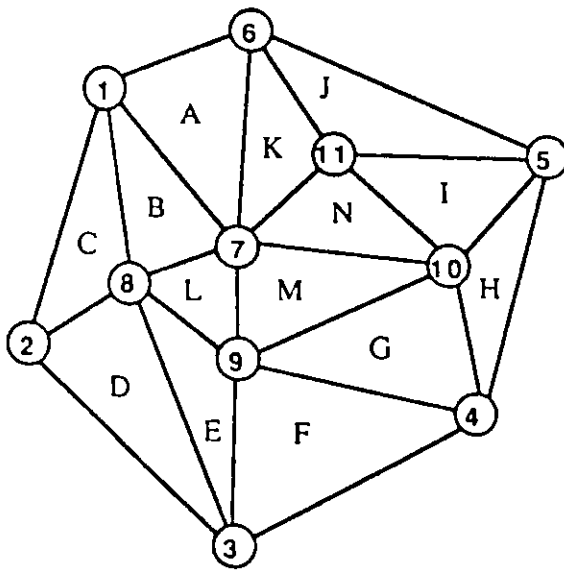
environmental and urban planning; remote sensing; soil science; agriculture, forestry, meteorology and climatology

- environmental impact studies; industrial site location; geometric and radiometric correction of remote sensing data; support of image classification in remote sensing; soil erosion modelling; pollution dispersion models

Earth Sciences

geology, geomorphology, hydrology, and glaciology
require network capabilities (drainage)

- drainage basin monitoring (flood and pollution control); hydrological runoff modelling; geological interpretation and mapping



X-Y COORDINATES	
node	coordinates
1	x1, y1
2	x2, y2
3	x3, y3
:	
11	x11, y11

Z COORDINATES	
node	coordinate
1	z1
2	z2
3	z3
:	
11	z11

EDGES	
Δ	adjacent Δ
A	B, K
B	A, C, L
C	B, D
D	C, E
E	D, F, L
F	E, G
G	F, H, M
H	G, I
I	H, J, N
J	I, K
K	A, J, N
L	B, E, M
M	G, L, N
N	I, K, M

NODES	
Δ	node
A	1, 6, 7
B	1, 7, 8
C	1, 2, 8
D	2, 3, 8
E	3, 8, 9
F	3, 4, 9
G	4, 9, 10
H	4, 5, 10
I	5, 10, 11
J	5, 6, 11
K	6, 7, 11
L	7, 8, 9
M	7, 9, 10
N	7, 10, 11

Figure 6.18 The Structure of a TIN. The TIN is a topological data model. The data are stored in a set of tables that retain the coordinate values as well as the spatial relations of the facets, as explained in the text. (Adapted from an illustration by ESRI, Redlands, California.)

DATA-BASE MANAGEMENT SYSTEMS

Introduction

- data base --> information to be stored
- GISs are first and foremost, information management systems
- data base is a collection of one or more data files or tables stored in a structured manner
- data base management systems (dbms) --> computer software used to manage a data base

Data-Base Management Systems (DBMS)

- software with the purpose of storing, manipulating and retrieving data from a data base (maintenance and management)
- are an integrated and crucial component of successful GISs
- initially developed in GIS for handling map attribute data but also increasingly for digital cartographic data
- allow the data to be independent from the application programs (DBMS provide data in the format required by the application)
- provide for efficient data-sharing within and between organizations
- provide multiple views / presentations

Data Models (DBMS Structure)

- the conceptual organization of a data base (data model)

Data Files: **Records** ---> **Fields** ---> **Keys vs Attribute Fields**

Record - the information pertaining to a particular entity or element (object, event, concept)

Field - an item of data related to entity or element (defines where a particular type of data can be found in the record)

Key - label comprised of one or more fields (means of retrieving a record or group of records from the data)

Attribute Fields - fields not designated as keys

- fewer key fields --> compact data file
- > quicker access (search/query)
- > types of queries are restricted

1. Hierarchical Data Model

- relationships among entities are defined by the organization of the hierarchy
- organization is encoded in the data records for each entity
- top of th hierarchy is the root, comprised of one entity
- a set of parent-child pointers from one level down to the next
- (field designated as the key organizes the hierarchy/structure)
- represents a one-to-one or many-to-one relationship (element can have only one parent)

Advantages

- easy to understand and update
- high speed access to large databases if all desired access paths follow the parent-to-child linkages

Disadvantages

- queries are restricted to the hierarchical data structure - cannot bypass levels within the hierarchy
- inflexible structure is placed on the problem at the outset, when the record type constituting the tree structure is set up
- many-to-many relationships do not fit naturally into the structure (requires extensive pointers)
- searches cannot be performed on attribute fields (pointer needed to modify database organization)

2. Network

- a entry can have multiple parent as well as multiple child relations (no root required)
- data records can be directly searched without traversing the entire hierarchy above that record
- although the network model cannot handle many-to-many relations, a modification can be implemented using intersection records
- reduced duplication in terms of data stored
- can accommodate more complex data structures
- limited flexibility compared to relational data model

3. Relational

- no hierarchy of data fields within a record
- every data field can be used as a key
- simple records (tuples)
- tuples are grouped together in a series of two-dimensional tables (relation - table representing relationships between attributes)
- queries can be made on any attribute field from any table
- searched on related attributes in different tables can be performed by selecting common attribute in one or more table
- new tables generated with associated data fields ("virtual tables")

Advantages

- organization of the model is simple (easy to develop SQL -Standard Query Language)
- no restriction on the types of queries performed (provided there are common data fields)
- flexible, in that data manipulation is not restricted by the way the data model is structured ..

Disadvantages

- difficult to implement
- slower performance due to lack of physical (coded) pointers (matches made between relational tables)

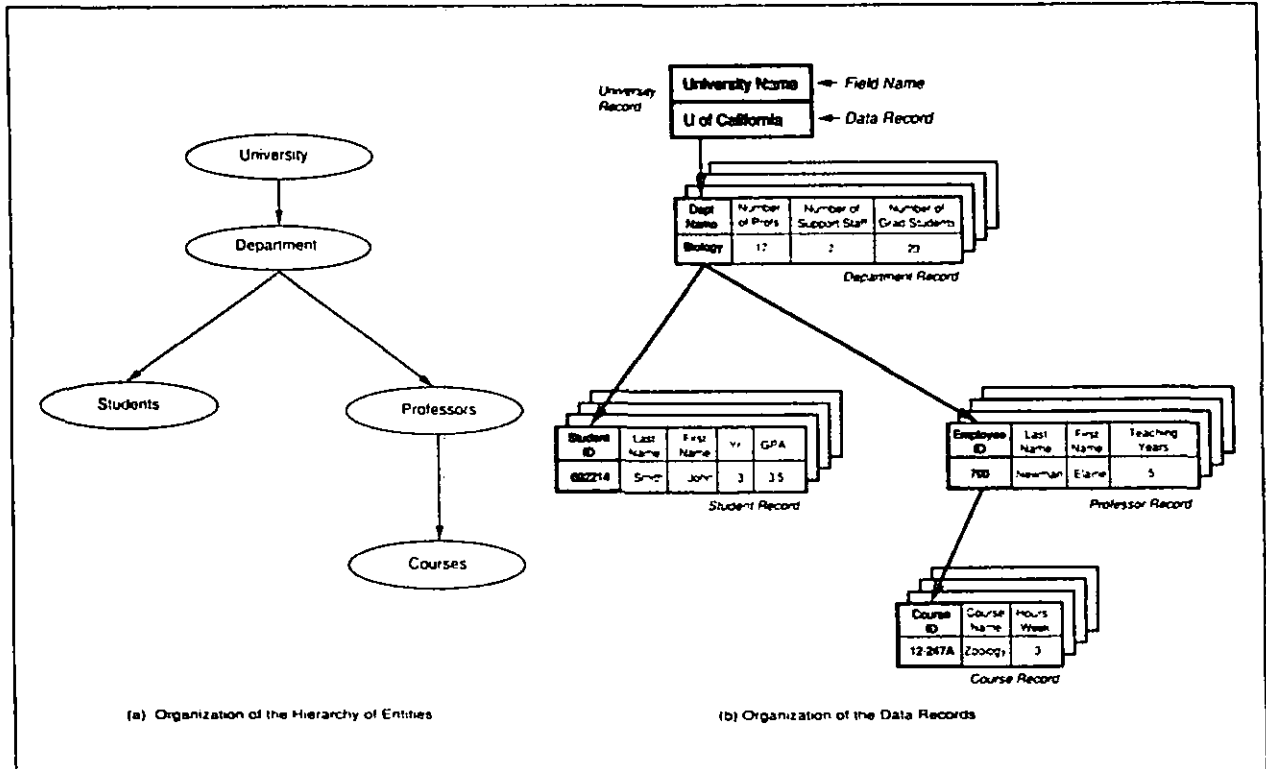


Figure 6.5 Organization of a Data Base Using the Hierarchical Data Model.

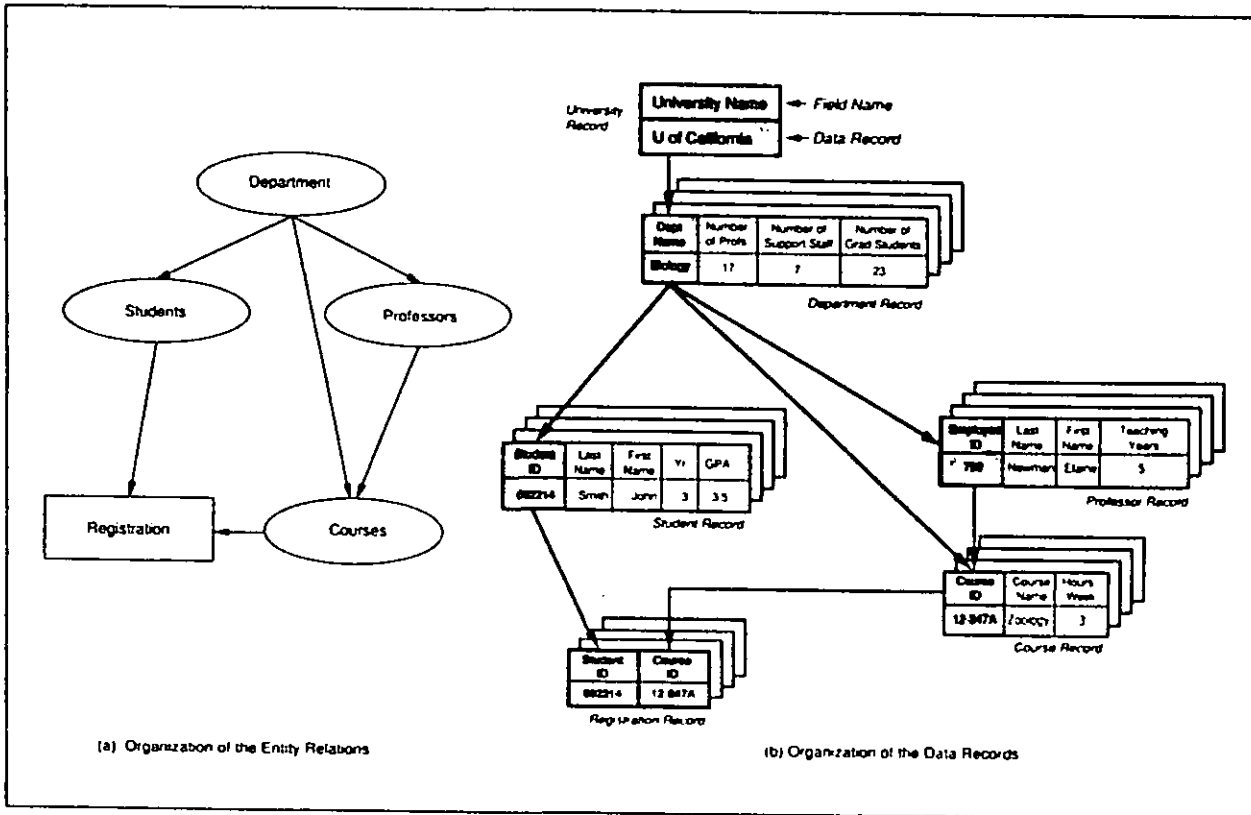


Figure 6.6 Organization of a Data Base Using the Network Data Model.

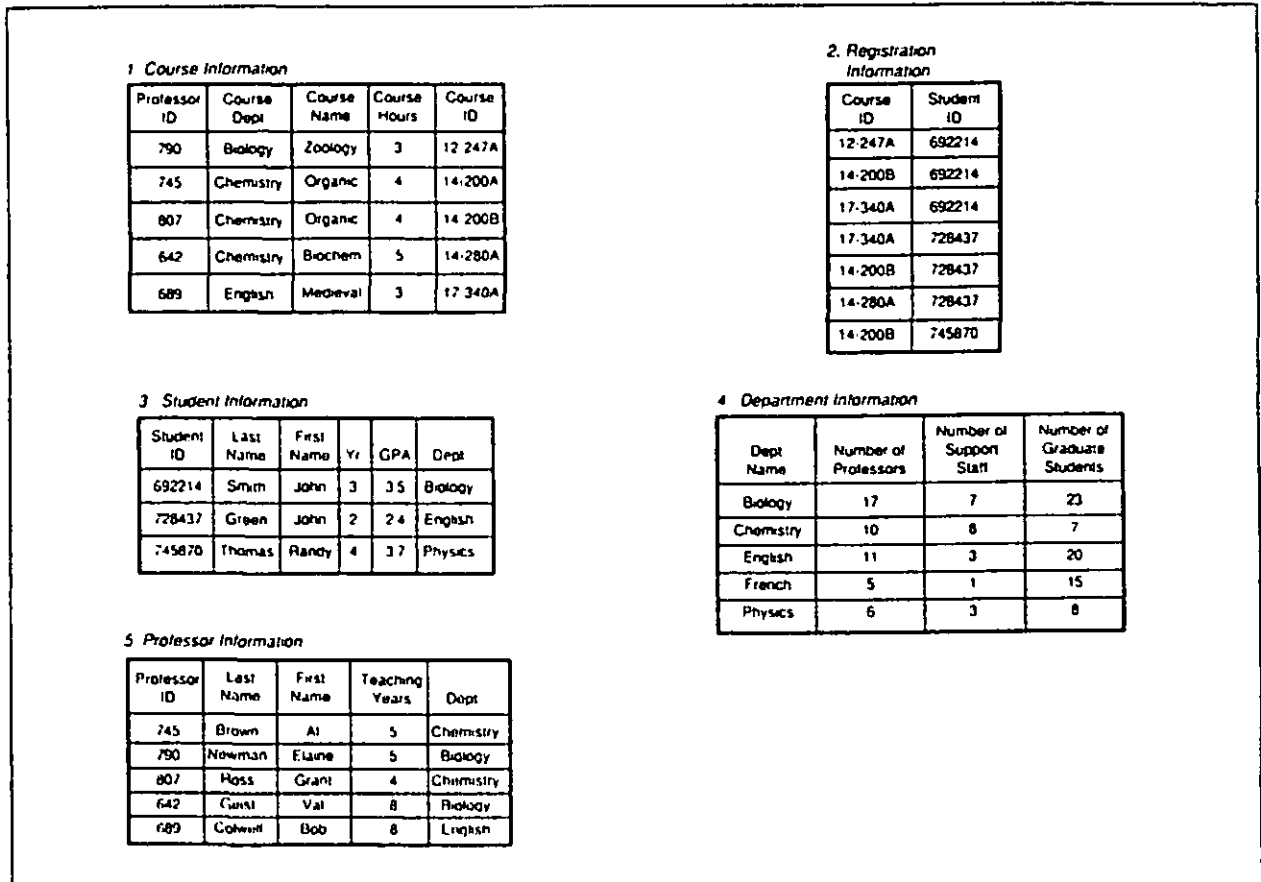


Figure 6.7 Organization of a Data Base Using the Relational Data Model.

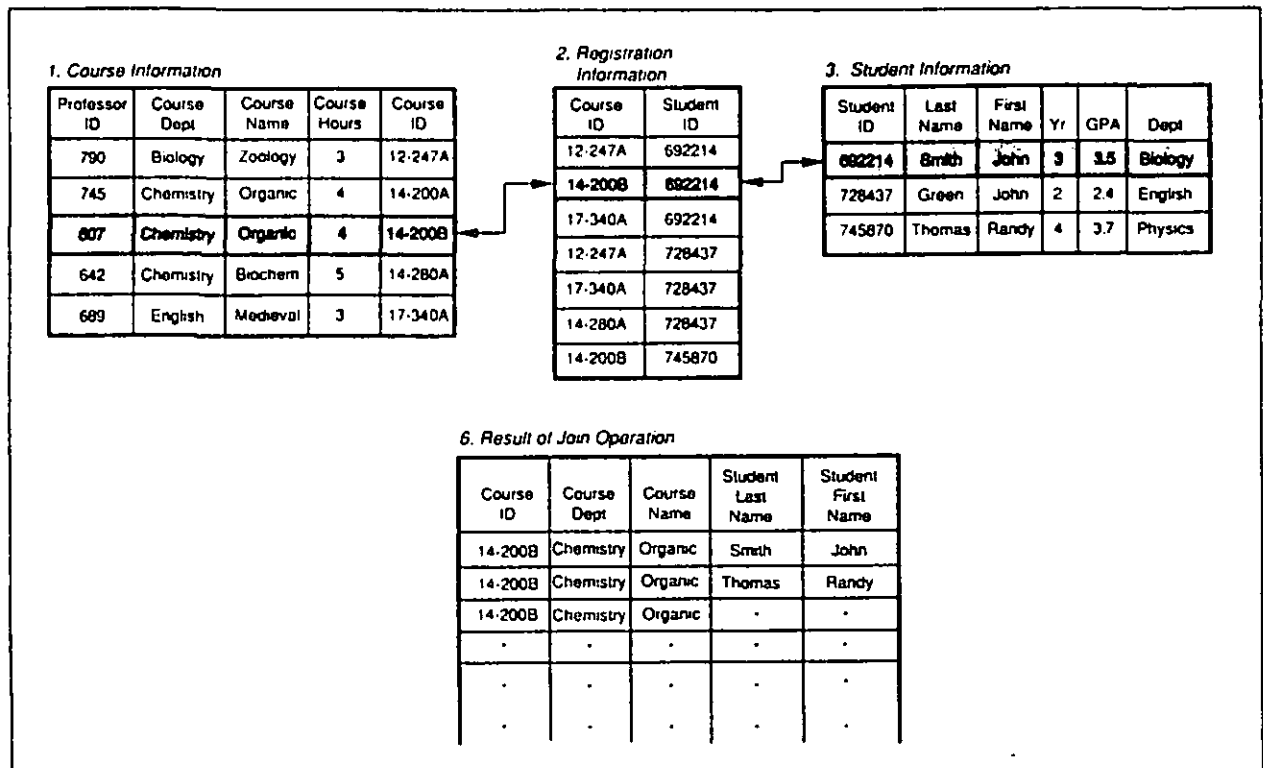


Figure 6.8 The Relational Join Operation. The data from three relational tables are used to generate a student list for a course (Table 6). Common data fields (indicated by the arrows) are used to interrelate the records in different tables.

160 GIS: A Management Perspective

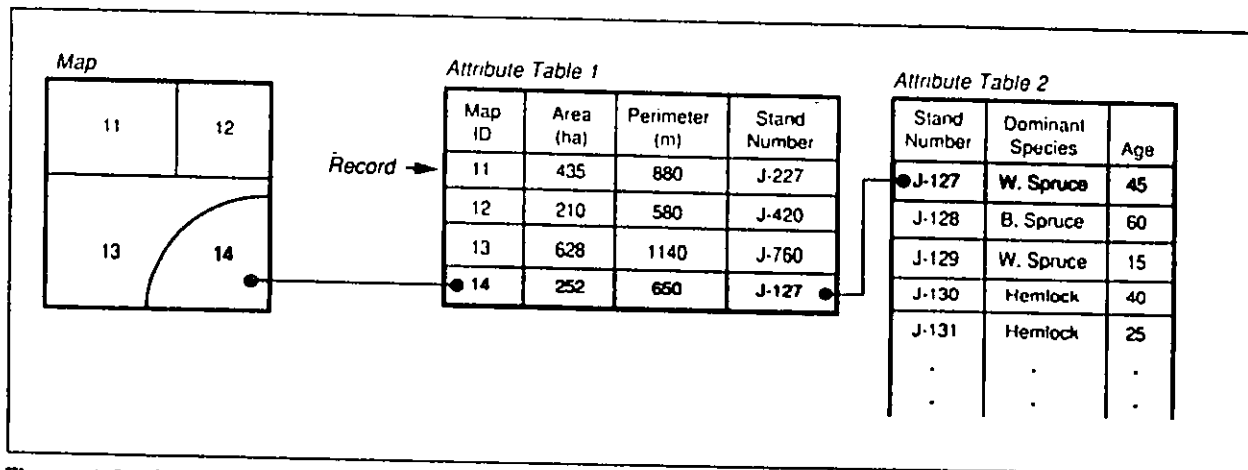


Figure 6.9 Storage of GIS Attribute Information in a Relational Data Base.

GIS ANALYSIS FUNCTIONS

Introduction

- in order to perform appropriate spatial analyses, require a systematic framing of the questions to be addressed
- also requires an understanding of the data and data format/storage

Data Layers

- a data layer consists of a set of logically related geographic features and their attributes
- e.g., thematic organization - OBM - drainage, transport

Classification of GIS Analysis Functions

A. Maintenance and Analysis of Spatial Data

- transformation, editing and accuracy assessment

Format Transformation

- compatible with the host GIS format (e.g., build topology from coordinate data - dxf to ARC/INFO)

Geometric Transformation

- registration - different data layers are registered to a common coordinate system

Transformations between Geometric Projections

- a map projection is a mathematical transformation that is used to represent a spherical surface in a two dimension map
- distortion results in one or more of area, shape, distance or direction
- in North America, for scale > 1:500,000 the UTM is most commonly used standard

Conflation

- reconciling the positions of corresponding features in different data layers (prevent slivers during overlay analysis)

Edge Matching

- procedures to adjust the position of features that extend across adjacent map boundaries

Editing Functions

- slivers, dangling arcs, snap-to-node, polygons that are not closed

Line Coordinate Thinning

- reduce data volume while maintaining proper shape of graphic element

B. Maintenance and Analysis of Non-Spatial Attribute Data

- functions for the editing, quality checking and analysis of non-spatial attribute data

Attribute Editing Functions

- database management system

Attribute Query Functions

C. Integrated Analysis of Spatial and Attribute Data

Retrieval, Classification, and Measurement Functions

- **Retrieval** - selective search, manipulation and output of data
- **Classification and Generalization** - to display patterns
- **Measurement Functions** - distances, lengths, perimeters, areas

Overlay Operations

- arithmetic or logical overlay operations
- raster-based models are more suited to overlay operations

Neighbourhood Operations

- evaluating the characteristics of the area surrounding a specified location
 - one or more target locations
 - specify the neighbourhood around each target
 - function to be performed on the elements within the neighbourhood

Line-in-Polygon and Point-in-Polygon Operations

Topographic Functions (Gradient, Aspect)

Thiessen (Voronoi) Polygons

- areas of influence around a set of points (extension of point data)
- polygon boundaries are equidistant from the neighbouring points
- used to predict the values at surrounding points from a single observation
- shape and area of Thiessen polygon is dependent on the location of the observations and may not reflect the true nature of the phenomenon being mapped
- since each polygon is derived from a single point measure, no error estimates can be derived

Interpolation

- prediction of unknown values using known values at neighbouring locations (raster / TIN)
- variety of techniques for estimating the unknown values (polynomial regression; moving averages, kriging)
- dependent on accuracy, number and distribution of the known points
- optimal results when the mathematical function best models the phenomenon under study

D. Connectivity Functions

- use functions that accumulate values over the area being traversed (running total of results is obtained)

Requirements:

1. specification of the way spatial elements are connected
(e.g., *drainage map defining way in which tributaries are connected*)
2. rules defining the method of movement along these connections
(*movement is downstream*)
3. units of measurement (*km*)

e.g. Ambulance dispatch (time versus distance)

Contiguity

- evaluate characteristics of spatial units that are connected
- a contiguous area consists of a group of spatial units that share a single or multiple number of characteristics and can form a homogeneous unit
- common measures of contiguity include size of the area and shortest and longest straight-line distances across the area
(e.g. area **and** area/perimeter ratio for landscape patch analysis - mammal movement)

Proximity

- measure distance between features
- target locations, unit of measure, function to calculate proximity, area to be analysed
- buffer zones

Network Functions

- a set of interconnected linear features that form a distinct pattern
(routing)

Network Analyses include:

1. Prediction of network loading
- stream flow modeling to predict the magnitude and location of flooding
2. Route optimization (e.g., emergency response times)
3. Resource allocation
- division of region into optimal zones for fire, police and ambulance dispatching or servicing

Spread Functions

- characteristics of both network and proximity functions
- evaluate phenomenon that accumulate with distance
- a running total of the function that is being evaluated is derived creating a surface
- advantage of a spread function is that irregularly distributed factors can be accommodated
(e.g., surface cover for surface water runoff)

Seek or Stream Functions

- directed search outward based on certain decision rules or criteria
(e.g., trace the flow of water over a DEM to determine erosion hazard based on the frequency(volume) of water flowing over certain locations (also incorporate cover type)

Intervisibility Functions (Viewshed Mapping- Perspective).

- use DEM to determine "line-of-sight"

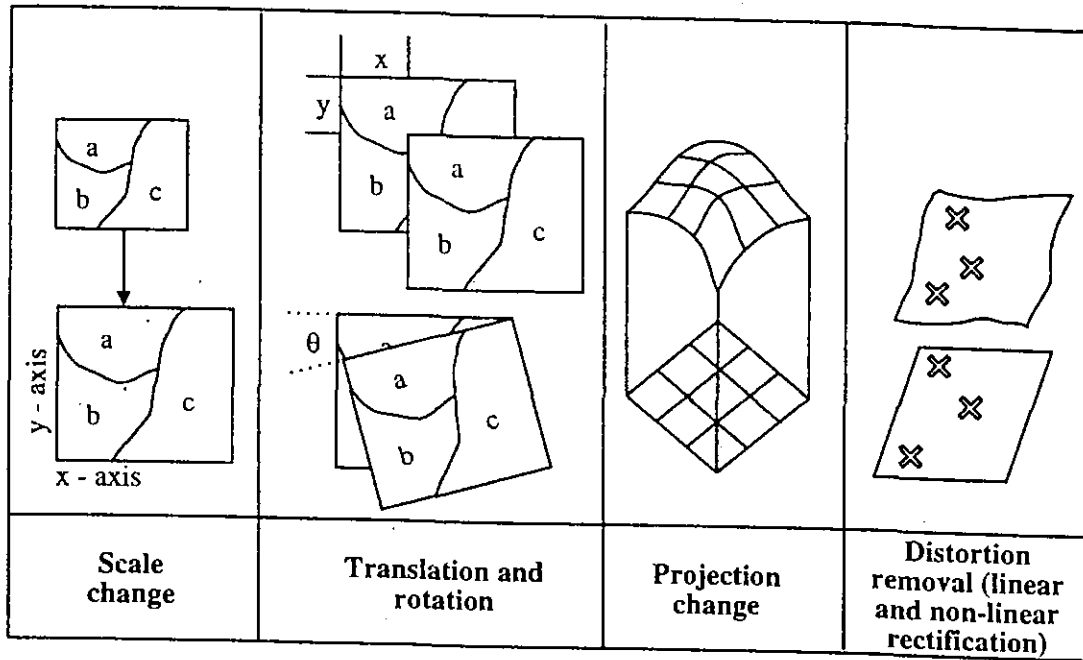


Figure 10-9 Fundamental geometric manipulation of GIS database files.

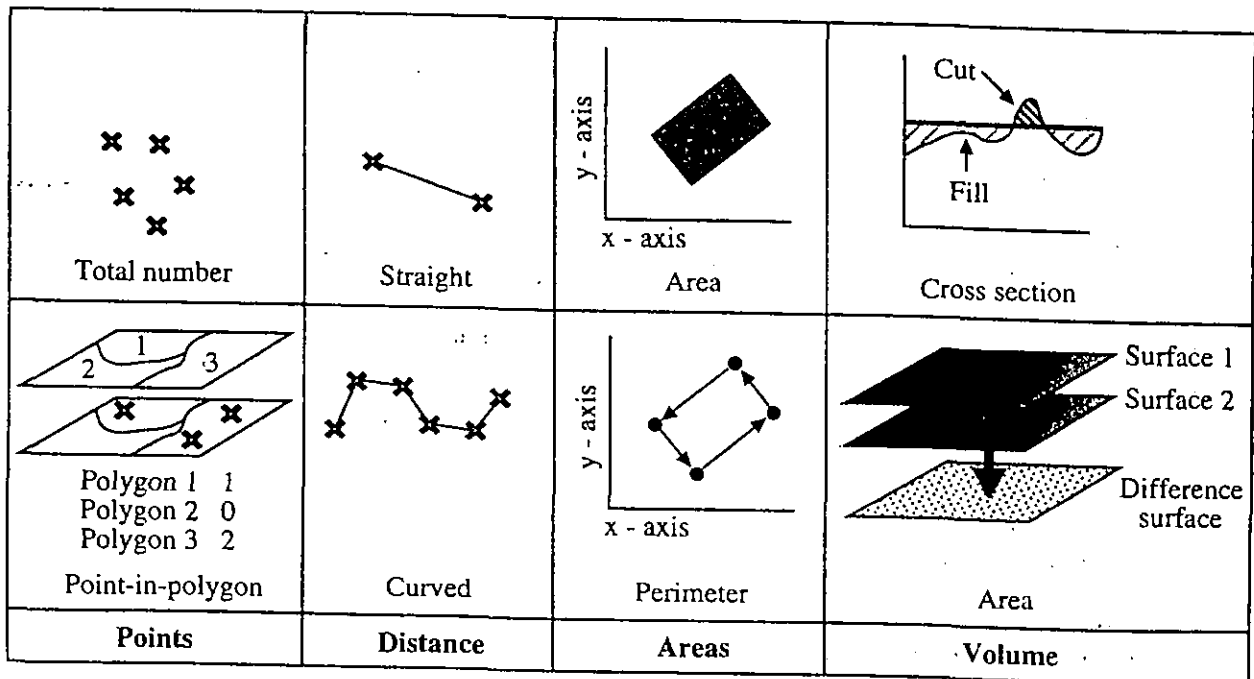


Figure 10-10 Measurement of points, distance, area, and volume in a GIS.

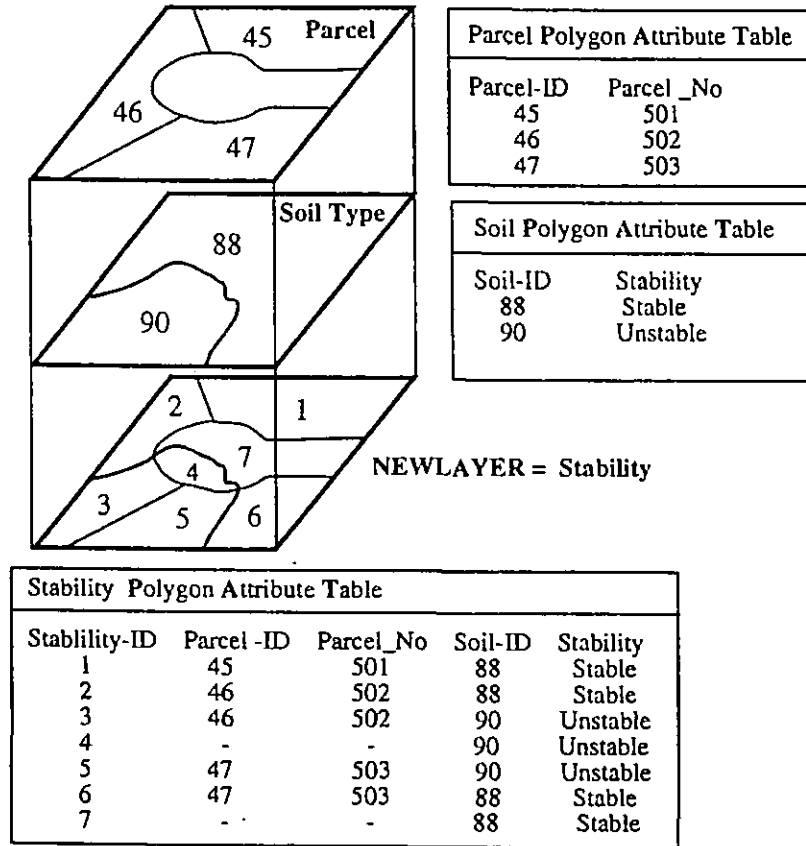


Figure 10-11 Polygon overlay of parcel and soil-type coverages to obtain the stability NEWLAYER. Note how the individual attribute tables are joined in the relational database to create a new attribute table, which may be queried to identify suitable parcels for development.

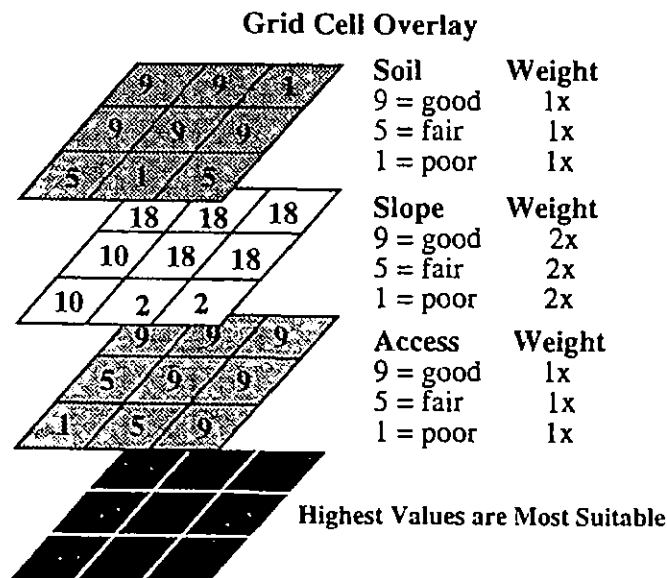


Figure 10-12 Logic of grid cell overlay using soils, slope, and access information to identify land suitability. The slope variable is weighted more heavily than the other two variables.

Data Integration

SPATIAL DATA INTEGRATION**Data sets can possess a diverse set of map characteristics**

- projection / geodetic datum
- accuracy (positional / attribute) (standards)
- error propagation
- data structure (raster / vector)
- spatial resolution / scale)
- completeness
- time
- lineage

Data Quality: Accuracy and Error**Introduction**

- in order to use digital data appropriately, knowledge of the quality of the data is required (should be quantitative)
- since GIS provides a wide range of analysis capabilities, using a variety of data sources, data accuracy becomes an important issue
- standards for defining, assessing and reporting geographic data provide users with information suited to decision making

Micro Level Components

- data quality factors that pertain to individual data elements
- statistical analysis (reference to "truth")

Positional/Planimetric Accuracy

- mapped position in reference to true ground position
 - systematic error (bias)
 - mean positional error of sample points
 - random error (precision)
 - estimated by standard deviation

Assessment of Positional Accuracy

- root mean square error (RMS) or circular standard error (σ_c)
- do not separate bias and precision components of accuracy
- can subtract systematic error from the data set (see Treitz *et al.*, 1993)

Thematic Accuracy (Attribute Accuracy)

- attributes can be discrete or continuous
- to assess accuracy of continuous variables, use procedures similar to that of positional accuracy assessment
- assessing accuracy of discrete variables falls within the realm of "classification accuracy assessment"
- affected by # of classes, similarity of classes (confusion between classes), shape and size of individual areas, the manner in which validation (test) sites are selected

Assessment of Thematic Accuracy

- accepted procedures for assessing thematic accuracy (originate from the remote sensing literature)
- accuracy assessments reported along with resulting map

Logical Consistency

- relationship between boundaries of different layers that should match
- slivers (i.e., polygon resulting from inconsistent boundaries in overlay analysis)
- “fuzzy boundaries” - tolerance level
- best addressed during data input stage (conflation)

Resolution (Scale)

- smallest discernible unit or the smallest unit represented
 - images - spatial resolution (lines/mm, pixel)
 - thematic maps (pixel; minimum mapping unit)
- smallest units to include in a map are selected during map compilation
- presentation and storage are issues to be addressed
- data can be presented a variety of scales
- however, data accuracy and precision are suited to specific scales

Macro Level Components

- pertain to the data set as a whole (not assessed statistically)

Completeness

- qualitative assessment
- coverage, classification and verification

Time

- time is an important attribute for spatial data

Lineage

- includes not only the source of the original data but the processing stages used to derive it

Sources of Error

- “the objective in dealing with error should not be to eliminate it but to manage it”

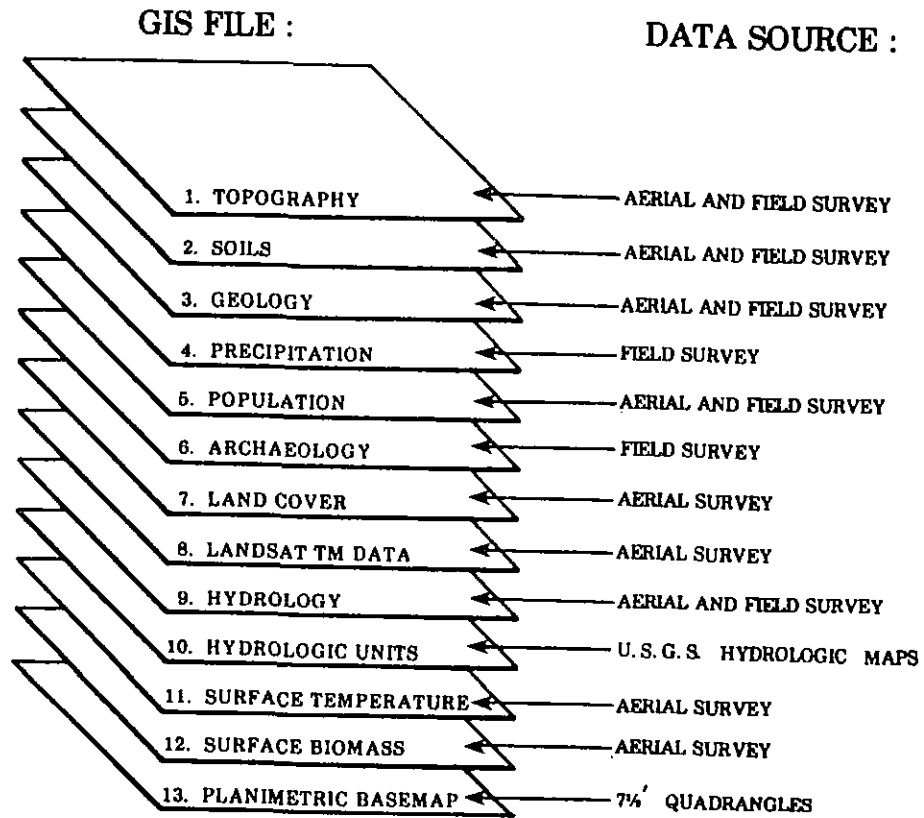


Figure 10-6 A computerized geographic information system can be conceptualized as a base map accompanied by numerous registered overlays (files). This example illustrates a grid-based GIS where 13 matrices are in near-perfect registration. Information in the data base was derived from a variety of sources.

REMOTE SENSING AND GIS INTEGRATION

- both remote sensing and GIS are used to collect, analyze and report information about the earth's resources and the infrastructure humankind has developed to use them
- 1. GIS applications can benefit from the information that remote sensing data can generate.
- 2. Remote sensing analyses are improved by the verification data that can be retrieved from a GIS.

Satellite data differ from all other geographic data in their:

- (i) consistency;
- (ii) high spatial and temporal resolution; and
- (iii) low level of human interpretation or abstraction.

Problem: integrated analysis requires multiple data structures and a software that supports a wide range of spatial queries and promote statistical and deterministic modelling

Why Integrate GIS and RS?

Advantages for GIS

- global coverage (uniform with respect to date and level of detail)
- up-to-date (repetitive)
- data is readily available (archived)
- data acquisition is relatively inexpensive
- satellite image data are in digital form.

Advantages for RS

- abundance of spatial data already collected can enhance remote sensing analyses

GLOBAL POSITIONING SYSTEMS (GPS) DATA

What is GPS?

- satellite-based navigation, positioning and timing system
- the GPS consists of a constellation of satellites orbiting the earth at very high altitudes (20,000 km)
- funded by the US Department of Defense - US DoD (designed by the US DoD to simplify accurate navigation by measuring: position; velocity; and time)
- will provide the user with the ability to locate their position anywhere on the earth 24 hours a day
- the system uses satellites and computers to triangulate position

How does GPS Work?

1. Triangulation from satellites is the basis of the system.

GPS is based on satellite *ranging* (meaning that we figure our position on earth by measuring our distance from a group of satellites in space). The satellites act as precise reference points for us.

2 - dimensional triangulation (*latitude / longitude*) (Figure 1)

3 - dimensional triangulation (*altitude*) (Figure 2)

2. To triangulate position, the system measures the distance from each satellite by calculating the travel time of a coded microwave signal.

Distance from receiver to satellite: $D = V \times T$

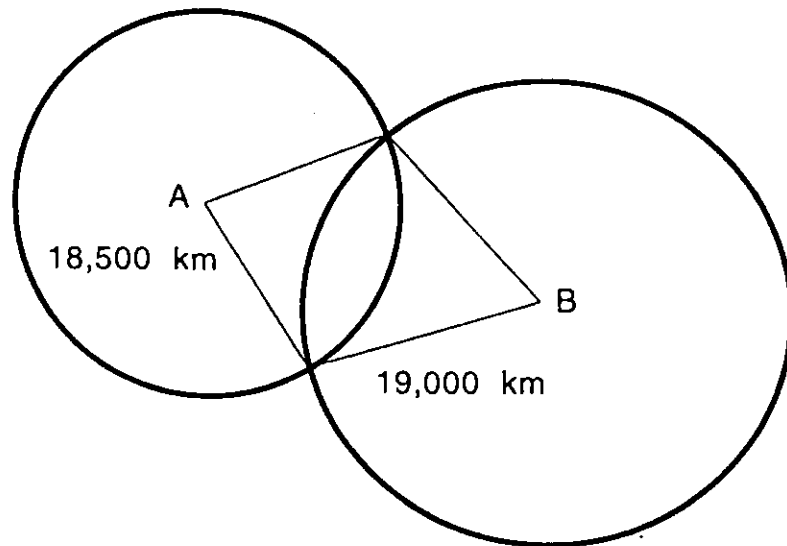
- V (velocity) of microwave energy is known (3×10^8 m/sec)

The clocks in the GPS satellites and receivers are synchronized to generate the same signal code at the same time.

- T (time) is determined by comparing the satellite signal with the signal produced by the receiver.
- C/A code (standard Civilian/Acquisition) 1.023 MHz.
- P code (Precise or Protected Code) 10.23 MHz
- satellites and receivers are synchronized to generate the same signal code at the same time (this is necessary to figure out exactly when the signal left the satellite)
- then when you receive the coded signal from the satellite all you have to do is look back to when the receiver generated the same signal
- the time difference is how long the signal took to get down to us.

Triangulation (in Two-Dimensional Space)

a)



b)

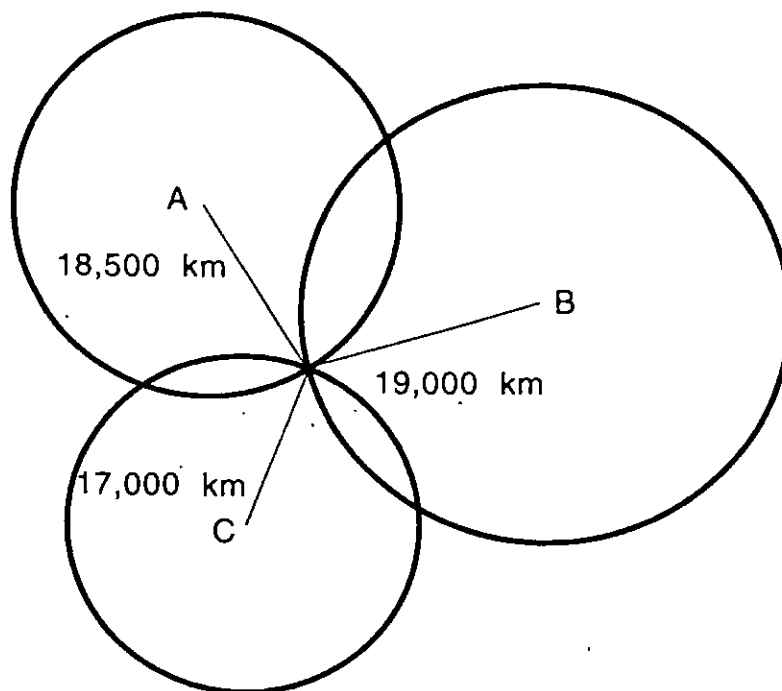
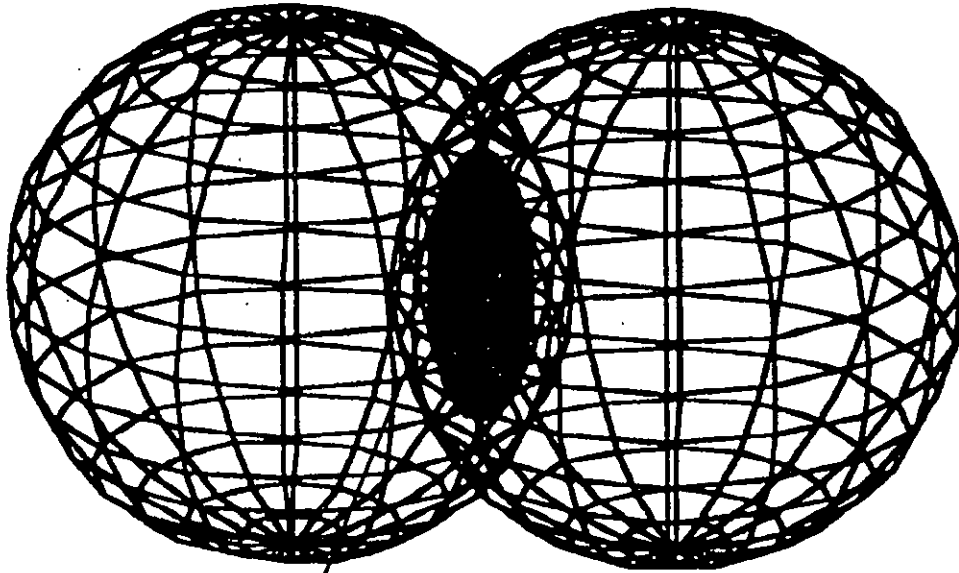


Figure 1

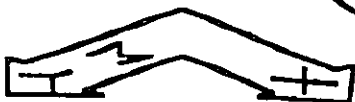
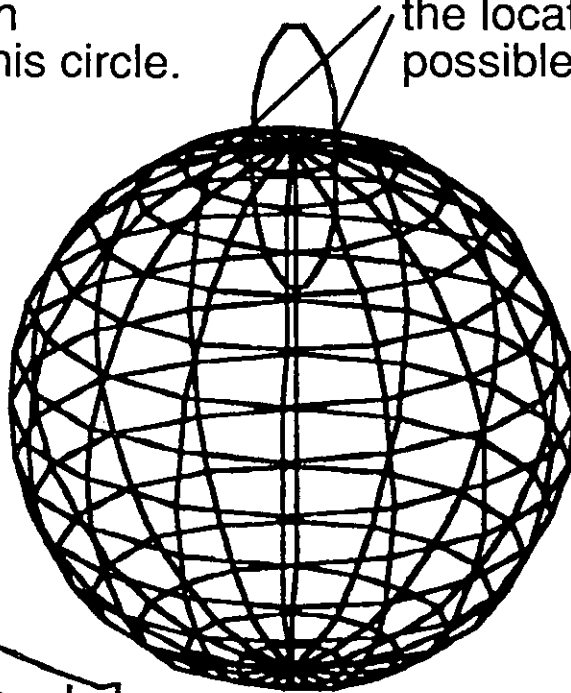
A third measurement (i.e., from C) is not necessary, since the system can recognize that one of the points is not logical (e.g., in a different hemisphere). Therefore, if two **precise** measurements can be made, an accurate position can be located in two-dimensional space.

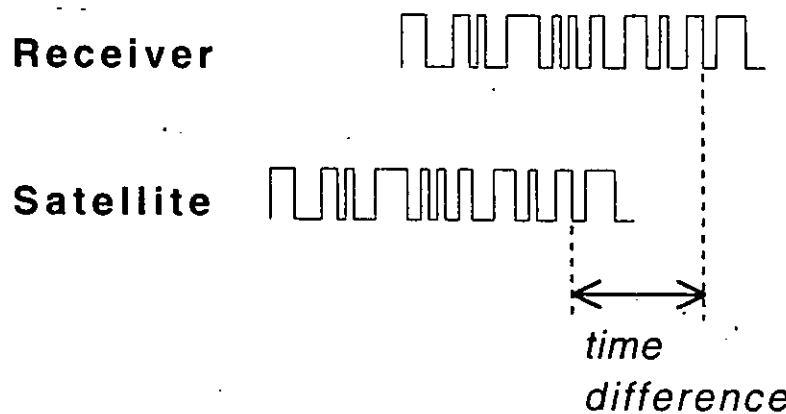
Triangulation (in Three-Dimensional Space)



Two measurements place the location somewhere on this circle.

Three measurements place the location at one of two possible points.





- satellites possess 4 atomic clocks for precise timing
- time measured to the nearest nanosecond (1×10^{-9} s)
- receivers possess less accurate clocks (additional satellite range is required to obtain position) (Figure 3)
- whereas three **precise** distance measurements can determine 3-dimensional positioning, four **imprecise** measurements can achieve the same results, as long as the offset is consistent).
- triangulation corrects for the timing offset

3. Orbit characteristics

- are programmed into the data recorder so that it knows where each satellite is at any given moment in time
- 20,000 km orbit with no atmospheric drag is very stable (predictable).
- however, DoD monitors each orbit twice a day
- satellites transmit data re their orbit parameters

4. Sources of Error

Ionospheric and Atmospheric Effects (Delays)

- affect the speed of light
- minimize this error by predicting what the typical speed variation will be on an average day, under average ionospheric conditions
- water vapor in the atmosphere also affects the signal, however, these are very difficult to model based on the random character of water vapor distribution in the atmosphere

Atomic Clocks

- subject to small variations (monitored by DoD)

Receivers

- e.g., electrical interference might cause an erroneous correlation of the pseudorandom codes

Geometry

- selection of satellites to optimize angular relationships for the calculation of point locations

Correcting for Clock Offset

(requirements for an additional satellite range measurement)

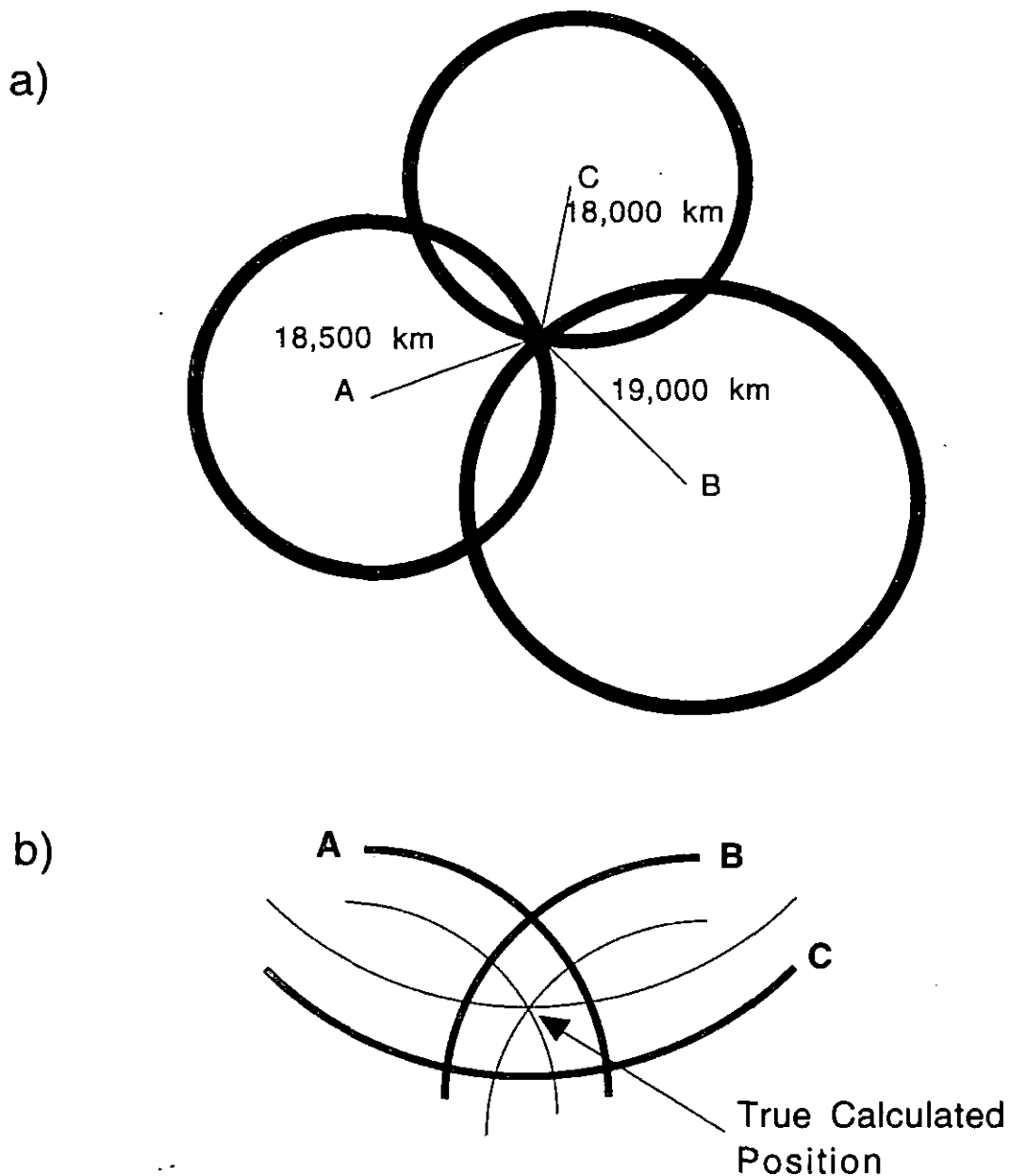
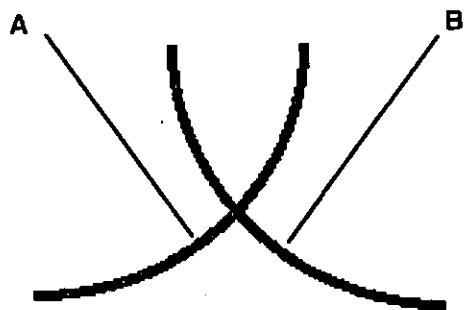
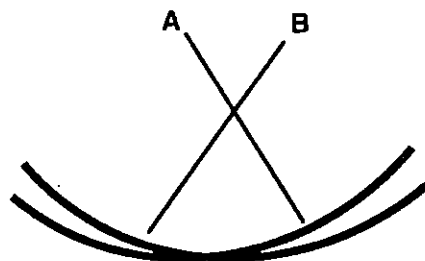


Figure 3

Since the clock on the receiver is not sufficiently precise, a third measurement is necessary for the accurate location of a position in two dimensions. Likewise a fourth measurement is necessary to accurately locate a position in three dimensions.



At large angles, the region of overlap is smaller.



At small angles, the region of overlap is larger.

Selective Availability

- accuracy purposely degraded by DoD
- largest component of GPS error

Differential GPS

- a technique to further improve accuracy
- requires a minimum of two receivers
- one at a known location is used to model the errors that the satellite data contains
- this error correction can then be transmitted to other GPS receivers in the area in order to correct their position solutions
- since the satellites are so high up, the errors experienced by one receiver, are almost identical to other receivers in the same locale
- able to model virtually all errors in the system

Code-based GPS Positioning for Mapping Systems

Benefits

- require only a fraction of a second to compute a position (high productivity)
- differential C/A code positioning can be performed in real-time or post-processed (accurate navigation)
- C/A code receivers do not require a constant lock with satellites to calculate positions (harsher environments)
- positions can be computed either differentially from two receivers or autonomously from one receiver

Drawbacks

- limited accuracy (horizontal accuracy ranging from sub-metre to metres)

Carrier-based GPS Positioning for Mapping Systems

Benefits

- horizontal accuracies to a few centimetres
- vertical accuracy also within the centimetre range

Drawbacks

- longer data acquisitions times (minimum 10 minutes) to achieve centimetre accuracy
- must maintain continuous lock with a minimum of four satellites to compute position (unobstructed view of horizon)
- require elaborate post-processing requirements
- carrier-based GPS positions can only be computed differentially