PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

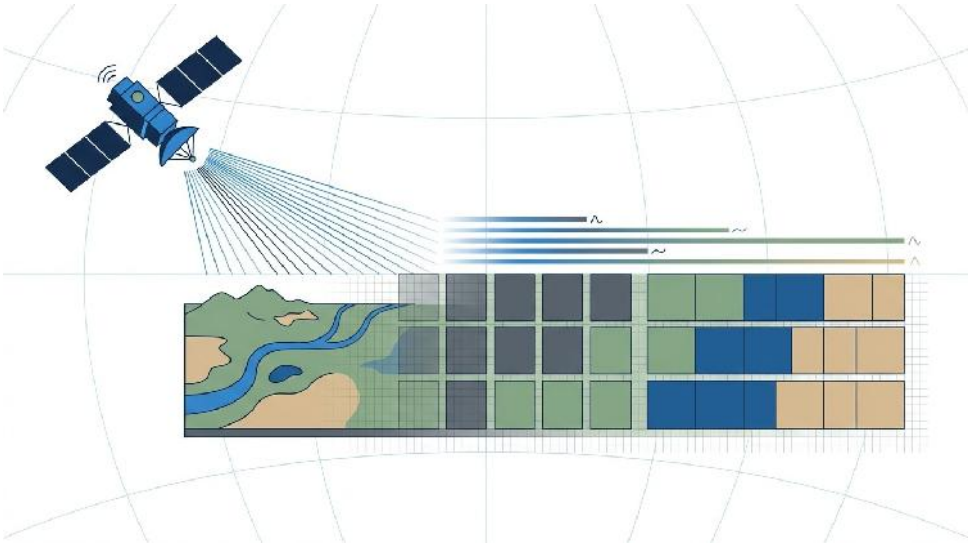
**UNIVERSITY OF OUM EL BOUAGHI**

**INSTITUTE OF URBAN TECHNIQUES MANAGEMENT**

## Applied Geomatics 2

# INITIATION TO REMOTE SENSING

A Pedagogical Handout for the Master's Programme



**1st-Year Master -Urban Techniques Management-**

PREPARED BY: .DR. ABDERRAZIQ DJAKJAK

Associate Professor - Institute of Urban Techniques Management

ACADEMIC YEAR 2025 – 2026

# Applied Geomatics 2

# INITIATION TO REMOTE SENSING

## Course Handout — Licence 2

**Applied Geomatics 2: (Introduction to Remote Sensing)**

**Target audience**

This handout is intended for students in the 1st year of the Master's program in "GTU" (Urban Techniques Management), specializing in city management.

**Identification of the course — Semester: *S2***

**Teaching Unit (UE): Methodological Unit (UEM) — Course 2 title: Applied Geomatics 2**

**Credits: 3**

**Coefficient: 3**

**General teaching objective:**

1. Deepening knowledge in the processing and extraction of information from satellite images
2. Mastering remote sensing tools

**Recommended prior knowledge**: Basic notions of aerial photography; fundamental notions of cartography and GIS

**Course content**

- Definitions
- Physical foundations of remote sensing
- Electromagnetic radiation
- Signal complexity and interfering media
- Spectral behavior of objects (vegetation, water, minerals)
- 3- Sensor performance
- Spatial resolution
- Spectral resolution
- Radiometric resolution
- Temporal resolution
- Thematic approach to exploiting satellite images (application using ENVI 5. software)
- Introduction and getting started with ENVI 5.1 software
- Two-dimensional histogram and band cross-plotting
- Index calculation (Vegetation, Water, Built-up areas)
- Supervised classification on multispectral images
- Producing a land-use / land-cover map
- Layout of image maps (spatiomaps) (in ENVI and with ArcGIS)
- Geometric corrections and diachronic (multitemporal) analysis of satellite images

# Table of content


**Introduction** ..... **1**

**Chapter 1 — Foundations of Spaceborne Remote Sensing** ..... **3**

1.1 What is remote sensing? ..... 3

1.2 The remote sensing measurement chain ..... 4

1.3 Passive and active systems ..... 5

1.4 A brief history of remote sensing ..... 5

1.5 Why remote sensing matters for urban and territorial management ..... 6

**Chapter 2 — The Physical Basis of Remote Sensing** ..... **7**

2.1 Electromagnetic radiation ..... 7

2.2 The electromagnetic spectrum ..... 7

2.3 Blackbody radiation, Planck's law, and Wien's law ..... 8

2.4 Interactions with the atmosphere ..... 10

2.4.1 Scattering ..... 11

2.4.2 Absorption ..... 11

2.4.3 Atmospheric windows ..... 11

2.5 Radiometric quantities ..... 12

**Chapter 3 — Data Acquisition: Platforms, Sensors, and Orbits** ..... **13**

3.1 Platforms ..... 13

3.2 Sensors: passive and active ..... 13

3.3 Orbits ..... 13

3.3.1 Geostationary orbit ..... 14

3.3.2 Polar and Sun-synchronous orbits ..... 14

3.3.3 Low Earth orbit and constellations ..... 14

**Chapter 4 — Sensor Performance: The Four Resolutions** ..... **16**

4.1 The concept of resolution ..... 16

4.2 Spatial resolution ..... 16

4.3 Spectral resolution ..... 17

4.4 Radiometric resolution ..... 17

4.5 Temporal resolution ..... 18

4.6 The fundamental trade-off ..... 18

**Chapter 5 — Spectral Behaviour of Surface Materials** ..... **19**

5.1 The spectral signature ..... 19

5.2 Vegetation ..... 19

5.3 Water ..... 20

5.4 Soil ..... 20

5.5 Vegetation indices ..... 20

**Chapter 6 — Image Pre-processing and Corrections** ..... **22**

6.1 Why correction is necessary ..... 22

6.2 Radiometric correction ..... 22

6.3 Atmospheric correction ..... 22

6.4 Geometric correction ..... 23

6.5 Resampling ..... 23

**Chapter 7 — Storage, Enhancement, and Multispectral Composites ..... 24**

7.1 The digital image as a raster ..... 24

7.2 Contrast enhancement ..... 24

7.3 Colour composites ..... 24

**Chapter 8 — A Survey of Earth-Observation Satellites ..... 26**

8.1 Overview ..... 26

8.2 The Landsat programme ..... 26

8.3 The SPOT programme ..... 27

8.4 ASTER and the Terra platform ..... 27

8.5 Very-high-resolution commercial systems ..... 27

**Chapter 9 — Image Classification and Thematic Mapping ..... 29**

9.1 The goal of classification ..... 29

9.2 Unsupervised classification ..... 29

9.3 Supervised classification ..... 30

9.4 A practical workflow ..... 30

9.5 Accuracy assessment ..... 31

**Chapter 10 — Spectral Indices: A Practical Catalogue ..... 32**

10.1 What is a spectral index? ..... 32

10.2 A catalogue of common indices ..... 32

10.3 Choosing and using an index ..... 33

**Chapter 11 — Photogrammetry, Stereoscopy, and Elevation Models ..... 34**

11.1 Stereoscopy and parallax ..... 34

11.2 Generating a digital elevation model ..... 34

11.3 Surface versus terrain models ..... 35

11.4 Applications ..... 35

**Chapter 12 — Accuracy Assessment and Sampling Design ..... 36**

12.1 Why assess accuracy? ..... 36

12.2 Sampling designs ..... 36

12.3 The confusion matrix and its measures ..... 36

**Chapter 13 — Integrating Remote Sensing with GIS ..... 38**

13.1 Complementary technologies ..... 38

13.2 Raster and vector ..... 38

13.3 Spatial analysis for urban management ..... 38

**Chapter 14 — Field Data, Validation, and Project Design ..... 40**

14.1 The role of field data ..... 40

14.2 Collecting reference data ..... 40

14.3 Designing a project ..... 40

**Chapter 15 — Machine Learning for Image Classification ..... 42**

15.1 From statistical to machine-learning classifiers ..... 42

15.2 Common classifiers ..... 42

15.3 Deep learning and convolutional networks ..... 42

15.4 Requirements and pitfalls ..... 43

**Chapter 16 — Image Fusion and Pansharpening ..... 44**

16.1 Why fuse images? ..... 44

16.2 Pansharpening ..... 44

16.3 Other forms of fusion ..... 44
**Chapter 17 — Elements of Visual Image Interpretation ..... 46**
17.1 Why visual interpretation still matters ..... 46
17.2 The classical elements of interpretation ..... 46
17.3 Applying the elements ..... 46
**Chapter 18 — Change Detection ..... 48**
18.1 The purpose of change detection ..... 48
18.2 Families of methods ..... 48
18.3 Interpreting a change map ..... 48
**Chapter 19 — Microwave and Radar Remote Sensing ..... 50**
19.1 Why microwaves? ..... 50
19.2 The radar signal and backscatter ..... 50
19.3 Radar bands and polarization ..... 51
19.4 Synthetic aperture radar ..... 51
19.5 Radar interferometry ..... 52
19.6 Applications ..... 52
**Chapter 20 — LiDAR and Three-Dimensional Remote Sensing ..... 53**
20.1 The principle of lidar ..... 53
20.2 Returns and the point cloud ..... 53
20.3 Surface, terrain, and canopy models ..... 54
20.4 Applications ..... 54
**Chapter 21 — Thermal and Hyperspectral Remote Sensing ..... 55**
21.1 Thermal-infrared remote sensing ..... 55
21.2 Hyperspectral remote sensing ..... 56
**Chapter 22 — Data Sources, Archives, and Cloud Platforms ..... 57**
22.1 Open archives and their significance ..... 57
22.2 The main free satellite families ..... 57
22.3 Cloud platforms ..... 57
**Chapter 23 — Practical Tutorials: QGIS, ENVI, and ArcGIS ..... 59**
23.1 Tutorial A — Computing NDVI in QGIS ..... 59
23.2 Tutorial B — Supervised classification in ENVI ..... 59
23.3 Tutorial C — Finishing and analysis in ArcGIS ..... 60
23.4 Good practice common to all software ..... 60
**Chapter 24 — Case Studies in Urban and Territorial Management ..... 61**
24.1 Monitoring urban expansion ..... 61
24.2 Mapping a flood ..... 62
24.3 The urban heat island ..... 62
24.4 Agricultural monitoring at the urban fringe ..... 63
**Chapter 25 — Applications, Conclusion, and Perspectives ..... 64**
25.1 From measurement to decision ..... 64
25.2 Applications in urban and territorial management ..... 64
25.3 Trends and perspectives ..... 64
25.4 Conclusion ..... 65
**Conclusion ..... 66**
**Appendix A — Exercises with Solutions ..... 67**

A.1 Radiation and physics ..... 67
A.2 Resolutions and sensors ..... 67
A.3 Indices and classification ..... 67
A.4 Radar, lidar, and thermal ..... 68
A.5 Integration and project design ..... 68
**Appendix B — Answers to Self-Assessment Questions ..... 69**
**Appendix C — Reference Tables ..... 71**
C.1 Physical constants ..... 71
C.2 Spectral regions ..... 71
C.3 Key formulas ..... 71
**Appendix D — Acronyms and Abbreviations ..... 72**
**Glossary (English – French) ..... 73**
**List of Tables ..... 75**
**List of Figures ..... 77**
**References ..... 78**

## Introduction

In the field of geographic information systems (GIS), imagery has now become a crucial epistemological element for the dynamic understanding of environments and territories. Professionals in the sector unanimously recognize that these visual representations offer an essential analytical dimension, making it possible not only to observe spatial transformations but also to contextualize complex data.

Recent technological developments have significantly expanded the scope and precision of imagery resources. A remarkable progression can be observed, both in terms of availability and of informational richness. Digital orthophotography, traditionally regarded as a documentary foundation, now stands alongside more sophisticated satellite imaging technologies, notably high-resolution colour and multispectral systems.

This technological shift is characterized by a constant improvement in spatial and spectral fidelity, substantially increasing the capacity to extract and interpret geographic information. GIS professionals thus have at their disposal increasingly powerful tools to decipher contemporary environmental dynamics, transforming imagery into a genuine scientific language for understanding territory.

Furthermore, imagery represents a fundamental resource for the acquisition, updating, and assessment of spatial data. Orthophotos and satellite images constitute privileged data sources that enable the precise digitization of structuring geographic features.

The main mapped features include linear infrastructure such as road networks, land-use zoning, building footprints, and public utility networks. The essential contribution of these technologies lies in their ability to dynamically document territorial changes, accurately identifying areas that have been recently developed and not yet incorporated into existing geospatial databases.

The optimization of these mapping processes now relies on the development of automated image-processing methods. These algorithmic approaches aim to significantly reduce the traditionally tedious workload associated with manual digitization tasks, by offering more efficient and accurate techniques for extracting geographic features.

The spectral analysis of imagery data represents a sophisticated scientific field that offers multidisciplinary methodological perspectives for the characterization and dynamic understanding of territorial systems. This approach allows for a nuanced exploration of land cover and land use through the extraction of precise spectral signatures, enabling in-depth investigations across several strategic domains.

The scientific applications of this methodology extend to several critical sectors, notably environmental mapping, infrastructure assessment, and territorial monitoring. Spectral techniques enable a detailed characterization of surfaces, allowing for the precise identification of construction materials, the structural assessment of road pavements, and the comparative analysis of spatial transformations.

Diachronic change detection constitutes a particularly innovative dimension, offering the possibility of documenting the temporal evolution of territories through the comparative analysis of images collected at different points in time. This approach generates robust scientific knowledge that can be directly mobilized in several strategic decision-making contexts: territorial planning, environmental assessments, heritage management, and institutional communication.

These advanced spectral methodologies thus represent a powerful analytical tool, enabling a multidimensional and dynamic understanding of territories and their transformations.

Within this handout, we undertake an in-depth exploration of the field of spaceborne remote sensing. The main objective lies in a systematic and multidimensional analysis of the mechanisms inherent to the satellite observation of our planet.

Our approach aims to deconstruct the fundamental principles of this discipline by rigorously examining its theoretical and practical components. We will first focus on a comprehensive understanding of the mechanisms of remote sensing, analyzing its structural principles, its technological advantages, and its intrinsic limitations. Particular attention will be given to the historical and epistemological evolution of terrestrial space observation, making it possible to contextualize contemporary developments.

The study will then address the physical foundations underlying spaceborne remote sensing, with an exploration of the scientific principles that govern this discipline. A fine-grained spectral analysis will make it possible to discriminate and interpret the spectral information originating from the various land covers, thus offering a nuanced reading of the collected data.

An essential part of this handout will be devoted to becoming familiar with satellite image-processing software (ENVI, ArcGIS, and QGIS), drawing on the knowledge developed in this field and thereby complementing our analysis with an empirical and practical dimension.

# Chapter 1 — Foundations of Spaceborne Remote Sensing

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Define remote sensing and distinguish it from in-situ measurement.
- Describe the essential components of a remote sensing system.
- Trace the historical development of the discipline from early aerial photography to modern satellite constellations.
- Explain why remote sensing has become indispensable for urban and territorial management.

## 1.1 What is remote sensing?

Remote sensing is the science, and to a large extent the art, of acquiring information about an object, an area, or a phenomenon through the analysis of data collected by a device that is not in physical contact with the target under investigation. In practice, the object of study is the surface of the Earth, and the acquisition device is a sensor mounted on an aircraft, a drone, or an artificial satellite. The defining characteristic of the discipline is therefore distance: measurements are taken from afar, without disturbing or touching the observed scene.

The information carrier that links the target to the sensor is electromagnetic radiation. Every object at a temperature above absolute zero emits, reflects, transmits, and absorbs electromagnetic energy in a manner that depends on its physical and chemical nature. A remote sensing instrument records the intensity of this radiation in one or several intervals of the electromagnetic spectrum. Because different materials interact with radiation in characteristic ways, the recorded signal can be interpreted to identify and map the composition, condition, and spatial arrangement of surface features.

It is useful to contrast remote sensing with in-situ, or ground-based, observation. A soil scientist who collects a sample and measures its moisture content in a laboratory is performing an in-situ measurement: the instrument is in contact with the target, the sampling is local, and the coverage is limited to the points that were physically visited. Remote sensing, by contrast, produces synoptic coverage: a single image can describe thousands of square kilometres simultaneously and repeatedly. This capacity for wide-area, repeatable, and consistent observation is what makes the technology transformative for disciplines such as urban planning, agriculture, hydrology, forestry, geology, and environmental monitoring.

**Working definition**

Remote sensing is the set of techniques that allow the physical and biological properties of the Earth's surface to be measured and interpreted from a distance, using the electromagnetic radiation reflected or emitted by that surface.

### 1.2 The remote sensing measurement chain

A complete remote sensing system can be decomposed into a chain of physical and logical stages. Understanding each stage is essential because a limitation or error introduced at any point propagates through the entire chain and ultimately constrains the quality of the information product delivered to the end user.

1. Energy source. An external or internal source of electromagnetic energy illuminates the scene. For passive systems the source is usually the Sun; for active systems the sensor carries its own source, such as a radar antenna or a laser.
2. Propagation through the atmosphere. As radiation travels from the source to the target and back to the sensor, it interacts with the atmosphere through scattering and absorption. These interactions modify the intensity and spectral distribution of the signal.
3. Interaction with the target. At the surface, energy is partly reflected, partly absorbed, and partly transmitted. The proportions depend on the wavelength and on the nature of the target, giving rise to the spectral signature of each material.
4. Recording by the sensor. The sensor collects the returning radiation, disperses it into spectral bands, and converts it into an electrical signal that is quantized into digital numbers.
5. Transmission, reception, and pre-processing. The raw data are transmitted to ground receiving stations, where they are calibrated, geometrically and radiometrically corrected, and archived.
6. Interpretation and analysis. Analysts and algorithms extract thematic information from the corrected imagery, producing maps, indices, and statistics.
7. Application. The extracted information is delivered to the user, who applies it to a decision problem such as monitoring urban growth or assessing crop health.

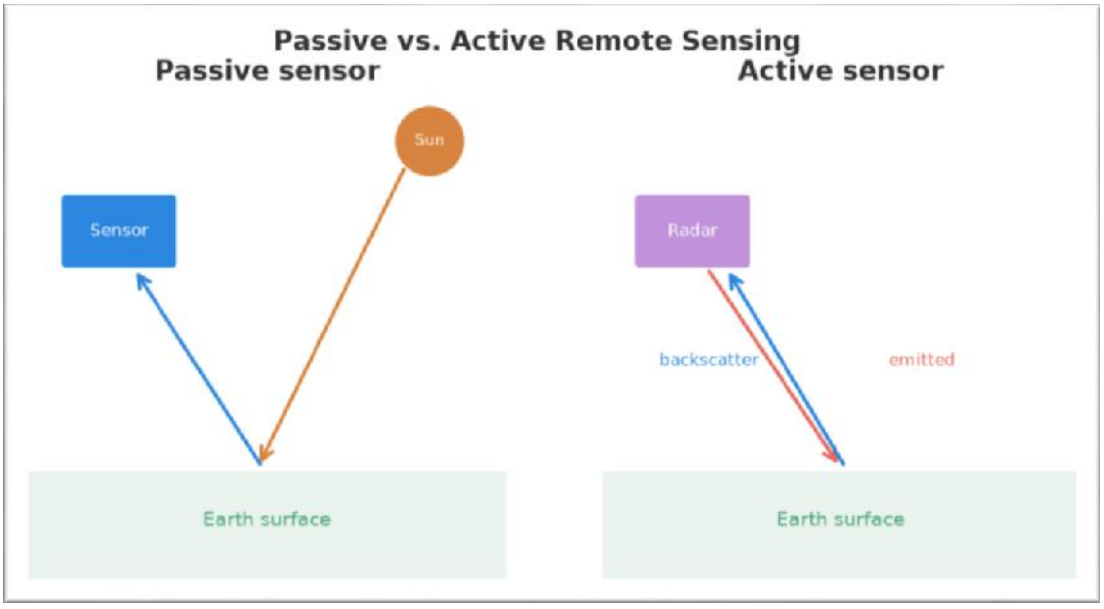



Figure 1.1 — The energy pathway for passive and active remote sensing systems. In a passive system the Sun illuminates the scene and the sensor records reflected radiation; in an active system the instrument both emits and receives the signal.

### 1.3 Passive and active systems

Remote sensing systems are divided into two broad families according to the origin of the energy they exploit. Passive systems detect natural radiation that is either reflected sunlight or thermal energy emitted by the surface itself. Optical sensors operating in the visible and infrared regions, and thermal sensors operating in the emissive infrared, are the most familiar passive instruments. Because they depend on the Sun, most passive optical systems can only acquire useful reflective imagery during daylight and under clear-sky conditions.

Active systems generate their own illumination. Radar (Radio Detection and Ranging) emits microwave pulses and measures the fraction of energy that is scattered back toward the antenna; lidar (Light Detection and Ranging) does the same with laser light. Because they supply their own energy, active systems can operate day or night, and microwave systems in particular can penetrate cloud cover, smoke, and light rain. This all-weather, all-time capability makes radar indispensable for regions that are frequently cloudy and for applications such as flood mapping and ground-deformation monitoring.

### 1.4 A brief history of remote sensing

The intellectual roots of remote sensing lie in the invention of photography and in the human desire to observe the Earth from above. The following milestones summarize the major stages of the discipline's development.

**Table 1.1 — Selected milestones in the history of remote sensing.**

| | | SIGNIFICANCE |
|---|---|---|
| **1839** | Invention of photography (Daguerre, Niépce) | Provides the first permanent recording medium for reflected light. |
| **1858** | First aerial photograph from a balloon (Nadar, Paris) | Demonstrates the value of the overhead perspective. |
| **1909** | First photographs from an aircraft (Wilbur Wright) | Establishes powered flight as an observation platform. |
| **1914-1918** | Systematic military aerial reconnaissance (First World War) | Drives rapid advances in cameras and photo interpretation. |
| **1939-1945** | Colour and infrared film; radar developed (Second World War) | Extends sensing beyond the visible and into all-weather microwave. |
| **1957** | Launch of Sputnik 1 | Opens the space age and the possibility of orbital platforms. |
| **1960** | TIROS-1, first meteorological satellite | Begins operational observation of the Earth from space. |
| **1972** | Launch of ERTS-1, later renamed Landsat 1 | Inaugurates continuous civilian land observation from orbit. |
| **1986** | Launch of SPOT-1 (France) | Introduces high-resolution, steerable, commercial imaging. |
| **1999** | Launch of IKONOS and Terra (ASTER, MODIS) | Brings sub-metre commercial imagery and advanced multispectral sensors. |
| **2008** | Opening of the Landsat archive at no cost | Democratizes access and transforms scientific practice. |
| **2014-2017** | Sentinel-1 and Sentinel-2 (Copernicus) | Delivers free, frequent, global radar and optical coverage. |

Two observations emerge from this chronology. First, each major advance in sensing was preceded by an advance in an enabling technology: photography, powered flight, rocketry, electronics, and digital computing. Second, the trajectory of the discipline has been toward finer spatial detail, richer spectral content, more frequent revisits, and, crucially, wider and cheaper access to data. The opening of the Landsat archive in 2008 and the free-and-open data policy of the European Copernicus programme have together placed petabytes of imagery in the hands of researchers, planners, and citizens worldwide.

### 1.5 Why remote sensing matters for urban and territorial management

For the manager of a city or a region, remote sensing offers a unique combination of properties that no other information source can match simultaneously: a bird's-eye synoptic view, systematic and repeatable acquisition, a permanent and objective archive, and the ability to measure quantities that the human eye cannot perceive, such as near-infrared reflectance or surface temperature. These properties translate directly into practical capabilities: mapping and updating land use and land cover, monitoring urban sprawl and the sealing of soils, detecting informal settlements, assessing the state of green infrastructure, planning transport corridors, evaluating exposure to natural hazards, and documenting change over time for regulatory and legal purposes.

**Relevance to the Master programme**

For students of urban techniques management, remote sensing is not an end in itself but a source of spatial data that feeds geographic information systems (GIS). The skills developed in this course — understanding what a sensor measures, correcting imagery, and extracting thematic classes — are precisely the skills required to build the reliable spatial databases on which sound urban decisions depend.

**Self-assessment 1**

1. In your own words, explain the difference between remote sensing and in-situ observation, and give one example of each in an urban context.
2. List the seven stages of the remote sensing measurement chain and state one source of error associated with each.
3. Why can radar acquire useful imagery at night and through clouds while an optical camera cannot?
4. Identify two historical milestones that you consider most important and justify your choice.

# Chapter 2 — The Physical Basis of Remote Sensing

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Describe electromagnetic radiation as both a wave and a stream of photons.
- Relate wavelength, frequency, and energy through the fundamental equations.
- State and apply Planck's law and Wien's displacement law.
- Explain how the atmosphere scatters and absorbs radiation, and define atmospheric windows.
- Define the principal radiometric quantities used to describe the signal.

## 2.1 Electromagnetic radiation

All remote sensing in the optical and microwave domains relies on electromagnetic radiation, a form of energy that propagates through space at the speed of light. Electromagnetic radiation exhibits a dual nature. In the wave description, it consists of coupled oscillating electric and magnetic fields, perpendicular to each other and to the direction of propagation. In the particle description, it consists of discrete packets of energy called photons. Both descriptions are necessary: the wave model explains phenomena such as interference and diffraction, while the photon model explains how radiation is emitted and absorbed by matter.

A wave is characterized by its wavelength, denoted by the Greek letter lambda, which is the distance between two successive crests, and by its frequency, denoted by the Greek letter nu, which is the number of oscillations passing a fixed point per second. Wavelength and frequency are linked by the speed of light c through the relation c equals lambda times nu. Because c is constant in a vacuum, wavelength and frequency are inversely proportional: the shorter the wavelength, the higher the frequency.

The energy carried by a single photon is proportional to its frequency, according to the Planck relation Q equals h times nu, where h is Planck's constant. Combining the two relations shows that photon energy is inversely proportional to wavelength: short-wavelength radiation such as ultraviolet light carries far more energy per photon than long-wavelength radiation such as microwaves. This has a practical consequence for sensor design: because long-wavelength radiation carries little energy, microwave and thermal sensors must collect energy over larger ground areas or longer times to obtain a measurable signal, which is one reason such sensors typically have coarser spatial resolution than visible-light sensors.

**Fundamental relations**

Speed, wavelength, frequency: $c = \lambda \nu$, with $c \approx 3.0 \times 10^8$ m/s.

Photon energy: $Q = h\nu = hc/\lambda$, with $h \approx 6.626 \times 10^{-34}$ J.s.

Consequence: energy increases as wavelength decreases.

## 2.2 The electromagnetic spectrum

The electromagnetic spectrum is the ordered continuum of all possible wavelengths of electromagnetic radiation, from the extremely short gamma rays to the very long radio waves. Remote sensing exploits only certain portions of this

continuum, chosen because the atmosphere is sufficiently transparent there and because the surface materials of interest interact with radiation in informative ways. The regions of greatest importance are the visible (approximately 0.4 to 0.7 micrometres), the near infrared (0.7 to 1.3 micrometres), the shortwave infrared (1.3 to 3 micrometres), the thermal infrared (3 to 14 micrometres), and the microwave (1 millimetre to 1 metre).

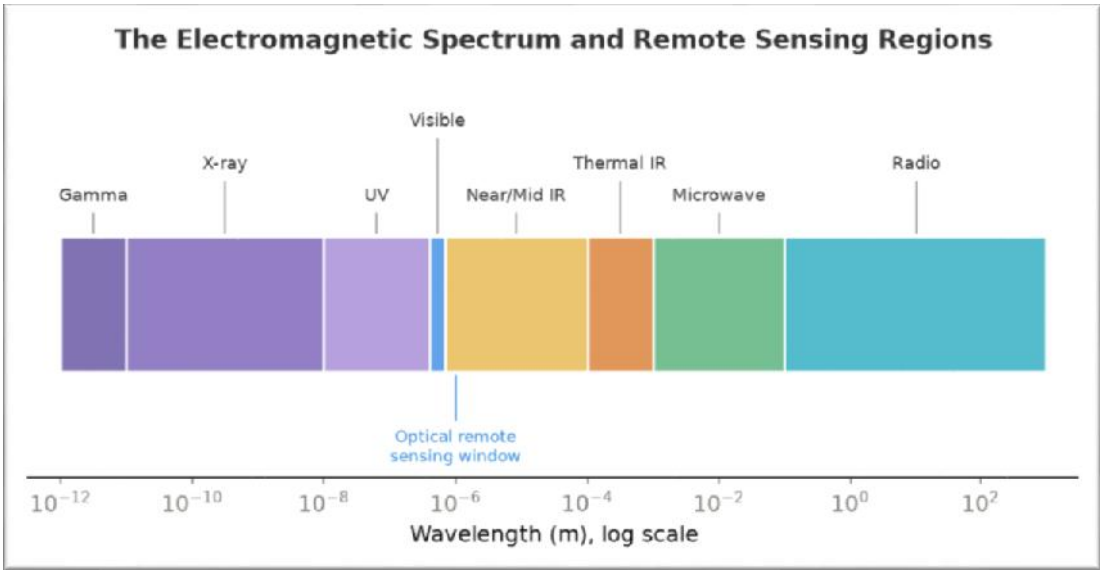



Figure 2.1 — The electromagnetic spectrum. The visible region exploited by human vision and by optical cameras occupies only a narrow band; remote sensing extends observation into the infrared and microwave regions that the eye cannot perceive.

The visible region is the only part of the spectrum to which the human eye is sensitive, and it is conventionally divided into the blue, green, and red bands. Beyond the red lies the infrared, which is subdivided into the reflective infrared, where the recorded energy is predominantly reflected sunlight, and the thermal infrared, where the recorded energy is predominantly emitted by the surface according to its temperature. The microwave region, at still longer wavelengths, is the domain of radar.

**2.3 Blackbody radiation, Planck's law, and Wien's law**

To understand emitted radiation we introduce the concept of a blackbody, an idealized object that absorbs all radiation incident upon it and re-emits energy with perfect efficiency. The spectral distribution of the energy emitted by a blackbody depends only on its absolute temperature and is described by Planck's law. The law predicts that, at any temperature above absolute zero, a blackbody emits radiation across a broad range of wavelengths, with a characteristic peak whose height and position depend on temperature.

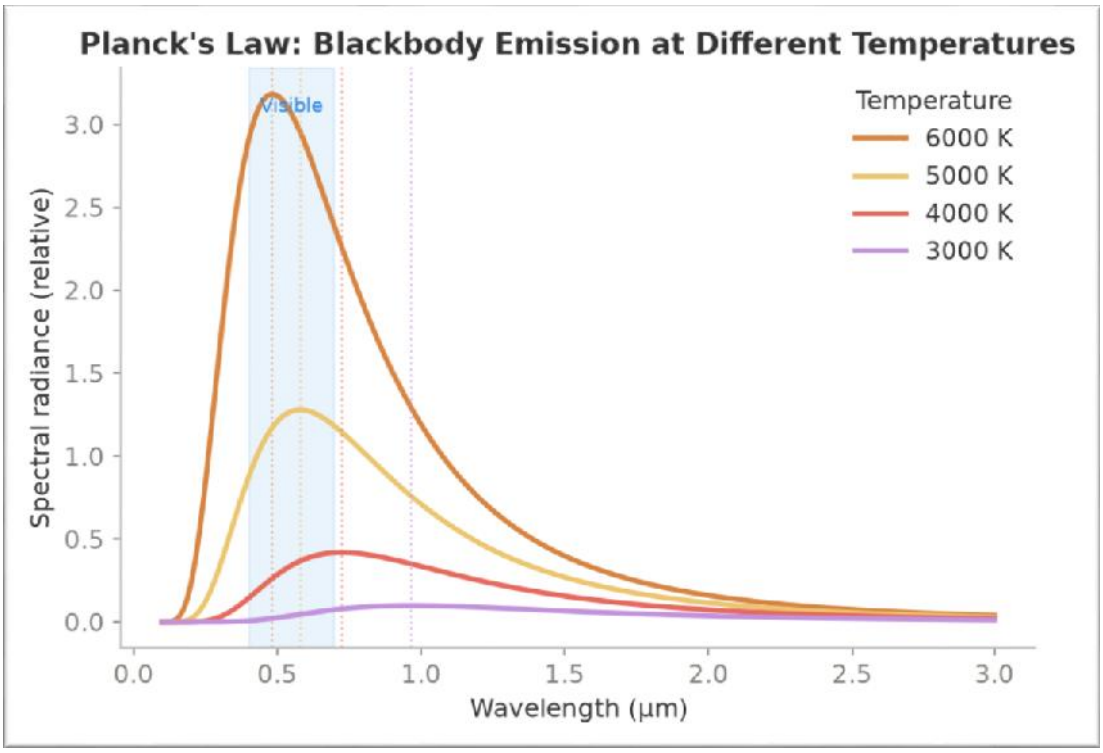



Figure 2.2 — Planck curves for blackbodies at several temperatures. Hotter bodies emit more energy at every wavelength, and the peak of emission shifts toward shorter wavelengths as temperature increases.

Two consequences of Planck's law are of direct interest. First, the hotter the body, the greater the total energy emitted at every wavelength; the total radiant emittance increases with the fourth power of the absolute temperature, a result known as the Stefan-Boltzmann law. Second, the wavelength at which emission reaches its maximum shifts toward shorter wavelengths as temperature rises. This second result is Wien's displacement law, which states that the peak wavelength is inversely proportional to absolute temperature.

**Wien's displacement law**

lambda_max = b / T, where b approximately equals 2898 micrometre-kelvin.

For the Sun (T approximately 5800 K), lambda_max is about 0.50 micrometres, in the visible green.

For the Earth (T approximately 300 K), lambda_max is about 9.7 micrometres, in the thermal infrared.

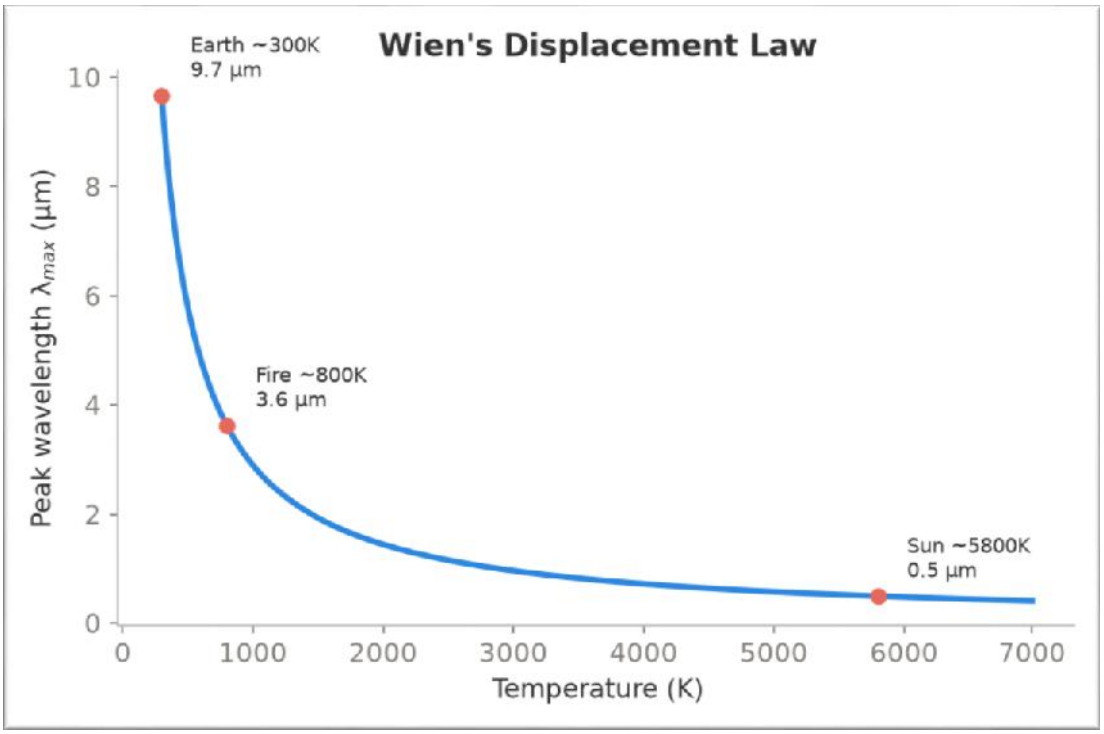



Figure 2.3 — Wien's displacement law. The wavelength of peak emission decreases as temperature increases, explaining why the Sun peaks in the visible while the Earth peaks in the thermal infrared.

These laws explain a fundamental division of labour in remote sensing. Because the Sun emits most strongly in the visible and near infrared, sensors operating in these regions record reflected sunlight and are most useful for characterizing surface reflectance. Because the Earth emits most strongly near ten micrometres, sensors operating in the thermal infrared record energy emitted by the surface and are used to map surface temperature. The two regimes require different instrument designs and different physical models of interpretation.

> **Worked example 2.1 — Applying Wien's law**
>
> Problem: A wildfire front burns at an effective temperature of about 800 K. At what wavelength does its thermal emission peak, and which spectral band would you select to detect it?
>
> Solution: Applying Wien's law, lambda_max = 2898 / 800 = 3.6 micrometres. The peak lies in the mid-wave (shortwave-to-mid) thermal infrared. A sensor band centred near 3.5 to 4.0 micrometres is therefore well suited to detecting active fires, which is precisely why fire-detection channels on operational satellites are placed in this region.

### 2.4 Interactions with the atmosphere

Between the surface and the sensor lies the atmosphere, a mixture of gases and suspended particles that modifies radiation through two principal mechanisms: scattering and absorption. Both must be understood because they degrade the signal and because, if left uncorrected, they introduce systematic errors into quantitative analysis.

### 2.4.1 Scattering

Scattering is the redirection of radiation by particles in the atmosphere. Its intensity depends on the size of the particles relative to the wavelength. Rayleigh scattering occurs when the particles, such as air molecules, are much smaller than the wavelength; it is inversely proportional to the fourth power of the wavelength and therefore affects short blue wavelengths far more than long red ones, which is why the clear sky appears blue. Mie scattering occurs when the particles, such as aerosols, smoke, and dust, are comparable in size to the wavelength; it affects longer wavelengths and contributes to the whitish appearance of a hazy sky. Non-selective scattering occurs when the particles, such as water droplets in clouds, are much larger than the wavelength; it affects all visible wavelengths equally and is why clouds appear white.

### 2.4.2 Absorption

Absorption is the conversion of radiant energy into heat within atmospheric molecules. It is highly selective: certain gases absorb strongly at specific wavelengths. Water vapour, carbon dioxide, and ozone are the principal absorbers. Water vapour absorbs strongly in several infrared bands; carbon dioxide absorbs in the thermal infrared; and ozone absorbs harmful ultraviolet radiation in the stratosphere. Where absorption is strong, little or no surface radiation reaches the sensor, and those wavelengths are unusable for surface observation.

### 2.4.3 Atmospheric windows

The wavelength regions where the atmosphere is relatively transparent, allowing radiation to pass with little attenuation, are called atmospheric windows. Remote sensing instruments are deliberately designed to observe within these windows. The principal windows are found in the visible and near infrared, in several shortwave-infrared intervals, in two thermal-infrared intervals near three-to-five and eight-to-fourteen micrometres, and across a broad range of microwave wavelengths. The choice of spectral bands for any sensor is dictated first by the location of these windows and second by the spectral features of the targets to be studied.

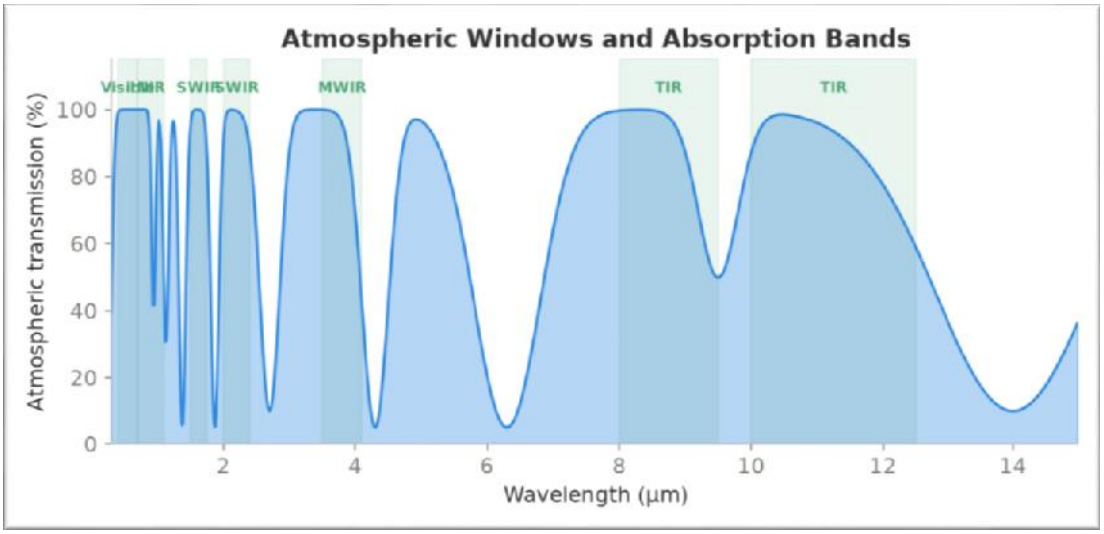



Figure 2.4 — Atmospheric transmission as a function of wavelength. Peaks of high transmission are the atmospheric windows used by remote sensing; troughs correspond to strong absorption by water vapour, carbon dioxide, and other gases.

### 2.5 Radiometric quantities

To describe the energy that flows through the remote sensing chain quantitatively, radiometry defines a set of standard quantities. A precise vocabulary is important because the numbers recorded by a sensor are ultimately measurements of one of these quantities, and quantitative applications require that we know exactly which one.

**Table 2.1 — Principal radiometric quantities.**

| QUANTITY | SYMBOL | DEFINITION | UNIT |
|---|---|---|---|
| **RADIANT ENERGY** | Q | Total energy carried by radiation | joule (J) |
| **RADIANT FLUX** | Phi | Energy per unit time | watt (W) |
| **IRRADIANCE** | E | Flux received per unit area of a surface | W/m^2 |
| **RADIANT EXITANCE** | M | Flux emitted per unit area of a surface | W/m^2 |
| **RADIANCE** | L | Flux per unit area per unit solid angle in a given direction | W/m^2/sr |
| **REFLECTANCE** | rho | Ratio of reflected to incident flux (dimensionless, 0-1) | — |

Of these quantities, radiance is the one most directly related to what an optical sensor measures, because a sensor collects energy arriving from a particular direction within a small solid angle. Reflectance, the ratio of reflected to incident energy, is the quantity most directly related to the nature of the surface, because it is largely independent of the illumination intensity. A central goal of radiometric calibration and atmospheric correction is to convert the raw digital numbers recorded by the sensor into radiance and then into surface reflectance, so that measurements acquired at different times or by different sensors can be compared on a common physical scale.

**Self-assessment 2**

1. A sensor records radiation at 11 micrometres. Is it more likely measuring reflected sunlight or emitted terrestrial radiation? Justify with reference to Wien's law.
2. Explain why the sky is blue during the day and reddish at sunset, using the wavelength dependence of Rayleigh scattering.
3. Define an atmospheric window and explain why sensor bands are placed within windows.
4. Distinguish radiance from reflectance and state why reflectance is preferred for comparing images acquired on different dates.

# Chapter 3 — Data Acquisition: Platforms, Sensors, and Orbits

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Distinguish the main types of platforms used to carry sensors.
- Classify sensors as passive or active and describe representative instruments.
- Compare geostationary, polar, and low Earth orbits and their uses.
- Explain the trade-offs that govern the design of an acquisition system.

### 3.1 Platforms

A platform is the vehicle or structure that carries a remote sensing instrument. The choice of platform determines the altitude of observation, the area covered in a single acquisition, the achievable spatial detail, and the frequency with which a given site can be revisited. Three families of platforms are in common use: ground-based platforms such as masts and towers used for calibration and field spectroscopy; airborne platforms such as aircraft and, increasingly, unmanned aerial vehicles; and spaceborne platforms, namely artificial satellites orbiting the Earth. This course concentrates on spaceborne platforms because they provide the systematic, repetitive, and wide-area coverage that underpins operational monitoring.

Altitude is the single most influential property of a platform. A low-altitude aircraft can resolve very fine detail but covers only a small area and cannot revisit a site frequently or cheaply. A satellite in orbit covers vast areas and returns to the same region on a predictable schedule, but the great distance from the surface imposes a limit on the spatial detail that its optics can resolve. Every acquisition system is therefore a compromise between competing objectives.

### 3.2 Sensors: passive and active

As introduced in Chapter 1, sensors are classified by the origin of the energy they detect. Passive sensors measure natural radiation, whether reflected sunlight in the visible and reflective infrared or thermal energy emitted by the surface. They range from simple broadband radiometers to sophisticated imaging spectrometers that record hundreds of contiguous narrow bands. Active sensors supply their own energy: imaging radar illuminates the scene with microwave pulses and measures the backscattered signal, while lidar uses laser pulses to measure distance and to build precise three-dimensional models of terrain and structures.

The distinction has practical consequences for urban applications. Passive optical imagery is intuitive to interpret because it resembles a photograph and directly conveys the colour and reflectance of surfaces, but it is blocked by cloud and unavailable at night. Radar is less intuitive because its brightness encodes surface roughness, geometry, and moisture rather than colour, yet its all-weather capability makes it valuable for monitoring construction, subsidence, and flooding in any climate.

### 3.3 Orbits

A satellite follows a path around the Earth called an orbit, whose shape and altitude are chosen to serve the mission. Two orbit types dominate Earth observation, and a third is important for communications and certain scientific missions.

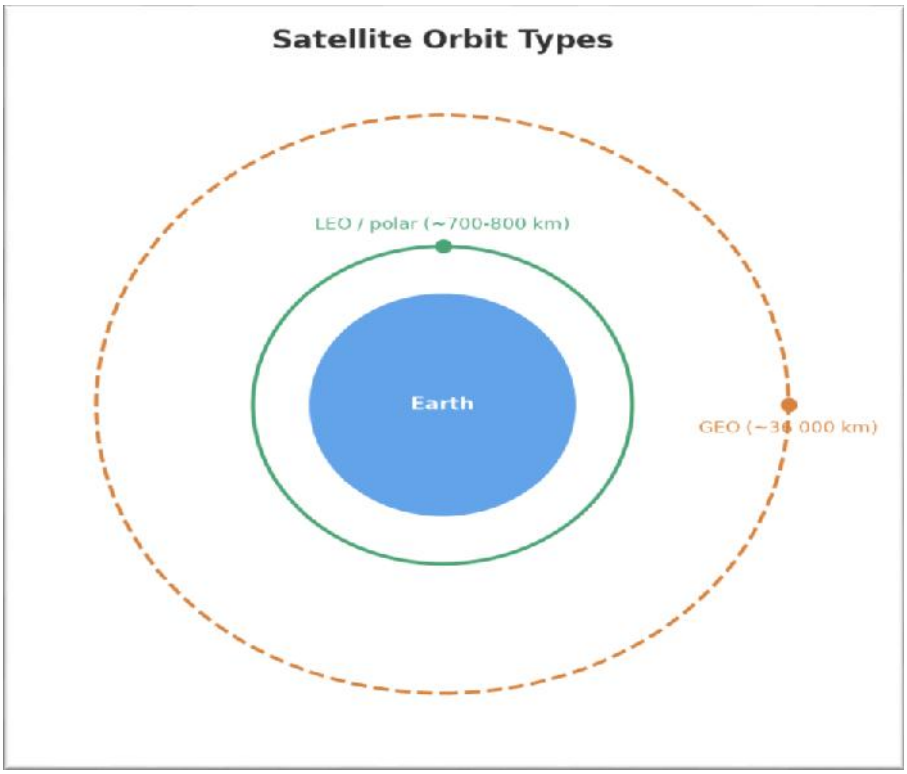



Figure 3.1 — Schematic comparison of a low Earth (polar) orbit and a geostationary orbit. Low orbits pass close to the surface and cross the poles; geostationary orbits are far away and remain fixed above a point on the equator.

### 3.3.1 Geostationary orbit

A geostationary satellite orbits at an altitude of approximately thirty-six thousand kilometres above the equator, completing one revolution in exactly the time the Earth takes to rotate once. As a result it appears to hover permanently above a fixed point on the equator, continuously viewing the same hemisphere. This configuration is ideal for meteorology and for the continuous monitoring of large-scale, rapidly changing phenomena such as weather systems, because a single satellite can image the entire visible disc every few minutes. The disadvantage is coarse spatial resolution, an inevitable consequence of the very great observing distance.

### 3.3.2 Polar and Sun-synchronous orbits

A polar-orbiting satellite travels at a much lower altitude, typically between six hundred and eight hundred kilometres, on a path that passes near both poles. As the satellite orbits, the Earth rotates beneath it, so that successive passes cover different strips of the surface until the entire globe has been imaged. Most land-observation satellites are placed in a special polar orbit called a Sun-synchronous orbit, arranged so that the satellite crosses the equator at the same local solar time on every pass. This ensures consistent illumination conditions, which greatly simplifies the comparison of images acquired on different dates — a prerequisite for reliable change detection.

### 3.3.3 Low Earth orbit and constellations

Beyond the classic Sun-synchronous configuration, many modern missions deploy constellations of several satellites sharing the same orbit. By distributing multiple identical instruments around the orbital plane, a constellation can revisit any location far more frequently than a single satellite could, reducing the revisit interval from weeks to days or even

hours. This strategy underlies the high temporal frequency of contemporary systems and is central to applications, such as monitoring rapid urban change or agricultural growth, that demand frequent observation.

**Choosing an orbit**

If the goal is continuous observation of large, fast-changing phenomena, choose a geostationary orbit and accept coarse resolution. If the goal is detailed, globally consistent mapping of the land surface, choose a Sun-synchronous polar orbit. If frequent revisit is essential, use a constellation.

**Self-assessment 3**

1. Why does a geostationary satellite appear stationary in the sky, and what limits its spatial resolution?
2. What advantage does a Sun-synchronous orbit provide for change detection?
3. Explain how a constellation reduces the revisit interval without improving the individual sensor.
4. For monitoring the daily progression of a wildfire over a region, which platform and orbit would you recommend, and why?

# Chapter 4 — Sensor Performance: The Four Resolutions

**Learning outcomes :** *By the end of this chapter you should be able to:*

- Define spatial, spectral, radiometric, and temporal resolution.
- Explain the trade-offs among the four resolutions.
- Interpret resolution specifications in sensor documentation.
- Select an appropriate sensor for a given application.

### 4.1 The concept of resolution

The performance of an imaging sensor is described by four complementary notions of resolution, each answering a different question about the detail the instrument can capture. Spatial resolution concerns how small an object can be distinguished; spectral resolution concerns how finely the spectrum is sampled; radiometric resolution concerns how precisely brightness is measured; and temporal resolution concerns how often the same place can be observed. A competent analyst must understand all four because they jointly determine whether a sensor is suitable for a given task, and because improving one usually comes at the expense of another.

### 4.2 Spatial resolution

Spatial resolution is the size of the smallest feature that a sensor can resolve on the ground, commonly expressed as the ground dimension of a single picture element, or pixel, also called the ground sample distance. A sensor with a spatial resolution of ten metres represents each ten-by-ten-metre patch of ground by a single averaged value. Finer resolution reveals smaller objects: streets, individual buildings, and vehicles become visible as resolution improves from tens of metres to less than one metre. Coarser resolution blurs such detail but allows a wider area to be imaged in one pass.

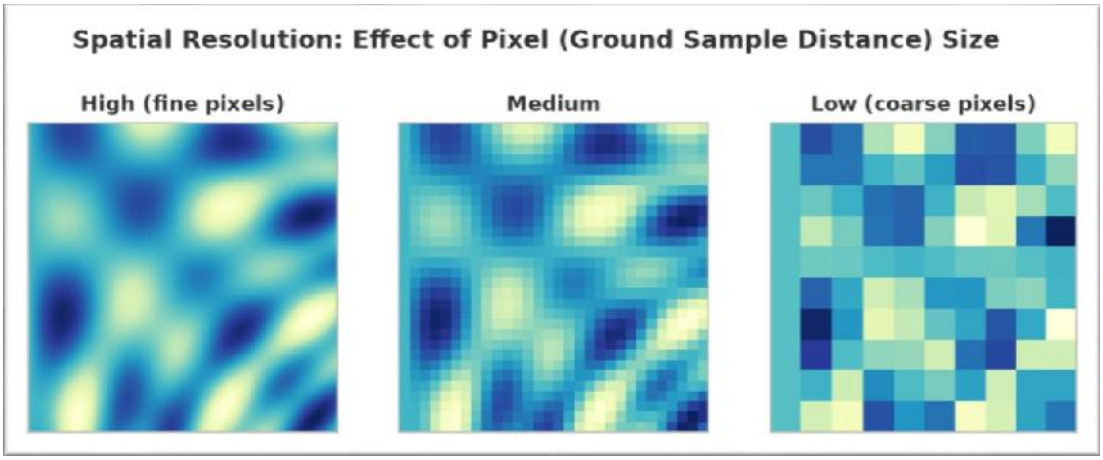



Figure 4.1 — The effect of spatial resolution. As the ground sample distance increases from fine to coarse, small features merge and detail is lost, while the same scene is represented by progressively fewer pixels.

For urban applications the choice of spatial resolution is critical. Mapping the general expansion of a city may be accomplished with medium-resolution imagery of ten to thirty metres, whereas identifying individual dwellings in an informal settlement or auditing the condition of a road surface requires very-high-resolution imagery finer than one

metre. The finer the resolution, however, the smaller the area covered per scene, the larger the data volume, and generally the higher the cost.

**4.3 Spectral resolution**

Spectral resolution refers to the number and width of the spectral bands a sensor records. A panchromatic sensor has a single broad band spanning much of the visible spectrum and produces a grey-scale image of high spatial detail. A multispectral sensor records several discrete bands — typically blue, green, red, near infrared, and shortwave infrared — enabling colour composites and spectral analysis. A hyperspectral sensor records tens or hundreds of narrow, contiguous bands, so that a nearly continuous reflectance spectrum can be reconstructed for every pixel, allowing subtle material distinctions such as mineral or vegetation species identification.

The narrower and more numerous the bands, the greater the ability to discriminate materials with similar appearance. This power comes at a cost: narrow bands collect less energy, which must be compensated by larger pixels or more sensitive detectors, and the resulting data volumes are large and demanding to process.

**4.4 Radiometric resolution**

Radiometric resolution is the sensitivity of a sensor to differences in the intensity of radiation, expressed as the number of discrete brightness levels used to record each measurement. It is usually stated in bits: an eight-bit sensor records two hundred and fifty-six levels, while a twelve-bit sensor records four thousand and ninety-six. Higher radiometric resolution allows the sensor to capture subtle variations in brightness, which is especially valuable in dark areas such as shadows or water and in very bright areas such as sand or snow, where a coarse scale would compress meaningful differences into a single value.

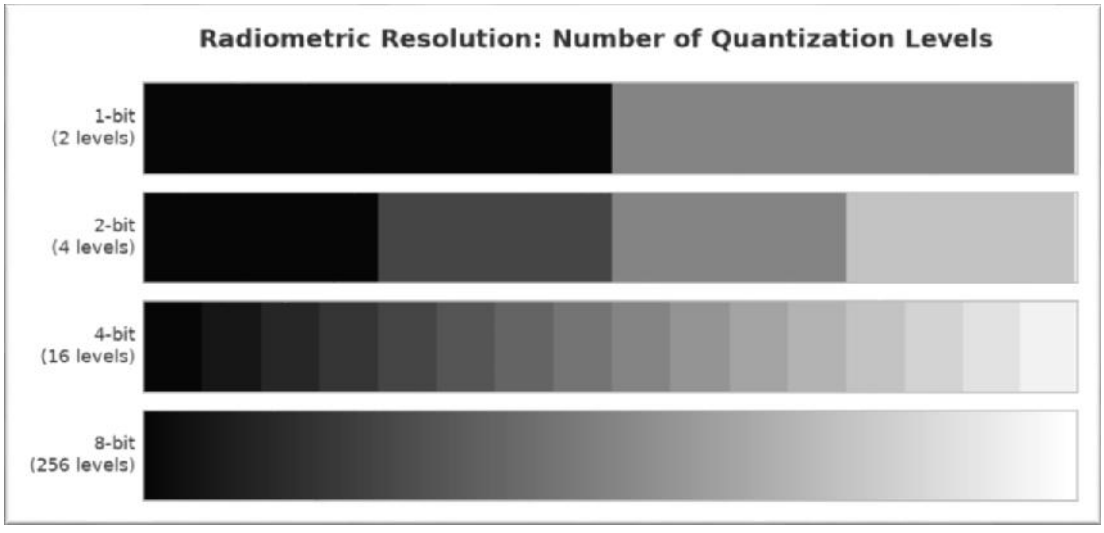



Figure 4.2 — The effect of radiometric resolution. As the number of quantization levels increases from two to two hundred and fifty-six, a smooth gradient of brightness is represented with progressively greater fidelity.

### 4.5 Temporal resolution

Temporal resolution, also called the revisit period, is the time that elapses between two successive observations of the same location by the same system. A short revisit period allows rapid change to be monitored and increases the chance of obtaining a cloud-free image within a useful time frame. Temporal resolution depends on the orbit, the width of the imaged swath, and, for agile sensors, the ability to point off-nadir toward a target on neighbouring passes. Constellations of satellites dramatically improve temporal resolution, as discussed in Chapter 3.

### 4.6 The fundamental trade-off

The four resolutions cannot all be maximized simultaneously because they draw on the same finite budget of energy and data. A detector element that views a smaller ground area, uses a narrower spectral band, or records more brightness levels collects less energy per measurement, which tends to increase noise. Designers therefore balance the resolutions according to the mission's purpose. A meteorological sensor sacrifices spatial detail for frequent, wide coverage; a very-high-resolution commercial sensor sacrifices swath width and spectral richness for fine spatial detail. Recognizing this trade-off is the key to selecting the right data for a given problem rather than assuming that finer is always better.

**Rule of thumb**

There is no single best sensor. The best sensor is the one whose balance of spatial, spectral, radiometric, and temporal resolution matches the scale, the material distinctions, and the observation frequency that your specific application requires.

**Self-assessment 4**

1. Define each of the four resolutions in a single sentence.
2. Why does improving spatial resolution tend to reduce the area covered by a single scene?
3. An analyst must map individual rooftops and update the map weekly. Which two resolutions are most critical and what values would you require?
4. Explain why a twelve-bit sensor can reveal detail in shadows that an eight-bit sensor may miss.

# Chapter 5 — Spectral Behaviour of Surface Materials

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the concept of a spectral signature.
- Describe and interpret the spectral behaviour of vegetation, water, and soil.
- Define and compute vegetation indices, including NDVI and WDVI.
- Relate spectral behaviour to practical mapping decisions.

## 5.1 The spectral signature

Every material reflects, absorbs, and transmits electromagnetic radiation in proportions that vary with wavelength. The curve that describes how the reflectance of a material changes across the spectrum is called its spectral signature. Because different materials have different signatures, the spectral signature is the physical basis for identifying and mapping surface cover from remotely sensed imagery. The art of interpretation consists largely of recognizing and exploiting the diagnostic features of these curves.

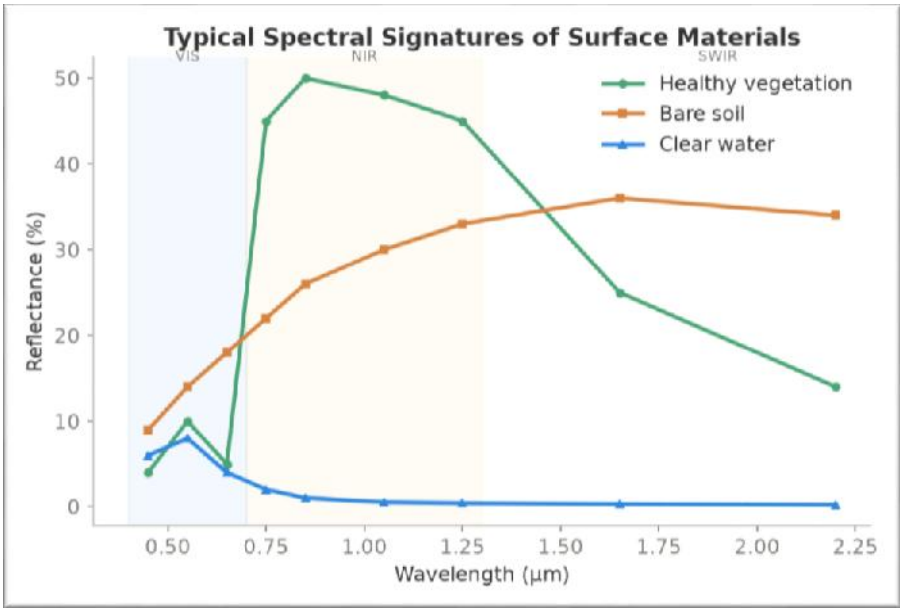



*Figure 5.1 — Typical spectral signatures of healthy vegetation, bare soil, and clear water across the visible, near-infrared, and shortwave-infrared regions.*

## 5.2 Vegetation

Healthy green vegetation displays one of the most distinctive and useful signatures in nature. In the visible region, chlorophyll in the leaves absorbs strongly in the blue and red bands to drive photosynthesis, while reflecting moderately in the green, which is why foliage appears green to the eye. At the boundary between the red and the near infrared the reflectance rises very steeply, a feature known as the red edge. In the near infrared, the internal cellular structure of leaves reflects strongly, producing high reflectance. In the shortwave infrared, absorption by leaf water content reduces reflectance again.

This combination — low red reflectance driven by chlorophyll absorption and high near-infrared reflectance driven by cell structure — gives healthy vegetation a large contrast between the red and near-infrared bands. When a plant is stressed, diseased, or senescent, chlorophyll declines, red reflectance rises, near-infrared reflectance falls, and the red-to-near-infrared contrast weakens. This behaviour makes the two bands an extraordinarily sensitive indicator of vegetation presence and vigour.

**5.3 Water**

Clear, deep water has a signature almost opposite to that of vegetation. It reflects weakly across the visible region, with the greatest reflectance in the blue and a rapid decline toward longer wavelengths, and it absorbs almost completely in the near and shortwave infrared, where its reflectance approaches zero. This strong infrared absorption makes water appear very dark in infrared bands and provides a simple and robust means of delineating water bodies. Suspended sediment, algae, and dissolved substances modify the visible portion of the signature and can be exploited to assess water quality.

**5.4 Soil**

Bare soil exhibits a comparatively smooth signature in which reflectance increases gradually and steadily from the visible through the near infrared. The overall level and shape of the curve depend on soil moisture, organic-matter content, iron-oxide content, mineral composition, and surface roughness. Moist soils are darker, reflecting less than dry soils; soils rich in iron oxides show enhanced reflectance in the red. Because the soil signature lacks the sharp red edge of vegetation, the two are readily separated in the red and near-infrared bands, which is the foundation of vegetation indices.

**5.5 Vegetation indices**

A vegetation index is an arithmetic combination of two or more spectral bands designed to enhance the contribution of vegetation while suppressing the influence of soil background, illumination, and atmosphere. The most widely used index is the Normalized Difference Vegetation Index, or NDVI, which exploits the contrast between the near-infrared and red bands described above.

**Normalized Difference Vegetation Index (NDVI)**

NDVI = (NIR - RED) / (NIR + RED) where NIR is near-infrared reflectance and RED is red reflectance.

NDVI ranges from -1 to +1. Dense healthy vegetation typically yields values from about 0.5 to 0.9; bare soil gives low positive values near 0.1 to 0.2; water gives negative values.

NDVI is popular because the normalization by the sum of the two bands compensates for much of the variation caused by differences in illumination and topography, producing a value that depends chiefly on the amount and vigour of green vegetation. It is widely used to map vegetation cover, monitor crop condition, track seasonal cycles, and detect drought and deforestation.

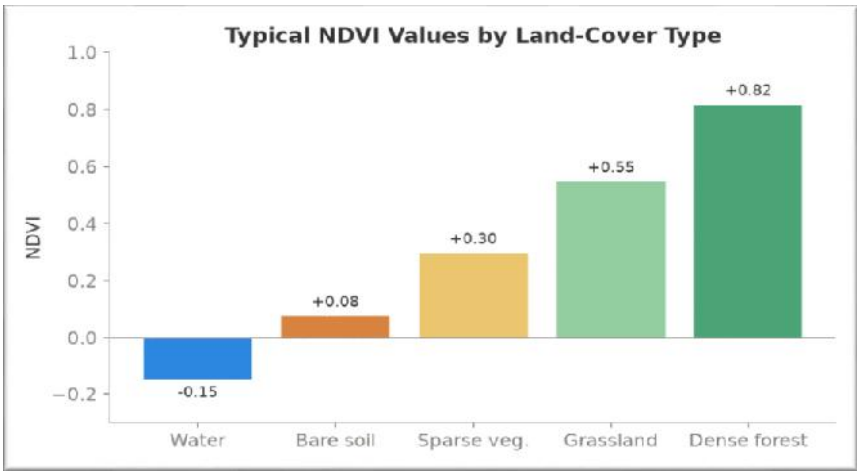



*Figure 5.2 — Typical NDVI values for different land-cover types. Water yields negative values, bare soil low positive values, and dense vegetation high positive values.*

NDVI has a known limitation: at low vegetation cover the signal is contaminated by the reflectance of the soil background, and at high cover the index saturates and becomes insensitive to further increases in biomass. To reduce the influence of the soil, alternative indices have been proposed. The Weighted Difference Vegetation Index, or WDVI, subtracts a weighted multiple of the red reflectance from the near-infrared reflectance, where the weight is the slope of the soil line, the locus of bare-soil points in red-near-infrared space. By aligning the correction with the soil line, WDVI minimizes the soil contribution and provides a more reliable estimate of green biomass at low to moderate cover.

**Weighted Difference Vegetation Index (WDVI)**

WDVI = NIR - g x RED, where g is the slope of the soil line (the ratio of near-infrared to red reflectance for bare soil).

By subtracting the soil contribution, WDVI reduces the sensitivity of the index to soil brightness.

**Worked example 5.1 — Computing NDVI**

Problem: A pixel over an irrigated field has red reflectance of 0.08 and near-infrared reflectance of 0.52. Compute its NDVI and interpret the result.

Solution: NDVI = (0.52 - 0.08) / (0.52 + 0.08) = 0.44 / 0.60 = 0.73. A value of 0.73 indicates dense, healthy, actively photosynthesizing vegetation, consistent with a well-watered crop at peak growth.

**Self-assessment 5**

1. Sketch, from memory, the spectral signatures of vegetation, water, and soil, and label the red edge.
2. Why does clear water appear almost black in a near-infrared image?
3. Compute the NDVI for a pixel with RED = 0.20 and NIR = 0.25, and state whether it represents vegetation or bare soil.
4. What problem with NDVI does the WDVI attempt to solve, and how?

# Chapter 6 — Image Pre-processing and Corrections

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain why raw imagery must be corrected before analysis.
- Describe radiometric and atmospheric correction.
- Describe geometric correction, georeferencing, and orthorectification.
- Explain resampling and compare the common resampling methods.

## 6.1 Why correction is necessary

The digital numbers recorded by a sensor are not, in their raw state, faithful measurements of surface properties. They are affected by the response characteristics of the instrument, by the intervening atmosphere, by the geometry of the acquisition, and by the shape and relief of the terrain. Before an image can be analyzed quantitatively or compared with another image, these distortions must be removed or reduced through a sequence of corrections. The overall workflow, from raw data to a finished thematic map, is summarized in Figure 6.1.

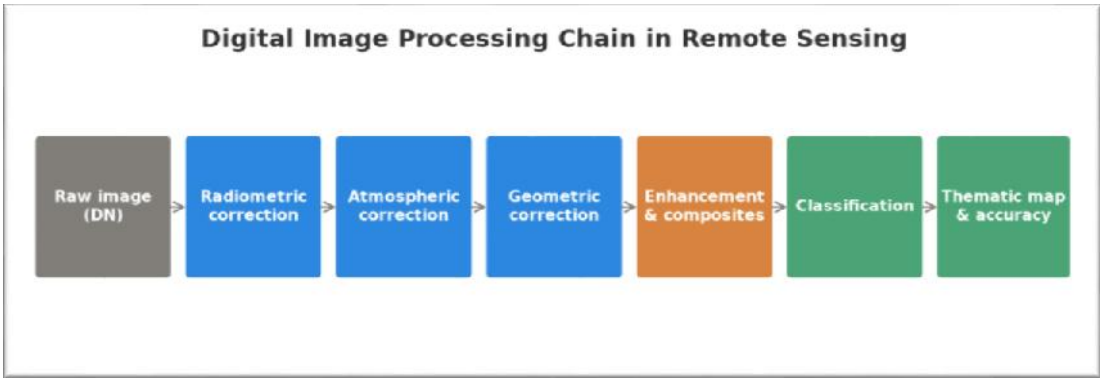



Figure 6.1 — The digital image processing chain, from raw digital numbers through radiometric, atmospheric, and geometric correction to enhancement, classification, and the final thematic map with accuracy assessment.

## 6.2 Radiometric correction

Radiometric correction addresses errors in the recorded brightness values. Some detectors may be more or less sensitive than their neighbours, producing striping or banding in the image; individual detectors may fail, producing dropped lines; and the sensor's response drifts over its lifetime. Radiometric correction uses calibration coefficients, determined before launch and monitored in orbit, to convert raw digital numbers into physically meaningful radiance values and to remove instrument artefacts. This step is a prerequisite for any comparison of measurements across time or across sensors.

## 6.3 Atmospheric correction

As shown in Chapter 2, the atmosphere scatters and absorbs radiation, adding a haze contribution and attenuating the surface signal. Atmospheric correction removes these effects to recover the true surface reflectance. Approaches range from simple image-based methods, such as dark-object subtraction, which estimates the additive haze from the darkest pixels in the scene, to physically based radiative-transfer models that use information about the atmospheric

composition at the time of acquisition. Atmospheric correction is essential when reflectance values must be compared across dates, for example in multitemporal monitoring of vegetation, or when applying quantitative models calibrated in physical units.

### 6.4 Geometric correction

Geometric correction removes spatial distortions so that each pixel is placed at its correct location on the Earth. Distortions arise from the curvature and rotation of the Earth, from variations in the platform's altitude and attitude, and from the viewing geometry of the sensor. Georeferencing assigns real-world map coordinates to the image, typically by matching identifiable ground control points to their known positions and fitting a transformation. Orthorectification goes further, using a digital elevation model to correct the displacement caused by terrain relief, so that the corrected image has the geometric fidelity of a map even in mountainous areas. Accurate geometric correction is indispensable when imagery is to be overlaid with other spatial data in a geographic information system.

### 6.5 Resampling

When an image is geometrically transformed, the pixels of the corrected image no longer align with the pixels of the original. New pixel values must therefore be interpolated from the original grid, a process called resampling. Three methods are in common use, each with characteristic advantages.

**Table 6.1 — Comparison of resampling methods.**

| METHOD | PRINCIPLE | ADVANTAGES | DRAWBACKS |
|---|---|---|---|
| NEAREST NEIGHBOUR | Assigns the value of the closest original pixel | Preserves original values; fast; suitable for thematic data | Produces a blocky appearance; can displace features by up to half a pixel |
| BILINEAR INTERPOLATION | Averages the four nearest pixels | Smoother output than nearest neighbour | Alters original values; slightly blurs edges |
| CUBIC CONVOLUTION | Weights the sixteen nearest pixels | Sharpest, most visually pleasing result | Most computationally intensive; alters original values |

**Choosing a resampling method**

Use nearest-neighbour resampling when the pixel values must be preserved exactly, as with classified maps or categorical data. Use bilinear or cubic convolution when a visually smooth continuous image is preferred and slight modification of values is acceptable.

**Self-assessment 6**

1. Name three sources of geometric distortion in satellite imagery.
2. Distinguish georeferencing from orthorectification.
3. Why is atmospheric correction particularly important for multitemporal studies?
4. Which resampling method would you use for a land-cover classification map, and why?

# Chapter 7 — Storage, Enhancement, and Multispectral Composites

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Describe how digital images are stored as raster arrays.
- Explain contrast enhancement and histogram operations.
- Construct and interpret natural- and false-colour composites.

### 7.1 The digital image as a raster

A digital remote sensing image is a raster: a regular grid of pixels, each holding one numerical value per spectral band. A multispectral image can therefore be visualized as a stack of co-registered layers, one per band, sharing the same grid. The value in each cell is the digital number, an integer whose range is set by the radiometric resolution. Understanding this structure is essential because every processing operation, from enhancement to classification, manipulates these arrays of numbers.

### 7.2 Contrast enhancement

Raw images often occupy only a fraction of the available brightness range, appearing dull and low in contrast. Contrast enhancement stretches the range of digital numbers to improve visual interpretability. A linear stretch maps the minimum and maximum observed values to the full display range; a histogram equalization redistributes values so that the display range is used more uniformly, emphasizing the most frequent brightness levels. Enhancement changes only the appearance of the image for display; it does not add information and, for quantitative analysis, is applied for visualization rather than measurement.

### 7.3 Colour composites

The human eye perceives colour as a combination of red, green, and blue light. A colour composite is formed by assigning three spectral bands to these three display channels. When the red, green, and blue bands of the sensor are assigned to the corresponding display channels, the result is a natural-colour composite that resembles what the eye would see. When other bands are assigned, the result is a false-colour composite in which surface features appear in unfamiliar but highly informative colours.

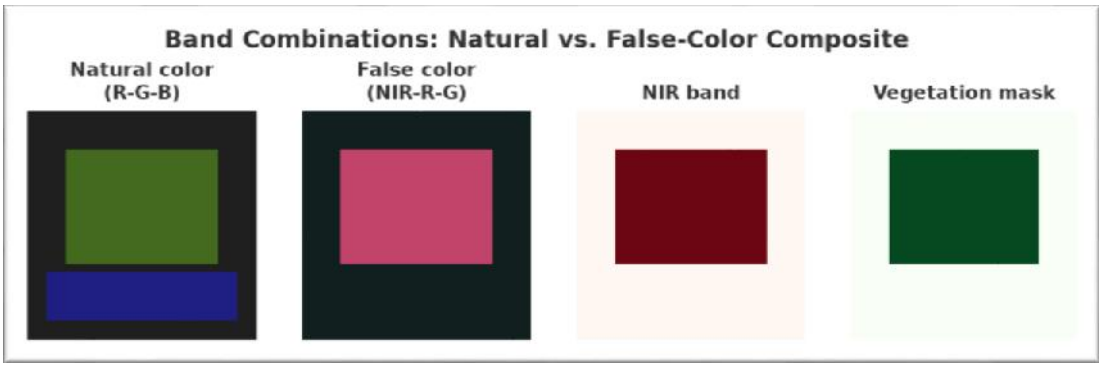



*Figure 7.1 — Band combinations. A natural-colour composite assigns red, green, and blue bands to the display channels; a standard false-colour composite assigns near-infrared, red, and green, causing healthy vegetation to appear bright red.*

The most widely used false-colour composite assigns the near-infrared band to the red display channel, the red band to green, and the green band to blue. Because healthy vegetation reflects strongly in the near infrared, it appears in vivid shades of red in this composite, which makes vegetation vigour immediately apparent and helps distinguish crop types, detect stressed plants, and separate vegetation from bare ground and built surfaces. The skilled analyst selects the band combination that best highlights the features of interest for a given task.

**Self-assessment 7**

1. What information does a single pixel of a multispectral image contain?
2. Explain the difference between a linear stretch and histogram equalization.
3. In a standard false-colour composite, why does healthy vegetation appear red?
4. Propose a band assignment to emphasize open water and justify it using the signatures from Chapter 5.

# Chapter 8 — A Survey of Earth-Observation Satellites

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Describe the characteristics of the principal land-observation satellite families.
- Compare sensors in terms of spatial, spectral, and temporal resolution.
- Match a satellite to an application.

## 8.1 Overview

Since the launch of the first civilian land-observation satellite in 1972, a large and diverse fleet of Earth-observation systems has been deployed by public agencies and commercial operators. They span an enormous range of capabilities, from coarse-resolution sensors that image the entire globe daily to very-high-resolution instruments that resolve objects smaller than half a metre. Figure 8.1 places several representative sensors on a common scale of spatial resolution, and the sections that follow describe the most influential families.

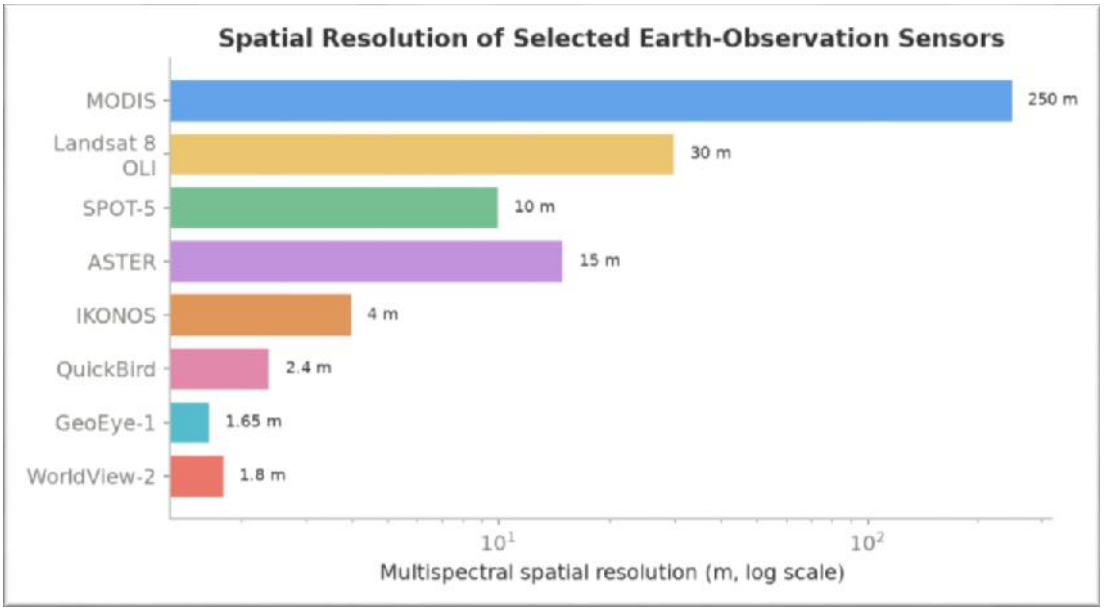



Figure 8.1 — Multispectral spatial resolution of selected Earth-observation sensors, plotted on a logarithmic scale from coarse (hundreds of metres) to very high (about one metre).

## 8.2 The Landsat programme

The Landsat programme, operated by the United States, is the longest continuous record of the Earth's land surface, beginning in 1972 and continuing to the present. Its medium spatial resolution of thirty metres in the multispectral bands, combined with a fifteen-metre panchromatic band on recent satellites, and its rich set of visible, near-infrared, shortwave-infrared, and thermal bands, make it the workhorse of land-cover mapping and long-term change studies. The opening of the Landsat archive at no cost in 2008 revolutionized the discipline by enabling continental- and global-scale analyses of change over decades.

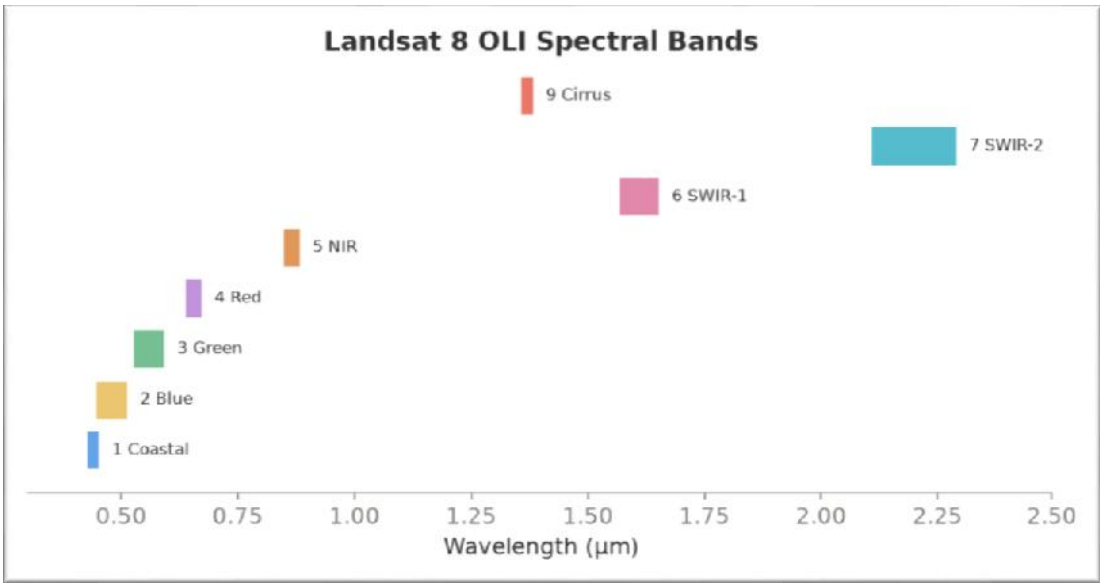



Figure 8.2 — The spectral bands of the Landsat 8 Operational Land Imager, spanning the coastal, visible, near-infrared, and shortwave-infrared regions.

**8.3 The SPOT programme**

The SPOT series, developed by France, introduced several innovations upon its debut in 1986, including a steerable mirror that allowed the sensor to point off-nadir. This pointing capability improved revisit frequency and enabled the acquisition of stereoscopic pairs for producing digital elevation models. SPOT satellites provided high-resolution imagery, progressing over successive generations from ten metres to two and a half metres, well suited to detailed land-use mapping and urban studies.

**8.4 ASTER and the Terra platform**

The Advanced Spaceborne Thermal Emission and Reflection Radiometer, or ASTER, carried on the Terra platform launched in 1999, offers a distinctive combination of visible and near-infrared bands at fifteen metres, shortwave-infrared bands at thirty metres, and thermal-infrared bands at ninety metres. Its along-track stereo capability and rich thermal coverage make it valuable for geological mapping, surface-temperature studies, and the generation of elevation models.

**8.5 Very-high-resolution commercial systems**

A family of commercial satellites has pushed spatial resolution below the one-metre threshold. IKONOS, launched in 1999, was the first to offer one-metre panchromatic and four-metre multispectral imagery to the civilian market. QuickBird followed with resolution finer than two-thirds of a metre. GeoEye-1 and the WorldView series advanced resolution further, with WorldView-2 adding eight multispectral bands, including unusual coastal, yellow, red-edge, and second near-infrared channels that improve material discrimination. These systems, with their sub-metre detail and agile pointing, are the data of choice for cadastral mapping, infrastructure inspection, and detailed urban analysis, though their scenes are small and their cost comparatively high.

**Table 8.1 — Characteristics of selected Earth-observation sensors (approximate values).**

| | | | | |
|---|---|---|---|---|
| **LANDSAT (TM/ETM+/OLI)** | USA | 1972 | 15 m pan / 30 m MS | Land-cover, long-term change |
| **SPOT** | France | 1986 | 2.5 m pan | Land use, DEMs, urban mapping |
| **ASTER (TERRA)** | USA/Japan | 1999 | 15 m VNIR | Geology, thermal, DEMs |
| **IKONOS** | USA (commercial) | 1999 | 1 m pan / 4 m MS | Detailed urban mapping |
| **QUICKBIRD** | USA (commercial) | 2001 | 0.6 m pan | Very-high-resolution mapping |
| **GEOEYE-1** | USA (commercial) | 2008 | 0.41 m pan | Precision mapping |
| **WORLDVIEW-2** | USA (commercial) | 2009 | 0.46 m pan / 8 MS bands | Detailed material discrimination |

**Self-assessment 8**

1. Why is the Landsat archive considered uniquely valuable for change detection?
2. What innovation did SPOT introduce, and what two capabilities did it enable?
3. For mapping individual buildings in a neighbourhood, would you select Landsat or WorldView-2? Justify your answer.
4. What advantage do the additional bands of WorldView-2 provide over a standard four-band sensor?

# Chapter 9 — Image Classification and Thematic Mapping

**Learning outcomes**

*By the end of this chapter you should be able to:*

- Explain the goal of image classification.
- Distinguish supervised from unsupervised classification.
- Describe the K-means and ISODATA algorithms and common supervised classifiers.
- Outline a practical workflow in ENVI, QGIS, and ArcGIS, including accuracy assessment.

## 9.1 The goal of classification

Image classification is the process of assigning each pixel of an image to one of a set of thematic classes, such as water, vegetation, bare soil, or built-up area, thereby converting a continuous multispectral image into a discrete thematic map. Classification is the bridge between the physical measurements recorded by the sensor and the categorical information needed by planners and decision-makers. It rests on the premise, established in Chapter 5, that different surface materials occupy different regions of the multidimensional space defined by the spectral bands.

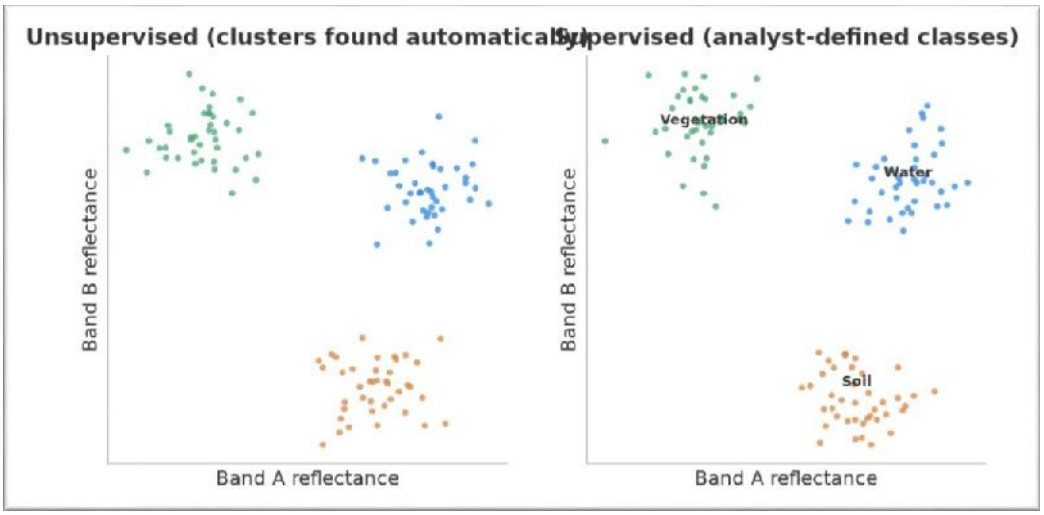



Figure 9.1 — The two paradigms of classification, shown in a two-band feature space. Unsupervised classification discovers natural clusters automatically; supervised classification assigns pixels to classes defined in advance by the analyst using training samples.

## 9.2 Unsupervised classification

In unsupervised classification the algorithm groups pixels into clusters based purely on the statistical structure of the data, without prior knowledge of the ground. The analyst specifies only the desired number of clusters and lets the algorithm partition the feature space; afterward, each cluster is interpreted and labelled by reference to field knowledge or ancillary data. This approach is useful for exploring an unfamiliar scene and for situations where training data are scarce. The K-means algorithm is the archetypal unsupervised method. It begins by placing a chosen number of cluster centres in the feature space, assigns each pixel to the nearest centre, recomputes each centre as the mean of its assigned pixels, and repeats the assignment and update steps until the centres stabilize. The ISODATA algorithm extends K-

means with rules that split clusters that are too dispersed, merge clusters that are too close, and discard clusters that are too small, allowing the number of clusters to adapt to the data.

### 9.3 Supervised classification

In supervised classification the analyst first defines the classes of interest and delineates representative training samples for each, drawing on field surveys, aerial photographs, or expert knowledge. The algorithm then learns the spectral characteristics of each class from the training data and assigns every remaining pixel to the class it most closely resembles. Common decision rules include the minimum-distance classifier, which assigns a pixel to the class whose mean is nearest; the maximum-likelihood classifier, which models each class as a statistical distribution and assigns a pixel to the most probable class; and modern machine-learning classifiers such as support vector machines and random forests, which can capture complex, non-linear boundaries between classes.

**Table 9.1 — Supervised versus unsupervised classification.**

| PRIOR KNOWLEDGE | REQUIRES TRAINING SAMPLES FOR EACH CLASS | REQUIRES ONLY THE NUMBER OF CLUSTERS |
|---|---|---|
| **ANALYST EFFORT** | High, before classification | High, after classification (labelling) |
| **CLASS DEFINITION** | Defined by the analyst | Emerges from the data |
| **TYPICAL USE** | When classes and ground truth are known | When exploring unfamiliar data |

### 9.4 A practical workflow

A typical classification project proceeds through a sequence of steps that combine the concepts of the preceding chapters. The following workflow is representative of practice using software such as ENVI, the free and open-source QGIS, and ArcGIS.

8. Prepare the imagery: apply the radiometric, atmospheric, and geometric corrections described in Chapter 6.
9. Explore the scene: build colour composites and compute indices such as NDVI to understand the distribution of cover types.
10. Define a classification scheme: decide on the thematic classes appropriate to the objective and the resolution of the data.
11. Collect training or reference data: delineate training polygons for a supervised approach, or set the number of clusters for an unsupervised one.
12. Run the classifier: apply the chosen algorithm to assign every pixel to a class.
13. Post-classification refinement: apply filters to remove isolated misclassified pixels, merge or relabel classes, and clean the map. In ENVI, feature-extraction tools such as the object-based workflow can group pixels into meaningful segments before labelling.
14. Assess accuracy: compare the classified map with independent reference data using a confusion matrix.
15. Export and integrate: deliver the thematic map to a geographic information system such as ArcGIS or QGIS for cartographic finishing and spatial analysis.

### 9.5 Accuracy assessment

No classification is perfect, and its usefulness depends on knowing how reliable it is. Accuracy is assessed by comparing the classified result with independent reference data at a sample of locations and tabulating the outcome in a confusion matrix, also called an error matrix. The rows and columns of the matrix represent the classified and reference classes; the diagonal entries count correctly classified samples, while off-diagonal entries reveal confusions between classes. From this matrix are derived the overall accuracy, the proportion of all samples classified correctly, and the per-class producer's and user's accuracies, as well as the kappa coefficient, which measures agreement while accounting for chance.

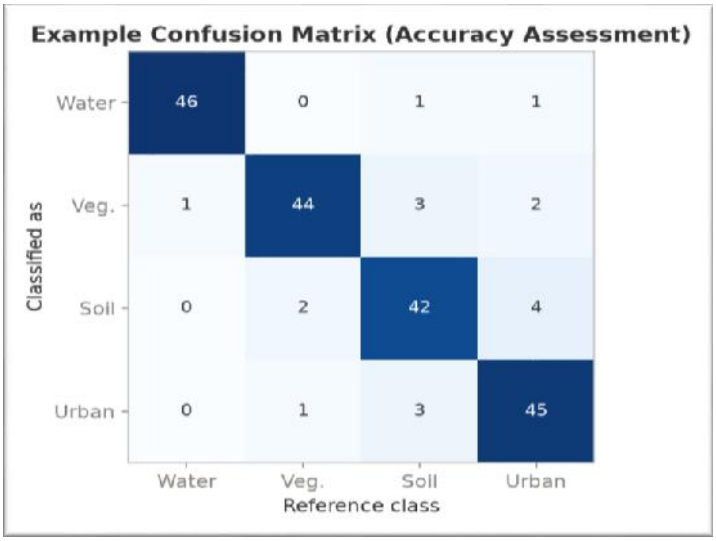



Figure 9.2 — An example confusion matrix. Diagonal cells (dark) count correctly classified samples; off-diagonal cells reveal the classes that are confused with one another.

**Worked example 9.1 — Reading a confusion matrix**

Problem: In the confusion matrix of Figure 9.2, the soil row reads 0, 2, 42, 4 against the reference classes water, vegetation, soil, and urban. Interpret these numbers.

Solution: Of the pixels the classifier labelled as soil, 42 were truly soil (correct), 2 were actually vegetation, and 4 were actually urban. The classifier therefore confuses a small number of vegetation and urban pixels with soil, which is plausible given that sparsely vegetated and some built surfaces can resemble bare soil spectrally. The user's accuracy for the soil class is 42 divided by 48, or about 88 percent.

**Self-assessment 9**

1. State the essential difference between supervised and unsupervised classification.
2. Describe the four steps of the K-means algorithm and explain how ISODATA extends it.
3. List, in order, the main steps of a classification workflow from raw image to accuracy assessment.
4. Given a confusion matrix, explain how to compute the overall accuracy and one class's user's accuracy.

# Chapter 10 — Chapter X — Spectral Indices: A Practical Catalogue

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain what a spectral index is and why indices are useful.
- Compute and interpret the principal vegetation, water, and built-up indices.
- Select an appropriate index for a given management question.

## 10.1 What is a spectral index?

A spectral index is a simple arithmetic combination of two or more bands designed to emphasize a particular surface property while suppressing unwanted variation such as brightness or soil background. Because they reduce several bands to a single, interpretable number per pixel, indices are among the most widely used tools in applied remote sensing. The archetype is the normalized difference vegetation index introduced in Chapter 5, but a large family of related indices has been developed to isolate vegetation, water, built-up areas, burnt surfaces, and more.

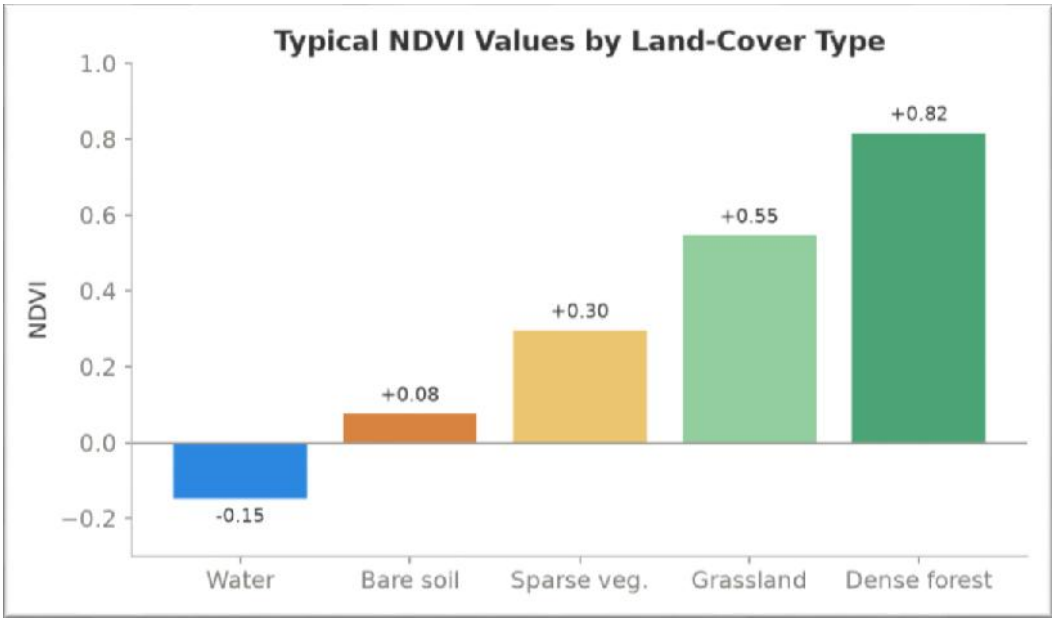



Figure 10.1 — The normalized difference vegetation index exploits the contrast between low red and high near-infrared reflectance of healthy vegetation.

## 10.2 A catalogue of common indices

The following table collects the indices most useful in urban and territorial management, with their formulas and typical purpose. In every case the bands are expressed as reflectances, and the near-infrared, red, green, blue, and shortwave-infrared bands are denoted NIR, R, G, B, and SWIR.

Table 10.1 — Common spectral indices.

| NDVI | (NIR - R)/(NIR + R) | VEGETATION VIGOUR AND COVER |
|---|---|---|
| **RVI** | NIR / R | Simple ratio vegetation index |
| **SAVI** | (NIR - R)(1 + L)/(NIR + R + L) | Vegetation over bright soil (L~0.5) |
| **EVI** | 2.5(NIR - R)/(NIR + 6R - 7.5B + 1) | Vegetation, reduced atmosphere effect |
| **NDWI** | (G - NIR)/(G + NIR) | Open water bodies |
| **MNDWI** | (G - SWIR)/(G + SWIR) | Water, suppresses built-up noise |
| **NDBI** | (SWIR - NIR)/(SWIR + NIR) | Built-up and impervious surfaces |
| **NBR** | (NIR - SWIR)/(NIR + SWIR) | Burnt area and fire severity |

### 10.3 Choosing and using an index

No index is universally best; each is a tool matched to a question. Over sparse vegetation on bright soils, the soil-adjusted index reduces the distorting influence of the background better than the plain normalized difference. Where water must be separated from dark built surfaces, the modified water index using the shortwave-infrared band outperforms the version using the near infrared. For mapping impervious surfaces in a city, the built-up index provides a useful first approximation. The skilled analyst chooses the index whose design matches the property of interest, and always interprets its values in the light of the spectral behaviour described in Chapter 5.

**Worked example X.1 — Computing SAVI**

Problem: A sparsely vegetated pixel over bright soil has R = 0.20 and NIR = 0.35. Compute NDVI and SAVI (with L = 0.5) and compare.

Solution: NDVI = (0.35 - 0.20)/(0.35 + 0.20) = 0.15/0.55 = 0.27. SAVI = (0.35 - 0.20)(1.5)/(0.35 + 0.20 + 0.5) = 0.225/1.05 = 0.21. The soil-adjusted value is lower because it discounts the brightening effect of the soil, giving a more realistic estimate of the modest vegetation cover.

**Indices are ratios, not truth**

An index highlights a property but does not measure it directly. Always calibrate your interpretation against field knowledge, and be aware that atmospheric effects, soil background, and sensor differences all shift index values.

**Self-assessment X**

1. What is a spectral index, and what two things does a good index emphasize and suppress?
2. Write the formulas for NDWI and NDBI and state what each maps.
3. Why is SAVI preferred over NDVI over sparse vegetation on bright soil?
4. Which index would you choose to map impervious surfaces, and why?

# Chapter 11 —Photogrammetry, Stereoscopy, and Elevation Models

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the principle of stereoscopy and parallax.
- Describe how digital elevation models are generated.
- Distinguish the main sources of elevation data.
- Identify uses of elevation models in territorial management.

### 11.1 Stereoscopy and parallax

Long before satellites, the third dimension was recovered from overlapping aerial photographs through the science of photogrammetry. When two images of the same scene are taken from different positions, a feature appears to shift between them by an amount, called parallax, that depends on its height: the closer or taller the object, the greater the shift. By measuring these shifts across a stereoscopic pair, the elevation of every point can be reconstructed. The same principle applies to modern satellites able to acquire stereo pairs, such as the pointing sensors described in Chapter 8.

### 11.2 Generating a digital elevation model

A digital elevation model is a raster in which each cell stores the elevation of the ground. Such models are generated by several methods that recur throughout this handout. Stereo-photogrammetry matches features between overlapping optical images and computes their height from parallax. Radar interferometry, introduced in Chapter 12, derives elevation from the phase difference between two radar images. Lidar, introduced in Chapter 13, measures elevation directly from the timing of laser pulses. Each method has characteristic accuracy, cost, and coverage, and the choice among them depends on the application.

**Table 11.1 — Sources of digital elevation data.**

| STEREO OPTICAL | PARALLAX BETWEEN IMAGE PAIR | 1-30 M | NEEDS CLEAR, TEXTURED SCENES |
|---|---|---|---|
| **RADAR INTERFEROMETRY** | Phase difference (InSAR) | 10-30 m | All-weather; global datasets exist |
| **AIRBORNE LIDAR** | Laser pulse timing | 0.5-2 m | Very accurate; higher cost |
| **GLOBAL DEMS** | Spaceborne missions | 30-90 m | Free, near-global coverage |

### 11.3 Surface versus terrain models

As with lidar, a distinction must be drawn between a digital surface model, which includes buildings and vegetation, and a digital terrain model, which represents the bare earth. Which one is required depends on the task: hydrological modelling of water flow needs the bare-earth terrain, whereas line-of-sight analysis or the modelling of a cityscape needs the full surface. Confusing the two is a common and consequential error.

### 11.4 Applications

Elevation models are fundamental to territorial management. They are used to produce orthophotographs, in which the relief displacement of an image is removed; to derive slope and aspect for planning and hazard assessment; to model the flow of water and delineate watersheds and flood-prone areas; to compute cut-and-fill volumes for engineering; to analyse visibility and the visual impact of proposed structures; and to build the three-dimensional city models increasingly used in urban planning and solar-potential studies.

**Self-assessment X**

1. Explain parallax and how it reveals height in a stereo pair.
2. Name three methods of generating a digital elevation model.
3. When would you need a terrain model rather than a surface model?
4. List three uses of elevation models in territorial management.

# Chapter 12 —Accuracy Assessment and Sampling Design

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain why accuracy assessment is essential.
- Describe common sampling designs for reference data.
- Compute and interpret accuracy measures and the kappa coefficient.

### 12.1 Why assess accuracy?

A thematic map is a model of reality, and like any model it contains errors. A map whose accuracy is unknown cannot be used responsibly for decisions, because the decision-maker has no way to judge how much to trust it. Accuracy assessment quantifies the reliability of a classification by comparing it against independent, higher-quality reference data at a sample of locations, and expresses the result in a set of standard measures. It is not an optional final flourish but an integral part of any credible mapping project.

### 12.2 Sampling designs

Because it is impractical to check every pixel, accuracy is estimated from a sample of reference points, and how those points are chosen strongly affects the validity of the estimate. In simple random sampling, points are placed at random across the scene, giving each pixel an equal chance of selection. In stratified random sampling, the scene is divided by class and points are allocated to each, ensuring that even rare classes are adequately represented. In systematic sampling, points are placed on a regular grid, which is easy to implement but risks aligning with periodic patterns in the landscape. Stratified random sampling is usually preferred for land-cover mapping because it guarantees a fair assessment of every class.

**Table 12.1 — Common sampling designs for reference data.**

| DESIGN | PRINCIPLE | ADVANTAGE | DRAWBACK |
|---|---|---|---|
| **SIMPLE RANDOM** | Points placed at random | Unbiased; simple | Rare classes under-sampled |
| **STRATIFIED RANDOM** | Random within each class | Fair to all classes | Needs a preliminary map |
| **SYSTEMATIC** | Regular grid of points | Even coverage; easy | May align with landscape periodicity |

### 12.3 The confusion matrix and its measures

The results are tabulated in a confusion matrix whose diagonal counts agreements and whose off-diagonal entries reveal specific confusions, as introduced in Chapter 9. From this matrix several measures are computed. The overall accuracy is the proportion of all sample points classified correctly. The producer's accuracy, for a given class, is the proportion of reference points of that class that the map got right, reflecting errors of omission. The user's accuracy is the proportion of points the map labelled as that class that truly belong to it, reflecting errors of commission. The kappa coefficient summarizes the agreement while correcting for the agreement expected by chance.

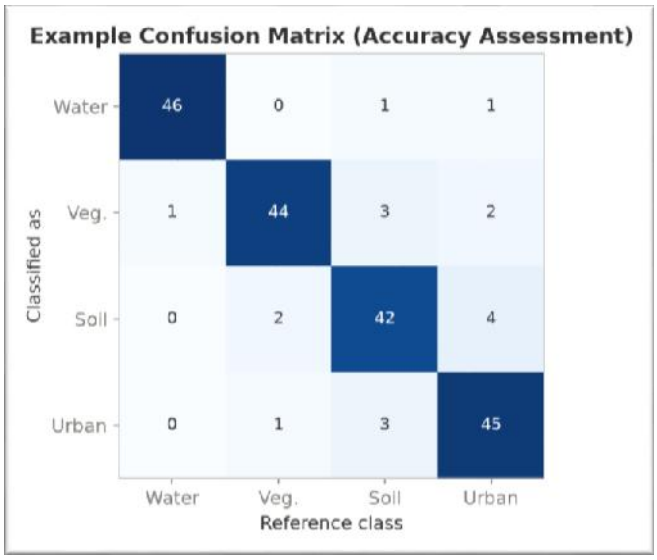



Figure X.1 — A confusion matrix. Diagonal cells count correct classifications; off-diagonal cells reveal which classes are confused with one another.

**Table 12.2 — Standard accuracy measures.**

| Measure | Definition | Reveals |
|---|---|---|
| Overall accuracy | Correct / total sample | General reliability |
| Producer's accuracy | Correct / reference total (class) | Errors of omission |
| User's accuracy | Correct / classified total (class) | Errors of commission |
| Kappa coefficient | Agreement beyond chance | Chance-corrected agreement |

**Worked example 12.1 — Computing kappa**

Problem: A classification of 200 points has an overall accuracy of 0.90. The expected agreement by chance, computed from the marginal totals, is 0.30. Compute the kappa coefficient.

Solution: kappa = (observed - expected)/(1 - expected) = (0.90 - 0.30)/(1 - 0.30) = 0.60/0.70 = 0.86. A kappa of 0.86 indicates strong agreement well beyond what chance alone would produce.

**Report more than one number**

Overall accuracy alone can hide serious problems in individual classes. Always report the per-class producer's and user's accuracies alongside the overall figure and kappa, so that the reliability of each class is transparent.

**1Self-assessment X**

1. Why can a map not be used responsibly without an accuracy assessment?
2. Contrast simple random, stratified random, and systematic sampling.
3. Distinguish producer's accuracy from user's accuracy.
4. Given observed agreement 0.85 and chance agreement 0.25, compute kappa.

# Chapter 13 —Integrating Remote Sensing with GIS

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the complementary roles of remote sensing and GIS.
- Describe how raster and vector data are combined.
- Outline spatial-analysis operations relevant to urban management.

### 13.1 Complementary technologies

Remote sensing and geographic information systems are distinct but deeply complementary. Remote sensing is a source of current, spatially continuous observations of the surface; a geographic information system is a framework for storing, integrating, analysing, and presenting spatial data of all kinds. The thematic maps produced by the methods of this handout become most valuable when they enter a GIS, where they are combined with cadastral boundaries, road and utility networks, demographic data, and administrative limits to answer the practical questions of territorial management.

### 13.2 Raster and vector

Spatial data come in two principal models. The raster model represents space as a grid of cells, the natural form of remote sensing imagery and of continuous surfaces such as elevation or temperature. The vector model represents space as points, lines, and polygons with attributes, the natural form of discrete features such as parcels, roads, and administrative units. A GIS holds both and converts between them; a classified raster map, for example, may be converted to vector polygons so that the area of each land-cover class within each administrative unit can be tabulated.

**Table 13.1 — The raster and vector data models.**

| ASPECT | RASTER | VECTOR |
|---|---|---|
| **REPRESENTATION** | Grid of cells | Points, lines, polygons |
| **BEST FOR** | Continuous surfaces, imagery | Discrete features, boundaries |
| **EXAMPLES** | Imagery, DEM, temperature | Parcels, roads, districts |
| **ANALYSIS** | Map algebra, filtering | Overlay, network, topology |

### 13.3 Spatial analysis for urban management

Once imagery-derived information sits alongside other layers in a GIS, a range of analyses becomes possible. Overlay combines layers to answer questions such as which parcels fall within a flood-prone zone. Zonal statistics summarize a raster within vector zones, for example the mean surface temperature or the proportion of green space per district. Buffering and network analysis support the planning of services and accessibility. Change detection, combined with cadastral data, reveals unauthorized construction. Through such operations the objective observations of remote sensing are transformed into the actionable information on which sound urban and territorial decisions depend.

### One coordinate system

The single most common practical obstacle to integration is mismatched coordinate reference systems. Before any overlay, confirm that every layer, raster and vector alike, shares the same projection and datum.

### Self-assessment X

1. State the complementary roles of remote sensing and GIS.
2. Contrast the raster and vector data models and give an example of each.
3. Describe two spatial-analysis operations useful in urban management.
4. What is the most common practical obstacle to integrating layers?

# Chapter 14 —Field Data, Validation, and Project Design

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the role of field data in a remote sensing project.
- Describe good practice in collecting reference data.
- Outline the design of a complete remote sensing project.

### 14.1 The role of field data

However sophisticated the imagery and algorithms, a remote sensing project is anchored to reality by field data. Ground observations serve three distinct purposes: they provide training samples that teach a supervised classifier what each class looks like; they provide independent reference data for the accuracy assessment; and they provide the local knowledge that guides interpretation and the choice of classes. A project that neglects fieldwork risks producing a map that is internally consistent but disconnected from the ground it claims to represent.

### 142 Collecting reference data

Good reference data are located accurately, using satellite positioning, and recorded consistently, using an agreed classification scheme and standard field forms. Observations should be made as close as possible in time to the image acquisition, since the surface changes; should sample the full variability of each class; and should be kept strictly independent between the training set and the validation set, so that accuracy is not flattered by testing on the same data used for training. Photographs and notes taken in the field are invaluable when interpreting ambiguous areas later at the desk.

**Table 14.1 — Uses of field data in a project.**

| USE | PURPOSE | TIMING |
|---|---|---|
| **TRAINING DATA** | Teach the classifier each class | Before classification |
| **VALIDATION DATA** | Assess map accuracy | After classification |
| **INTERPRETATION SUPPORT** | Resolve ambiguous areas | Throughout |

### 14.3 Designing a project

A successful remote sensing project is planned backwards from the question it must answer. The steps below outline a complete design that draws together the whole course.

16. State the objective and the decision it will support, and define the thematic classes and the accuracy required.
17. Choose imagery whose spatial, spectral, temporal, and radiometric resolution suit the objective and budget.
18. Plan and carry out fieldwork to collect training and validation data.
19. Preprocess the imagery: radiometric, atmospheric, and geometric correction.
20. Apply the chosen analysis: enhancement, indices, classification, or change detection.
21. Assess accuracy with independent reference data and report all standard measures.
22. Integrate the result into a GIS, analyse it, and communicate it clearly to decision-makers.

**Worked example X.1 — Independence of samples**

Problem: An analyst collects 300 field points and uses all of them both to train the classifier and to assess its accuracy, reporting 95 percent overall accuracy. Why is this figure misleading?

Solution: Training and validation were not independent, so the classifier was tested on the very data it learned from. The reported accuracy measures how well the model fits its training data, not how well it generalizes. The points should have been split, or separate sets collected, so that validation is independent of training.

**Self-assessment X**

1. State the three purposes of field data in a remote sensing project.
2. Why must training and validation data be kept independent?
3. Why should field observations be made close in time to image acquisition?
4. List, in order, the main steps of a complete project design.

# Chapter 15 — Chapter X — Machine Learning for Image Classification

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain how machine learning extends traditional classification.
- Describe the principal machine-learning classifiers used in remote sensing.
- Outline the idea of deep learning and convolutional networks.
- Recognize the requirements and pitfalls of machine-learning methods.

### 15.1 From statistical to machine-learning classifiers

The supervised classifiers introduced in Chapter 9, such as maximum likelihood, rest on explicit statistical assumptions about the distribution of each class. Machine-learning classifiers relax these assumptions: instead of assuming a particular form for the data, they learn the relationship between the input bands and the class label directly from the training examples. This flexibility allows them to model complex, non-linear boundaries between classes and to exploit many input features at once, and it has made them the dominant approach in contemporary image classification.

### 15.2 Common classifiers

Several machine-learning classifiers are now routine in remote sensing. A decision tree splits the data by a sequence of simple thresholds on the bands, producing an interpretable set of rules. A random forest combines many such trees, each trained on a random subset of the data and features, and lets them vote; it is robust, accurate, and requires little tuning, which has made it extremely popular. A support vector machine finds the boundary that best separates classes with the widest possible margin and performs well even with limited training data. Each has strengths, but all share the same logic of learning from labelled examples.

**Table X.1 — Machine-learning classifiers in remote sensing.**

| CLASSIFIER | PRINCIPLE | STRENGTH |
|---|---|---|
| **DECISION TREE** | Sequential threshold rules | Interpretable, fast |
| **RANDOM FOREST** | Ensemble of voting trees | Robust, accurate, low tuning |
| **SUPPORT VECTOR MACHINE** | Maximum-margin boundary | Effective with few samples |
| **NEURAL NETWORK** | Layers of weighted units | Models complex relationships |

### 15.3 Deep learning and convolutional networks

Deep learning is a branch of machine learning based on neural networks with many layers. For imagery, the convolutional neural network has proved especially powerful: rather than classifying each pixel from its spectral values alone, it learns spatial patterns — edges, textures, shapes — across neighbourhoods of pixels, much as a human interpreter uses texture and pattern. Convolutional networks now achieve state-of-the-art accuracy in tasks such as land-cover mapping, building and road extraction, and the detection of objects like vehicles or informal dwellings, at the cost of requiring large training datasets and substantial computing power.

**Spectral plus spatial**

The key advantage of convolutional networks is that they combine spectral and spatial information automatically. Where a per-pixel classifier sees only the colours of a pixel, a convolutional network also sees the shapes and textures around it, which is often decisive in complex urban scenes.

### 15.4 Requirements and pitfalls

The power of machine learning comes with responsibilities. These methods are data-hungry: their accuracy depends on abundant, representative, and correctly labelled training data, and biased or scarce training data produce biased or unreliable maps. They are prone to overfitting, learning the noise of the training set rather than the general pattern, which is why independent validation, as described in the accuracy chapter, is indispensable. And the more complex models are difficult to interpret, so their results must always be checked against physical reasoning and ground knowledge rather than accepted blindly.

**Self-assessment X**

1. How do machine-learning classifiers differ from maximum-likelihood classification?
2. Describe the principle of a random forest and why it is popular.
3. What extra information does a convolutional neural network use, and why does it help?
4. State two pitfalls of machine-learning methods and how to guard against them.

# Chapter 16 —Image Fusion and Pansharpening

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the purpose of image fusion.
- Describe pansharpening and how it works.
- Identify other forms of data fusion and their uses.
- Recognize the limits and cautions of fusion.

### 16.1 Why fuse images?

No single image contains all the information one might want. A sensor may offer either fine spatial detail or rich spectral content, but rarely both at once, and different sensors capture complementary properties of the same scene. Image fusion is the family of techniques that combine two or more images into a single product that is more informative than any of its inputs. The aim is always the same: to bring together the best qualities of each source, whether that means sharper detail, more spectral information, or the joining of optical and radar observations.

### 16.2 Pansharpening

The most common form of fusion is pansharpening, which addresses a design choice built into many satellites. To balance the trade-offs of Chapter 4, such platforms carry a single panchromatic band at fine spatial resolution alongside several multispectral bands at coarser resolution. Pansharpening merges the two, using the sharp geometric detail of the panchromatic band to increase the apparent spatial resolution of the colour bands, producing an image that is both detailed and coloured. The result greatly improves visual interpretation and the mapping of small urban features, provided the two images are precisely co-registered.

**Table 16.1 — Forms of data fusion.**

| FUSION TYPE | INPUTS COMBINED | BENEFIT |
|---|---|---|
| **PANSHARPENING** | Panchromatic + multispectral | Detail with colour |
| **MULTI-SENSOR** | Images from different sensors | Complementary properties |
| **OPTICAL + RADAR** | Reflectance + backscatter | Spectral and structural cues |
| **OPTICAL + LIDAR** | Imagery + elevation | What a surface is, plus its shape |

### 16.3 Other forms of fusion

Beyond pansharpening, fusion combines fundamentally different observations. Merging optical imagery with radar joins the spectral information of the former with the structural and all-weather information of the latter, improving classification in difficult conditions. Merging optical imagery with lidar, as noted in the lidar chapter, joins what a surface is with how tall and how shaped it is, allowing classes that share a spectral signature but differ in height to be separated. Such multi-source fusion is increasingly central to advanced mapping.

**Worked example16.1 — A resolution gain**

Problem: A satellite provides multispectral bands at 8 m and a panchromatic band at 2 m. By what factor does pansharpening improve the linear spatial detail of the colour product, and what is the corresponding gain in pixel count per unit area?

Solution: The linear detail improves by 8/2 = 4 times. Because area scales as the square of the linear dimension, the number of pixels per unit area increases by 4 x 4 = 16 times.

**Fusion is enhancement, not new measurement**

Pansharpening makes colour bands look sharper, but it does not add real spectral measurement at the finer scale; the spectral values are interpolated under the guidance of the panchromatic band. For quantitative spectral analysis, work from the original multispectral bands, not the pansharpened product.

**Self-assessment X**

1. What is the general aim of image fusion?
2. Explain how pansharpening produces a detailed colour image.
3. Give one benefit each of optical-radar and optical-lidar fusion.
4. Why should quantitative spectral analysis use the original bands rather than a pansharpened image?

# Chapter 17 — Elements of Visual Image Interpretation

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the role of visual interpretation alongside automated methods.
- Describe the classical elements of image interpretation.
- Apply these elements to recognize features in urban and rural scenes.

### 17.1 Why visual interpretation still matters

Although much modern analysis is automated, the trained human interpreter remains indispensable. The eye and brain integrate spatial context, prior knowledge, and subtle combinations of cues in ways that simple pixel-based classifiers cannot. Visual interpretation is used to define classes, to select and validate training data, to check the plausibility of automated results, and to analyse very-high-resolution imagery where the arrangement of features carries more information than their spectra alone. A competent analyst therefore masters both the quantitative methods of the preceding chapters and the qualitative art described here.

### 10.2 The classical elements of interpretation

Interpreters recognize features by combining a set of visual cues that have been formalized over decades of practice. They are usually presented as a hierarchy, from the most immediate to the most inferential.

**Table 17.1 — The elements of visual image interpretation.**

| ELEMENT | DEFINITION | EXAMPLE OF USE |
|---|---|---|
| TONE / COLOUR | The relative brightness or hue of a feature | Water is dark; bare soil is bright |
| SHAPE | The geometric form of a feature | Rectangular fields; circular pivots |
| SIZE | The dimensions of a feature, absolute or relative | Distinguishing a house from a warehouse |
| PATTERN | The spatial arrangement of features | Regular street grids; orchard rows |
| TEXTURE | The frequency of tonal change in an area | Smooth water versus rough forest canopy |
| SHADOW | The dark area cast by a raised feature | Estimating building or tree height |
| SITE | The topographic or geographic setting | Vegetation type by slope and elevation |
| ASSOCIATION | Features that occur together | A school beside a sports field |

### 17.3 Applying the elements

No single element is decisive; interpretation is the disciplined combination of several. A dark, smooth, irregularly shaped feature at the bottom of a valley, associated with a river, is almost certainly a body of water. A set of bright, small, regularly spaced rectangles arranged along linear features, casting short shadows, is readily interpreted as a residential neighbourhood along a street grid. The interpreter reasons from the immediate cues of tone and shape to the inferential cues of association and site, converging on an identification that a purely spectral classifier might miss.

### Shadow as information

Shadows are often treated as a nuisance, but they are also a resource. The length of a shadow, combined with the known solar elevation at the time of acquisition, allows the height of a building or tree to be estimated from a single image.

### Self-assessment 10

1. Why does visual interpretation remain valuable in an age of automated classification?
2. List five of the classical elements of interpretation and give an example of each.
3. Explain how association and site help identify a feature that tone alone cannot.
4. How can a shadow be used to estimate the height of a building?

# Chapter 18 — Change Detection

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the purpose of change detection and its requirements.
- Distinguish the principal families of change-detection methods.
- Interpret a change map in a management context.

### 18.1 The purpose of change detection

Much of the value of remote sensing lies not in a single image but in the comparison of images acquired at different times. Change detection is the set of techniques that identify where, and often how, the surface has changed between two or more dates. For the manager of a territory it answers essential questions: where has the city expanded, where has forest been cleared, where has a flood reached, where has farmland been abandoned. Because the whole method rests on comparing images, the images must first be made comparable, through the geometric and radiometric corrections of Chapter 6, so that a detected difference reflects a real change on the ground and not a difference in registration, illumination, or atmosphere.

### 18.2 Families of methods

Change-detection methods fall into two broad families. In the first, pre-classification comparison, the raw or transformed images are compared directly. Image differencing subtracts one date from another band by band, so that unchanged areas appear near zero and changed areas stand out; index differencing does the same with an index such as NDVI, isolating vegetation change. These methods are simple and sensitive but do not by themselves say what kind of change has occurred. In the second family, post-classification comparison, each date is classified independently into thematic classes and the class labels are then compared pixel by pixel; this yields an explicit from-to change matrix, such as vegetation converted to built-up, at the cost of accumulating the errors of both classifications.

**Table 18.1 — Change-detection approaches compared.**

| APPROACH | PRINCIPLE | STRENGTH | LIMITATION |
|---|---|---|---|
| IMAGE DIFFERENCING | Subtract band values of two dates | Simple, sensitive to subtle change | Does not identify type of change |
| INDEX DIFFERENCING | Subtract NDVI or similar | Isolates vegetation change | Limited to the chosen phenomenon |
| POST-CLASSIFICATION | Compare two classified maps | Explicit from-to change classes | Combines errors of both maps |

### 18.3 Interpreting a change map

The product of change detection is a change map, and its interpretation must always be tied to the management question that motivated it. Figure 11.1 illustrates the kind of quantified trajectory that a multitemporal classification yields: the steady increase of built-up area at the expense of vegetation and soil around a growing city. Read in context,

such a result identifies not only how much change has occurred but where and in what direction, guiding decisions about zoning, the protection of agricultural land, and the provision of services.

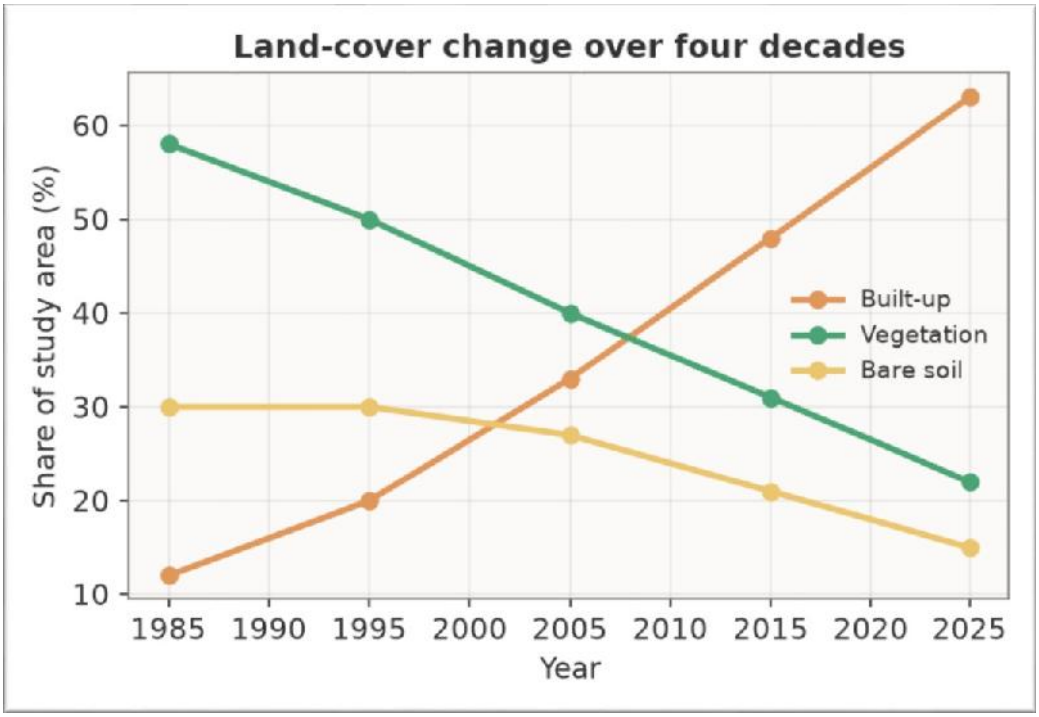



Figure 18.1 — A quantified change trajectory from post-classification comparison: built-up area rises steadily over four decades while vegetation and bare soil decline.

**Making images comparable**

The most common cause of spurious change is inadequate preprocessing. Before differencing, ensure the two images are precisely co-registered and radiometrically or atmospherically normalized; otherwise misregistration and illumination differences will masquerade as real change.

**Self-assessment 11**

1. Why must images be corrected before change detection?
2. Contrast pre-classification and post-classification change detection.
3. What unique product does post-classification comparison provide?
4. Give one management decision that a change map can inform.

# Chapter 19 — Microwave and Radar Remote Sensing

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the principle of imaging radar and active microwave sensing.
- Describe how roughness, moisture, and geometry control the radar signal.
- Define synthetic aperture radar and interferometry.
- Identify applications of radar in territorial management.

### 19.1 Why microwaves?

The optical sensors of the preceding chapters share a fundamental limitation: they depend on sunlight and cannot see through cloud. In many regions, and for urgent applications such as flood response, cloud cover makes optical imagery unavailable precisely when it is most needed. Microwave remote sensing overcomes this limitation. Because microwaves have wavelengths from about one centimetre to a metre, far longer than those of visible light, they pass through cloud, haze, and light rain; and because radar systems are active, supplying their own energy, they operate equally well by day or night. This all-weather, day-and-night capability is the defining advantage of radar.

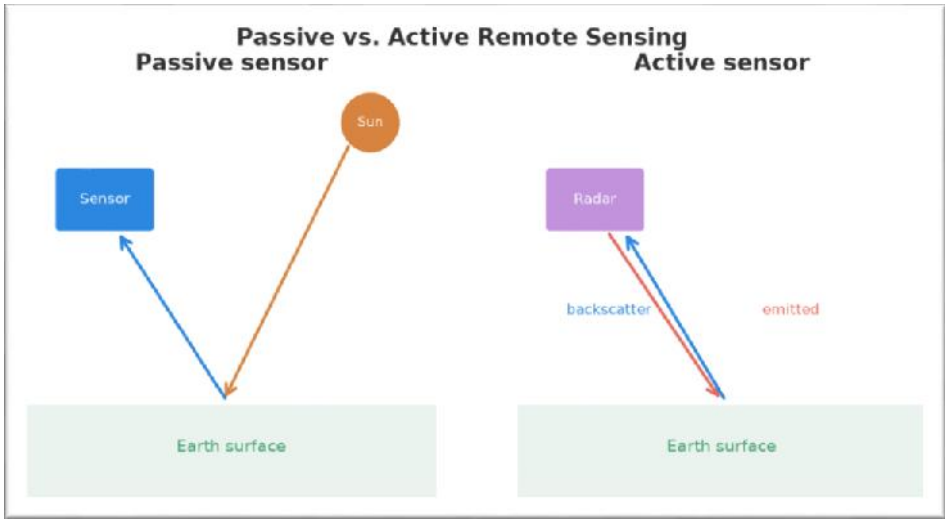



Figure 19.1 — Radar is an active system: it emits a microwave pulse and measures the portion scattered back from the surface, independent of solar illumination.

### 19.2 The radar signal and backscatter

An imaging radar transmits a pulse of microwave energy toward the surface at an angle and measures the strength and timing of the energy that returns, called the backscatter. The strength of the backscatter depends on properties quite different from those governing optical reflectance. Three factors dominate. Surface roughness, judged relative to the wavelength, controls how much energy returns toward the sensor: smooth surfaces such as calm water act as mirrors and reflect energy away, appearing dark, while rough surfaces such as forest canopies scatter energy in all directions, appearing bright. The dielectric properties of the surface, which depend strongly on moisture, control absorption, so

radar is sensitive to soil moisture. Finally, the geometry of features relative to the look direction can produce very bright returns from objects, such as buildings, oriented toward the sensor.

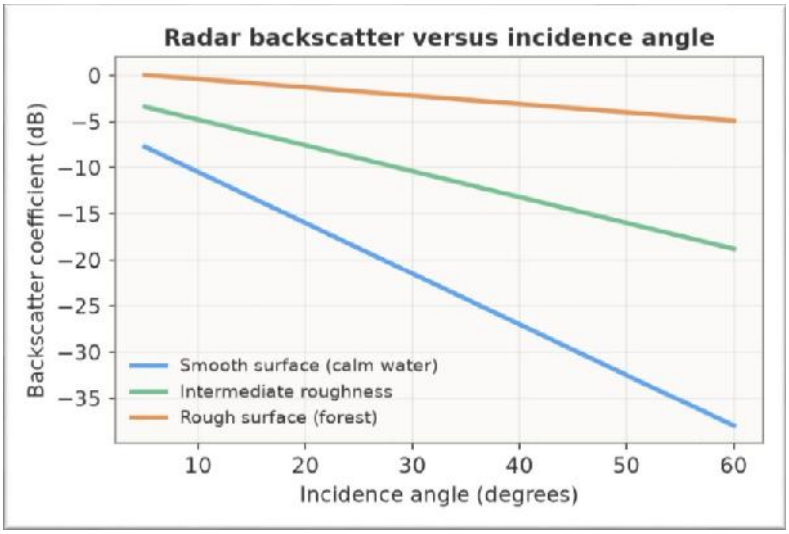



Figure 19.2 — Radar backscatter as a function of incidence angle for surfaces of increasing roughness. Smooth surfaces return little energy; rough surfaces return much more.

### 19.3 Radar bands and polarization

Radar systems operate in named wavelength bands, the most common for Earth observation being the X-band at about three centimetres, the C-band at about five and a half centimetres, and the L-band at about twenty-three centimetres. Shorter wavelengths interact with the top of a canopy and with small features, while longer wavelengths penetrate deeper into vegetation and even into dry soil. Radar can also transmit and receive in different polarizations, that is, orientations of the wave's electric field; comparing polarization combinations reveals the structure of the surface, distinguishing for example the volume scattering of a forest from the surface scattering of a field.

**Table 19.1 — Common radar bands and their behaviour.**

| BAND | WAVELENGTH | PENETRATION | TYPICAL USE |
|---|---|---|---|
| X-BAND | ~2.4-3.8 cm | Canopy top, small features | Urban mapping, high detail |
| C-BAND | ~3.8-7.5 cm | Upper canopy, moderate | Sentinel-1; broad monitoring |
| L-BAND | ~15-30 cm | Through canopy, into dry soil | Forestry, soil, subsurface |

### 19.4 Synthetic aperture radar

The spatial resolution of a radar along the flight direction depends on the length of its antenna, and a fine resolution would require an impractically long one. Synthetic aperture radar, or SAR, solves this problem by using the motion of the platform to simulate a very long antenna. As the satellite moves, it records the returns from each ground point over a span of the orbit and combines them, through sophisticated processing, as if collected by a single enormous antenna. This yields fine resolution from a modest physical antenna, and SAR is now the standard technique for spaceborne imaging radar.

**19.5 Radar interferometry:** One of the most powerful capabilities of SAR is interferometry, which exploits the phase of the returned wave. By comparing the phase of two SAR images of the same area acquired from slightly different positions or at different times, an interferogram is formed whose fringes encode differences in distance to the surface. Images from different positions reveal topography and can build a digital elevation model; images from the same position at different times reveal millimetre-scale movements of the ground, making it possible to measure subsidence, landslides, and deformation from earthquakes and volcanoes with extraordinary precision.

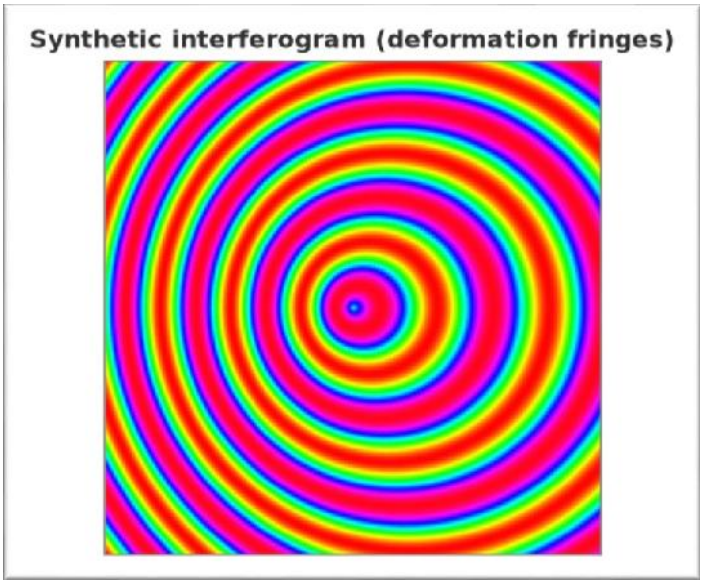



Figure 19.3 — A synthetic interferogram. Each complete colour cycle, or fringe, corresponds to a fixed increment of ground displacement or elevation.

**Radar for city managers**

Radar interferometry allows the monitoring of ground subsidence beneath cities, caused for example by groundwater extraction or tunnelling, at the scale of individual buildings and with millimetre precision, using freely available Sentinel-1 data.

**19.6 Applications**

Radar's distinctive sensitivities make it valuable across territorial management. Its all-weather capability makes it the primary tool for mapping flood extent, since calm floodwater appears strikingly dark against rougher surroundings. Its sensitivity to moisture supports monitoring of soil water and irrigation. Its interferometric capability underlies the monitoring of ground stability in cities and along infrastructure. And its penetration of vegetation and independence from illumination make it valuable for mapping forests, monitoring crops, and observing persistently cloudy regions.

**Self-assessment 12**

1. Give two reasons why radar can image when optical sensors cannot.
2. Explain why calm water appears dark and a forest appears bright in a radar image.
3. What problem does synthetic aperture radar solve, and how?
4. Describe one territorial-management application of radar interferometry.

# Chapter 20 — LiDAR and Three-Dimensional Remote Sensing

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain the operating principle of lidar.
- Distinguish digital surface, terrain, and canopy-height models.
- Describe how a point cloud is processed into usable products.
- Identify urban and environmental applications of lidar.

### 20.1 The principle of lidar

Light Detection and Ranging, or lidar, is an active technique that uses pulses of laser light instead of microwaves. The instrument emits many thousands of short laser pulses each second and measures, for each one, the time taken for the light to travel to the surface and back. Because the speed of light is known, each travel time is converted into a precise distance and, combined with the exact position and orientation of the sensor provided by satellite navigation and inertial instruments, into the three-dimensional coordinates of the point that reflected the pulse. Repeated over an area, this produces a dense three-dimensional point cloud describing the shape of the surface and the objects on it.

### 20.2 Returns and the point cloud

A single laser pulse may be partly reflected by several surfaces along its path, for example the top of a tree, a lower branch, and finally the ground, producing multiple returns. This ability to record several returns per pulse is what allows lidar to see both the top of a forest canopy and the ground beneath it. The resulting point cloud, containing millions of individually located points, is the raw product of a lidar survey and the starting point for the surface models that follow.

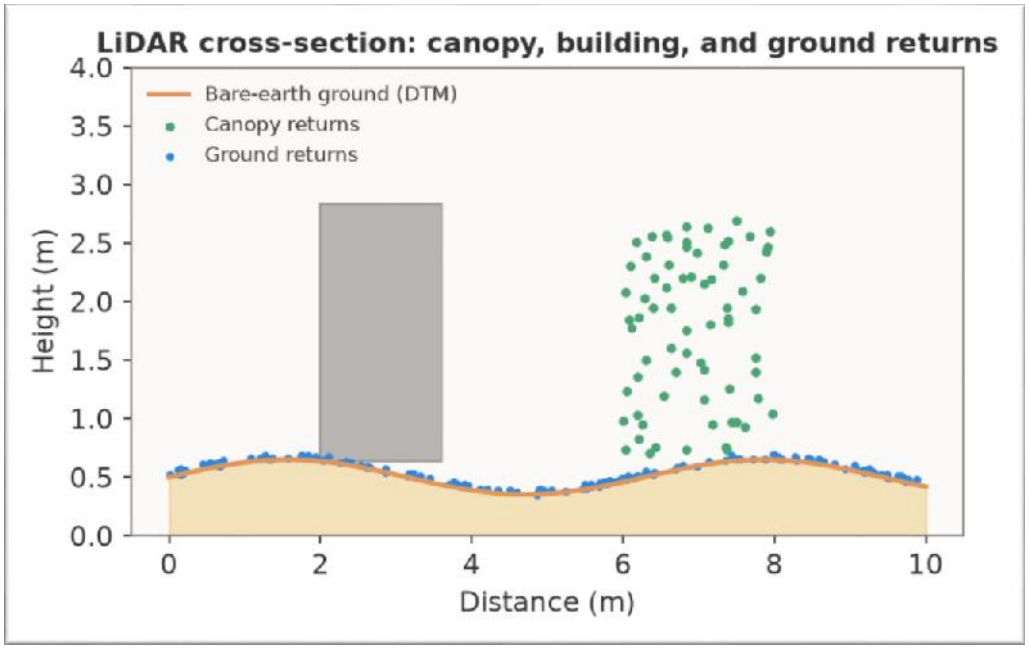



Figure 20.1 — A lidar cross-section. Multiple returns record the tops of buildings and vegetation as well as the underlying ground, allowing separate models of surface and terrain to be built.

### 20.3 Surface, terrain, and canopy models

From the classified point cloud three complementary products are derived. The digital surface model represents the elevation of the topmost surface, including buildings and vegetation. The digital terrain model represents the bare earth after buildings and vegetation are removed, revealing the underlying ground. The difference between the two, the normalized surface or canopy-height model, gives the height of objects above the ground, from which building heights or forest canopy height and structure can be measured directly. This separation of surface, terrain, and object height is the principal analytical strength of lidar.

**Table 20.1 — Elevation products derived from lidar.**

| PRODUCT | REPRESENTS | TYPICAL USE |
|---|---|---|
| **DIGITAL SURFACE MODEL (DSM)** | Top surface incl. buildings and trees | Line-of-sight, solar, urban form |
| **DIGITAL TERRAIN MODEL (DTM)** | Bare-earth ground surface | Hydrology, slope, flood modelling |
| **CANOPY / NORMALIZED MODEL (NDSM)** | Height of objects above ground | Building heights, forest structure |

### 20.4 Applications

For urban and territorial management, lidar has become indispensable wherever the third dimension matters. It provides accurate building heights and three-dimensional city models for planning, visual-impact studies, and the estimation of rooftop solar potential. Its precise bare-earth terrain models underpin the modelling of floods and drainage, since water flow depends on fine differences in ground elevation. In forestry and green-space management it measures canopy height and biomass, and in cultural-heritage work it can reveal archaeological features hidden beneath vegetation by stripping the canopy from the terrain model.

**Combining lidar with imagery**

Lidar and optical imagery are complementary: imagery tells you what a surface is, through its spectral signature, while lidar tells you its shape and height. Fusing the two yields richer classifications, for example separating low grass from tall trees that share the same NDVI.

**Self-assessment 13**

1. How does lidar convert a travel time into a three-dimensional coordinate?
2. Why can a single laser pulse produce more than one return?
3. Distinguish the DSM, the DTM, and the canopy-height model.
4. Give two urban applications where lidar's three-dimensional information is essential.

# Chapter 21 — Thermal and Hyperspectral Remote Sensing

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Explain what thermal-infrared sensors measure and how temperature is derived.
- Describe applications of thermal imagery.
- Explain the principle and promise of hyperspectral imaging.

## 21.1 Thermal-infrared remote sensing

Whereas the visible and near-infrared bands sense reflected sunlight, the thermal-infrared bands sense radiation emitted by the surface itself according to its temperature, as described by the physics of Chapter 2. Every object above absolute zero emits thermal radiation, and warmer objects emit more; by measuring this emitted radiation in the atmospheric window between about eight and fourteen micrometres, a thermal sensor can estimate the temperature of the surface. Converting the measured radiation to true temperature requires accounting for the emissivity of the surface, since materials of the same temperature but different emissivity radiate differently.

Thermal imagery supports a range of applications in territorial management. It maps the urban heat island, revealing where dense, sealed surfaces make a city hotter than its surroundings; it detects active fires and monitors volcanic activity; it reveals thermal pollution where warm water is discharged into rivers; it helps map soil moisture and evapotranspiration; and it can identify heat loss from buildings. Figure 14.1 shows the characteristic form of an urban heat-island transect derived from a thermal band.

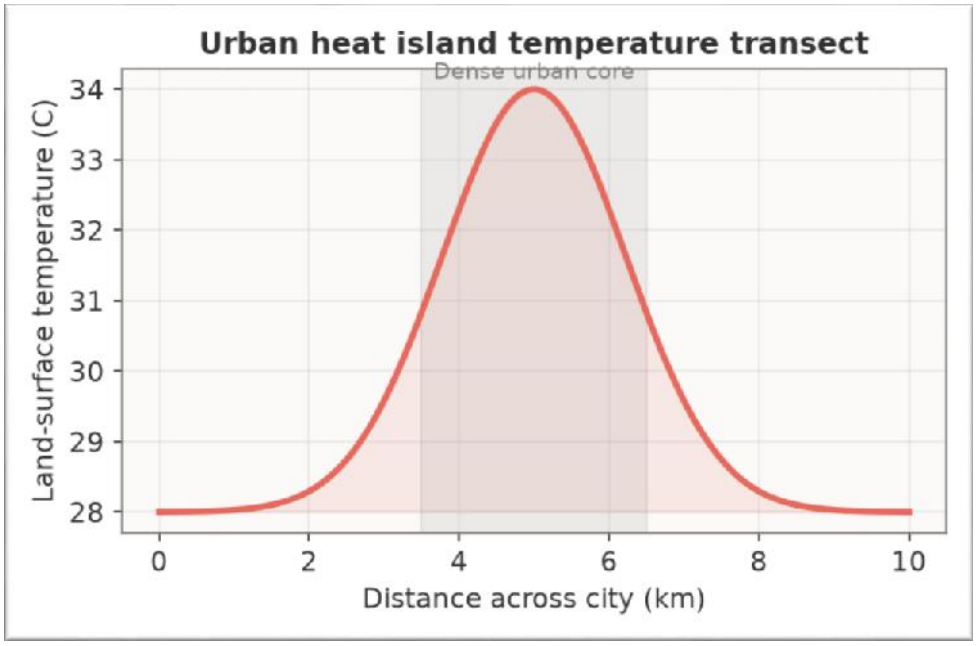



Figure 21.1 — A land-surface-temperature transect across a city derived from a thermal-infrared band, showing the warm core of the urban heat island and cooler vegetated margins.

### 21.2 Hyperspectral remote sensing

The multispectral sensors discussed so far record a handful of relatively broad bands. Hyperspectral sensors, by contrast, record hundreds of very narrow, contiguous bands, so that each pixel carries an almost continuous reflectance spectrum rather than a few samples of it. This near-complete spectrum allows materials to be identified by their diagnostic absorption features with a precision impossible for a broadband sensor: specific minerals, plant species, and pollutants can be distinguished by the fine detail of their spectral signatures.

**From colours to spectra**

If a multispectral image is like seeing the world in a few colours, a hyperspectral image is like seeing it in hundreds. The reward is fine material discrimination; the cost is far larger data volumes and more demanding processing.

Hyperspectral imaging has proven valuable in geology and mineral exploration, in precision agriculture, in monitoring water quality, and in detecting subtle vegetation stress before it is visible to the eye. Its principal costs are the very large data volumes generated by hundreds of bands and the more demanding processing required to exploit them, which is why hyperspectral data complement rather than replace the multispectral imagery that remains the workhorse of operational mapping.

**Self-assessment 14**

1. What does a thermal-infrared sensor measure, and why must emissivity be considered?
2. List three applications of thermal imagery in territorial management.
3. How does a hyperspectral sensor differ from a multispectral one?
4. State one advantage and one cost of hyperspectral imaging.

# Chapter 22 — Data Sources, Archives, and Cloud Platforms

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Identify the principal sources of free and commercial satellite imagery.
- Explain the significance of open-data policies.
- Describe cloud platforms for large-scale analysis.

## 22.1 Open archives and their significance

For much of the history of remote sensing, imagery was costly and access was limited. The situation changed decisively when major archives were opened at no cost. The opening of the Landsat archive by the United States Geological Survey in 2008, followed by the free-and-open data policy of the European Copernicus programme and its Sentinel satellites, placed decades of consistent, frequently updated imagery in the hands of anyone with an internet connection. This democratization transformed the discipline, enabling continental- and global-scale studies, long time series of change, and the participation of students, small organizations, and developing countries that could never have afforded commercial data.

**Table 22.1 — Principal sources of satellite imagery.**

| SOURCE / PORTAL | PROVIDER | DATA | ACCESS |
|---|---|---|---|
| **USGS EARTHEXPLORER** | USGS (USA) | Landsat, ASTER, and more | Free |
| **COPERNICUS DATA SPACE** | ESA / EU | Sentinel-1, -2, -3 | Free |
| **NASA EARTHDATA** | NASA (USA) | MODIS, VIIRS, and more | Free |
| **COMMERCIAL PROVIDERS** | Maxar, Planet, Airbus | Very-high-resolution imagery | Commercial |

## 22.2 The main free satellite families

Two families dominate free operational imagery. The Landsat series provides medium-resolution imagery at thirty metres in a rich set of bands, with a record extending back to 1972, ideal for long-term change. The Sentinel-2 mission of Copernicus provides imagery at ten to twenty metres with a revisit of a few days, well suited to monitoring vegetation and land cover, while Sentinel-1 provides free C-band radar for all-weather monitoring. Together these freely available systems cover the great majority of the needs of territorial management.

## 22.3 Cloud platforms

The sheer volume of modern imagery, amounting to petabytes, has made it impractical to download and process large archives on a personal computer. Cloud platforms have emerged in response, hosting vast catalogues of imagery alongside the computing power to analyse them, so that the analysis is brought to the data rather than the data to the analyst. On such platforms a user can compute an index over an entire country, or assemble a decade-long time series, with a short script and without downloading a single scene. These platforms have further lowered the barriers to large-scale analysis and are now central to operational and research practice.

### Recording provenance

Whatever the source, always record the sensor, the acquisition date, the processing level, and the coordinate reference system of every image you use. This provenance is what makes an analysis reproducible and defensible.

### Self-assessment 15

1. Why was the opening of the Landsat archive in 2008 so significant?
2. Name one free source each for optical and for radar imagery.
3. What problem do cloud platforms solve, and how?
4. What items of provenance should be recorded for every image?

# Chapter 23 — Practical Tutorials: QGIS, ENVI, and ArcGIS

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Follow a complete NDVI computation in QGIS.
- Follow a supervised classification workflow in ENVI.
- Understand how results are integrated and finished in ArcGIS.
- Appreciate good practice common to all three environments.

This chapter turns the concepts of the course into concrete, reproducible procedures using freely available Landsat or Sentinel-2 imagery. The steps are deliberately software-specific so that students can carry them out, but the underlying logic is identical across all image-processing packages.

### 23.1 Tutorial A — Computing NDVI in QGIS

QGIS is a free, open-source geographic information system with full raster-analysis capabilities. The following procedure computes and displays an NDVI image from a Sentinel-2 scene.

1. Download a Sentinel-2 Level-2A scene (already atmospherically corrected) for your study area from the Copernicus Data Space, and unzip it.
2. In QGIS, use Layer, Add Raster Layer to load the red band (B4) and the near-infrared band (B8), both at ten-metre resolution.
3. Open the Raster Calculator from the Raster menu.
4. Enter the NDVI expression, dividing the difference of near-infrared and red by their sum: ( B8 - B4 ) / ( B8 + B4 ).
5. Set an output file name and run the calculation to produce a new single-band raster of NDVI values.
6. Right-click the output, open Properties, Symbology, choose a singleband pseudocolour renderer, and apply a green colour ramp from low to high NDVI.
7. Interpret the result: dark tones over water and built-up areas, bright green over vigorous vegetation, consistent with the values in Chapter 5.

**Avoiding integer truncation**

If your NDVI comes out as only 0 and 1, the bands are being treated as integers. Cast the bands to floating point, or multiply using floating-point values, so that the division returns fractional results.

### 23.2 Tutorial B — Supervised classification in ENVI

ENVI is a widely used commercial package specialized for image analysis. The following procedure performs a supervised maximum-likelihood classification.

1. Open the multispectral image and build a false-colour composite (NIR-Red-Green) to aid interpretation.
2. Open the Region of Interest tool and digitize several training polygons for each class, for example water, vegetation, bare soil, and built-up, choosing pure, representative areas.

3. Inspect the separability of the training classes using the computed statistics; adjust the polygons if two classes overlap too much in feature space.
4. Run Classification, Supervised, Maximum Likelihood, supplying the training regions.
5. Apply a post-classification majority filter to remove isolated misclassified pixels, and merge or rename classes as needed.
6. Use the Confusion Matrix tool with independent reference points to compute overall accuracy, producer's and user's accuracies, and the kappa coefficient.
7. Export the classified image as a GeoTIFF for use in a GIS.

> **Practical note — Choosing training samples**
>
> Good training samples are the single most important control on classification quality. Collect several small, spectrally pure polygons per class, spread across the scene rather than concentrated in one area, and covering the natural variation within each class, for instance both bright and shaded roofs within the built-up class. Poor or too few training samples cause far more errors than the choice of algorithm.

### 23.3 Tutorial C — Finishing and analysis in ArcGIS

Once a thematic map has been produced, ArcGIS is commonly used to integrate it with other spatial data and to prepare cartographic output.

1. Add the classified GeoTIFF to a new map and confirm its coordinate system matches the other layers.
2. Overlay cadastral boundaries, road networks, and administrative limits to place the classification in its planning context.
3. Use zonal statistics to summarize land cover within each administrative unit, for example the proportion of built-up area per district.
4. Compute area change by comparing classifications from two dates to quantify urban expansion.
5. Compose a finished map with legend, scale bar, north arrow, and title in the layout view, and export it as PDF for reporting.

### 23.4 Good practice common to all software

Whatever the software, a few principles apply universally. Always record the provenance of the imagery so that results can be reproduced and defended. Keep the coordinate reference system consistent across all layers. Preserve intermediate products so that a mistake at one stage does not require restarting from the beginning. And always accompany a classified map with a statement of its accuracy, because a thematic map without a known accuracy is of limited value for decision-making.

> **Self-assessment 16**
>
> 1. Write the QGIS raster-calculator expression for NDVI and explain each term.
> 2. Why is the selection of training polygons the most critical step in supervised classification?
> 3. Name two operations in a GIS that turn a classified image into planning information.
> 4. List three practices that make an image-analysis workflow reproducible.

# Chapter 24 — Case Studies in Urban and Territorial Management

**Learning outcomes:** *By the end of this chapter you should be able to:*

- See the full remote sensing workflow applied to real management problems.
- Connect specific data and methods to specific decisions.
- Interpret results in a planning context.

The four case studies in this chapter show how the principles of the course combine to answer concrete questions faced by managers of cities and territories. Each follows the same logic: a question, the data and method chosen, the result, and its interpretation.

**24.1 Monitoring urban expansion**

A planning authority wishes to quantify how much agricultural land around a growing city has been converted to built-up use over four decades. Because the question spans a long period, the free Landsat archive is the natural data source, providing comparable thirty-metre imagery from the 1980s to the present. For several dates a cloud-free summer scene is selected, atmospherically corrected, and classified into built-up, vegetation, and bare-soil classes; the built-up area from each date is then measured and compared.

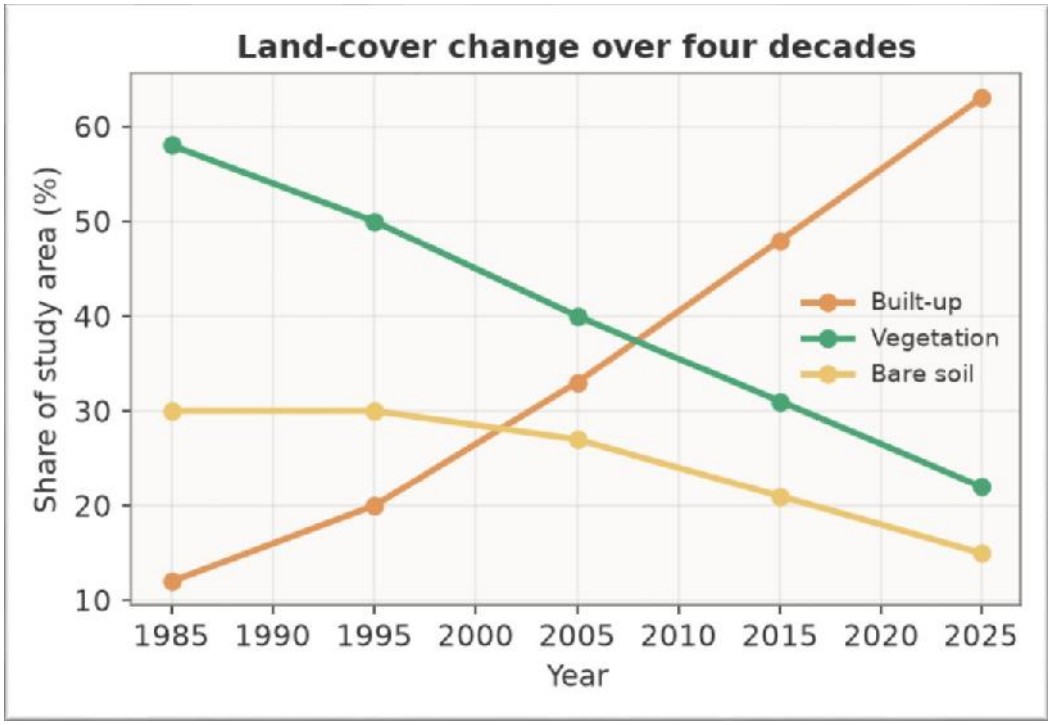



Figure 24.1 — Illustrative results of a multitemporal classification: the built-up share of the study area rises steadily while vegetation and bare soil decline.

The result shows a steady increase in the built-up fraction at the expense of vegetation and soil. Interpreted in a planning context, such a trajectory quantifies the rate of soil sealing, identifies the directions of growth, and provides objective evidence to revise zoning, protect remaining agricultural land, and plan the extension of services.

### 24.2 Mapping a flood

After heavy rain, emergency managers need to know, within hours and under a cloud-covered sky, which areas are inundated. Optical imagery is useless beneath cloud, so the choice falls on synthetic aperture radar, for which free Sentinel-1 C-band data are routinely available. A radar image acquired during the flood is compared with one from before the event. Calm floodwater is smooth and returns little energy, appearing dark; the newly dark areas that were not water before reveal the flood extent, mapped by thresholding the backscatter and overlaying the result on road and settlement layers in a GIS.

The interpretation is immediate and operational: the flood map directs rescue and relief to affected settlements, identifies cut roads, and, once the event has passed, supports damage assessment and the revision of flood-risk zoning. This case illustrates why the all-weather capability of radar is a decisive operational advantage.

### 24.3 The urban heat island

A municipality concerned with summer heat and public health wishes to locate the hottest parts of the city and relate them to land cover. The thermal-infrared band of Landsat is used to derive land-surface temperature, while the NDVI from the same scene measures vegetation cover. Mapping the two together, and taking a transect across the city, reveals the characteristic urban heat island: the dense, sealed, vegetation-poor centre is markedly warmer than the vegetated periphery.

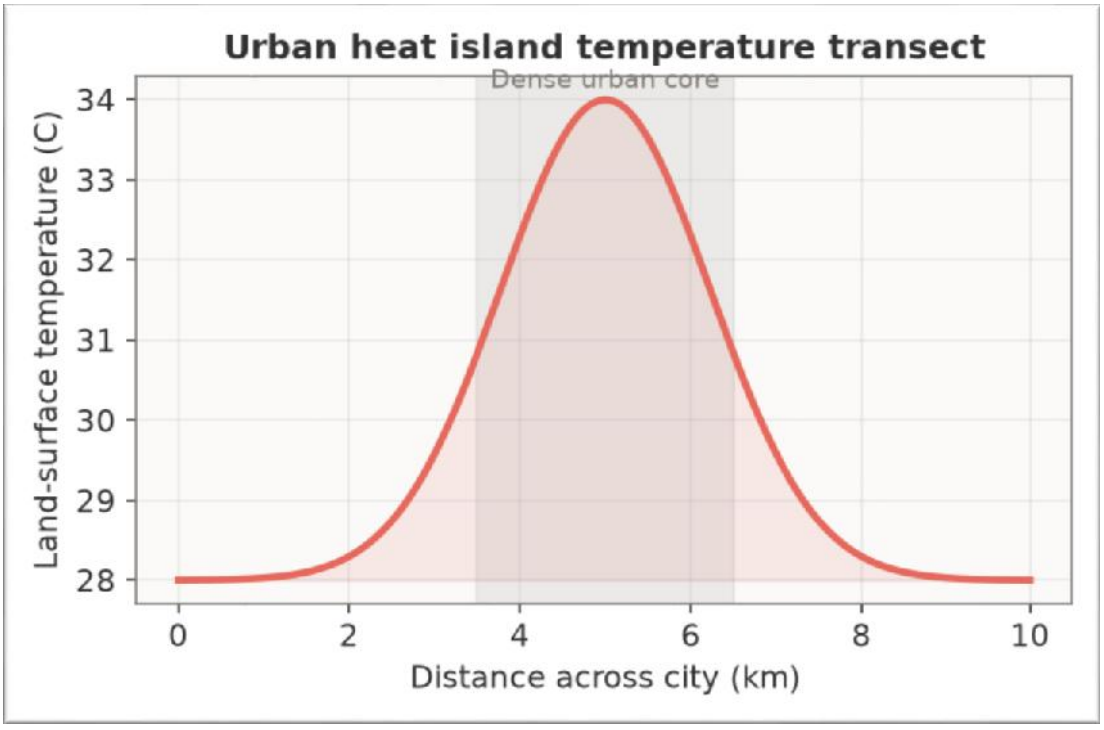



Figure 24.2 — A land-surface-temperature transect across a city, showing the warm core of the urban heat island and cooler vegetated margins.

The inverse relationship between vegetation and temperature gives planners a direct, spatially explicit argument for green infrastructure: parks, street trees, and green roofs in the identified hot spots. Remote sensing here not only diagnoses the problem but helps target and, in later imagery, evaluate the remedy.

### 24.4 Agricultural monitoring at the urban fringe

Managing the agricultural belt around a city requires knowing what is grown where, and how crops develop through the season. A single image cannot distinguish crops that look alike on one date but follow different growth cycles. The solution is a time series of NDVI images through the growing season, which captures the phenology of each field. Different crops trace different NDVI curves: an annual crop rises to a sharp peak and falls, while permanent vegetation stays high throughout.

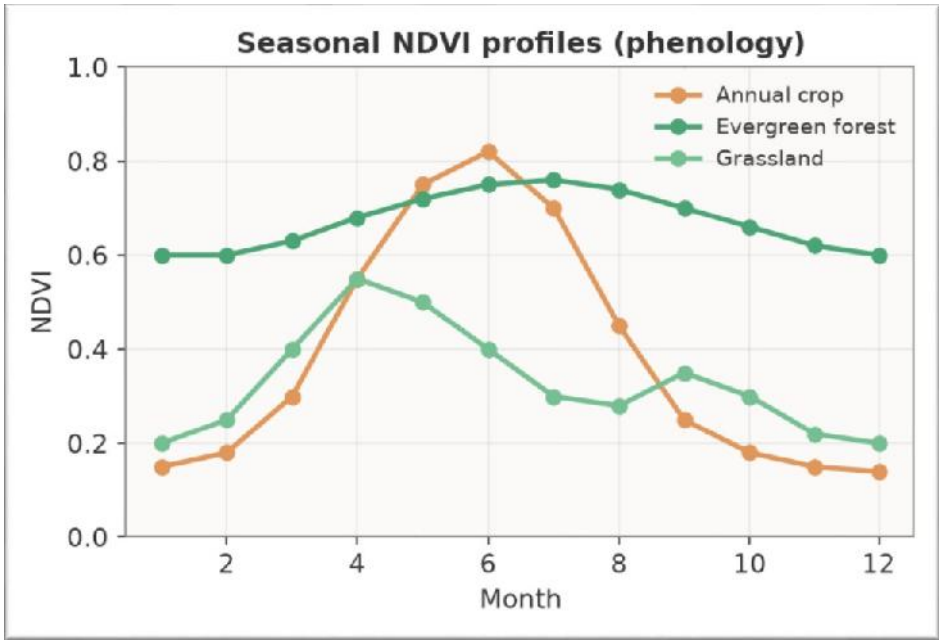



Figure 24.3 — Seasonal NDVI profiles for different vegetation types. The shape of each curve, not a single value, identifies the crop.

By classifying fields on the shape of their NDVI curve rather than a single date, the analyst distinguishes crop types, detects fallow land, and monitors the health and progress of the harvest. For the territorial manager this supports the protection of prime farmland, the planning of water resources, and the early detection of stress or abandonment.

**Self-assessment 17**

1. Why is the Landsat archive, rather than a very-high-resolution commercial sensor, the natural choice for a four-decade urban-growth study?
2. Explain, in terms of backscatter, why floodwater is easy to map with radar.
3. Which two remote sensing measurements are combined to study the urban heat island, and why?
4. Why does a time series of NDVI distinguish crops better than a single image?

# Chapter 25 — Applications, Conclusion, and Perspectives

**Learning outcomes:** *By the end of this chapter you should be able to:*

- Synthesize the concepts of the course into an integrated view.
- Describe representative applications in urban and territorial management.
- Identify current trends and future directions of the discipline.

### 25.1 From measurement to decision

The chapters of this handout have traced a complete path: from the physics of electromagnetic radiation, through its interaction with the atmosphere and the surface, to the design of sensors and platforms, the correction and enhancement of imagery, and finally the extraction of thematic information by classification, change detection, and three-dimensional and microwave techniques. Each stage informs the next, and the reliability of the final map depends on sound choices at every step. The essential lesson is that remote sensing is not merely the acquisition of pretty pictures but a rigorous measurement discipline whose products must be understood in terms of their physical basis and their limitations.

### 25.2 Applications in urban and territorial management

For the manager of cities and territories, remote sensing supplies the spatial evidence on which planning and regulation rest. Representative applications include the mapping and periodic updating of land use and land cover; the measurement of urban expansion and soil sealing; the detection and monitoring of informal settlements; the assessment of green infrastructure and urban heat; the planning and monitoring of transport and utility corridors; the evaluation of exposure and damage from floods, landslides, and earthquakes; and the maintenance of an objective, dated archive for regulatory and legal purposes. In each case the imagery feeds a geographic information system, where it is combined with cadastral, demographic, and infrastructural data to support analysis and decision.

**Integration with GIS**

Remote sensing and geographic information systems are complementary. Remote sensing provides current, spatially continuous observations of the surface; the GIS stores, integrates, and analyses those observations alongside other spatial data. Competence in both is the foundation of modern territorial management.

### 25.3 Trends and perspectives

The discipline continues to evolve rapidly. Free-and-open data policies have made vast, frequently updated imagery available at no cost, transforming who can use remote sensing and for what. Constellations of small satellites now deliver near-daily global coverage at metre-scale resolution. Cloud-based platforms allow petabytes of imagery to be analysed without downloading a single scene. Advances in machine learning, especially deep learning, are automating the extraction of features and classes with increasing accuracy. Together these trends are lowering the barriers to entry and expanding the range of problems to which remote sensing can be applied.

### 25.4 Conclusion

Remote sensing has become an indispensable source of spatial information for understanding and managing the Earth's surface. For the student of urban techniques management, mastery of its principles provides both a powerful practical toolkit and a rigorous way of thinking about spatial evidence. The concepts introduced here are the foundation on which more advanced study, and effective professional practice, can be built.

## Conclusion

Throughout this handout, remote sensing has been presented not as an end in itself but as a bridge between measurement and decision. Starting from the physics of electromagnetic radiation and its interaction with the Earth's surface, we have followed the complete chain that transforms photons captured by a distant sensor into thematic maps that describe the real territory. Each stage of that chain — understanding spectral signatures, choosing the appropriate combination of spatial, spectral, radiometric, and temporal resolution, correcting the imagery, computing indices, and classifying the scene — contributes a piece to a coherent and rigorous methodology.

The practical component, centred on ENVI and ArcGIS, has shown that these concepts are directly operational. Producing a land-use / land-cover map, computing vegetation, water, and built-up indices, laying out image maps, and comparing images from different dates to reveal urban expansion are no longer specialist tasks reserved for a few experts; they are accessible skills that any well-trained urban manager can and should master. The diachronic analysis, in particular, illustrates the unique strength of remote sensing: its ability to quantify change objectively across time, turning a succession of images into a measurable narrative of how a city grows, densifies, and reshapes its surroundings.

For the discipline of urban techniques management, the implications are significant. Reliable, up-to-date, and spatially explicit information is the raw material of sound planning, and remote sensing provides it at a scale, frequency, and cost that no other method can match. Monitoring unplanned settlement, assessing the loss of agricultural land at the urban fringe, mapping the urban heat island, or supporting risk and environmental management are all concrete applications where the techniques studied here make a direct difference.

At the same time, the reader should remember that a satellite image is a model of reality, not reality itself. Its value depends on the rigour of the analyst — on careful correction, appropriate method selection, field validation, and honest accuracy assessment. Technology will continue to evolve, with ever-finer resolutions, richer hyperspectral data, radar and lidar sources, and cloud platforms that place vast archives within everyone's reach. What will remain constant is the need for a critical, well-trained user who understands both the power and the limits of the tool. It is that user — informed, methodical, and responsible — that this handout has sought to help form.

## Appendix A — Exercises with Solutions

The following exercises consolidate the quantitative and conceptual skills developed in the course. Full solutions are provided so that students can check their reasoning.

### A.1 Radiation and physics

**Exercise A.1**

A body has a temperature of 1200 K. Using Wien's law, find the wavelength of peak emission and state the spectral region.

Solution: lambda_max = 2898 / 1200 = 2.42 micrometres, which lies in the shortwave infrared.

**Exercise A.2**

Convert a wavelength of 0.65 micrometres to frequency, using c = 3 x 10^8 m/s.

Solution: nu = c / lambda = (3 x 10^8) / (0.65 x 10^-6) = 4.6 x 10^14 Hz.

**Exercise A.3**

Explain why the blue band of an optical image is usually the haziest, referring to Rayleigh scattering.

Solution: Rayleigh scattering is inversely proportional to the fourth power of wavelength, so it is strongest at short wavelengths. The blue band, having the shortest wavelength of the visible bands, receives the most scattered atmospheric light, which adds haze and reduces contrast.

### A.2 Resolutions and sensors

**Exercise A.4**

A sensor records 11 bits per pixel. How many brightness levels can it distinguish?

Solution: 2 to the power 11 equals 2048 levels.

**Exercise A.5**

A scene of 185 by 185 km is imaged at 30 m resolution. Estimate the number of pixels per band.

Solution: 185000 / 30 = 6167 pixels per side, so about 6167 x 6167 = 3.8 x 10^7 pixels per band, roughly 38 million pixels.

### A.3 Indices and classification

**Exercise A.6**

A pixel has red reflectance 0.12 and near-infrared reflectance 0.60. Compute NDVI and interpret.

Solution: NDVI = (0.60 - 0.12) / (0.60 + 0.12) = 0.48 / 0.72 = 0.67, indicating dense, healthy vegetation.

**Exercise A.7**

In a confusion matrix, the vegetation class has 44 correct out of a classified total of 50, and out of 47 reference vegetation pixels. Compute the user's and producer's accuracy.

Solution: User's accuracy = 44 / 50 = 88 percent. Producer's accuracy = 44 / 47 = 94 percent.

**Exercise A.8**

An overall classification has 180 correct out of 200 reference points. State the overall accuracy and comment.

Solution: Overall accuracy = 180 / 200 = 90 percent, generally a good result for a land-cover classification, though per-class accuracies should also be inspected.

### A.4 Radar, lidar, and thermal

**Exercise A.9**

Explain why a calm lake appears very dark in a radar image while an adjacent forest appears bright.

Solution: The calm lake is smooth relative to the radar wavelength and acts as a specular reflector, sending energy away from the sensor, so little returns and it appears dark. The forest canopy is rough at that scale and scatters energy in all directions, so a large part returns to the sensor and it appears bright.

**Exercise A.10**

A lidar pulse returns 1.2 x 10^-7 seconds after emission. Using c = 3 x 10^8 m/s, find the distance to the surface.

Solution: The pulse travels to the surface and back, so the one-way distance is (c x t)/2 = (3 x 10^8 x 1.2 x 10^-7)/2 = 36/2 = 18 metres.

**Exercise A.11**

Using Wien's law, find the peak emission wavelength of the Earth's surface at 290 K and state why a thermal band near 10 micrometres is used.

Solution: lambda_max = 2898/290 = 10.0 micrometres. The surface emits most strongly near 10 micrometres, and this falls within an atmospheric window, so a thermal band there captures the strongest available signal.

### A.5 Integration and project design

**Exercise A.12**

A district of 400 hectares contains 90 hectares classified as built-up. Express the built-up proportion as a percentage, and state which GIS operation produced this figure.

Solution: The built-up proportion is 90/400 = 22.5 percent. The figure is produced by zonal statistics, which summarize a classified raster within a vector zone (the district boundary).

**Exercise A.13**

Two Landsat classifications, 1994 and 2024, show built-up area of 1200 and 3300 hectares. Compute the total and mean annual increase.

Solution: The total increase is 3300 - 1200 = 2100 hectares over 30 years, a mean annual increase of 2100/30 = 70 hectares per year.

## Appendix B — Answers to Self-Assessment Questions

Concise answers to the self-assessment questions that close each chapter. Students should attempt the questions before consulting these answers.

### Foundations and physical basis

Remote sensing acquires information about the surface from a distance using electromagnetic radiation; its components are an energy source, the atmosphere, the target, the sensor, and the processing-interpretation chain. The wave relation is c = lambda times nu, and photon energy E = hc/lambda rises as wavelength falls. Wien's law gives lambda_max = 2898/T, so at 300 K the peak is near 9.7 micrometres. Atmospheric windows are wavelength regions of high transmission within which sensors must operate. Radiance is the directional flux the sensor measures; reflectance is the ratio of reflected to incident energy, derived after correction.

### Sensors, resolutions, and spectral behaviour

Radar works at night and through cloud; airborne sensors give fine detail over small areas while spaceborne sensors give synoptic, repetitive coverage; sun-synchronous orbits give consistent illumination for comparing dates. The four resolutions are spatial (pixel ground size), spectral (number and width of bands), radiometric (brightness levels), and temporal (revisit interval), and they are traded off against one another. Vegetation has low red and high near-infrared reflectance with a sharp red edge; water absorbs strongly in the near infrared; NDVI is the normalized difference of near-infrared and red.

### Processing, satellites, and classification

Geometric distortion arises from Earth curvature and rotation, platform motion, and sensor geometry; georeferencing assigns map coordinates while orthorectification also removes relief displacement. Atmospheric correction matters most for multitemporal work; nearest-neighbour resampling preserves class values. In a false-colour composite vegetation appears red because it reflects strongly in the near infrared. The Landsat archive is uniquely valuable for change detection because it is long, consistent, and free. Supervised classification uses analyst-defined training classes; unsupervised finds clusters automatically; accuracy is assessed with a confusion matrix yielding overall, producer's, and user's accuracies.

### Interpretation, change, and advanced sensing

Visual interpretation combines tone, shape, size, pattern, texture, shadow, site, and association, and remains valuable for defining and validating classes. Change detection requires comparable, corrected images; pre-classification differencing is sensitive but does not name the change, while post-classification comparison yields explicit from-to classes. Radar is active and long-wavelength, so it works at night and through cloud; smooth water is dark and rough forest bright; SAR synthesizes a long antenna from platform motion, and interferometry measures millimetre subsidence. Lidar times laser pulses to build a three-dimensional point cloud, from which DSM, DTM, and canopy-height models are derived. Thermal sensors measure emitted radiation to estimate temperature; hyperspectral sensors record hundreds of narrow bands for fine material discrimination. Free imagery comes from USGS EarthExplorer, the Copernicus Data Space, and NASA Earthdata, and cloud platforms bring computation to the data.

### Tutorials and case studies

The QGIS NDVI expression is (B8 - B4)/(B8 + B4), the normalized difference of near-infrared and red. The selection of training polygons dominates classification accuracy. Zonal statistics and change detection turn a classified image into planning information. Reproducibility requires recording provenance, keeping one coordinate reference system, and reporting accuracy. Landsat suits a four-decade study because of its long free archive; floodwater is smooth and dark in radar; the thermal band and NDVI together reveal the heat island; an NDVI time series captures phenology that a single image cannot.

## Appendix C — Reference Tables

### C.1 Physical constants

**Table C.1 — Useful physical constants.**

| CONSTANT | SYMBOL | VALUE |
|---|---|---|
| SPEED OF LIGHT | c | 2.998 x 10^8 m/s |
| PLANCK CONSTANT | h | 6.626 x 10^-34 J.s |
| BOLTZMANN CONSTANT | k | 1.381 x 10^-23 J/K |
| WIEN CONSTANT | b | 2.898 x 10^-3 m.K |
| STEFAN-BOLTZMANN CONSTANT | sigma | 5.670 x 10^-8 W/m2/K4 |

### C.2 Spectral regions

**Table C.2 — Spectral regions used in remote sensing.**

| REGION | APPROX. WAVELENGTH | MAIN USE |
|---|---|---|
| VISIBLE (VIS) | 0.4-0.7 um | Natural colour, water quality |
| NEAR INFRARED (NIR) | 0.7-1.3 um | Vegetation vigour, NDVI |
| SHORTWAVE INFRARED (SWIR) | 1.3-3 um | Moisture, minerals, burn scars |
| MID-WAVE INFRARED (MWIR) | 3-5 um | Fire and hot-spot detection |
| THERMAL INFRARED (TIR) | 8-14 um | Surface temperature |
| MICROWAVE | 1 mm - 1 m | Radar: all-weather imaging |

### C.3 Key formulas

**Table C.3 — Formulas used in this handout.**

| NAME | FORMULA | NOTES |
|---|---|---|
| WAVE RELATION | c = lambda x nu | Links wavelength and frequency |
| PHOTON ENERGY | E = hc/lambda | Higher for shorter wavelengths |
| WIEN'S LAW | lambda_max = 2898/T | lambda in um, T in K |
| NDVI | (NIR - Red)/(NIR + Red) | Ranges -1 to +1 |
| WDVI | NIR - a x Red | a = soil-line slope |
| OVERALL ACCURACY | correct / total | From confusion matrix |

## Appendix D — Acronyms and Abbreviations

**Table D.1 — Common acronyms used in remote sensing.**

| ACRONYM | MEANING |
|---|---|
| **DN** | Digital Number |
| **DSM** | Digital Surface Model |
| **DTM** | Digital Terrain Model |
| **EM** | Electromagnetic |
| **FCC** | False-Colour Composite |
| **GIS** | Geographic Information System |
| **GCP** | Ground Control Point |
| **IFOV** | Instantaneous Field Of View |
| **INSAR** | Interferometric Synthetic Aperture Radar |
| **LIDAR** | Light Detection and Ranging |
| **NDVI** | Normalized Difference Vegetation Index |
| **NIR** | Near Infrared |
| **RADAR** | Radio Detection and Ranging |
| **SAR** | Synthetic Aperture Radar |
| **SWIR** | Shortwave Infrared |
| **TIR** | Thermal Infrared |
| **UHI** | Urban Heat Island |
| **WDVI** | Weighted Difference Vegetation Index |

## Glossary (English - French)

The following bilingual glossary lists the key terms of the course with concise definitions, to support students working across English and French scientific literature.

**Bilingual glossary of key terms.**

| ENGLISH TERM | FRENCH TERM | DEFINITION |
|---|---|---|
| REMOTE SENSING | Teledetection | Acquisition of information about the surface from a distance using electromagnetic radiation. |
| ELECTROMAGNETIC SPECTRUM | Spectre electromagnetique | The ordered continuum of all wavelengths of electromagnetic radiation. |
| WAVELENGTH | Longueur d'onde | The distance between two successive crests of a wave. |
| REFLECTANCE | Reflectance | The ratio of reflected to incident radiant energy, between 0 and 1. |
| RADIANCE | Luminance energetique | Radiant flux per unit area per unit solid angle in a given direction. |
| SPECTRAL SIGNATURE | Signature spectrale | The variation of a material's reflectance with wavelength. |
| ATMOSPHERIC WINDOW | Fenetre atmospherique | A wavelength region where the atmosphere is relatively transparent. |
| PASSIVE SENSOR | Capteur passif | A sensor that detects natural reflected or emitted radiation. |
| ACTIVE SENSOR | Capteur actif | A sensor that supplies its own energy, such as radar or lidar. |
| SPATIAL RESOLUTION | Resolution spatiale | The ground size of the smallest resolvable feature (pixel size). |
| SPECTRAL RESOLUTION | Resolution spectrale | The number and width of the spectral bands recorded. |
| RADIOMETRIC RESOLUTION | Resolution radiometrique | The number of brightness levels used to record each measurement. |
| TEMPORAL RESOLUTION | Resolution temporelle | The time between successive observations of the same location. |
| PIXEL | Pixel | The smallest element of a digital image; a single grid cell. |

| | | |
|---|---|---|
| **DIGITAL NUMBER** | Compte numerique | The integer value recorded for a pixel in a given band. |
| **GEOMETRIC CORRECTION** | Correction geometrique | Removal of spatial distortions to place pixels at their true locations. |
| **ORTHORECTIFICATION** | Orthorectification | Geometric correction that also removes terrain-induced displacement. |
| **RESAMPLING** | Reechantillonnage | Interpolation of new pixel values after a geometric transformation. |
| **FALSE-COLOUR COMPOSITE** | Composition coloree fausses couleurs | A colour image formed by assigning non-visible bands to display channels. |
| **NDVI** | Indice de vegetation NDVI | Normalized difference between near-infrared and red reflectance. |
| **CLASSIFICATION** | Classification | Assignment of pixels to thematic classes to produce a thematic map. |
| **CONFUSION MATRIX** | Matrice de confusion | A table comparing classified results with reference data to assess accuracy. |
| **BACKSCATTER** | Retrodiffusion | The portion of radar energy scattered back toward the sensor. |
| **INTERFEROMETRY** | Interferometrie | Use of the phase of radar waves to measure topography or ground movement. |
| **POINT CLOUD** | Nuage de points | The set of three-dimensional points produced by a lidar survey. |
| **CHANGE DETECTION** | Detection de changement | Identification of surface changes between images of different dates. |

# List of Tables and Figures

*Summary of all tables and figures in the handout, with their number, title, and page.*


| Type | No. | Title | Page |
|---|---|---|---|
| **TABLES** | | | |
| Table | **1.1** | Selected milestones in the history of remote sensing | 5 |
| Table | **2.1** | Principal radiometric quantities | 12 |
| Table | **6.1** | Comparison of resampling methods | 23 |
| Table | **8.1** | Characteristics of selected Earth-observation sensors | 28 |
| Table | **9.1** | Supervised versus unsupervised classification | 30 |
| Table | **10.1** | Common spectral indices | 33 |
| Table | **11.1** | Sources of digital elevation data | 34 |
| Table | **12.1** | Common sampling designs for reference data | 36 |
| Table | **12.2** | Standard accuracy measures | 37 |
| Table | **13.1** | The raster and vector data models | 38 |
| Table | **14.1** | Uses of field data in a project | 40 |
| Table | **15.1** | Machine-learning classifiers in remote sensing | 42 |
| Table | **16.1** | Forms of data fusion | 44 |
| Table | **17.1** | The elements of visual image interpretation | 46 |
| Table | **18.1** | Change-detection approaches compared | 48 |
| Table | **19.1** | Common radar bands and their behaviour | 51 |
| Table | **20.1** | Elevation products derived from lidar | 54 |
| Table | **22.1** | Principal sources of satellite imagery | 57 |
| Table | **C.1** | Useful physical constants | 71 |
| Table | **C.2** | Spectral regions used in remote sensing | 71 |
| Table | **C.3** | Formulas used in this handout | 71 |
| Table | **D.1** | Common acronyms used in remote sensing | 72 |
| **FIGURES / GRAPHS** | | | |
| Figure | **1.1** | The energy pathway for passive and active remote sensing systems | 4 |
| Figure | **2.1** | The electromagnetic spectrum | 8 |
| Figure | **2.2** | Planck curves for blackbodies at several temperatures | 9 |
| Figure | **2.3** | Wien's displacement law | 10 |
| Figure | **2.4** | Atmospheric transmission as a function of wavelength | 11 |
| Figure | **3.1** | Comparison of a low Earth (polar) orbit and a geostationary orbit | 14 |
| Figure | **4.1** | The effect of spatial resolution | 16 |
| Figure | **4.2** | The effect of radiometric resolution | 17 |
| Figure | **5.1** | Typical spectral signatures of vegetation, soil, and water | 19 |
| Figure | **5.2** | Typical NDVI values for different land-cover types | 21 |
| Figure | **6.1** | The digital image processing chain | 22 |
| Figure | **7.1** | Band combinations: natural- vs. false-colour composite | 25 |
| Figure | **8.1** | Multispectral spatial resolution of selected sensors | 26 |
| Figure | **8.2** | The spectral bands of the Landsat 8 OLI | 27 |
| Figure | **9.1** | The two paradigms of classification | 29 |
| Figure | **9.2** | An example confusion matrix | 31 |
| Figure | **10.1** | NDVI and the red / near-infrared contrast | 32 |
| Figure | **12.1** | A confusion matrix (accuracy assessment) | 37 |

| | | | |
|---|---|---|---|
| Figure | **18.1** | A quantified change trajectory (post-classification) | 49 |
| Figure | **19.1** | Radar as an active system | 50 |
| Figure | **19.2** | Radar backscatter versus incidence angle | 51 |
| Figure | **19.3** | A synthetic interferogram | 52 |
| Figure | **20.1** | A lidar cross-section | 53 |
| Figure | **21.1** | An urban heat-island temperature transect | 55 |
| Figure | **24.1** | Illustrative results of a multitemporal classification | 61 |
| Figure | **24.2** | A land-surface-temperature transect across a city | 62 |
| Figure | **24.3** | Seasonal NDVI profiles (phenology) | 63 |

## References


1. Baret, F., & Guyot, G. (1991). Potentials and limits of vegetation indices for LAI and APAR assessment. Remote Sensing of Environment, 35(2-3), 161-173.
2. Bonn, F., & Rochon, G. (1992). Precis de teledetection, Volume 1: Principes et methodes. Presses de l'Universite du Quebec / AUPELF.
3. Caloz, R., & Collet, C. (2001). Precis de teledetection, Volume 3: Traitements numeriques d'images de teledetection. Presses de l'Universite du Quebec.
4. Campbell, J. B., & Wynne, R. H. (2011). Introduction to remote sensing (5th ed.). Guilford Press.
5. Chuvieco, E. (2016). Fundamentals of satellite remote sensing: An environmental approach (2nd ed.). CRC Press.
6. Congalton, R. G., & Green, K. (2019). Assessing the accuracy of remotely sensed data: Principles and practices (3rd ed.). CRC Press.
7. Drury, S. A. (2001). Image interpretation in geology (3rd ed.). Blackwell Science.
8. Girard, M.-C., & Girard, C. M. (2003). Processing of remote sensing data. A. A. Balkema.
9. Jensen, J. R. (2007). Remote sensing of the environment: An earth resource perspective (2nd ed.). Pearson Prentice Hall.
10. Jensen, J. R. (2015). Introductory digital image processing: A remote sensing perspective (4th ed.). Pearson.
11. Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2015). Remote sensing and image interpretation (7th ed.). John Wiley & Sons.
12. Mather, P. M., & Koch, M. (2011). Computer processing of remotely-sensed images: An introduction (4th ed.). John Wiley & Sons.
13. McCloy, K. R. (2006). Resource management information systems: Remote sensing, GIS and modelling (2nd ed.). CRC Press.
14. Planck, M. (1901). Ueber das Gesetz der Energieverteilung im Normalspektrum. Annalen der Physik, 309(3), 553-563.
15. Rees, W. G. (2013). Physical principles of remote sensing (3rd ed.). Cambridge University Press.
16. Richards, J. A. (2013). Remote sensing digital image analysis: An introduction (5th ed.). Springer.
17. Robin, M. (2002). Teledetection: des satellites aux systemes d'information geographique. Nathan.
18. Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. In Third ERTS Symposium (NASA SP-351, Vol. 1, pp. 309-317). NASA.
19. Sabins, F. F. (1997). Remote sensing: Principles and interpretation (3rd ed.). W. H. Freeman.
20. Schowengerdt, R. A. (2007). Remote sensing: Models and methods for image processing (3rd ed.). Academic Press.
21. Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment, 8(2), 127-150.
22. Wilmet, J. (1996). Teledetection aerospatiale: methodes et applications. SIDES.