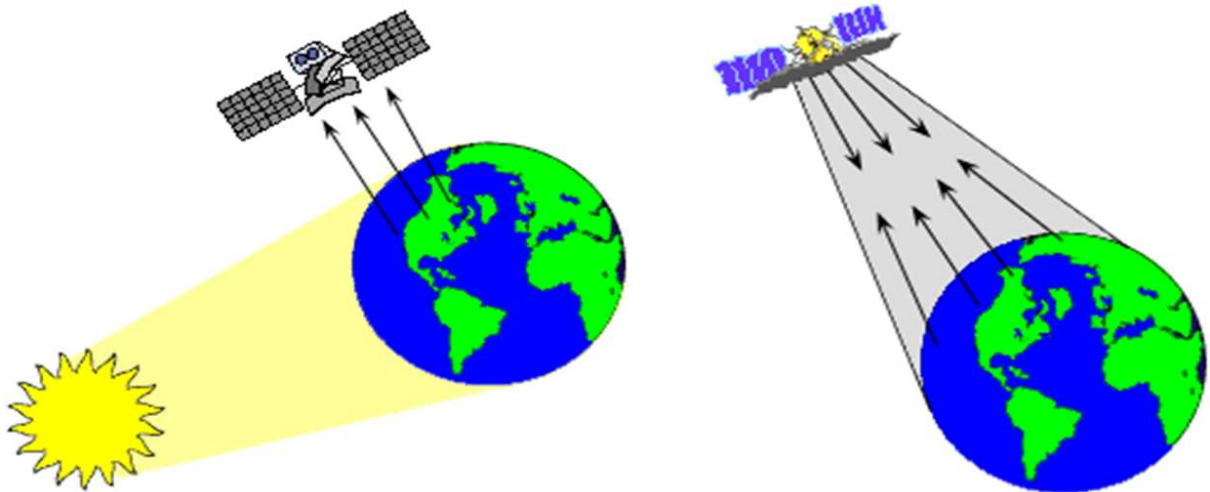


**People's Democratic Republic of Algeria**  
**Ministry of Higher Education and Scientific Research**  
**Ferhat Abbas University of Setif**

**Faculty of Nature and Life Sciences**

**Course Handout: “Remote Sensing and GIS”**

**For the students of the 3<sup>rd</sup> Year Bachelor's Degree in Ecology and Environment**



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## 1. Introduction

Remote Sensing and Geographic Information Systems (GIS) are transformative technologies that have revolutionized the way we collect, analyze, and interpret spatial and environmental data. These tools are fundamental in understanding Earth's physical features, processes, and the impact of human activities. Remote sensing refers to the acquisition of data about an object or phenomenon without making physical contact, often through satellites or airborne sensors. It enables the observation of large and inaccessible areas, providing valuable insights into land use, vegetation, urban planning, and environmental monitoring.

Remote sensing originated from the merging of two ancient inventions: the hot air balloon (the first aerial observation platform) and photography. In reality, modern remote sensing emerged from aerial photography, which saw significant development during the 20th century, especially during World War II.

The year that symbolizes the entry of remote sensing into the modern era is 1957 with the launch of Sputnik, the first artificial satellite placed in orbit around the Earth. Since then, many countries, including the USA, Canada, France, the former USSR (now Russia), China, Japan, and India, have developed their own remote sensing programs. Today, dozens of Earth observation satellites are in orbit, continuously providing thousands of images for civil applications.

A satellite observes a region of the Earth in a very different way. It does not have a camera on board, but instruments that are 'sensitive' to visible light, as well as other parts of the 'electromagnetic spectrum' such as infrared, ultraviolet, or microwaves. These instruments (scanners) scan the Earth's surface and record measurements of 'light,' which are then used by computer programs to create images.

Geographic Information Systems (GIS), on the other hand, are powerful platforms for storing, managing, and analyzing spatial data. GIS integrates various data types—such as maps, satellite images, and sensor data—allowing users to visualize, interpret, and analyze patterns and trends within a geographic context. Through GIS, complex spatial relationships can be explored, leading to more informed decision-making in areas like urban planning, disaster management, agriculture, and natural resource management.

This course provides a comprehensive introduction to both Remote Sensing and GIS, focusing on their applications in solving real-world problems. Students will gain hands-on experience in

collecting and analyzing spatial data, learning to interpret satellite images to manage and analyze geospatial information. The course covers the principles of data acquisition, processing, and interpretation, equipping students with the skills necessary for careers in environmental monitoring, land management, and urban planning.

By the end of this course, students will have a solid foundation in remote sensing techniques and GIS tools, preparing them for advanced studies or professional work in these rapidly growing fields. Through practical exercises and case studies, they will understand how these technologies contribute to sustainable development, environmental protection, and efficient resource management.

### **1.1. Definitions of remote sensing**

"Remote sensing is the science and art of obtaining information about an object, surface, or phenomenon through the analysis of data acquired by a means that is not in physical contact with the object, surface, or phenomenon under study" (**Lillesand & Kiefer, 1987**).

Remote sensing encompasses the knowledge and techniques used to determine the physical and biological characteristics of objects through measurements taken from a distance, without direct contact with them. "Remote" means "at a distance" and "sensing" means "to discover" or "to detect" (**Interministerial Commission on Aerospace Remote Sensing Terminology, 1988**).

Remote sensing is a discipline that aims to obtain information about the Earth by using images acquired by satellites or airborne platforms and by utilizing the electromagnetic radiation emitted or reflected by the Earth's surface (**Lillesand & Kiefer, 1994; Chuvieco, 1996**).

Remote sensing uses the physical properties of objects to acquire information about their nature. This involves an interaction between the energy transmitted by electromagnetic radiation and the objects. For most satellite platforms, this energy is recorded by a sensor and transmitted to a receiving station as a digital image (**Lillesand & Kiefer, 1994**).

### **1.2. History of remote sensing**

The history of remote sensing techniques can be divided into five major periods:

- From 1856, when a camera was first fixed on a balloon, to World War I, is considered the pioneering era, During which the possibilities of vertical aerial photography for mapping

are explored; the fundamental laws of stereoscopy and photogrammetry are discovered at the end of the 19th century.

- From World War I to the late 1950s, aerial photography becomes an operational tool for mapping, oil exploration, and vegetation monitoring. Continuous advancements are observed in aviation, cameras, and emulsions (color, black-and-white infrared, false-color infrared). Methods of photo-interpretation are refined and codified.
- The period from 1957 to 1972 marks the beginnings of space exploration and sets the stage for modern remote sensing. The launch of the first satellites, followed by manned spacecraft equipped with cameras, reveals the potential of space-based remote sensing. Concurrently, radiometer-imagers are developed and refined, along with the first airborne radars. The first operational application of space remote sensing appears in the 1960s with the ESSA series meteorological satellites.
- The launch of the ERTS satellite (later renamed Landsat 1) in 1972, the first satellite for Earth resource remote sensing, ushers in the era of modern remote sensing. The constant development of sensors and methods for processing digital data increasingly broadens the range of remote sensing applications, making it an essential tool for planet management and, increasingly, an economic tool.
- Since the 1970s, remote sensing has seen continuous development, notably characterized by:
  - The increase in the spatial resolution of sensors, as previously mentioned.
  - The diversification of sensors using increasingly varied and specialized domains of the electromagnetic spectrum. In the 1990s, there is a proliferation of satellites equipped with active sensors, particularly radars. In the visible and infrared radiation domains, very high spectral resolution sensors are now commonly used in their airborne versions and are beginning to appear on satellites.
- The commercialization of data, anticipated since the launch of the SPOT program in 1986, is now reflected in the launch of remote sensing satellites by private companies. Remote sensing data has become the subject of a competitive market.

The accelerated dissemination and increased power of computers continuously promote new methods for using the ever-growing data provided by space-based remote sensing. Data from meteorological and oceanographic satellites are now essential for numerical weather and climate prediction and are directly assimilated by numerical models. Remote sensing images intended for

detailed observation of the Earth's surface, including traditional aerial photography, are integrated into Geographic Information Systems (GIS) in digital form (Gueye, 2013).

### 1.3. Electromagnetic radiation

In remote sensing, the physical properties of observed objects, particularly their optical properties, are used to acquire information about the nature of these objects. This information is transmitted to the observation system using electromagnetic radiation, such as light, which is the visible manifestation of this radiation. The observation system receives this radiation and translates it into elements understandable to the user, such as images or numerical data (Bonn et al., 1996).

#### a. Electromagnetic waves

Energy can be transported from one point to another in the form of waves. Some waves require a favorable medium to propagate; this is the case for seismic waves, for example, which propagate through solid materials, or sound which travels through air or water. Sound is a longitudinal vibration that requires an elastic medium for transmission. No sound can be transmitted in a vacuum. On the other hand, electromagnetic radiations, such as light, can travel through a vacuum. According to Maxwell, electromagnetic radiation is a dynamic form of energy that manifests only through its interaction with matter. It behaves like a field of forces whose variations affect the electrical and magnetic properties of matter: a change in the magnetic field creates an electric current and vice versa, hence the term "electromagnetic," as the two manifestations are inseparable.

An electromagnetic wave is represented by two mutually perpendicular vectors, whose amplitude varies periodically over time: the electric field  $E$  and the magnetic field  $H$ . The direction of propagation of this wave is perpendicular to the plane defined by these two vectors.

Any wave can be mathematically described by its wave function, which associates time and space. For a plane wave, this function can be expressed as:

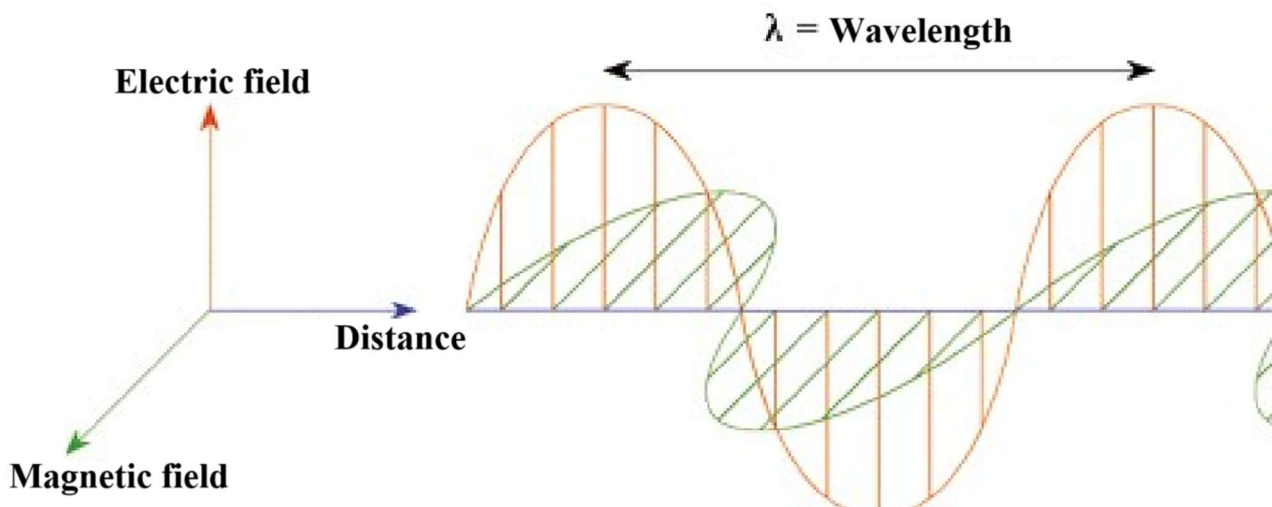
$$E = E_0 \cos(\omega t - kx + \phi) \text{ (eq. 1)}$$

where the direction of propagation is along  $x$  and the vibration is perpendicular to this axis, and where:

- " $t$ " is time (s)

- “ $E_0$ ” is the amplitude (V)
- “ $\omega$ ” is the angular frequency or pulsation ( $\omega=2\pi \nu$ ), where “ $\nu$ ” is the frequency defined below in eq. 2 ( $s^{-1}$ )
- “ $k$ ” is the wave number ( $2\pi/\lambda$ ), where “ $\lambda$ ” is the wave length defined below in eq. 3
- “ $\phi$ ” is the phase shift

These waves are known as plane waves because the phase of the wave is constant on the plane of space perpendicular to the direction of propagation. Equation 1 is represented by Figure 1.



**Figure 1: The Simple Electromagnetic Wave (Monochromatic, Plane) (Lillesand & Kiefer, 2000).**

Electromagnetic radiation is characterized by a period, a frequency, a propagation speed, a wavelength, and an amplitude.

The period  $T$  is the time during which the wave completes one full oscillation, and the frequency  $\nu$  is the inverse of the period. Frequency is the number of oscillations per second.

$$T = 2\pi / \omega = 1/\nu \quad (\text{Eq. 2})$$

The wavelength  $\lambda$  is the distance traveled by the wave at speed  $v$  during a period  $T$ .

$$\lambda = v T = 2\pi / k \quad (\text{Eq. 3})$$

Frequency “ $\nu$ ”, speed “ $v$ ”, and wave length “ $\lambda$ ” are related by the following expression, linking the spatial and temporal properties of the wave:

$$v = \lambda \nu = \omega / k \text{ (Eq. 4)}$$

More the frequency is higher, the wave length is shorter. Frequency is independent of the propagation medium; however, speed and wavelength are dependent on it. Thus, it is better to characterize a type of wave by its frequency rather than its wavelength, as the wavelength may differ in water or glass, for example.

In a vacuum and, almost the same in air, the speed of propagation of electromagnetic waves is:  $c = 300,000 \text{ km.s}^{-1} = 3 \times 10^8 \text{ m.s}^{-1}$ . Therefore, the relation (Eq. 4) can be written as:

$$\lambda = c / \nu \text{ (Eq. 5)}$$

Despite this, in the visible, ultraviolet, and infrared frequencies, radiation is often characterized by its wavelength, because when expressed in microns, the most commonly used wavelengths are represented by simple numbers. However, it should be noted that these wavelengths are only truly applicable in a vacuum or in air.

Propagation speeds and wavelengths are reduced in other media, such as water. The ratio of speed reduction compared to a vacuum is called the refractive index  $n_m$  of the medium  $m$  considered.

$$n_m = c / v_m = \lambda_{\text{vacuum}} / \lambda_m \text{ (Eq. 6)}$$

By definition, the refractive index of a vacuum is 1, and that of air is nearly the same as that of a vacuum; the refractive index of water is 1.33, and that of the cellular components of a plant cell is close to 1.5 (Guyot, 1989). Refraction is accompanied by a phenomenon of spectral dispersion of light. Indeed, since the speed of propagation of the wave is a function of frequency, in any medium with a refractive index greater than 1, refraction reveals dispersion according to frequencies, as occurs with a prism. It is also accompanied by a geometric alteration of the optical path obeying Descartes' laws, which are the basis of geometric optics and the design of photographic lenses.

The amplitude " $E_0$ " represents the intensity " $I$ " of the electromagnetic wave. The greater the amplitude, the more intense the radiation (Bonn & Rochon, 1996).

## b. Radiation and energy

Electromagnetic radiation is a form of energy transport. An electromagnetic wave transports energy not continuously, but discretely (in the mathematical sense of the term), in elementary entities or quanta of energy. These energy quanta can be thought of as particles and are sometimes referred to as photons. The amount of energy associated with a photon depends on its frequency:

$$E = h \cdot \nu \text{ (Eq. 7)}$$

where:

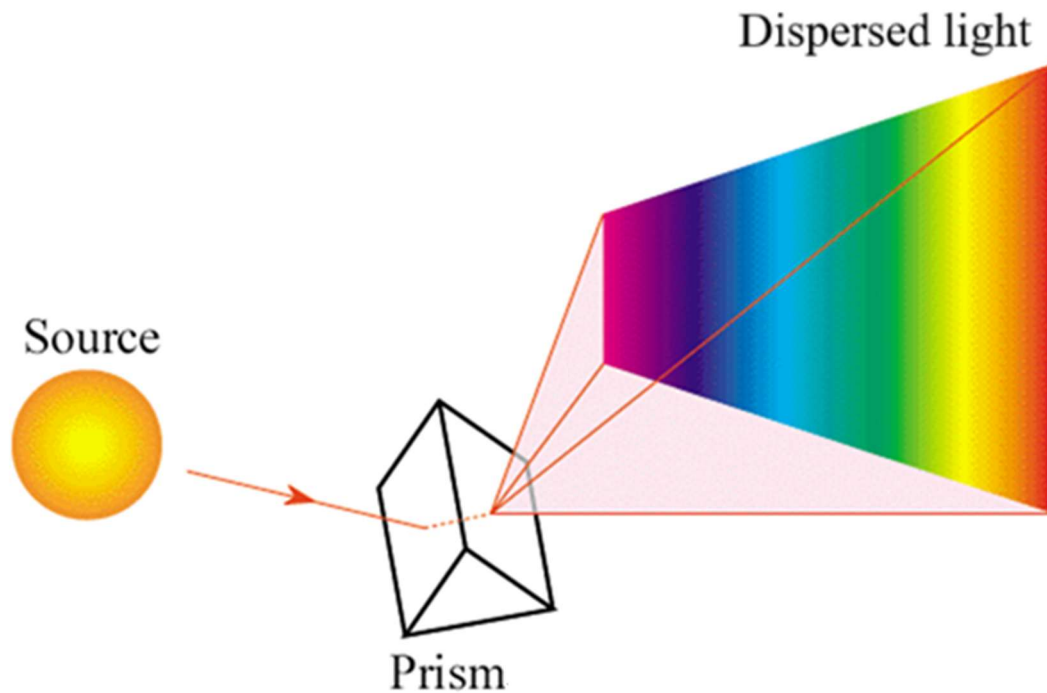
- “ $E$ ” is the amount of energy,
- “ $\nu$ ” is the frequency,
- “ $h$ ” is Planck's constant:  $h=6.63 \times 10^{-34}$  J·s

High-frequency or short-wavelength radiations (ultraviolet, visible light) thus transport much more energy than long-wavelength radiations (infrared, microwaves). It is the energy transported by electromagnetic radiation that is detected by the sensors used in remote sensing.

#### 1.4. The electromagnetic spectrum

The different electromagnetic waves that can be observed in nature result from the superposition of simple sinusoidal waves, each characterized by different amplitudes and frequencies, and therefore by their own wavelengths. The superposition of two sinusoidal waves can be visualized simply by two distinct waves of different amplitudes and frequencies overlapping to form a complex wave (Bonn *et al.*, 1996).

By analogy, it can be understood that any electromagnetic radiation can be decomposed into elementary sinusoidal waves, which are called spectral components of the radiation in question. The adjective "spectral" refers to the spectrum obtained when white light passes through a prism (Fig. 2). This concept of a spectrum has been extended to all electromagnetic waves, where the visible part corresponds to wavelengths ranging from 0.4 to 0.7  $\mu\text{m}$ .



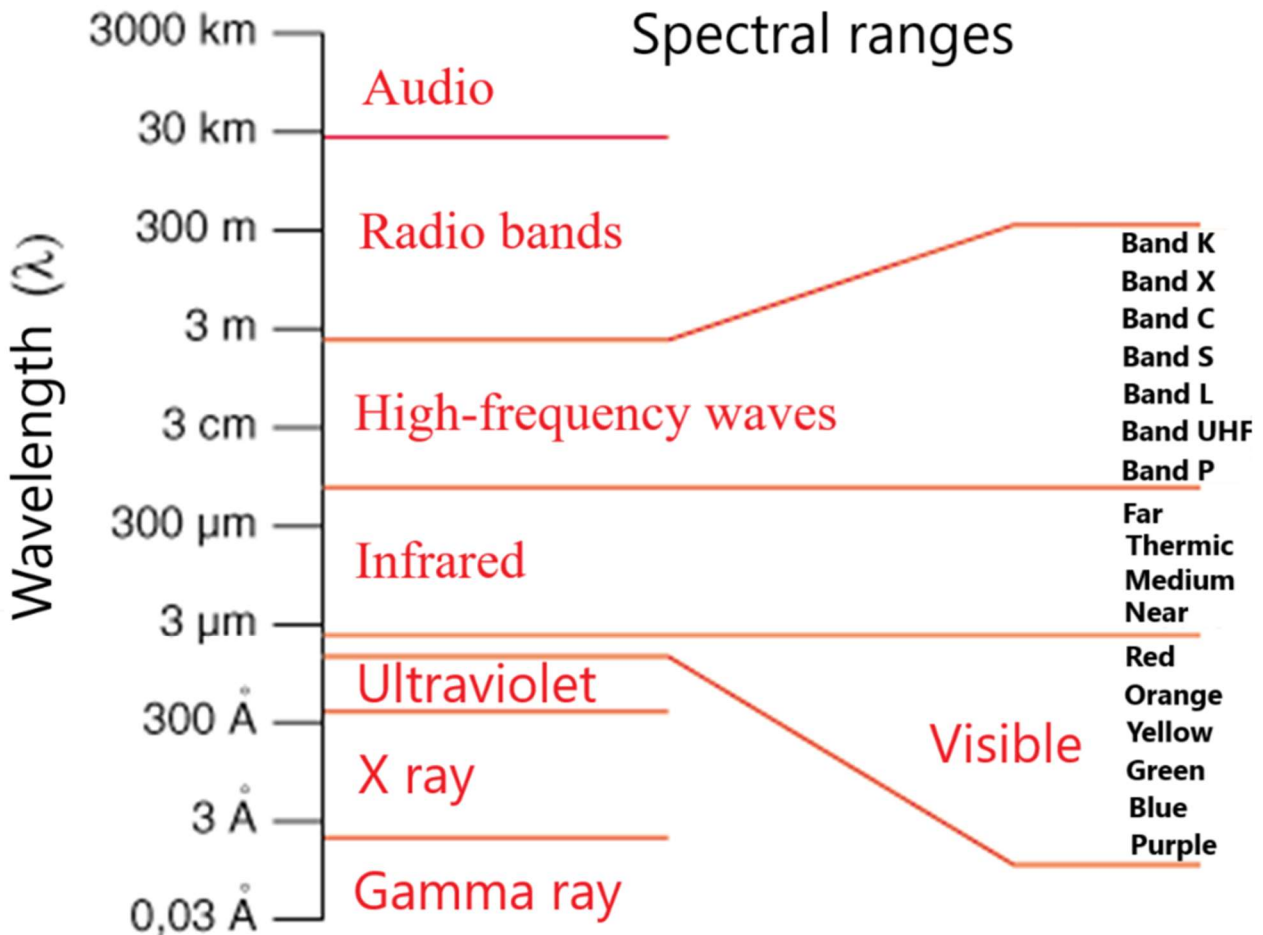
**Figure 2: Spectral Dispersion of Light Using a Prism (Bonn & Rochon, 1996).**

Figure 3 shows the electromagnetic spectrum, with different types of radiation classified according to their wavelength and frequency. The frequency scale, and thus the wavelength scale, is logarithmic in this figure.

The main regions of the spectrum where measurements are possible in remote sensing are:

- Ultraviolet (though rarely)
- Visible, from 0.4 to 0.7  $\mu\text{m}$ , often further subdivided into narrower spectral bands
- Near-infrared, i.e., close to visible, from 0.7 to 1.5  $\mu\text{m}$
- Mid-infrared, from 1.5 to 3  $\mu\text{m}$
- Thermal infrared, from 3 to 15  $\mu\text{m}$
- Microwave, also called radar waves, from 1 millimeter to 1 meter

In remote sensing, the use of electromagnetic waves as a medium for information is usually reflected in the measurement of their intensity using specific sensors. This is why it is important to detail the different quantities and units used in radiometry (**Bonn & Rochon, 1996**).



**Figure 3: Electromagnetic spectrum (Bonn & Rochon, 1996)**

Sources of radiation also vary according to the region of the spectrum:

- Ultraviolet, visible, or infrared radiation is emitted by bodies, objects, or surfaces depending on their temperature: solar radiation (UV, visible, and near-infrared) and terrestrial radiation (thermal infrared).
- Radiation with very short wavelengths (gamma rays, X-rays) is produced by the restructuring of atomic nuclei (radioactivity).
- Visible, infrared, or microwave radiation can be artificially produced by molecular vibration or rotation (fluorescence, lasers, microwave ovens).
- Radiation with long wavelengths is produced by electronic oscillations (antennas)

### 1.5. Radiometry concepts

Radiometry is the measurement of physical quantities related to light, and by extension, to all electromagnetic radiation. The term photometry is also used, which implies a limitation to the

visible part of the spectrum. It can be approached from three perspectives: the energetic perspective, the spectral perspective, and the luminous perspective (Bonn and Rochon, 1996).

### 1.5.1. Energetic quantities

Electromagnetic waves are characterized by different quantities:

- **Radiant energy (Q):** This is the amount of energy transported by the wave. It is expressed in joules (J).
- **Power or radiant flux ( $\phi$ ):** This is the amount of energy emitted by a point source per unit time in all directions. It is expressed in watts (W).
- **Radiant intensity (I):** This is the portion of the radiant flux emitted in a given direction ( $\theta$ ) by a point source. It is defined as:

$$I = d\phi / d\omega \text{ (Eq. 8)}$$

Where:  $\omega$  is the solid angle through which the power is radiated.

A solid angle can be represented as a cone with a given aperture. It is defined in three-dimensional space in a manner analogous to a two-dimensional plane angle. It is measured in steradians. There are  $4\pi$  steradians in a sphere. Thus, radiant intensity is expressed in watts per steradian ( $\text{W}\cdot\text{sr}^{-1}$ ).

- **Radiant luminance (L):** This is the intensity emitted per unit of apparent surface area in the direction  $\theta$  for a non-point source of area  $dA$  radiating through a solid angle  $\omega$ . It is sometimes mistakenly referred to by the English term "radiance." It is expressed as:

$$L = d\phi / d\omega * dA * \cos \theta = I / dA \cdot \cos \theta \text{ (Eq. 9)}$$

The units used are watts per square meter per steradian ( $\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$ ).

The apparent surface  $dA \cdot \cos \theta$  corresponds to the projection, in the plane perpendicular to the line of sight  $\theta$ , of the horizontal surface  $dA$  considered. If the energy emitted by a body in a direction making an angle  $\theta$  with the normal to the emitting surface is proportional to  $\cos \theta$ , then the luminance of such a body is independent of the emission direction: such bodies are said to be Lambertian. A sheet of matte white paper is an example of a Lambertian surface (Bonn & Rochon, 1996).

### - Radiant exitance (M)

Radiant exitance “M” is the total power  $\phi_e$  emitted into a hemisphere per unit area of the source. Some authors also use the term "emissive power" or the English term "emittance." Radiant exitance is expressed as:

$$M = d\phi_e / dA \text{ (Eq. 10)}$$

It is measured in watts per square meter ( $W \cdot m^{-2}$ ).

If the source is Lambertian, the radiant exitance will be equal to the radiant luminance multiplied by  $\pi$ . This corresponds to the integration of  $\cos \phi$  over an hemisphere.

### - Illuminance (E)

Illuminance “E”, sometimes also called irradiance, is the total hemispherical power  $\phi_i$  incident per unit area. Its definition is similar to that of radiant exitance, except that it concerns the radiation received rather than the radiation emitted. It is expressed in the same units ( $W \cdot m^{-2}$ ) and is defined as:

$$E = d\phi_i / dA \text{ (Eq. 11)}$$

In the case of terrestrial surfaces, illuminance is primarily provided by solar radiation, after diffusion and partial attenuation by the atmosphere. At a given location, it varies mainly with the solar angle, which is influenced by the time of day, season, and latitude of the location.

## 1.5.2. Spectral quantities

When dealing with electromagnetic waves that span multiple wavelengths, the total transported power is the sum of the powers associated with each wavelength. These spectral quantities are analogous to those defined earlier but are wavelength-dependent. In remote sensing, object identification often relies on spectral variations, known as spectral signatures. Spectral properties also play a crucial role in energy exchanges at the Earth's surface, which impact the food chains of ecosystems (Bonn & Rochon, 1996).

The main spectral quantities are:

- **Spectral power:** This measures the power transported per unit wave length.

$$\phi_{\lambda} = d\phi / d\lambda \text{ (Eq. 12)}$$

- **Spectral intensity:** This describes the intensity of the wave per unit wavelength.

$$I_{\lambda} = dI / d\lambda \text{ (Eq. 13)}$$

- **Spectral radiance:** This measures radiance per unit wavelength.

$$L_{\lambda} = dL / d\lambda \text{ (Eq. 14)}$$

- **Spectral exitance:** This expresses exitance per unit wavelength.

$$M_{\lambda} = dM / d\lambda \text{ (Eq. 15)}$$

- **Spectral irradiance:** This measures irradiance per unit wavelength.

$$E_{\lambda} = dE / d\lambda \text{ (Eq. 16)}$$

### 1.5.3. Luminous quantities

The human eye is a natural sensor sensitive to wavelengths between 0.4 and 0.7  $\mu\text{m}$ , thanks to photochemical processes in the retina. Its spectral response is maximum around 0.55  $\mu\text{m}$ . Wavelengths longer than 0.7  $\mu\text{m}$  (infrared) reach the retina without causing photochemical reactions. Conversely, wavelengths shorter than 0.4  $\mu\text{m}$  do not pass through the cornea but can damage it with prolonged exposure (fig. 4).

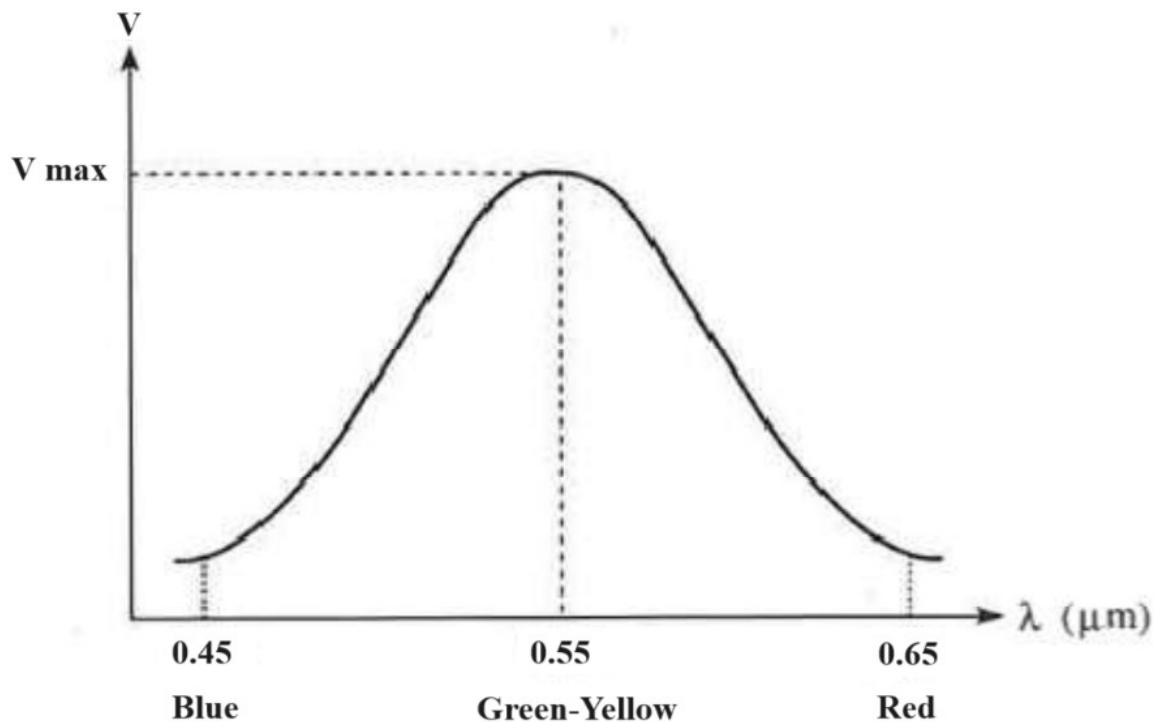


Figure 4: Spectral response of the human eye (Bonn & Rochon, 1996)

## 1.6. Interactions with the atmosphere

Between the observed Earth's surface and the airborne or satellite sensor, there is always an atmospheric layer that alters the received signal by affecting certain properties of the electromagnetic radiation.

Atmospheric perturbations result from two distinct entities: gas molecules and liquid or solid particles (aerosols, dust, droplets, etc.), causing three main types of interaction: absorption, scattering, and refraction of radiation. The atmosphere behaves as a stratified medium where the distribution of gases and particles varies in space and time. Consequently, the atmosphere acts as a highly variable filter that affects all remote sensing measurements (Bonn & Rochon, 1996).

### 1.6.1. Absorption and transmission: atmospheric windows

The absorption of radiation by the atmosphere, which determines its transmission capacity, is due to electronic transitions of atoms and molecules in the visible and near-infrared regions, as well as rotational and vibrational transitions of molecules in the microwave and far-infrared regions. The main absorbing gases in the atmosphere include oxygen (O<sub>2</sub>), ozone (O<sub>3</sub>), water vapor (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), nitrogen (N<sub>2</sub>), carbon monoxide (CO), and methane (CH<sub>4</sub>). Absorption results in signal attenuation in the direction of propagation. The radiation absorbed by the

atmosphere is re-emitted as heat, which leads to temperature and relative humidity differences, and thus expansions and movements of air masses characteristic of various climate systems.

In remote sensing, the focus is on the atmospheric transmission and scattering capabilities because they affect the signal received by the sensor by altering its informational content. This signal modification, which disturbs the spectral information about the surface, can, however, be used to study atmospheric composition (Royer *et al.*, 1990).

The atmosphere is opaque to electromagnetic radiation from the shortest wavelengths, corresponding to gamma rays and X-rays, up to about 0.35  $\mu\text{m}$  in the ultraviolet, very close to the visible range. Beyond 0.4  $\mu\text{m}$ , the atmosphere exhibits several spectral transmission windows before becoming opaque again from 14  $\mu\text{m}$  to 1 millimeter and up to 8 centimeters for microwaves, where it becomes nearly transparent. These spectral regions where the atmosphere is transparent to radiation are referred to as atmospheric windows, analogous to a window allowing light to pass through an opaque wall. Atmospheric windows can be classified by spectral domains, from ultraviolet to microwaves. The main windows of interest in remote sensing are summarized in Table 1.

**Table 1: Main atmospheric windows**

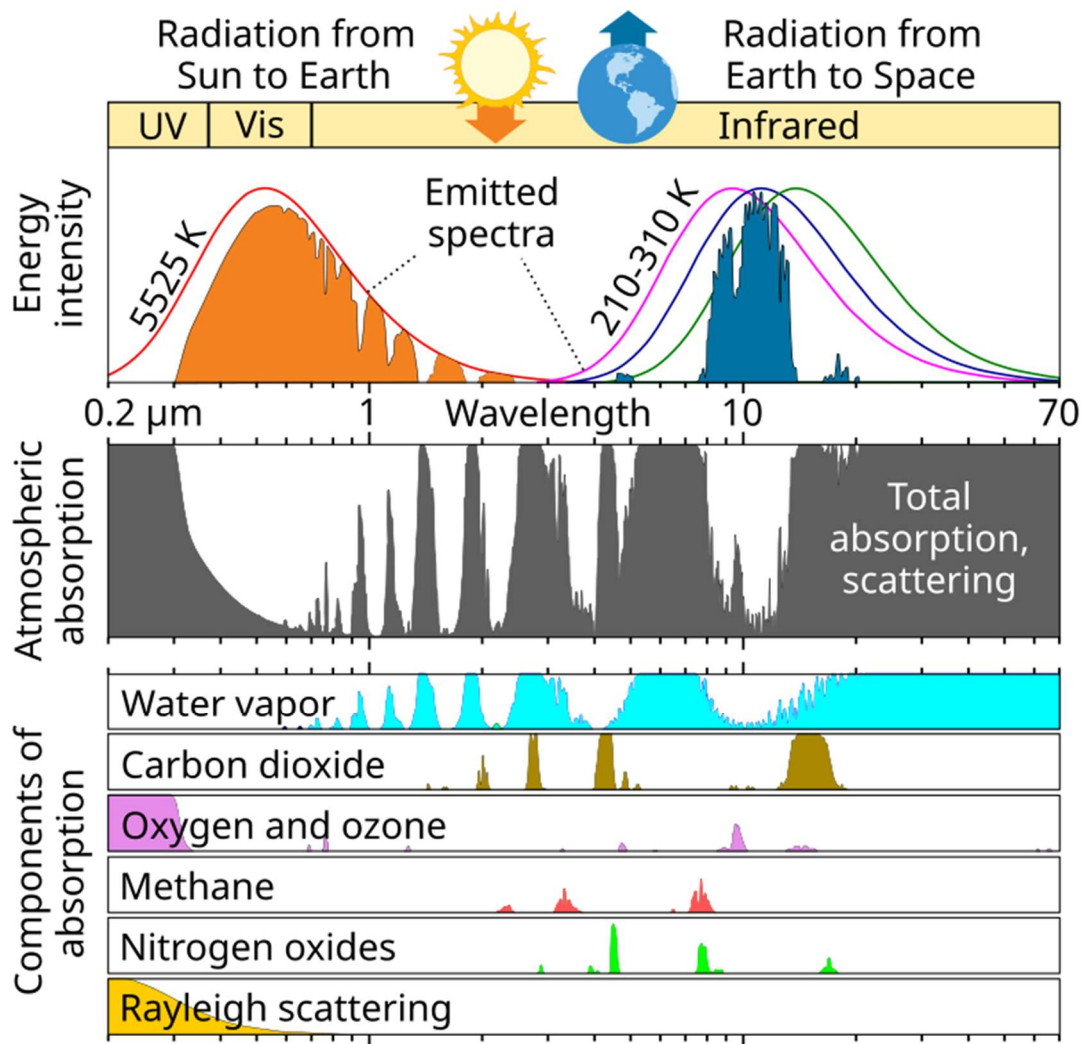
Spectral Range	Wavelength Range	Transparency	Description
Ultraviolet	0.1 - 0.35 $\mu\text{m}$	Opaque	The atmosphere is opaque to UV radiation.
Visible	0.4 - 0.7 $\mu\text{m}$	Transparent	Allows most visible light to pass through.
Near Infrared	0.7 - 1.5 $\mu\text{m}$	Transparent	Good transparency with some absorption.
Shortwave Infrared	1.5 - 3 $\mu\text{m}$	Variable	Partial transparency with varying absorption.
Midwave Infrared	3 - 5 $\mu\text{m}$	Variable	Partial transparency, higher absorption.
Thermal Infrared	5 - 14 $\mu\text{m}$	Opaque	The atmosphere absorbs most thermal radiation.
Microwaves	1 mm - 1 cm	Transparent	Generally transparent with some absorption.
Submillimeter / Millimeter	1 cm - 8 cm	Transparent	Transparent for longer wavelengths.

### 1.6.1.1. Ultraviolet

Ultraviolet (UV) radiation absorbed by the upper layers of the atmosphere leads to the dissociation of oxygen (O<sub>2</sub>), ozone (O<sub>3</sub>), or nitrogen (N<sub>2</sub>) molecules and the ionization of oxygen and nitrogen molecules. These interactions are so intense that ultraviolet solar radiation is essentially unusable in spaceborne remote sensing. However, these interactions protect Earth's surface from these destructive radiations. Maintaining the presence of ozone is particularly important in this context and represents a major global air quality issue. Since this gas is mainly located in the stratosphere, it affects remote sensing at lower altitudes less significantly. Nevertheless, the general atmospheric scattering in the ultraviolet contributes to making this spectral window less usable in remote sensing (**Bonn & Rochon, 1996**).

### 1.6.1.2. Visible

The visible spectrum contains the maximum solar energy reaching the Earth's surface. About 75% of the solar energy that reaches the upper layers of the atmosphere makes it to the Earth's surface. Visible radiation is significantly less absorbed than ultraviolet radiation. However, there are minor absorption bands in the visible range due to ozone around 0.6  $\mu\text{m}$ , oxygen, and water vapor between 0.69 and 0.76  $\mu\text{m}$ . Atmospheric particles also play a crucial role in remote sensing. Figure 5 shows the main absorption bands of the atmosphere in the visible and near-infrared regions.

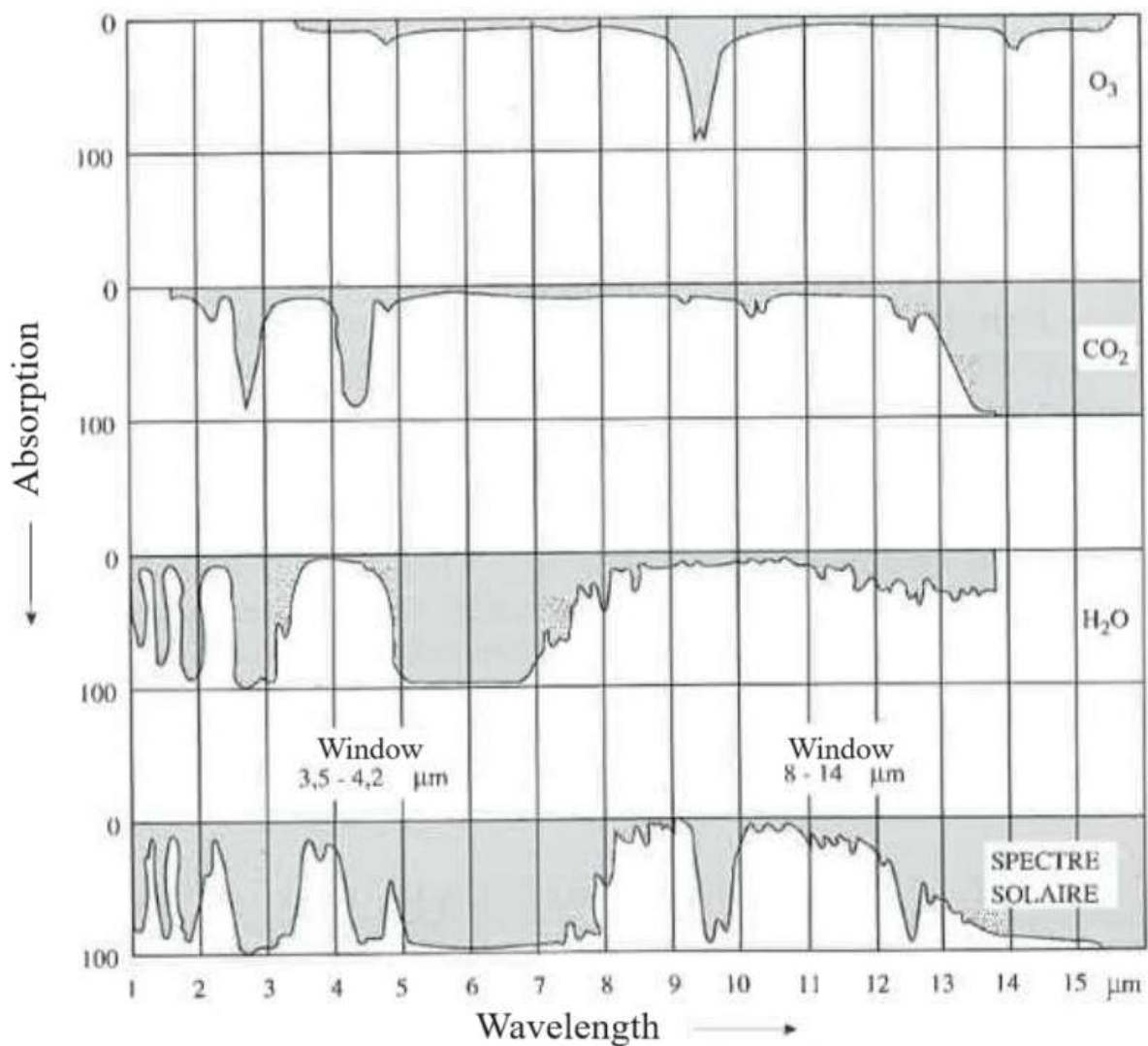


**Figure 5 : Atmospheric absorption of electromagnetic radiation and near-infrared** ([https://en.wikipedia.org/wiki/Atmospheric\\_window#/media/File:Atmospheric\\_Transmission.svg](https://en.wikipedia.org/wiki/Atmospheric_window#/media/File:Atmospheric_Transmission.svg))

### 1.6.1.3. Infrared

Absorption bands in the infrared are caused by vibrational transitions of molecules, primarily water vapor. The windows between 1.5 and 1.8  $\mu\text{m}$  and between 2.05 and 2.4  $\mu\text{m}$  are useful for detecting changes in humidity in vegetation. Between 3.5 and 5.0  $\mu\text{m}$ , forest fires, certain active volcanic lavas, and heavy industries emit their peak energy. In the thermal infrared, there are very strong absorption bands due to water vapor and carbon dioxide ( $\text{CO}_2$ ). The windows located between 8.0 and 9.2  $\mu\text{m}$  and between 10.2 and 12.4  $\mu\text{m}$  cover the region of normal emission of the Earth. These two windows are separated by the ozone absorption band centered around 9.6  $\mu\text{m}$ . For low-altitude detection, this absorption band is usually neglected due to the presence of ozone

in the upper layers of the atmosphere, and a large window of 8 to 14  $\mu\text{m}$  is considered. Figure 6 shows the main absorption zones and thus transmission regions of the atmosphere in the infrared.

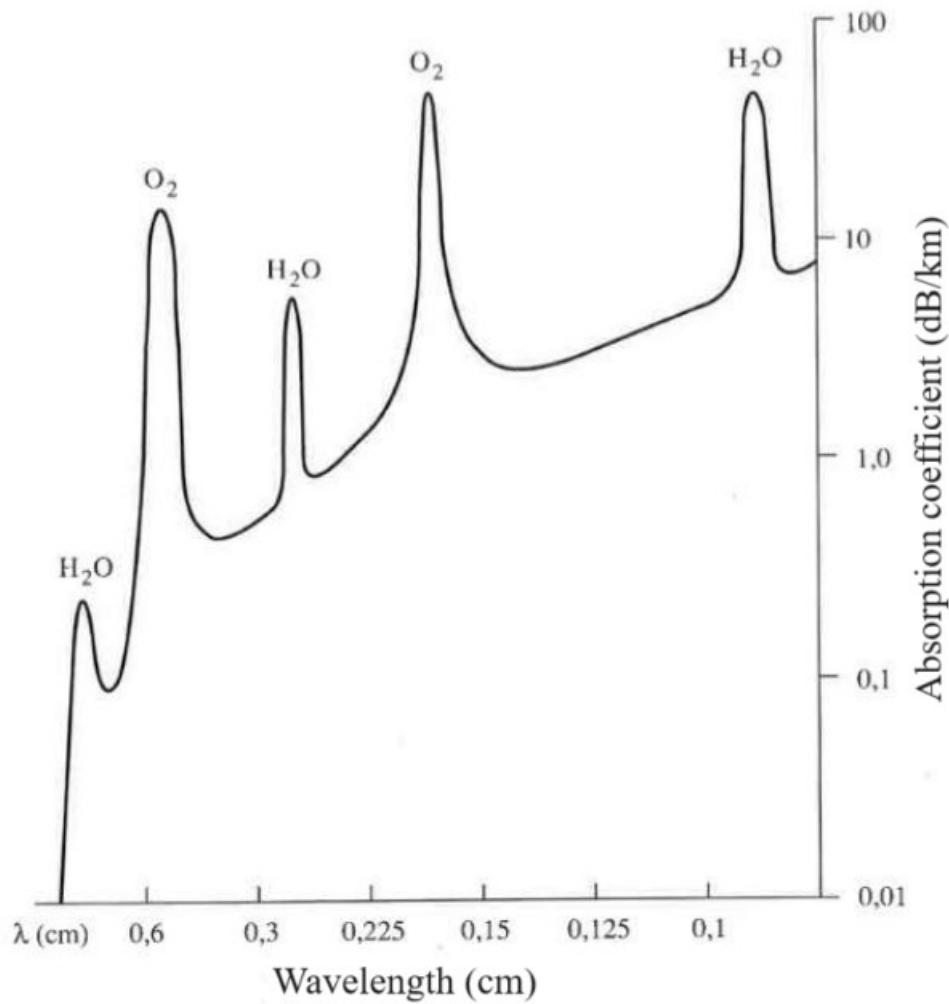


**Figure 6: Atmospheric absorption of electromagnetic radiation between 1 and 15  $\mu\text{m}$  (Bonn & Rochon, 1996)**

#### 1.6.1.4. Microwaves

For wavelengths greater than two centimeters, the atmosphere does not show significant absorption of active and passive microwaves, allowing for operation in all weather conditions, both day and night, and the ability to see through clouds. Weather radars that detect precipitation rely on the fact that rain droplets large enough to be on the order of the wavelength reflect an echo back to the source, which is detected and recorded. However, at higher microwave frequencies,

there are absorption bands associated with oxygen and water vapor that limit the use of certain bands, as shown in Figure 7.



**Figure 7: Atmospheric absorption in the microwave frequencies**

The observation of Figure 8 highlights the key points of the absorption phenomenon (Lillesand & Kiefer, 1987):

- Ultraviolet radiation ( $\lambda = 0.29 \mu\text{m}$ ) is completely absorbed by ozone.
- The spectral regions of visible light and near-infrared show very good transmission and are therefore extensively used by satellite sensors dedicated to Earth observation.
- In the mid-infrared and thermal infrared, only a few spectral bands allow for radiation transmission.
- Water vapor and carbon dioxide in the atmosphere absorb nearly all radiation in the far-infrared.

- In the microwave region, absorption is negligible, and the atmosphere is completely transparent to radiation.

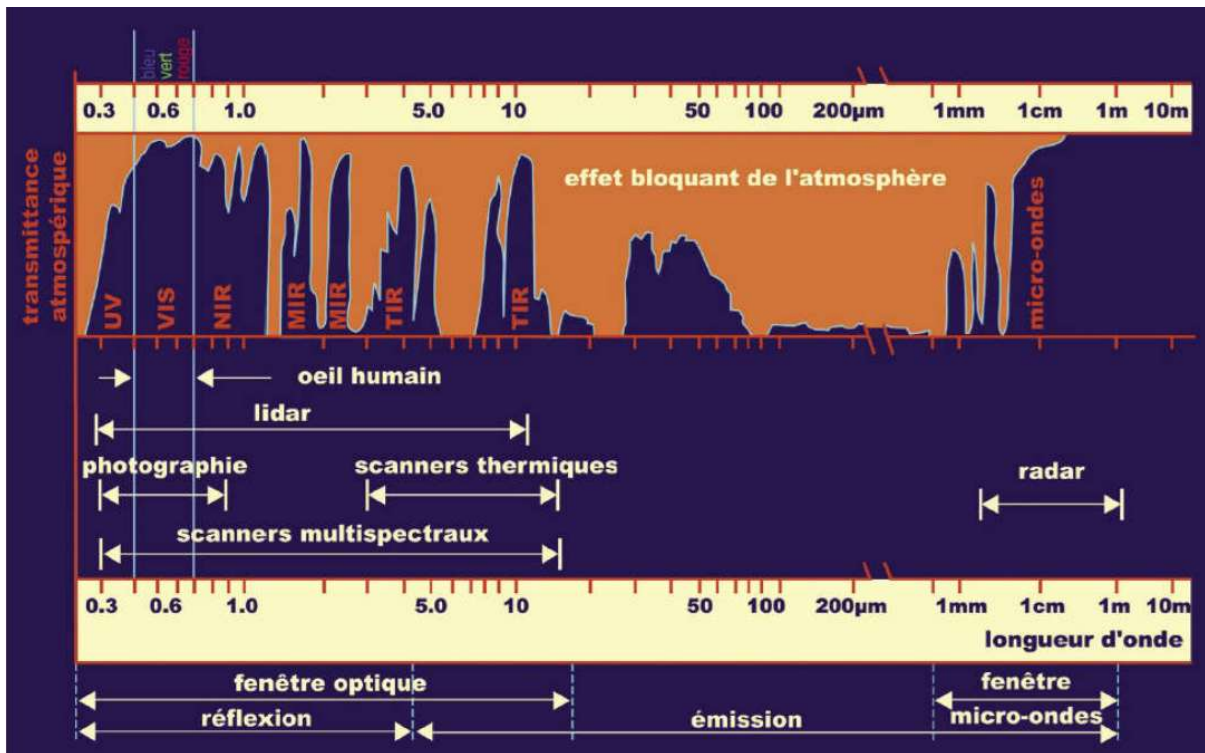


Figure 8: Atmospheric absorption of electromagnetic radiation (Lillesand & Kiefer, 1987)

### 1.6.2. Atmospheric scattering

Atmospheric scattering is due to the absorption of photons by atoms or molecules and the subsequent re-emission of electromagnetic radiation by these atoms or molecules at the same frequency as the incident radiation. This phenomenon must be considered from a quantum perspective, introducing the concept of energy levels or states. If the energy of the photon corresponds to the difference in energy between excited energy levels, elastic or resonant scattering occurs. This results in a decrease in radiation in the direction of propagation and an increase in radiation in other directions. If the atom or molecule re-emits electromagnetic radiation at a frequency different from that of the incident radiation, it is referred to as luminescence (fluorescence or phosphorescence) if the re-emission frequency is lower than the incident frequency, or Raman scattering if it is higher.

Depending on the size of the gas molecules or particles considered, the scattering mechanism varies. Atmospheric physicists commonly distinguish three types of scattering:

- Rayleigh scattering, caused by molecules whose size is small compared to the wavelength;

- Mie scattering, caused by particles with sizes comparable to the wavelength;
- Non-selective scattering, caused by particles much larger than the wavelength.

All these scattering phenomena depend on the ratio of wavelength to particle diameter; gas molecules produce significant Rayleigh scattering in the visible range, but raindrops cause the same type of scattering for millimeter waves (Bonn & Rochon, 1996).

### 1.6.3. Atmospheric refraction

Radiation propagating at an angle relative to the Earth's vertical does not follow a straight path; the angular deviation between the apparent position as seen from the ground and the actual position is due to the refraction phenomenon, which is a function of pressure, air constituents, and temperature. The effects of atmospheric refraction are more significant for an observer on the ground looking at a target located outside the atmosphere than for an observer outside the atmosphere aiming at the ground (fig.9). This phenomenon is particularly important when taking measurements from large-angle or panoramic images, with high incidence angles (Bonn & Rochon, 1996).

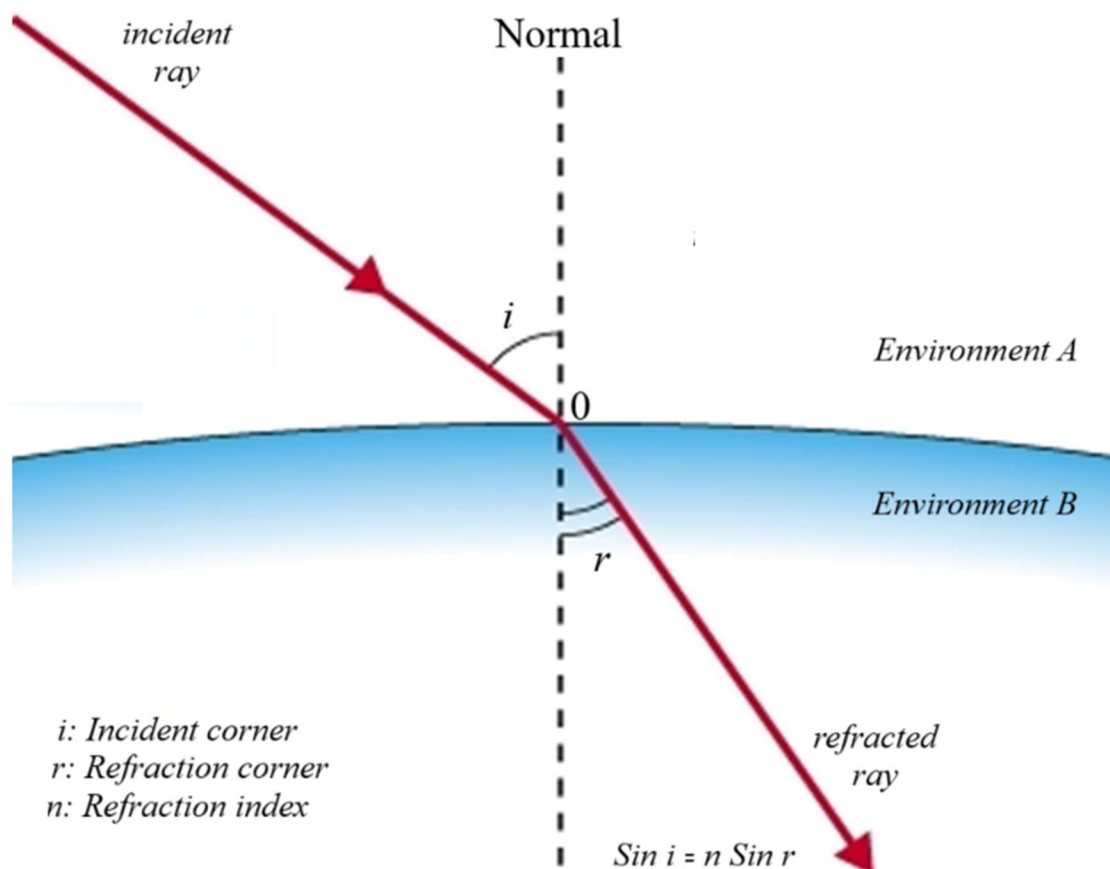


Figure 9: Atmospheric refraction (Bonn & Rochon, 1996)

#### **1.6.4. Atmospheric emission**

The atmosphere behaves like a black body between 200 and 300 K, and its maximum emission corresponds to a wavelength of nearly 10  $\mu\text{m}$ . This emission is of interest in thermography and microwave radiometry because it creates an additional source of radiation. A clear sky is usually less emissive and thus cooler than a cloudy or humid sky with particles. The contribution of celestial radiation is often neglected in thermography due to the surface emissivities close to 1 for most natural or vegetative surfaces, which affect the brightness temperature via their fourth root. However, it is significant in passive microwave measurements, where lower emissivities have a direct impact on the radiation measured by the sensor and include a non-negligible component of celestial radiation reflection.

#### **1.7. Passive and active detection**

The Sun is a very practical energy source for remote sensing. Solar energy is either reflected, as in the visible part of the spectrum, or absorbed and then re-emitted, as in the thermal infrared part of the spectrum. "Passive sensors" are remote sensing devices that measure naturally available energy. Passive sensors can only detect energy when it is naturally available (fig. 10).

Reflected energy can only be detected when the Sun illuminates the Earth. The solar-reflected energy is not available at night. However, as long as it is sufficient, naturally emitted energy (thermal infrared) can be recorded both day and night.

"Active sensors" are those that produce their own energy to illuminate the target. The sensor emits radiation directed at the observed target, then captures and measures the radiation reflected by the target. This provides the advantage of being able to take measurements at any time of day or season. Active sensors are used to examine wavelengths not produced by the Sun, such as microwaves, or to better control how a target is illuminated. They must produce a significant amount of energy to properly illuminate a target. Examples of active sensors include laser fluorimeters and synthetic aperture radar (SAR).

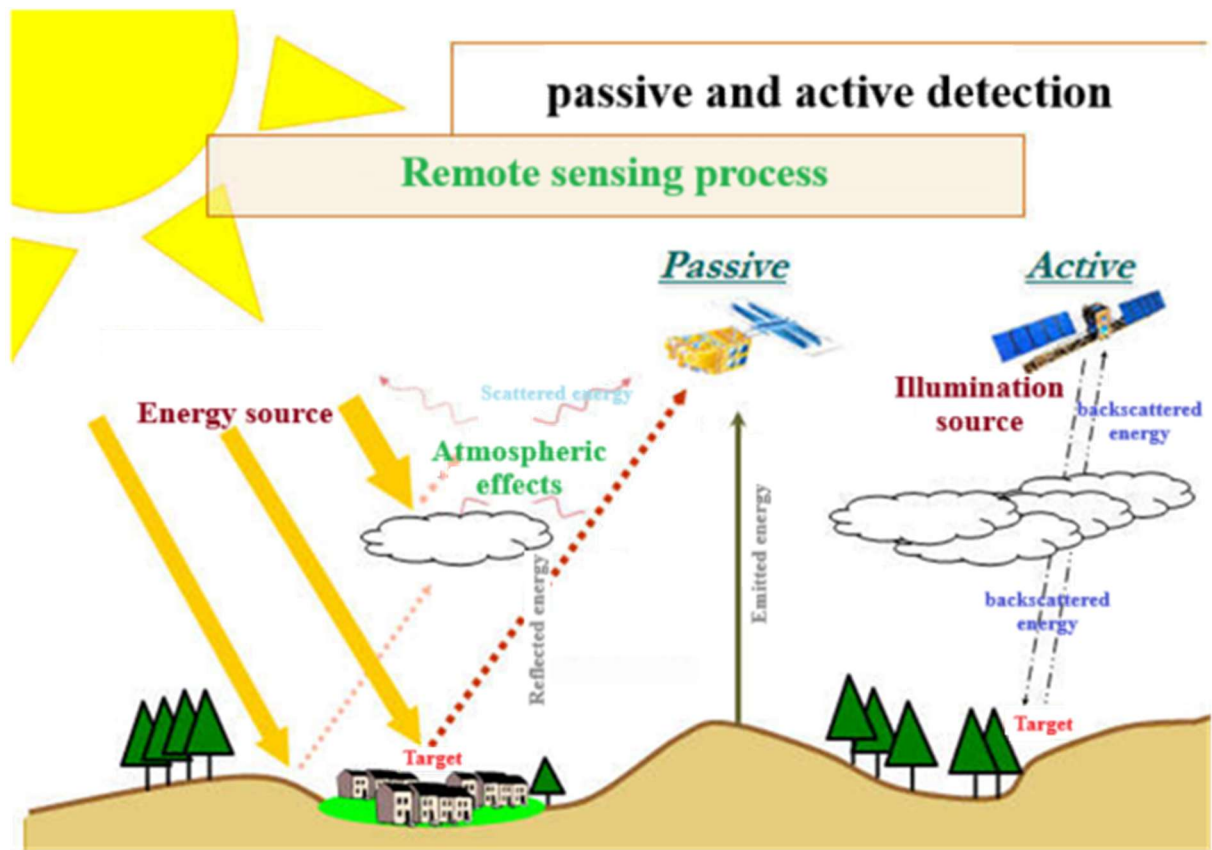
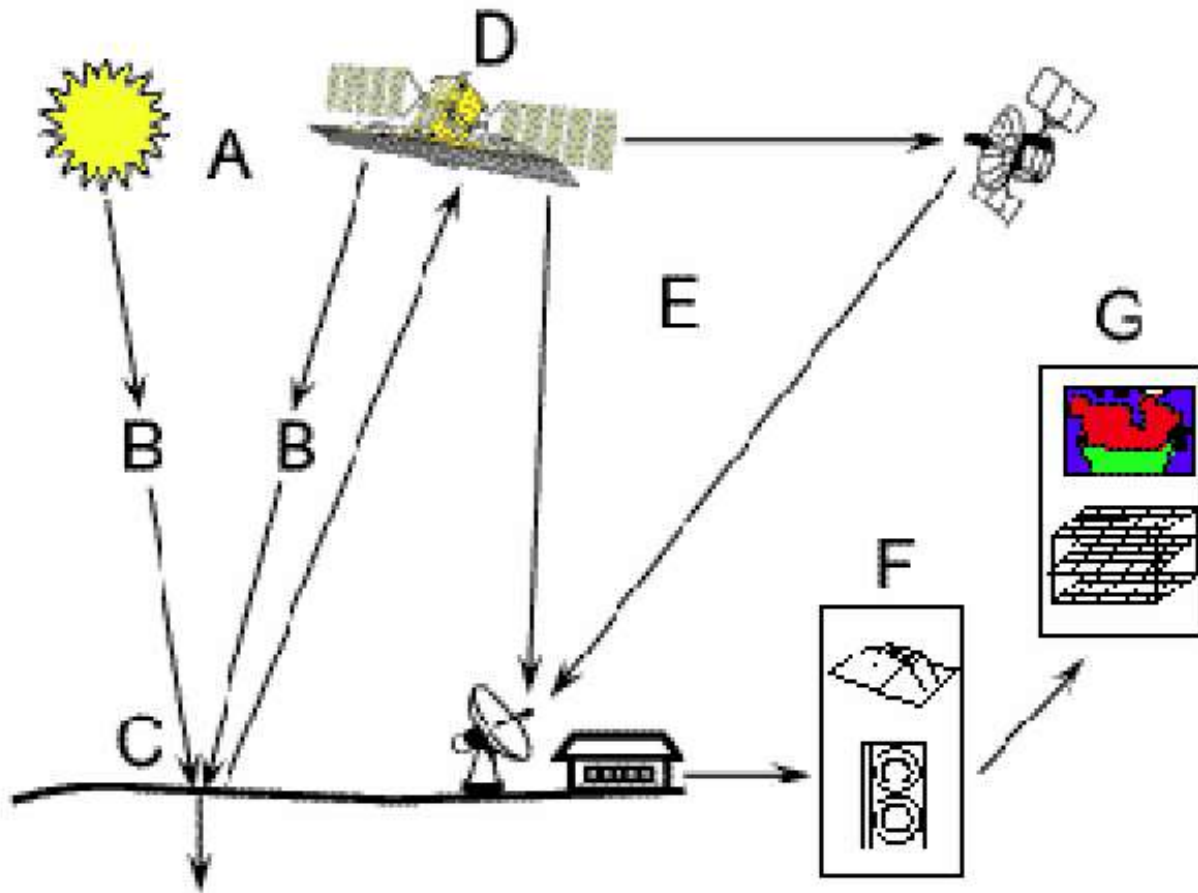


Figure 10: Passive and active detection

### 1.8. Remote sensing process

In most cases, remote sensing involves an interaction between incident energy and the targets. The remote sensing process using imaging systems consists of the following steps (fig. 10):



**Figure 10: Remote sensing process**

***A. Energy or illumination source***

At the heart of every remote sensing process is necessarily an energy source that illuminates the target by emitting an electromagnetic wave. In most cases, the energy source is the Sun. However, radar technology requires an emitter to be mounted on the satellite, in which case the satellite itself is the energy source. It is also possible to measure the heat emitted from the surface of the target, in which case the target itself is the energy source.

***B. Radiation and atmosphere***

During its journey from the energy source to the target, the radiation interacts with the atmosphere. A second interaction occurs on the path between the target and the sensor.

***C. Interaction with the target***

Once the energy reaches the target, it interacts with its surface. The nature of this interaction depends on the characteristics of the radiation and the properties of the surface.

#### ***D. Energy recording by the sensor***

Once the energy is scattered or emitted by the target, it must be captured remotely (by a sensor that is not in direct contact with the target) and then recorded.

#### ***E. Transmission and reception***

The energy recorded by the sensor is transmitted, often through electronic means, to a receiving station where the information is transformed into images (digital or photographic).

#### ***F. Interpretation and analysis***

A visual and/or digital interpretation of the processed image is then required to extract the information desired about the target.

#### ***G. Application***

The final step in the process is to use the information extracted from the image to better understand the target, uncover new aspects of it, or help solve a particular problem.

### **1.9. Characteristics of images**

An image is not a photograph: the difference between these two concepts is significant. An image is in digital format, whereas a photograph is in paper format. A satellite image is a matrix of pixels. The term 'pixel' refers to the smallest homogeneous area that makes up a recorded image.

Electromagnetic energy can be perceived either photographically or electronically. The photographic process uses a chemical reaction on a light-sensitive surface to capture and record variations in energy. In remote sensing, it is important to distinguish between the terms "image" and "photograph." An image is a graphical representation, regardless of the wavelength or remote sensing device used to capture and record the electromagnetic energy. A photograph specifically refers to any image captured and recorded on photographic film.

#### **1.9.1. Informative content**

From a thematic point of view, the image contains only a relative measurement of luminance expressed by a shade of gray. In addition to this thematic content of luminance, there is also the equally fundamental aspect of its positioning in the spatial dimension of reality. What distinguishes a digital image from a simple series of measurements is the spatial organization of those measurements (fig. 11).

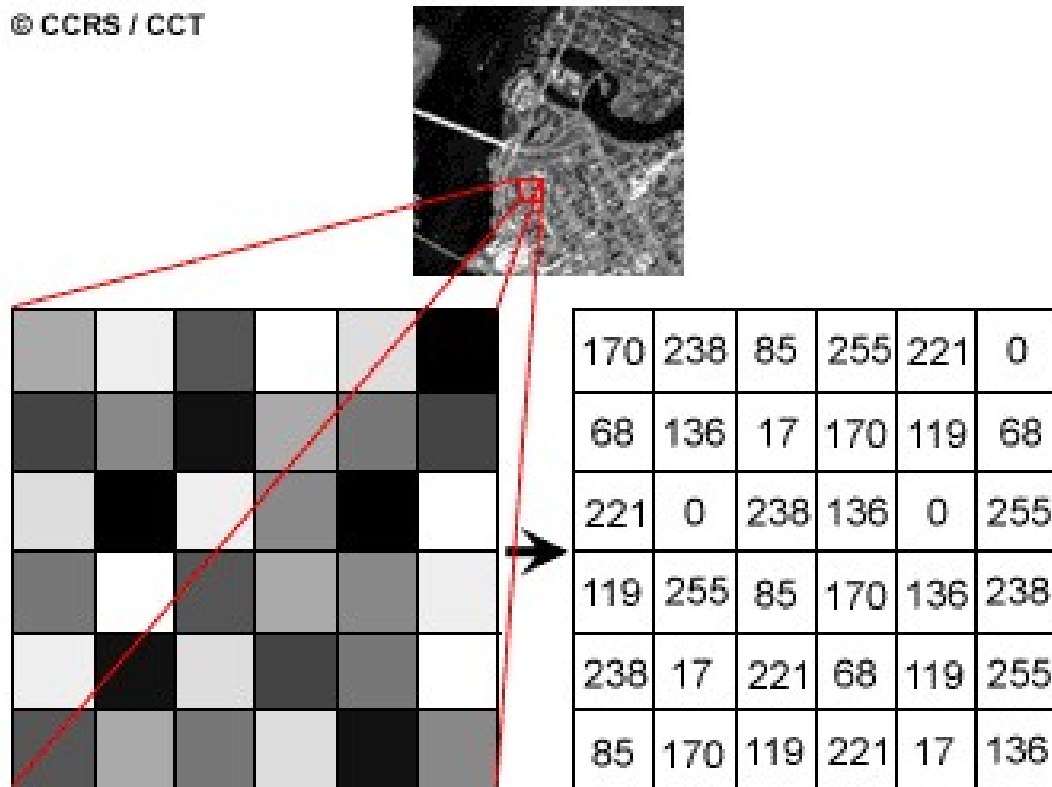
Thus, it can be stated that the raw information of an image consists of a relative measurement of luminance in its thematic dimension and a relative positioning of the observation units in its spatial dimension.



**Figure 11: Ottawa city**

The black and white photo (fig.11), depicting a portion of Ottawa, Canada, was obtained using the visible part of the spectrum. Photographs typically capture wavelengths between 0.3 and 0.9 micrometers (the visible and reflected infrared portions). With these definitions, we see that while every photograph is an image, not all images are photographs. Unless we are specifically referring to images captured by a photographic process, we use the term "image."

A photograph can be presented and displayed in digital format by dividing the image into small, equally sized and shaped pieces, known as pixels. The brightness of each pixel is represented by a numerical value (fig. 12).



**Figure 12: Numerical / Graphical format**

### 1.9.2. Technical features

The different characteristics of remote sensing images concern:

#### *a. Type*

We can find single-band and multi-band images (fig. 13).

#### *a. Image formats*

There are two main modes of organizing multiband image data: the BSQ (Band Sequential) format and BIL (Band Interleaved by Line) format. In the BSQ mode, the spectral bands are recorded one after another, while in BIL, the first line of each band is stored first, then the second line of each band, and so on (Fig.14).

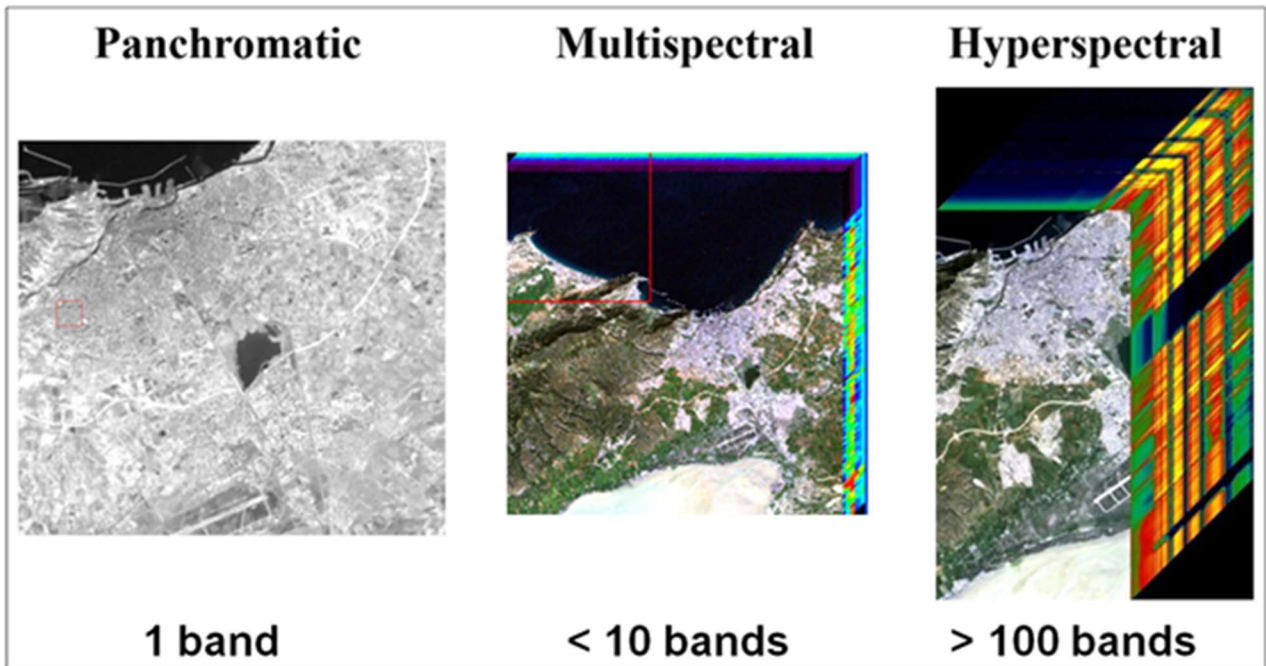


Figure 13: Image' types

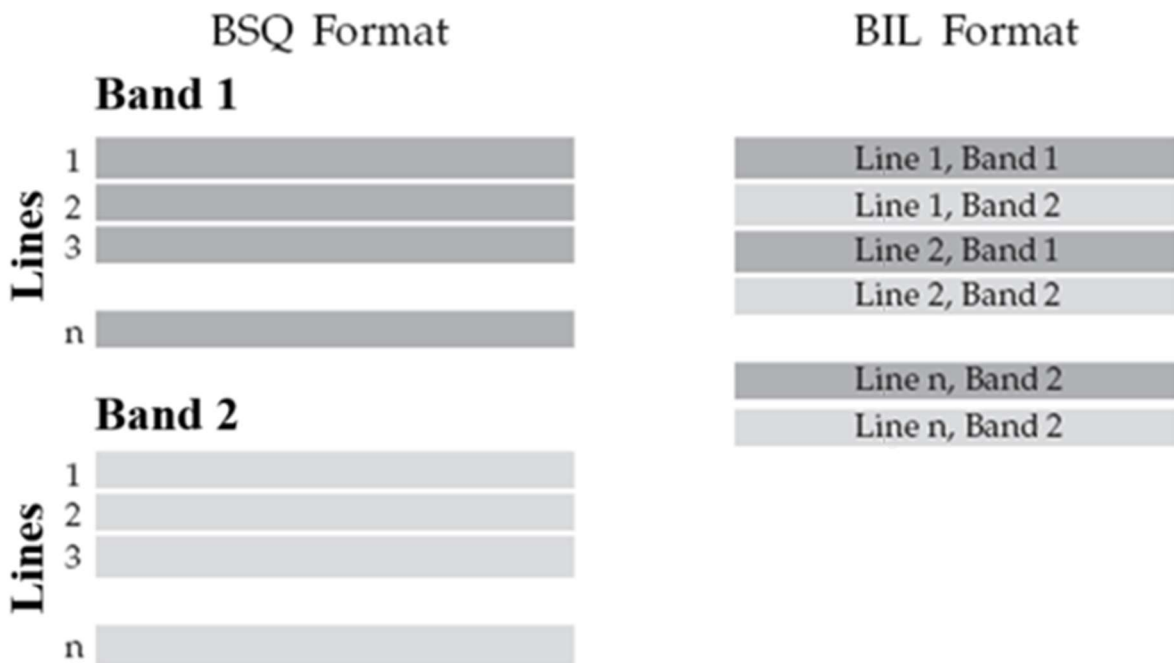


Figure 14: satellite image recording format

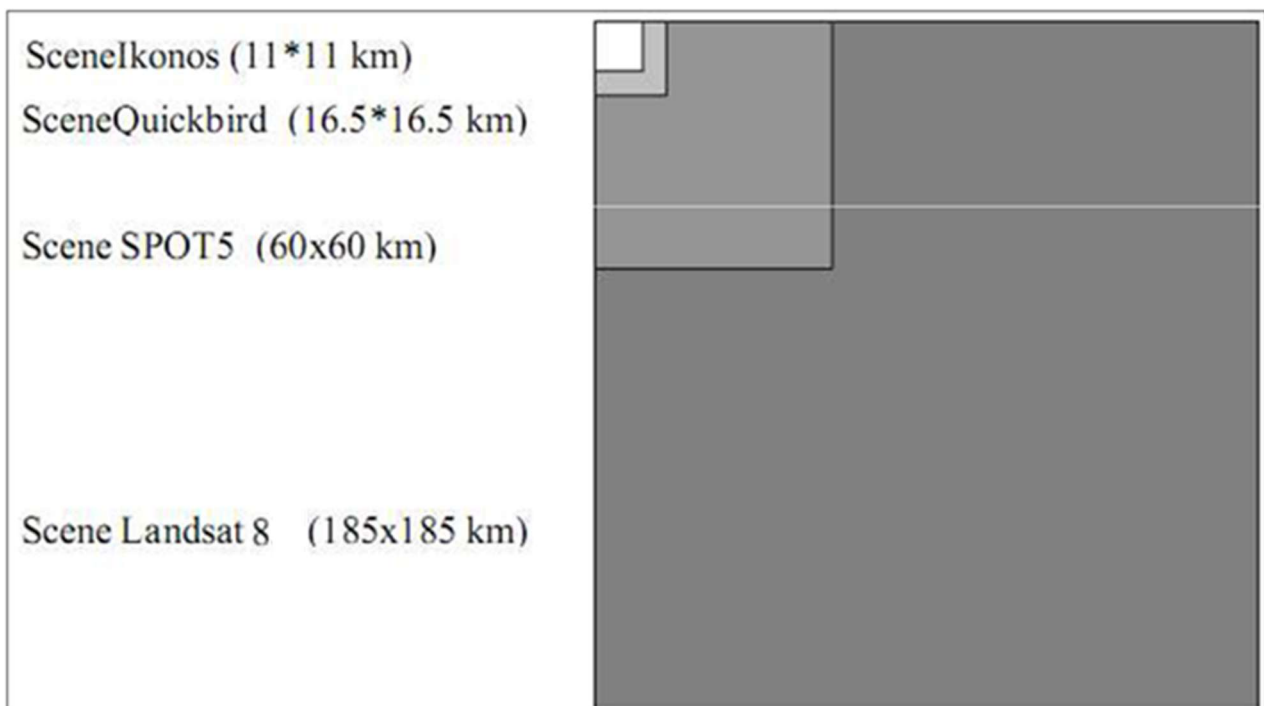
The most commonly used image exchange formats are:

- GIF (Graphic Interchange Format)
- TIFF (Tagged Image File Format)
- GEOTIFF (Geographic Tagged Image File Format)

- JPEG (Joint Photographic Experts Group)
- EPS (Encapsulated PostScript)
- BMP (Bit Map)

***b. Satellite image swath***

It determines the size of the overall observation field, that is, the size of the scene that the sensor can 'see,' and thus the maximum size of the image (fig.15).



**Figure.15: Satellite image swath**

***c. Different resolutions***

Resolution refers to the ability of an instrument to distinguish between two objects or two values that are close to each other. A satellite image is characterized by the following different resolutions:

- Spatial or geometric resolution
- Spectral resolution
- Radiometric or digital resolution
- Temporal resolution

**2. Data acquisition in remote sensing (Sensors)**

When discussing sensors in remote sensing, regardless of the spectral domain, it is important to distinguish between passive and active modes. In passive mode, sensors merely record natural energy (reflected or emitted) from the Earth. In active mode, sensors artificially illuminate the objects under study before recording the energy they reflect back to the sensor.

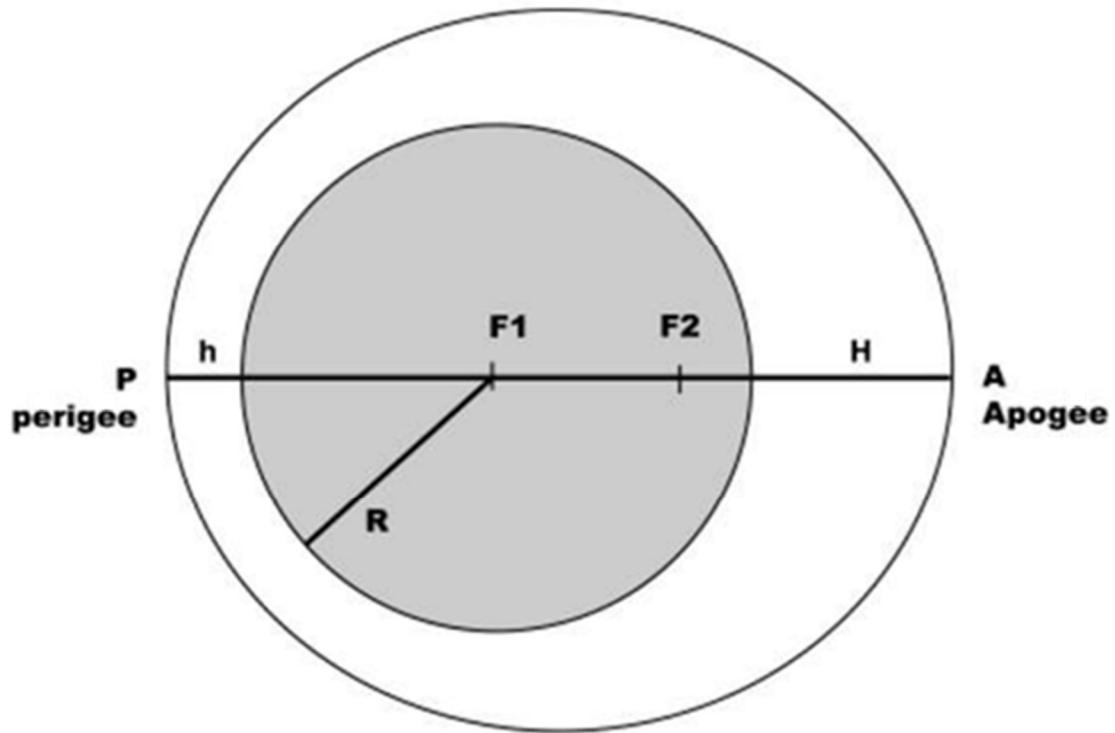
Among passive sensors are radiometers, thermal scanners, optical scanners, photographic cameras, vidicon tubes, scintillometers, spectroradiometers, and imaging spectrometers. Active sensors include radars, scatterometers, lidars, and fluorometers (**Bonn & Rochon, 1996**).

### 2.1. Satellite in orbit

The orbit refers to the trajectory followed by a satellite around the Earth. The laws governing satellite movement in orbit can be compared to those governing planetary movement, formulated by 16th and 17th-century astronomers and mathematicians: Kepler, Galileo, and Newton.

Once placed in orbit, a satellite is driven solely by inertia; in the absence of friction (beyond the atmosphere), the orbit should theoretically remain indefinitely stable. The centrifugal force counterbalances the Earth's gravitational pull. A satellite's orbit is always an ellipse, with the Earth occupying one of the foci (Fig 16). The distance between the two foci defines the eccentricity of the elliptical orbit.

In remote sensing, the chosen orbits are generally circular or nearly circular, meaning they have zero or very low eccentricity



**Figure 16: The Elliptical Orbit. F1 and F2 are the foci, h and H are the satellite's altitude at perigee and apogee, and R is the Earth's radius**

The speed of a satellite in orbit varies between a maximum at perigee, the lowest point of the orbit, and a minimum at apogee, the highest point. The period refers to the time required for the satellite to complete one revolution around the Earth (Bonn and Rochon, 1996).

$$V = \sqrt{\frac{g \cdot M}{R + Z}}$$

Where:

- “V” is the satellite's velocity,
- “R” is the Earth's radius,
- “z” is the satellite's altitude,
- “g” is the universal gravitational constant,
- “M” is the mass of the Earth.

Kepler's Third Law provides a relationship between the orbit's radius  $a = R + z$  and the period “T”:

$$\frac{a^3}{T^2} = \frac{g \cdot M}{4\pi^2}$$

where, after calculating the constant:

$$a = 21,627 \sqrt[3]{T^2}$$

(**a** is in kilometers (km), and **T** is in seconds)

$$v = \frac{2\pi(R+Z)}{T}$$

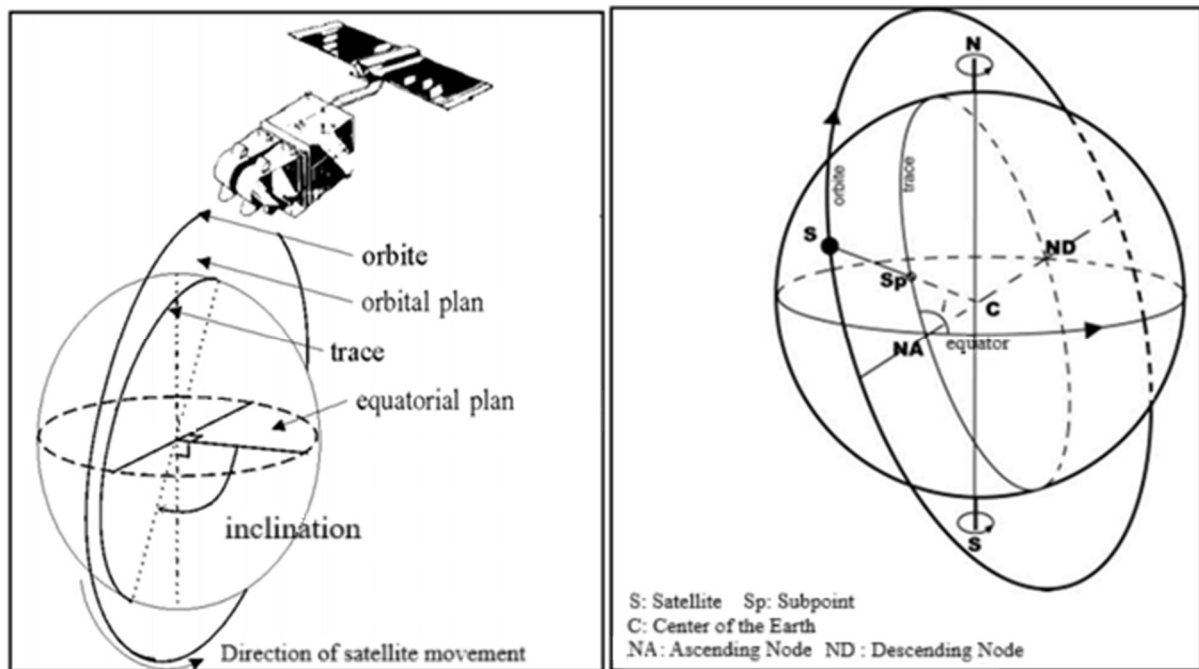
Finally, the relationship between the satellite's velocity and period:

## 2.2. Usual orbital geometry in remote sensing

One of the fundamental characteristics of orbits is their inclination, which is the angle between the orbital plane and the equatorial plane. The angle is measured considering the rotation direction of both the Earth and the satellite (Fig. 17). If the angle is less than  $90^\circ$ , the orbit is termed direct; otherwise, it is referred to as retrograde.

The projection of the orbit onto the Earth defines the satellite's ground track, and the projection of the satellite onto the Earth is called the subpoint. The point where the ground track crosses the Equator is called the ascending node when the satellite moves from South to North, and the descending node when the satellite moves from North to South. In remote sensing, a specific orbit is usually identified by the longitude of the ascending node (less commonly, the longitude of the descending node).

In a first approximation, we can consider the orbit to be fixed relative to the stars while the Earth rotates on its axis with a period of  $T=86164$  seconds (sidereal day). For a satellite located at an altitude of 850 km, which completes an orbit in 101 minutes, the displacement between the longitudes of the ascending nodes of two successive orbits is approximately  $25^\circ 30'$  of longitude, or about 2,800 km, given that the Earth's equatorial circumference is 40,000 km.



**Figure 17: Orbital Geometry (Example of a Retrograde Orbit) (adapted from M.C. & C.M. Girard, 1999)**

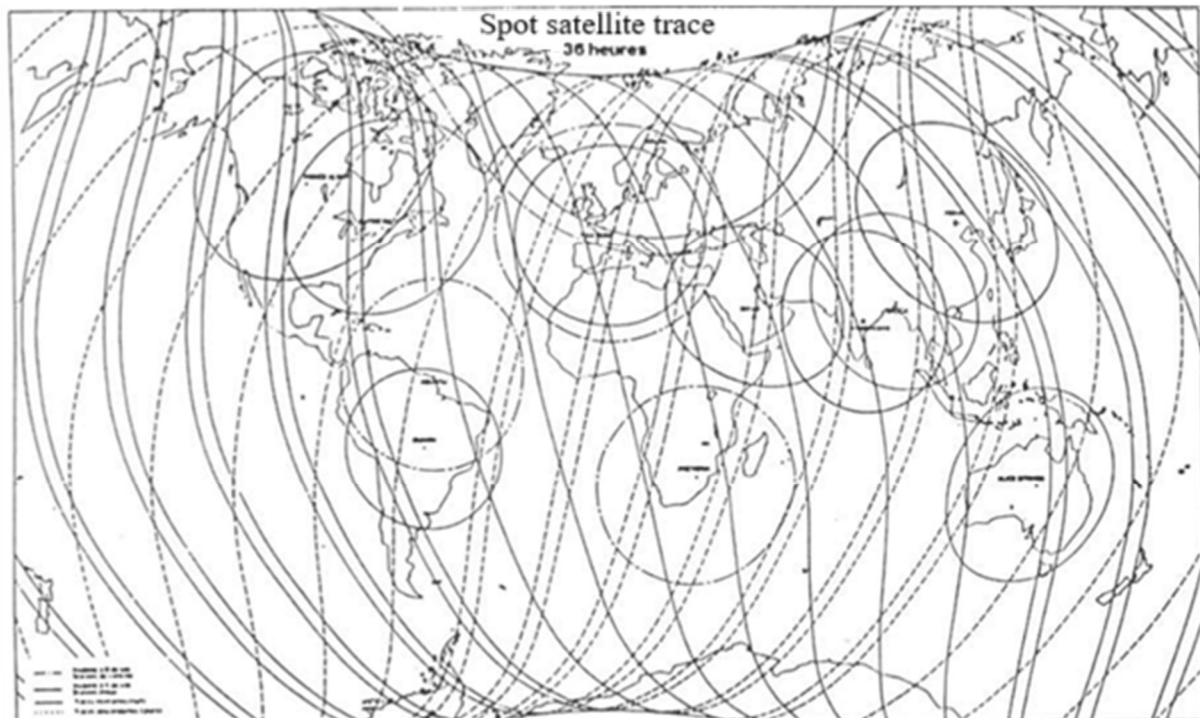
## 2.3. Types of orbits used in remote sensing

### a. Scanning satellites

A "scanning" satellite orbits at a low altitude (500 to 1500 km) with an orbital period ranging from 90 to 120 minutes. This is the case for most remote sensing satellites. These satellites complete between 12 and 16 orbits per day, allowing them to cover a wide range of regions since the orbit remains nearly fixed while the Earth rotates. The orbit's inclination relative to the Equator is usually close to  $90^\circ$ , enabling coverage of high-latitude regions. Such orbits are called quasi-polar, although passing directly over the poles is challenging. Typically, the orbit inclination is chosen to be close to  $100^\circ$  to meet heliosynchronous conditions, which are highly beneficial for remote sensing. Additionally, the orbital period is selected based on the sensor's field of view to ensure that, after a variable duration known as the orbital cycle, the satellite returns to the exact position of the previous cycle, allowing it to acquire images of the same regions at the same orbits and times. This synchronization means the orbits are phased relative to the Earth. Since the 1970s, the orbital characteristics of most remote sensing satellites have become increasingly similar, suggesting that optimal data acquisition capabilities have been achieved.

Two examples illustrate the relationship between orbit choice and Earth observation capabilities:

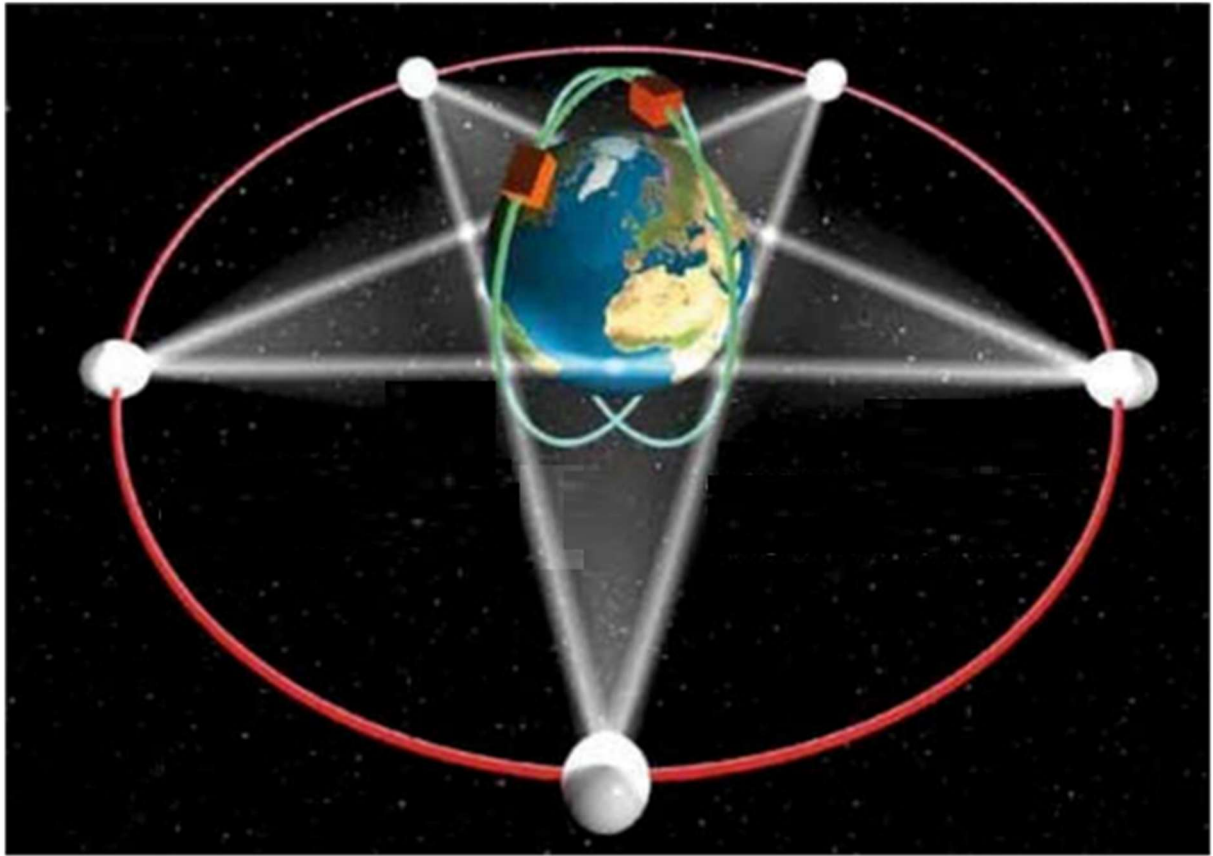
- The NOAA (National Oceanic and Atmospheric Administration) weather satellites are designed to provide high-resolution images (approximately 1 km) in both visible and near-infrared, as well as thermal infrared. The AVHRR sensor has an extremely wide field of view, over 2500 km. These satellites (six have been launched since 1978) follow low, quasi-polar, heliosynchronous orbits. The orbital period is about 100 minutes, corresponding to a spacing of approximately 2800 km between two successive equatorial crossings (ascending or descending node). The satellites complete between 14 and 15 orbits per day. Given the sensor's wide field of view, almost the entire Earth is covered twice daily, both day and night. This setup ensures at least one visible image (during the day) and two thermal images (day and night). At mid to high latitudes, the overlap of successive orbit fields allows for even more frequent coverage. The satellite's ground track, with an inclination of  $101^\circ$ , reaches latitudes up to  $82^\circ$  North or South, but the wide field of view enables images that cover the poles themselves. The chosen orbit perfectly meets meteorological needs: at least daily coverage, global Earth view, and day-and-night observations for measuring diurnal temperature variations.
- The SPOT satellite, a French remote sensing satellite, was designed to provide data in visible or near-infrared with very high spatial resolution for mapping and thematic studies. It was launched on February 22, 1986, by an Ariane rocket into a low (830 km), quasi-polar (inclination:  $98.7^\circ$ ), and heliosynchronous orbit. The orbital period is 101 minutes, meaning the satellite completes  $14 + 5/26$  orbits per day. Therefore, the orbital cycle is 26 days, after which the satellite, having completed 369 orbits, returns to exactly the same orbit it occupied 26 days earlier. The ground tracks of the 369 orbits completed during the cycle are spaced approximately 108 km apart (Fig. 18). Given the field of view of the two HRV sensors onboard, which cover a strip 117 km wide, the entire Earth, except for latitudes above  $82^\circ$ , is covered in 26 days. However, the repetitiveness of observations is significantly enhanced by the satellite's angular pointing capabilities, with an angle of  $\pm 27^\circ$ , which is a remarkable feature of the SPOT system (Verger, 1997).



**Figure 18: Successive ground tracks of the SPOT satellite over 24 hours and the visibility circles of ground reception stations**

### **b. Geostationary satellites**

Geostationary satellites are positioned in a circular orbit in the plane of the Equator (with zero inclination) and have an orbital period equal to the Earth's rotation period (geosynchronous orbit). The altitude is approximately 36,000 km. These satellites thus appear stationary at a given longitude relative to the Equator. The field of view of a geostationary satellite extends from 60° N to 60° S and over 120° of longitude. However, spatial resolution is limited due to the distance from the Earth. This type of orbit is used by weather satellites, which can provide highly repetitive global images of large portions of the Earth's surface (every 30 minutes for Meteosat). The global atmospheric monitoring system uses a combination of at least 5 geostationary satellites and low-orbit scanning satellites (Fig. 19). Geostationary satellites are also employed for telecommunications, relaying telephone communications and television images between continents (Verger, 1997).



**Figure 19: The global atmospheric monitoring system (complementarity of geostationary and scanning satellites). Source: European Space Agency**

#### 2.4. Sensors components

In remote sensing, sensors are crucial for capturing and recording data from Earth's surface. The composition of sensors typically includes several key components (**Bonn & Rochon, 1996**):

- a. **Optical system:** This component includes lenses and mirrors that gather and focus incoming electromagnetic radiation onto the sensor's detector. The optical system is designed to capture light within specific wavelength ranges, such as visible, infrared, or thermal bands.
- b. **Detector:** The detector converts the captured electromagnetic radiation into an electrical signal. Common types of detectors include:
  - **Photodetectors:** For capturing visible light and near-infrared radiation.
  - **Thermal Detectors:** For capturing thermal infrared radiation.
  - **Charge-Coupled Devices (CCDs):** For high-resolution imaging.
  - **Photodiodes:** For various wavelength ranges.

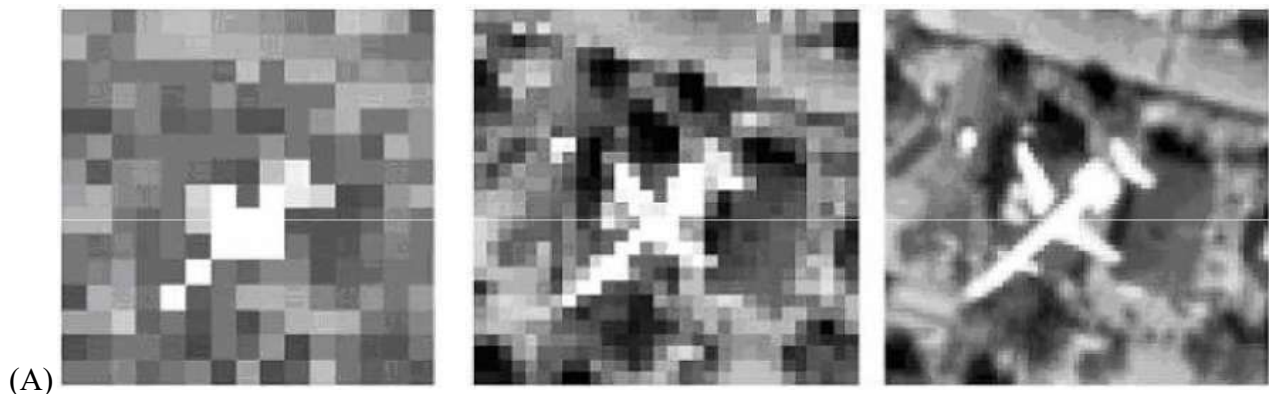
- c. **Spectral filters:** These filters isolate specific wavelength bands of the electromagnetic spectrum. They ensure that only the desired wavelengths are detected by the sensor, which is essential for capturing different types of data.

## 2.5. Resolutions

Satellite sensors are characterized by various technical capabilities collectively referred to as "resolutions." There are primarily four types of resolution in passive sensing: spatial, spectral, radiometric, and temporal. They function like a balancing act, where achieving an optimal balance among these resolutions is crucial. Currently, there is no single satellite that excels in spatial, spectral, radiometric, and temporal resolutions simultaneously. This is why satellite constellations are developed to address each of these limitations.

### 2.5.1. Spatial resolution (Geometric)

Spatial resolution is defined as 'the smallest separation between two objects, usually expressed in meters.' This definition determines the size of the smallest land surface that can be observed, which corresponds to a pixel in the image. The numerical value of the pixel corresponds to that measured by an individual detector. It represents the average value of all contributions from objects located within the same pixel (fig. 20).



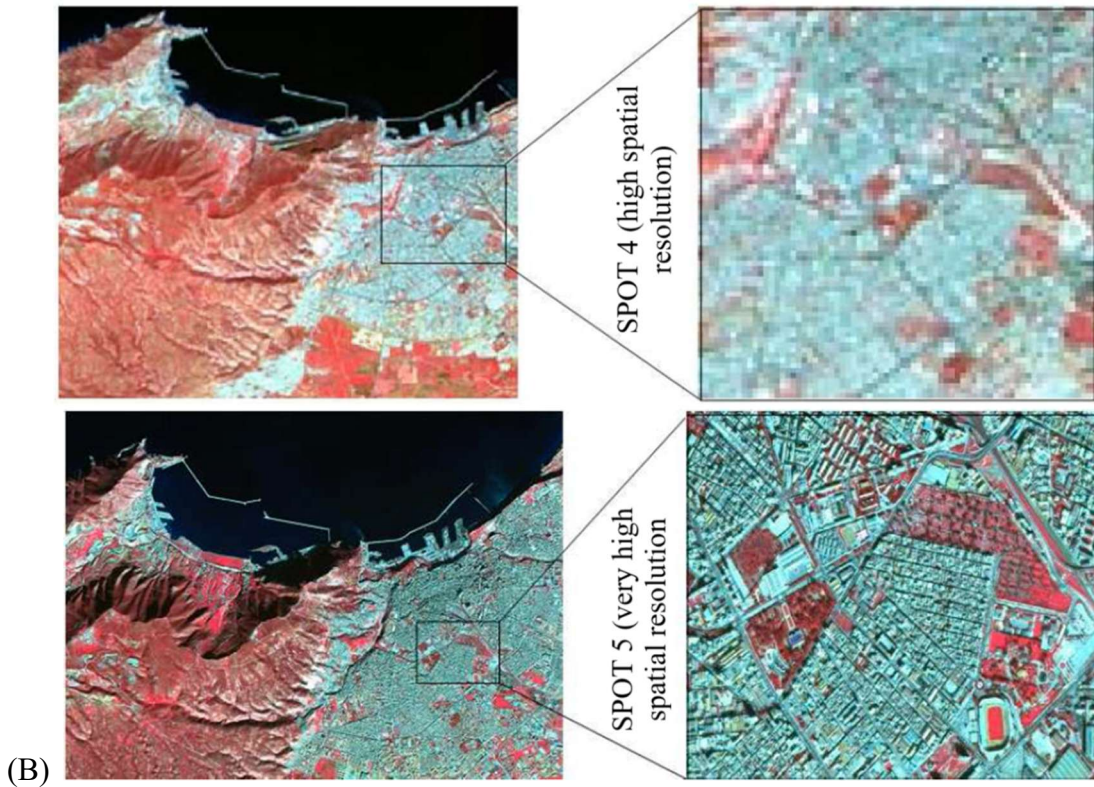


Figure. 20 : Same image (A & B) with deferent spatial resolution

### 2.5.2. Spectral resolution

It is defined as 'the ability of a detection system to distinguish electromagnetic radiation of different frequencies.' It describes the capability of a sensor to measure small wavelength windows. The finer the spectral resolution, the narrower the windows of the sensor's different channels. Therefore, it partly determines the width of the spectral bands. A single output value is obtained for each spectral band (Fig. 21).

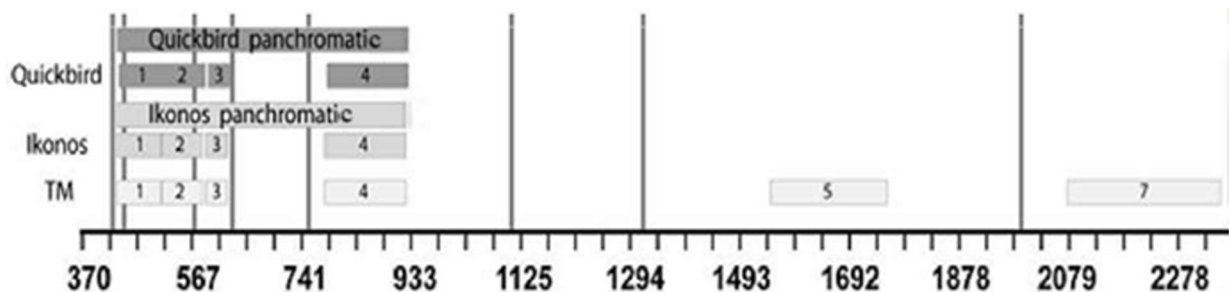
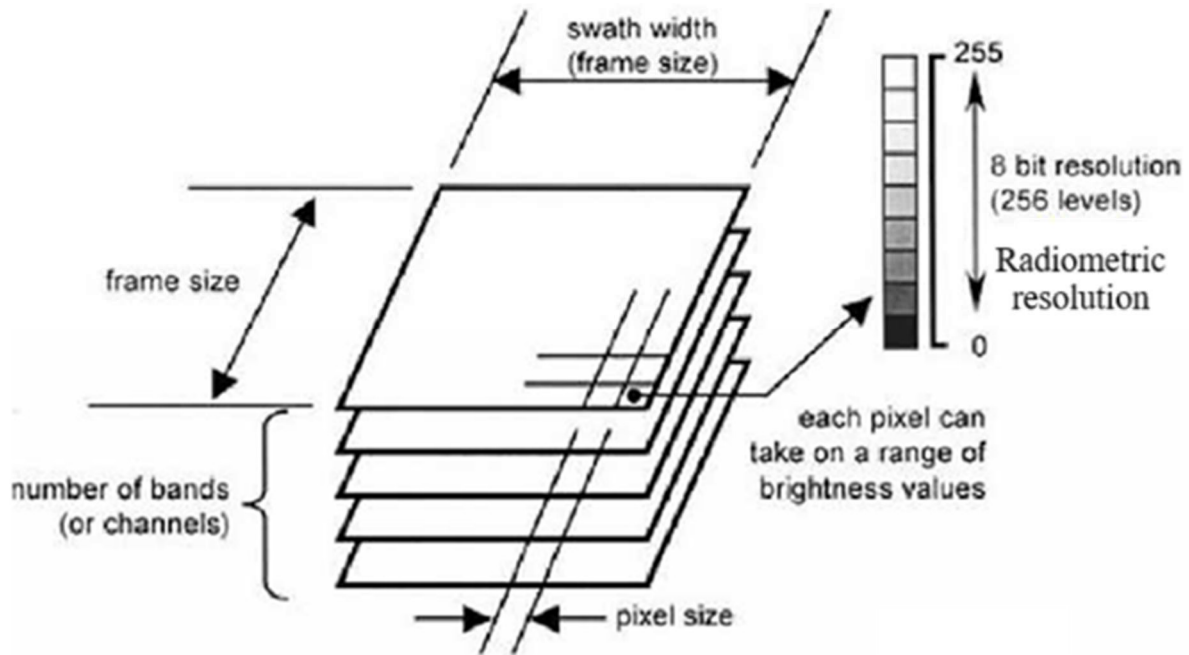


Figure. 21: Satellites / Spectral bands

### 2.5.3. Radiometric resolution

It is defined as 'the expected range of variation for each estimate of the observed reflectivity on an image.' It describes the sensor's ability to translate the precision of measurements onto the image. The finer the radiometric resolution of a sensor, the more sensitive the sensor is to small differences in the intensity of the received energy (Fig. 22).



**Figure 22: Radiometric resolution**

The following images are coded in 2 bits (4 possible values), 3 bits (8 possible values), and 8 bits (256 possible values). Thus, the digital resolution affects the thematic quality of the images (fig.23).



**Figure 23: Deferent radiometric resolutions generate deferent image's quality**

**Note:** *There are trade-offs between spatial, spectral, and radiometric resolution. To achieve high spatial resolution, the sensor must have a small instantaneous field of view. This reduces the amount of energy that the sensor receives. A decrease in the amount of energy leads to a reduction in radiometric resolution (the ability to discriminate differences in energy intensity). To increase the amount of energy reaching the sensor, and thereby improve the radiometric resolution, without reducing spatial resolution, the wavelength range detected by a sensor channel must be widened. This reduces the spectral resolution of the sensor.*

#### 2.5.4. Temporal resolution

Temporal resolution refers to the sensor's revisit time, or how often the satellite returns to observe the same area. This resolution can be associated with the time it takes for the satellite to pass over the same region again. In other words, it is 'the frequency of temporal coverage of a detection system.' Temporal resolution primarily depends on the sensor's orbit.

The time factor is important in remote sensing when:

- Cloud cover is persistent, limiting the times when it is possible to observe the surface.
- There is a need to monitor short-duration phenomena.
- Multitemporal images are required.
- Temporal changes in the appearance of a feature are used to differentiate it from another similar feature."

#### 2.6. Cameras and aerial photography

Cameras and aerial photography represent the simplest and oldest remote sensing system used to observe Earth's surface. Cameras are systems that capture a nearly instantaneous image of a region (A) of the surface. These cameras are passive optical sensors that use a lens (B) (or a lens system known as the optical system) to form an image on the focal plane (C), where the image is clearly defined.

The photographic film is sensitive to light (energy) with wavelengths ranging from 0.3 to 0.9 microns, covering ultraviolet (UV), visible, and near-infrared (NIR) regions. Panchromatic films are sensitive to wavelengths in the ultraviolet and visible ranges. These films produce black-and-white photographs and are the most commonly used in aerial photography. Ultraviolet photography also uses this type of film, but a filter is employed with the camera to absorb visible

light. This allows for the recording of targets that reflect ultraviolet light. However, this technique is not frequently used because the atmosphere scatters and absorbs much energy in these wavelengths. Black-and-white photography of infrared wavelengths uses film sensitive to this band and helps in detecting differences in vegetation cover.

Color and pseudo-color (or color infrared (CIR)) photography requires the use of three sensitivity levels in the film, with each level sensitive to three different wavelength bands. For normal color photography, the sensitivity levels are tuned to blue, green, and red light, similar to our eye. These photos appear to us as our eyes perceive the environment, with colors appearing normal (e.g., leaves are green). For color infrared photography, the three sensitivity levels record green, red, and a portion of the near-infrared, which are then processed to appear as blue, green, and red, respectively. For pseudo-color photographs, targets with high reflectivity in the near-infrared appear red, those with high reflectivity in the red band appear green, and those with high reflectivity in the green band appear blue (fig. 24).



**Figure 24: Image with Color and pseudo-color**

Cameras can be installed on various types of platforms (terrestrial, airborne, or spaceborne). Highly detailed photographs are taken from aircraft and are used where the identification of small details is necessary. The area covered by a photo depends on various factors, including the focal length of the lens, the altitude of the platform, and the size of the film. The focal length controls the angular field of view of the lens and determines the area 'seen' by the camera. Typical focal lengths for these cameras are 152 mm, but lenses with focal lengths of 90 mm and 210 mm are also used. The greater the focal length, the smaller the ground area covered but with more detail

(i.e., a larger scale). The area covered also depends on the altitude of the platform. At higher altitudes, the camera 'sees' a larger ground area but with less detail (i.e., a smaller scale). Aerial photographs can have a spatial resolution of less than 50 cm. The spatial resolution of an aerial photograph is a complex function that depends on several factors, which vary for each image.

Vertical photographs taken with a single-lens camera are the most common type of aerial photographs used in remote sensing and mapping. These cameras are specially designed to quickly capture a series of images while minimizing geometric distortion. They are often connected to an onboard navigation system in the aircraft, allowing for precise geographic coordinates to be automatically assigned to each photograph. Most of these systems also have a mechanism to compensate for the aircraft's movement relative to the ground, further reducing distortion in the image.

To obtain vertical aerial photographs, the aircraft flies over the Earth's surface along paths known as flight lines. Photos are taken rapidly with the camera pointed directly downward. Successive photos overlap by 50% to 60% (A). This overlap ensures complete coverage of the area along the flight line and facilitates stereoscopic visualization of the photographs. Due to the overlap, photos of the same region taken from different perspectives can be paired and viewed using a device called a stereoscope. This device provides a three-dimensional view of the region, known as a stereo model. This method of visualization is widely used.

Aerial photographs are particularly useful when spatial resolution is significantly more important than spectral resolution. The spectral resolution of these systems is generally much coarser compared to electronic sensor systems. The geometry used in vertical aerial photos is well-known, allowing for precise measurements to be made from these photos. These measurements are utilized in fields such as geology, forestry, cartography, and many others. Photogrammetry is the science concerned with measurements made from aerial photographs and has been known since the early use of these photos. These photos are often analyzed by humans in stereoscopic view but can also be digitized for computer analysis.

Multiband photographs are obtained using multi-lens systems equipped with filters to simultaneously capture images in several spectral bands. This type of camera has the advantage of recording reflected energy from the surface or target in multiple spectral windows, which helps differentiate and identify various features of the surface or target. However, simultaneous analysis of these multiple photographs can be challenging. Digital cameras that record electromagnetic energy electronically are very different from film-based cameras. In digital cameras, the film is

replaced by a grid of CCDs (Charge Coupled Devices). CCDs individually respond to the electromagnetic radiation they encounter, producing an electronic charge proportional to the intensity of the energy from the surface. A corresponding numeric value is then assigned to each pixel for each of the spectral bands used. The digital format of these images can be processed and stored on a computer or used to produce a photographic print. Digital cameras offer better control over spectral resolution and increased efficiency in data acquisition and archival data review. Digital cameras typically have a spatial resolution of about 0.3 meters and a spectral resolution ranging from 0.012 mm to 0.3 mm. The CCD grid size usually ranges from 512x512 to 2048x2048 pixels (Canadian Centre for Remote Sensing).

## 2.7. Satellites and earth observation sensors

### - *Landsat*

While several meteorological satellites are also used for monitoring the Earth's surface, they were not designed for detailed cartography of the terrestrial surface. Following the outstanding successes of early meteorological satellite images in the 1960s and images acquired during crewed space missions, the first Landsat-1 Earth observation satellite was launched by NASA in 1972. Originally known as ERTS-1 (Earth Resources Technology Satellite), Landsat was designed to test the feasibility of an unmanned multispectral Earth observation platform. Since then, the Landsat program has enabled the acquisition of data from all corners of the planet. Originally managed by NASA, the Landsat program came under the responsibility of NOAA (National Oceanic and Atmospheric Administration) in 1983. In 1985, the program was commercialized to provide data to various civilian users.

Among the factors contributing to Landsat's success are a combination of sensors with spectral domains tailored for Earth observation, functional spatial resolution, and good global coverage (swath and revisit time). The longevity of the program has allowed for the accumulation of extensive data archives on terrestrial resources, facilitating long-term monitoring as well as the maintenance of historical data and research. All Landsat satellites have been placed in a polar heliosynchronous orbit. The first three satellites (Landsat-1 to Landsat-3) were at an altitude of 900 km with an 18-day revisit cycle, while the later ones orbit at an approximate altitude of 700 km with a 16-day revisit cycle. All Landsat satellites cross the equator in the morning to take advantage of optimal lighting conditions.

The Landsat series satellites are equipped with several sensors, such as the RBV (Return Beam Vidicon) camera systems, the MSS (Multi-Spectral Scanner) system, and later, the TM (Thematic

Mapper). Each of these sensors has a swath of 185 km, with a complete scene of 185 km by 185 km.

The MSS (Multi-Spectral Scanner) captures electromagnetic radiation from the Earth's surface across four spectral bands. Each band has a spatial resolution of 60 by 80 meters and a radiometric resolution of 6 bits, or 64 digital values. The MSS captures radiation using a mechanical scanner with an oscillating mirror. Six scan lines can be simultaneously collected with each east-to-west mirror sweep. The following table describes the spectral ranges of the MSS bands.

**Table 2: Spectral ranges of MSS bands**

Bands		Wavelength
<b>Landsat 1,2,3</b>	<b>Landsat 4,5</b>	
MSS 4	MSS 1	0,5 - 0,6 (vert)
MSS 5	MSS 2	0,6 - 0,7 (rouge)
MSS 6	MSS 3	0,7 - 0,8 (proche infrarouge)
MSS 7	MSS 4	0,8 - 1,1 (proche infrarouge)

Routine data collection with the MSS ceased in 1982 due to the introduction of the TM (Thematic Mapper) sensor, which began with Landsat 4. The TM sensor brings several improvements over the MSS: enhanced spatial and radiometric resolution, narrower spectral bands, seven spectral bands compared to four for the MSS, and an increase in the number of detectors per band (sixteen for non-thermal bands compared to six for the MSS). Sixteen scan lines are captured simultaneously for each non-thermal spectral band (four for thermal bands). These sixteen lines are captured simultaneously using an oscillating mirror that sweeps in both directions (west to east and east to west). This difference from the MSS sensor increases the dwell time on a target and improves the geometric and radiometric integrity of the data. The spatial resolution limit of the TM is 30 meters for all bands except for thermal infrared, which is 120 meters. All bands are recorded with a range of 256 digital values (8 bits). The following table describes the spectral resolution of the individual TM bands and their applications.

The Landsat program has evolved significantly since its inception. Early satellites, such as Landsat 1 to 3, were equipped with the **MSS (Multispectral Scanner System)**, which provided basic multispectral imagery with limited spatial and spectral resolution. This was followed by the **TM (Thematic Mapper)** and later the **ETM+ (Enhanced Thematic Mapper Plus)** sensors on

Landsat 4 to 7, which offered improved spectral bands and spatial resolution. With **Landsat 8**, launched in 2013, the mission transitioned to more advanced sensors: the **OLI (Operational Land Imager)** and **TIRS (Thermal Infrared Sensor)**. These instruments deliver higher radiometric resolution, additional spectral bands (such as coastal and cirrus), and improved data quality, allowing for more precise and reliable Earth observation.

**Table 3:** Landsat 8 Sensor Band Characteristics (OLI + TIRS)

Band	Sensor	Wavelength (µm)	Resolution (meters)	Description
Band 1	OLI	0.43 – 0.45 (Coastal)	30 m	Coastal/aerosol studies
Band 2	OLI	0.45 – 0.51 (Blue)	30 m	Bathymetry, soil/vegetation discrimination
Band 3	OLI	0.53 – 0.59 (Green)	30 m	Assessing plant vigor
Band 4	OLI	0.64 – 0.67 (Red)	30 m	Vegetation differentiation
Band 5	OLI	0.85 – 0.88 (Near-IR)	30 m	Biomass and shoreline mapping
Band 6	OLI	1.57 – 1.65 (SWIR 1)	30 m	Soil moisture, vegetation health
Band 7	OLI	2.11 – 2.29 (SWIR 2)	30 m	Mineral and rock discrimination
Band 8	OLI	0.50 – 0.68 (Panchromatic)	15 m	Sharpening multispectral imagery
Band 9	OLI	1.36 – 1.38 (Cirrus)	30 m	Cirrus cloud detection
Band 10	TIRS	10.60 – 11.19 (Thermal 1)	100 m (resampled to 30 m)	Surface temperature
Band 11	TIRS	11.50 – 12.51 (Thermal 2)	100 m (resampled to 30 m)	Surface temperature

### - SPOT

The SPOT system (Système pour l'Observation de la Terre) is a series of Earth observation satellites designed and launched by the French National Center for Space Studies (CNES), with assistance from Belgium and Sweden. SPOT-1 was launched in 1986, followed by additional satellites launched every three to four years. All SPOT satellites are in a sun-synchronous polar orbit at an altitude of 830 km, resulting in a 26-day revisit period. They cross the equator around 10:30 local solar time. Designed to acquire remote sensing data for commercial purposes, SPOT was the first satellite to utilize the bar scanner or longitudinal scanning technology.

All SPOT satellites are equipped with two High-Resolution Visible (HRV) multi-band scanners with bar scanning capabilities, which can operate independently or simultaneously. Each HRV can capture in panchromatic mode (single band) and offers an excellent spatial resolution limit of 10

meters. They can also capture in multi-band mode (MLA) (three bands), providing a spatial resolution of 20 meters. Each bar scanner consists of four linear arrays of detectors:

- **One array of 6,000 elements** for recording in panchromatic mode.
- **One array of 3,000 elements** for each of the three multispectral bands.

The swath width for both modes is 60 km from the nadir.

**Table 4: SPOT 5 Sensor Band Characteristics**

Band	Wavelength ( $\mu\text{m}$ )	Resolution (meters)	Description
Panchromatic	0.48 – 0.71 (Pan)	2.5 m or 5 m	High-resolution black and white imagery
Band 1 (Green)	0.50 – 0.59	10 m	Vegetation vigor, water bodies
Band 2 (Red)	0.61 – 0.68	10 m	Vegetation discrimination, urban areas
Band 3 (NIR)	0.78 – 0.89	10 m	Biomass, water/land boundaries
Band 4 (SWIR)	1.58 – 1.75	20 m	Soil moisture, vegetation stress
HRS (optional)	Stereoscopic (0.48–0.71)	5–10 m (along-track stereo)	3D terrain modeling, elevation mapping

The sensors' pointing angle can be adjusted to view both sides of the nadir line. This enables oblique viewing, which increases the satellites' revisit frequency. This pointing capability (up to 27 degrees from nadir) allows SPOT satellites to cover an acquisition corridor of 950 km and enables multiple revisits per week. As the sensor moves away from nadir, the swath width increases from 60 to 80 km.

In addition to enhancing the ability to monitor a specific site and increasing the likelihood of acquiring cloud-free scenes, oblique viewing also allows for stereoscopic data acquisition. Images of the same area taken from two different angles can be viewed and analyzed in three dimensions, a technique essential for terrain interpretation, cartography, and visual terrain reproductions.

Oblique viewing increases the revisit frequency to 3 days at the equator (7 times during a 26-day cycle). Regions located at a latitude of 45 degrees can be imaged 11 times during the 26-day cycle due to the convergence of orbits towards the poles. By positioning both sensors to cover adjacent ground tracks, a ground track of 117 km (3 km overlap) can be observed. This operational mode

allows for the acquisition of either panchromatic or multispectral data, but not both simultaneously.

The SPOT system offers several advantages over other spaceborne sensors. Its fine resolution limit and sensor pointing capabilities are key reasons for its popularity. The data from the three multispectral bands are useful for creating false-color images, while the panchromatic band can be used to enhance the detail of multispectral data.

**SPOT** is useful for applications requiring excellent spatial resolution (such as urban mapping) and also combines the benefits of affordability and the ability to acquire satellite data at the optimal time. SPOT images find numerous applications in fields that require frequent imaging, such as forestry and agriculture. The acquisition of stereoscopic images has played an important role in cartographic applications and in deriving topographic information (Digital Elevation Models, DEMs) from satellite data.

#### - **IRS**

The IRS (Indian Remote Sensing) satellite series combines features from Landsat MSS and TM sensors and SPOT's HRV sensor. The third satellite in the series, IRS-1C, launched in December 1995, is equipped with three sensors: a high-resolution panchromatic camera (PAN), a four-band LISS-III (Linear Imaging Selfscanning Sensor) with medium resolution, and a two-band WiFS (Wide Field of View Sensor) with low resolution. The table below describes the characteristics of each sensor.

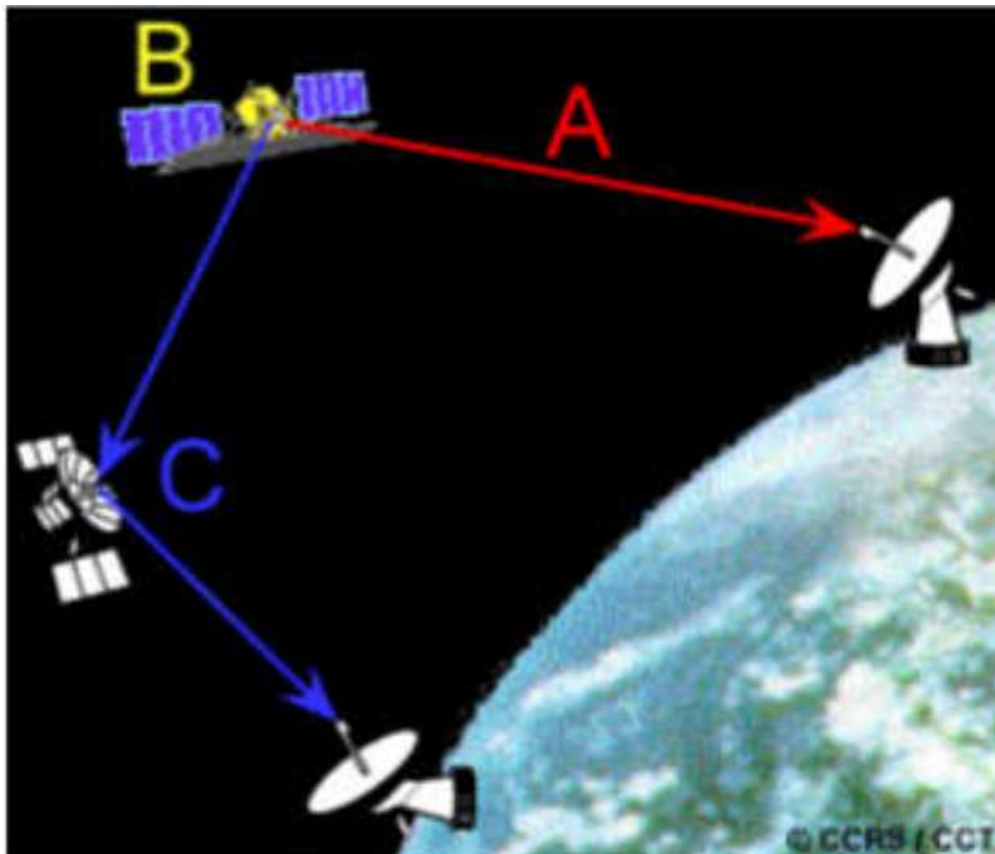
#### **Table 5: IRS captor characteristics**

Captor	Spectral domain	Spatial resolution	Swath width	Revisit time
<b>PAN</b>	0,5 - 0,75	5,8 m	70 km	24 jours
<b>LISS-II</b>				
<b>Green</b>	0,52 - 0,59	23 m	142 km	24 jours
<b>Red</b>	0,62 - 0,68	23 m	142 km	24 jours
<b>Near infrared</b>	0,77 - 0,86	23 m	142 km	24 jours
<b>Medium Infrared</b>	1,55 - 1,70	70 m	148 km	24 jours
<b>WiFS</b>				
<b>Red</b>	0,62 - 0,68	188 m	774 km	5 jours
<b>Near infrared</b>	0,77 - 0,86	188 m	774 km	5 jours

In addition to its high spatial resolution, the linear scanning of the panchromatic sensor can be off-pointed up to 26 degrees, allowing for the acquisition of stereoscopic images and increasing the satellite's revisit frequency (up to 5 days), similar to SPOT satellites. High-resolution data is useful for applications such as urban planning and mapping. The four LISS-III multispectral bands resemble bands 1 to 4 of the Landsat TM sensor. These are useful for vegetation discrimination, land mapping, and natural resource management. The WiFS sensor is similar to NOAA's AVHRR bands. The spatial resolution and coverage of this sensor are used for regional-scale vegetation monitoring (Canadian Centre for Remote Sensing).

## 2.8. Data reception, transmission and processing

Data collected by airborne sensors can be retrieved once the aircraft is back on the ground. It can then be processed and ultimately delivered to the user. On the other hand, data collected by a satellite must be transmitted electronically to a ground receiving station, as the satellite remains in orbit for several years. Transmission methods developed for satellites can also be used for aircraft if there is an urgent need for the data on the ground (Fig. 25).



**Figure 25: Reception, Transmission, and Processing of Data**

Three methods of data transmission are used:

A. Data can be transmitted directly to a ground receiving station if the satellite is within the station's reception circle.

B. If the satellite is not within the reception circle of a station, data can be stored by an onboard recorder on the satellite.

C. Data can also be retransmitted to the receiving station via communication satellites in geostationary orbit around the Earth. The data are passed from satellite to satellite until they can be retransmitted to the ground station.

Canada has two satellite data receiving stations operated by the CCT: one is located in Cantley (GSS), near Ottawa, and the other in Prince Albert (PASS) in Saskatchewan. The combination of the coverage circles of these two stations allows for the reception of data transmitted directly or recorded by almost all satellites passing over Canadian and continental U.S. territory. Several countries have also built receiving stations around the Earth to receive data from various satellites in orbit.

Raw data arrive at the receiving station in digital form. They are then processed to correct for atmospheric, geometric, and systematic distortions as necessary. They are subsequently converted into a standard format and stored on magnetic tapes, floppy disks, or CD-ROMs. Most receiving and processing stations also archive the data they acquire. Government agencies and private companies manage the archives for their respective sensors.

For many sensors, it is possible to quickly provide images to clients who have an urgent need. Real-time processing systems allow for the production of low-resolution images (on paper or digital) within a few hours after acquisition. These images can be sent to clients by fax or in digital format. This rapid data processing is used to provide images to ships navigating the Arctic Ocean: the images assist in navigating through ice fields by allowing ship pilots to assess ice conditions. Real-time image processing for airborne sensors is used to send thermal infrared images directly to firefighters combating wildfires.

Low-resolution "quick-look" images are used to verify archived images before purchasing. Although the spatial and radiometric quality of these products is lower, they are still useful for ensuring that quality, composition, and cloud cover are acceptable (Canadian Centre for Remote Sensing).

### **3. Image analysis**

To take advantage of remote sensing data, it is necessary to be able to extract meaningful information from the imagery. The goal of interpreting and analyzing remote sensing imagery is to identify and measure various targets in an image to extract useful information. In remote sensing, a target is defined as any observable structure or object in an image.

Targets can be points, lines, or areas. They can thus present various forms: a bus in a parking lot, an aircraft on a runway, a bridge, a road, a large field, or a body of water. The target must be distinctive, meaning it should contrast with the surrounding structures (fig. 26).



**Figure 26: Example of a target (Blue Circle)**

The interpretation and identification of targets in remote sensing are often done visually, meaning by a human interpreter. In many cases, imagery is presented in a photographic format, regardless of the type of sensors and how the data is acquired. In this case, the data are said to be in analog format. Remote sensing images can also be represented digitally on a computer as a matrix of pixels, where each pixel corresponds to a number representing the pixel's intensity level. In this case, the data are in digital format. Visual interpretation can also be performed by examining digital imagery on a computer screen. Both analog and digital imagery can be represented in black and white (monochromatic images) or in color composites by combining different channels or bands representing various wavelengths.

When remote sensing data are available in digital format, digital processing and analysis can be performed using a computer. Processing can enhance the data in preparation for visual interpretation. Digital processing and analysis can be done automatically to identify targets and extract information without human intervention. However, digital processing and analysis are almost always used to support and complement human interpretation.

Visual interpretation and analysis date back to the very beginning of remote sensing with the interpretation of aerial photographs. Digital processing and analysis are more recent with the advent of digital data recording and the development of computers. Both analog and digital techniques for interpreting remote sensing data have their respective advantages and disadvantages (<https://earthobservatory.nasa.gov/features/ColorImage>).

In general, visual interpretation requires little or no equipment, whereas digital analysis requires specialized and sometimes expensive equipment. Visual interpretation is often limited to a single data channel or image at a time due to the difficulty of performing visual interpretation with multiple images. Computers, capable of handling more complex images, allow for digital analysis from multiple channels. In this regard, digital analysis is useful for the simultaneous analysis of multiple spectral bands and can process data faster than a human interpreter. Human interpretation is a subjective process, meaning results can vary from one interpreter to another. Digital analysis, being based on numerical manipulation by a computer, is more objective, providing reproducible results. However, the accuracy of results from digital processing can be challenging to validate, as it requires validation by analysts.

It is important to note that visual and digital analyses of remote sensing imagery are not mutually exclusive. Both methods have their merits, and most analyses of imagery are conducted by combining both approaches. The final decision regarding the importance and usefulness of the information extracted at the end of the analysis process always rests with the analysts.

### 3.1. Visual interpretation elements

The analysis of remote sensing imagery requires the identification of different targets in an image. These targets can be natural or artificial structures, consisting of various points, lines, or areas. Targets can be defined based on how they reflect radiation. The intensity of radiation is measured and recorded by a sensor and then transformed into a usable product such as an aerial photograph or satellite image.

What makes interpreting imagery more challenging than interpreting our everyday surroundings? First, we lose our sense of perspective when viewing a two-dimensional image unless we view it stereoscopically to simulate a third dimension. Indeed, in many applications, stereo visualization is a significant asset for interpretation as it dramatically enhances target recognition. From an aerial view, objects can appear very different from what we are used to. The combination of an unusual perspective, a very different scale, and limited detail means that even the most familiar objects can

be unrecognizable in an image. Finally, since we are accustomed to seeing only wavelengths from the visible spectrum, it is more challenging to understand imagery from other wavelengths in the spectrum.

Target recognition is key to interpretation and information extraction. Observing differences between targets and their backgrounds involves comparing different targets based on a combination of the following characteristics: tone, shape, size, pattern, texture, shadow, and association. Consciously or unconsciously, we regularly use these characteristics for the visual interpretations we perform daily.

Observing satellite images in weather reports or viewing a high-speed pursuit from a helicopter are familiar examples of visual image interpretation. Identifying targets in remote sensing based on the 7 visual characteristics allows us to better interpret and analyze. Each of these interpretation characteristics is described below, with an example image for each case (<https://ebooks.inflibnet.ac.in/geop10/chapter/visual-interpretation/>).



**Figure 27: Tone**

**Tone**: refers to the relative brightness or color (hue) of objects in an image. Generally, the tone is the fundamental element for differentiating targets and structures. Variations in tone also allow for the differentiation of shapes, textures, and patterns of objects.



**Figure 28: Shape**

**Shape**: refers to the general appearance, structure, or outline of objects when viewed individually. Shape can be a very important clue for interpretation. Shapes with straight edges are typically found in urban areas or are agricultural fields, while natural structures, such as forest edges, are generally more irregular, except in places where humans have built a road or performed clear-cutting. Farms with fields irrigated by automatic sprinkler systems often exhibit circular shapes.

**Size**: of an object in an image depends on the scale. It is important to assess the size of a target relative to other objects in a scene (relative size) as well as its absolute size to aid in the interpretation of the target. A quick assessment of the approximate size of a target often facilitates interpretation. For example, in an image where different land use areas need to be distinguished and an area with buildings identified, large structures such as factories or warehouses would suggest commercial properties, while smaller elements would suggest residential areas.

**Pattern**: refers to the spatial arrangement of visually discernible objects. An ordered repetition of similar tones and textures creates a distinctive and easily recognizable pattern. Orchards with their regularly spaced trees or streets regularly lined with houses are good examples of patterns.



**Figure 29: Size**



**Figure 30: Pattern**

***Texture***: refers to the arrangement and frequency of tonal variations in specific areas of an image. Rough textures consist of striped tones where gray levels change abruptly in a small area, whereas smooth textures have little or no tonal variation. Smooth textures are often the result of uniform surfaces such as fields, pavements, or grassy areas. A target with a rough surface and irregular

structure, such as a forest, results in a texture that appears rough. Texture is one of the most important elements for differentiating structures in a radar image.



**Figure 31: Texture**

**Shadows**: are also useful for interpretation as they provide an idea of the profile and relative height of targets that can be easily identified. However, shadows can reduce or even eliminate interpretation in their vicinity, as targets located in shadows are less or not at all discernible. In radar imagery, shadows are particularly useful for enhancing or identifying topography and geological shapes.

**Association**: takes into account the relationship between the target of interest and other recognizable objects or structures nearby. Identifying elements that are normally expected to be found near other structures can provide information that aids in identification. For example, commercial properties can be associated with nearby roads, while residential areas would be associated with schools, playgrounds, and sports fields. In our example, a lake is associated with boats, a marina, and a nearby recreational park.



**Figure 32: Shadows**



**Figure 33: Association**

### **3.2. Digital image processing**

Nowadays, as most remote sensing data are recorded in digital format, nearly all image interpretation and analysis require some form of digital processing. Digital image processing can

involve various procedures, including data formatting and correction, digital enhancement to facilitate visual interpretation, or even automatic classification of targets and structures entirely by computer.

Digital processing of remote sensing imagery requires that the data be recorded and available in a suitable digital format for storage on disks or computer tapes.

Digital image processing obviously requires a computer system (or image analysis system) as well as the equipment and software to process the data. Several commercial software systems have been specifically developed for processing and analyzing remote sensing images.

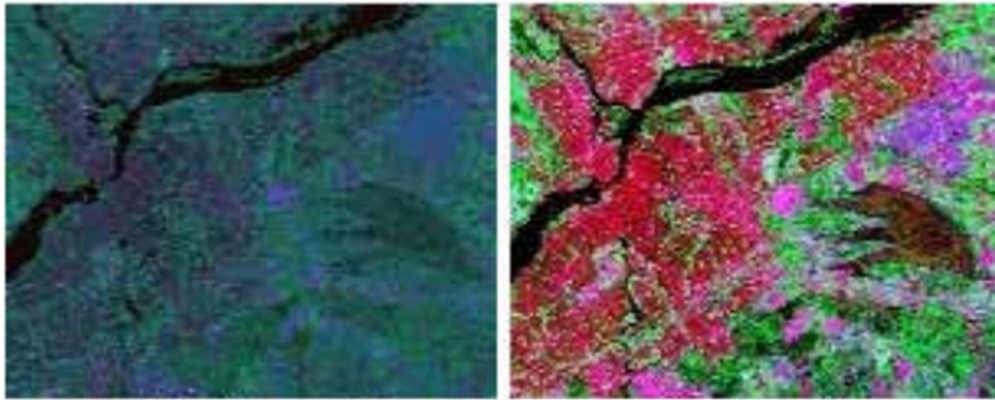
For the purposes of this course, we will categorize commonly available image processing functions into four main categories ([https://mlsu.ac.in/econtents/458\\_Digital%20Image%20Processing.pdf](https://mlsu.ac.in/econtents/458_Digital%20Image%20Processing.pdf)):

- Preprocessing
- Image Enhancement
- Image Transformation
- Image Classification and Analysis

Preprocessing functions are operations normally required before the main analysis and information extraction. They are divided into radiometric and geometric corrections. Radiometric corrections include, among other things, correcting data for sensor irregularities, noise from the sensor or atmosphere, and converting the data so that they accurately represent the reflected or emitted radiation measured by the sensor. Geometric corrections include correcting for geometric distortions due to variations in the Earth-sensor geometry and transforming the data into true coordinates (e.g., latitude and longitude) on the Earth's surface.

#### ➤ **Image enhancement functions**

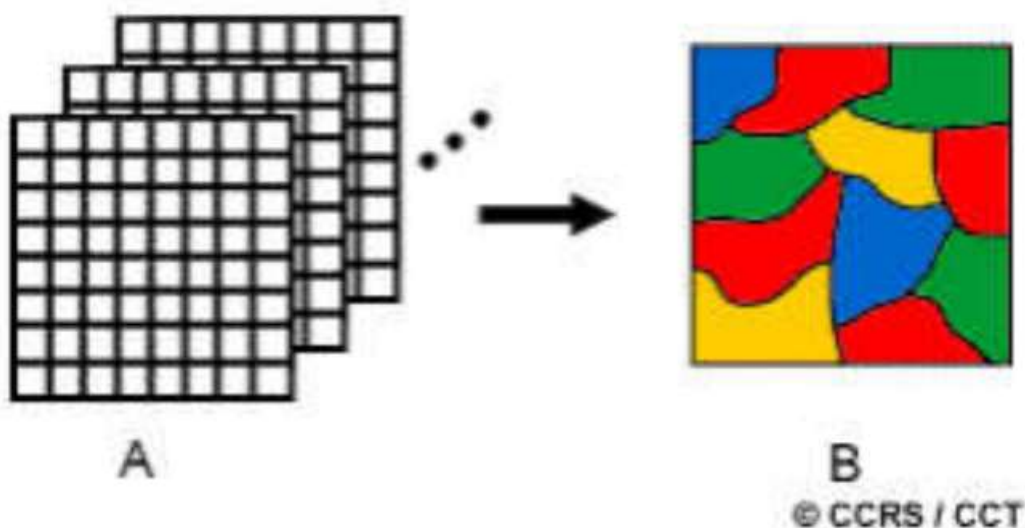
The purpose of enhancement functions is to improve the appearance of imagery to assist with visual interpretation and analysis. Enhancement functions allow for contrast stretching to increase the distinction of tones between different elements in a scene, and spatial filtering to enhance (or remove) specific spatial patterns in an image (fig. 34).



**Figure 34: Image enhancement**

➤ **Image Transformations**

Image transformations are operations similar to those used in image enhancement. However, while image enhancement is typically applied to a single data band at a time, image transformation involves processing data from multiple spectral bands. Arithmetic operations (i.e., addition, subtraction, multiplication, division) are performed to combine and transform the original bands into "new" images that more clearly show certain elements of the scene. We will examine some of these operations, including various band ratio methods, also known as spectral ratios, and a process called Principal Component Analysis (PCA), which is used to better represent information in multispectral imaging (fig. 35).



**Figure 35: Image transformation**

### 3.3. Preprocessing

Preprocessing refers to operations performed on images before any further processing to correct or improve them geometrically and thematically. There are three types of preprocessing: radiometric corrections, geometric corrections, and atmospheric corrections.

### 3.3.1. Radiometric corrections

Radiometric corrections are applied to images to reassign each pixel a radiometric value as close as possible to what was measured on the ground. Recorded variations may be due to sensor aging, malfunction, or defects during the design of the instruments. For example, SPOT images might have slight striping issues, and LANDSAT MSS and TM images (especially early in the series) might suffer from alignment problems. These radiometric preprocessing tasks (such as equalizing detector sensitivity) are often carried out by satellite image distributors, but it is possible to perform them using adapted procedures. For instance, Fourier analysis can help reduce striping in LANDSAT images.

### 3.3.2. Geometric Corrections

Geometric corrections are applied to images to reduce geometric distortions that occurred during the scene recording:

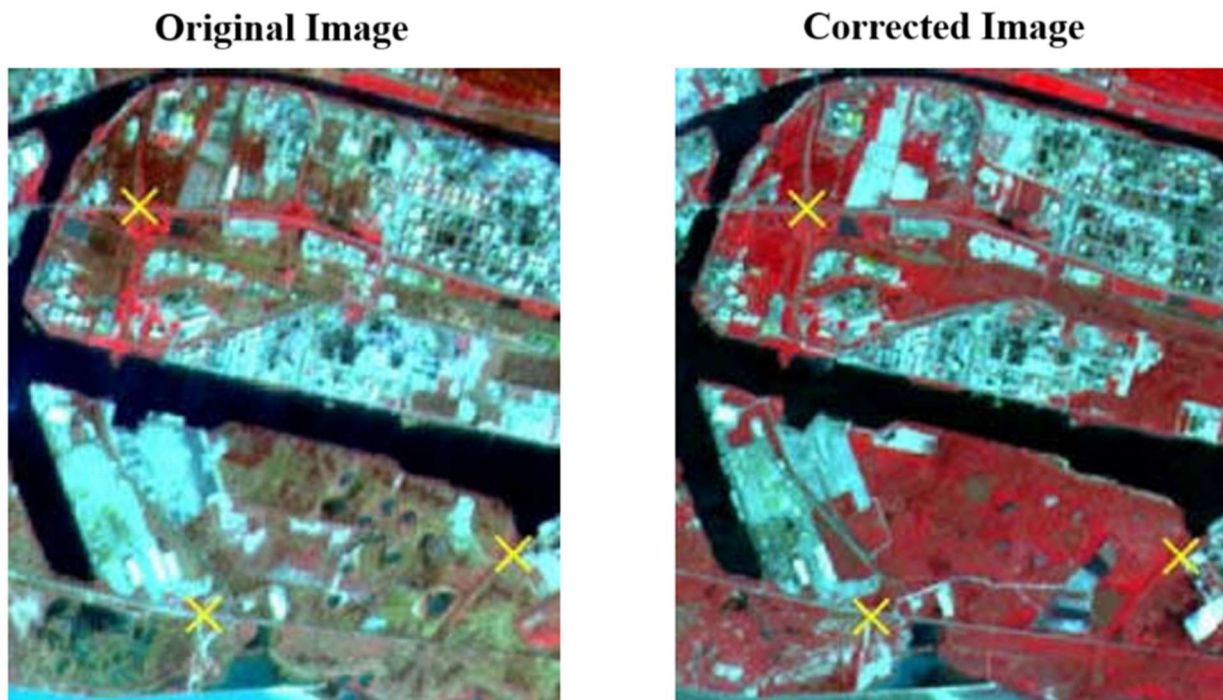
- Distortions caused by the environment (e.g., Earth curvature, ground altitude variation, atmospheric refraction)
- Distortions due to measurement system errors
- Distortions resulting from platform movements (e.g., roll, pitch, yaw)

Geometric corrections are also used to project and georeference images. There are two main methods for geometrically correcting images:

1. **Satellite navigation model method:** This method involves transforming the images after applying a mathematical model of the geometric recording parameters of the scene. Each satellite has its own navigation model.
2. **Polynomial method with ground control points:** This method involves finding the new position of every point in an image, represented by the function  $f(m,n)$ , in the coordinate system  $g(u,v)$ , using the function  $h$ . The relationship is described by

$$G(u,v) = f(m,n) h(m,n ; u,v)$$

The first step is to find common reference points (also known as control points or markers) between the reference source and the image to be corrected. The reference source can be a set of known and referenced points (geodetic points, GPS surveys, etc.), a topographic map, or even a georeferenced satellite image, as shown in the example below (**fig. 36**).



**Figure 36: Geometric correction**

The second step is to calculate the relationship between source points and reference points. The more deformations there are, the higher the degree of deformation model needed (that is, a high-degree deformation polynomial), and the greater the number of required control points. The minimum number of control points can be calculated as follows:

$$N = ((T+1) (T+2)) / 2$$

where N is the minimum number of control points required and T is the order of the chosen transformation. For example, with a second-degree polynomial:  $N = ((2+1)(2+2))/2 = 6$  control points at a minimum.

The third and final step is to apply the deformation polynomial to the image to be corrected to create a new image in the chosen reference system. Since the old and new grids do not match, it is necessary to apply a resampling algorithm to assign each new pixel in the created image a value that is as close as possible to that of the old image. Three resampling methods are possible:

- Nearest neighbor resampling assigns to each pixel in the new image the value of the closest pixel in the original image (in scheme #1, this is the pixel in the bottom left). This method is very fast and preserves the original radiometric values, but has poor geometric rendering (stair-step effect on diagonals, etc.). It is used when working with radiometric values (classifications, spectral analyses, etc.).
- Bilinear interpolation assigns to each pixel in the new image the value of the four closest neighbors (2x2) in the original image (see scheme #1). This method is slightly slower and results in a slight smoothing effect, but the spatial precision is satisfactory.
- Bicubic interpolation assigns to each pixel in the new image the value of the 16 closest neighbors (4x4) in the original image (see scheme #2). This is the slowest method and results in significant smoothing of the image. Nevertheless, the new image is very spatially accurate, making it perfectly suited for shape and texture analysis (photo-interpretation methods).

In areas with significant altitude variations, it is also possible, in addition to all these operations, to geometrically correct images by taking relief into account. For this, a digital elevation model is used, which further increases the spatial accuracy of the images. This process is called "orthorectification."

Organizations that distribute satellite remote sensing images provide data with varying degrees of geometric accuracy depending on the price paid. The table below shows the different levels of preprocessing performed by the distributor of SPOT images:

**Table 6: Different levels of preprocessing performed by the SPOT image distributor**

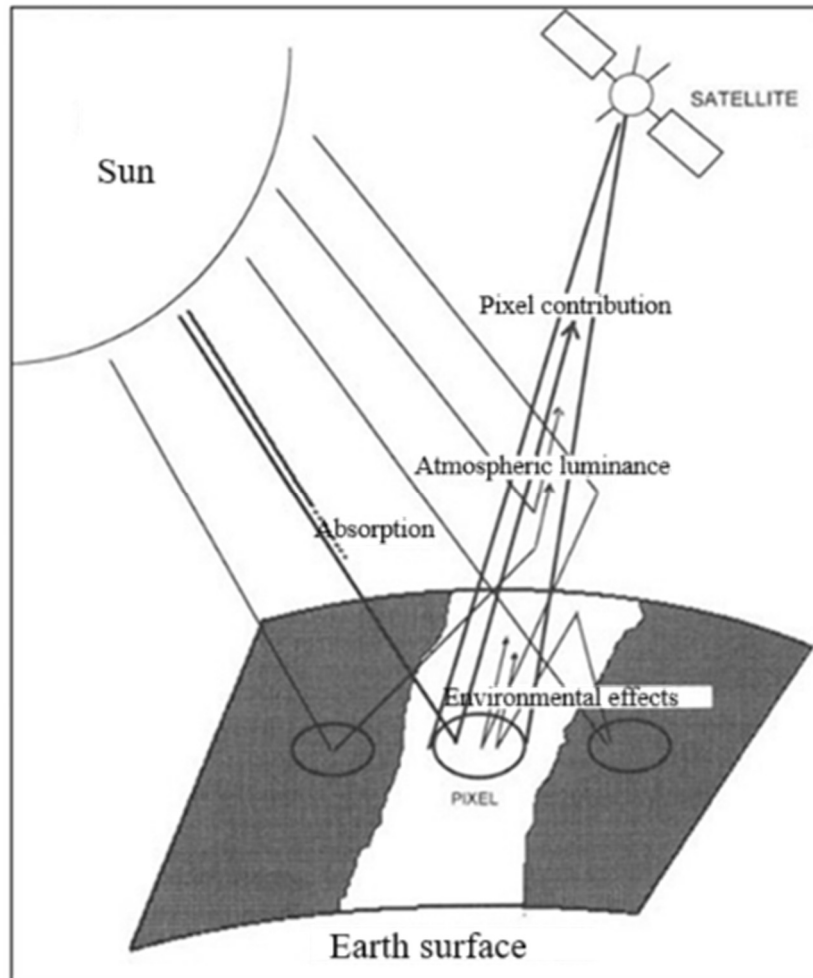
<b>Correction level</b>	<b>Radiometric correction</b>	<b>Geometric correction</b>	<b>Spatial accuracy</b>
<b>1A</b>	<b>Detector equalization</b>	<b>None</b>	<b>Low</b>
<b>1B</b>	<b>Detector equalization</b>	<b>Without ground reference</b>	500 m
<b>2A</b>	<b>Detector equalization</b>	<b>Georeferenced without ground reference</b>	-
<b>2B</b>	<b>Detector equalization</b>	<b>Georeferenced without ground reference With reference points</b>	30 m
<b>3</b>	<b>Detector equalization</b>	<b>Georeferenced without ground reference With reference points With a DEM or stereoscopy</b>	-
<b>S1 et S2</b>	<b>Detector equalization</b>	<b>Such as the B2 but with increased accuracy</b>	> à 10 m

### 3.3.3. Atmospheric corrections

The light signal measured by a satellite's sensors traverses the Earth's atmosphere twice (see figure below): first during the sun-to-target path and second during the target-to-sensor path. Each of these two traversals causes the electromagnetic radiation to undergo transformations due to the physicochemical properties of the two major components of the Earth's atmosphere, which are gases (oxygen, ozone, water vapor, etc.) and aerosols (dust, pollen, etc.).

The contribution of the atmosphere to the radiometric value of a pixel can exceed 50% at certain wavelengths, such as blue. Therefore, it is sometimes necessary to apply atmospheric corrections to images based on the thematic characteristics of the study area and the image processing method employed.

It is impossible to obtain the actual contribution of the atmosphere without having data describing the weather conditions at the time the image was captured. Consequently, atmospheric corrections are carried out through simulation to achieve the most accurate assessment possible of the atmospheric state during imaging.



**Figure 37: Reception of wavelengths**

Among the most well-known atmospheric correction software are **5S**, developed in France, and the series of LOWTRAN models, developed in the United States. The **5S** software (Simulation of Satellite Signal in the Solar Spectrum) was developed by the L.O.A. (Laboratory of Atmospheric Optics) in 1985 and 1986. It uses a radiative transfer simulation model through non-cloudy atmosphere to evaluate the significance of atmospheric effects on satellite images and to partially correct them. The **6S** software (Second Simulation of Satellite Signal in the Solar Spectrum) has improved many aspects of the previous version, albeit at the cost of increased complexity.

Once the contribution of the atmosphere is known, it can be subtracted from the radiometric value of the pixels.

### 3.4. Classification

The classification of a remote sensing image involves the automatic recognition of reflectance. The algorithm used to classify the image groups pixels based on their similarities. This allows for

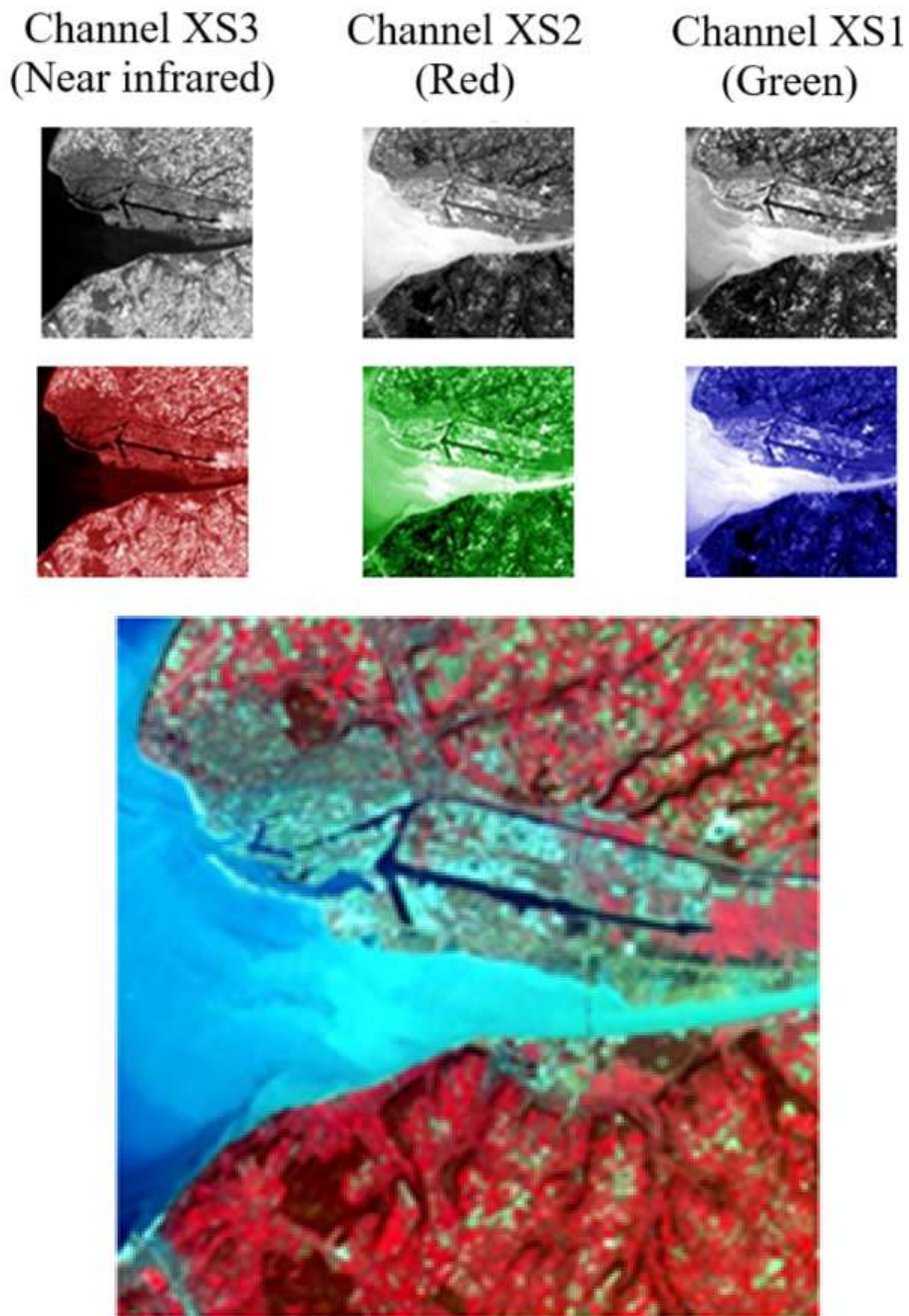
the automatic identification of different themes within an image (vegetation, water, built-up areas, etc.). Classification can be performed across a significant number of channels, though the speed of processing decreases as the volume of data increases.

There are numerous classification methods available: dynamic kernels, hierarchical clustering, hypercube segmentation, maximum likelihood, among others, as well as the latest artificial intelligence technologies such as neural networks. Classifications are divided into two categories: unsupervised classifications, which are completely automated and supervised classifications, where the user defines certain spatial or thematic parameters as input (<https://ecampusontario.pressbooks.pub/remotesensing/chapter/chapter-6-classification/>).

### 3.4.1. Color composition

All colors are formed by the addition of light from the three additive primary colors: red, green, and blue. Starting from black, which is the absence of light, varying amounts of red, green, and blue light are added to display a specific color. Each color is therefore a unique combination of the three primary colors, with white being the addition of all three primary colors at maximum intensity. This process is called additive trichromatic synthesis.

The three fundamental colors are thus associated with three channels of a satellite image. The illustration below (Fig. 38) shows the encoding of the three channels of a SPOT image using ENVI4.5 software: the XS3 channel (near infrared) is encoded in red, the XS2 channel (red) is encoded in green, and the XS1 channel (green) is encoded in blue. The result is called a color composition.



**Figure 38: Color composition 3,2,1 (SPOT5)**

**Note:** *The data to be merged (combined) must have: the same geometric reference system, the same encoding, and the same spatial resolution.*

### 3.4.2. Unsupervised classification

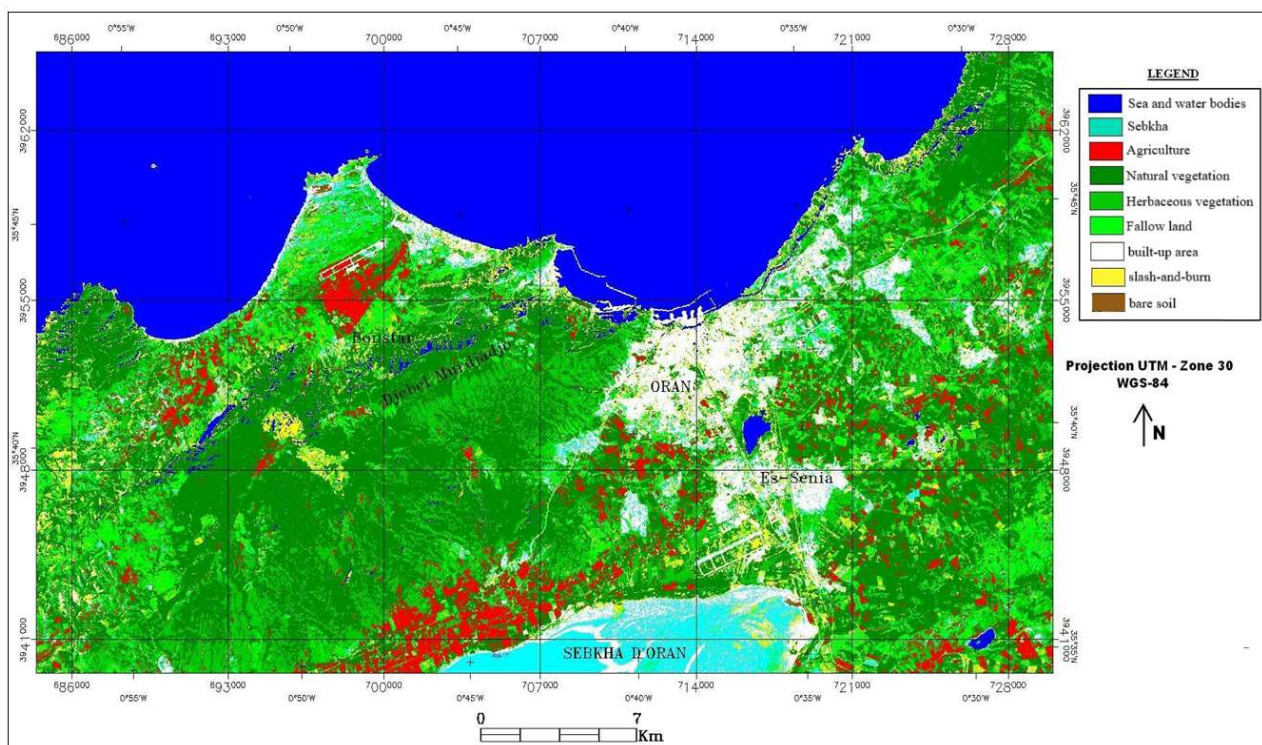
In unsupervised classifications, the user only inputs a limited number of parameters, while the computer handles the rest. User choices might include the desired number of classes or the

threshold at which the computer can consider the classification complete (since there are always nearly unclassifiable pixels).

### 3.4.3. Supervised classification

In supervised classifications, the user guides the computer by providing thematic or spatial information. This type of classification requires a minimum level of knowledge about the study area. While this approach often yields much better results, it is more time-consuming and can be seen as subjective.

The thematic parameters entered by the user might include radiometric ranges identified in the study area (for example, between 0 and 25 = pure water in the infrared). Spatial parameters could be polygons drawn on the image that will serve as benchmarks for the computer. The classification then involves comparing each pixel of the image to the defined classes and assigning it to the one deemed most similar (fig. 39).



**Figure 39: Classified image of the Oran region using the maximum likelihood algorithm**

### 3.4.4. Which algorithms are used?

The choice of a classification algorithm depends primarily on:

- *The expected application* → land use, lithology, etc.;
- *The nature of the data to be classified* → optical and/or radar;
- *The availability of prior knowledge about the dataset* → whether terrain-related knowledge is available or not.

**Note:** *In unsupervised classification, the algorithms k-means and Isodata are widely used. In supervised classification, many algorithms are used such as maximum likelihood, parallelepiped, minimum distance, ... ect.*

## 4. Applications of remote sensing

### 4.1. Forestry

The importance of forests as a food and protective resource, as a habitat, and as providers of paper, construction materials, and fuel, as well as medicinal plants, is undeniable. Forests also play a crucial role in carbon dioxide reserves and exchanges on Earth, acting as a key link between the atmosphere, geosphere, and hydrosphere.

Tropical forests, in particular, are composed of a vast diversity of tree species that exhibit much greater adaptability and survival capacity compared to our monoculture forests. These diverse forests also serve as habitats for numerous animal species, along with many plant species that are increasingly recognized for their medicinal value. Important themes in forest management include monitoring deforestation from natural sources (such as fires and infestations) and human activities (like clear-cutting, burning, and agricultural expansion), as well as tracking forest health and growth for conservation and commercial purposes.

Historically, humans have valued forest products more than the forests themselves. As a result, logging is a common practice worldwide. Given that deforestation has long-term effects on climate, soil conservation, biodiversity, and hydrological regimes, it is central to environmental monitoring efforts. Commercial forestry is a significant industry globally, where forests are cut down and replanted, and companies are constantly seeking new sources of wood.

With increasing pressure to conserve primary and virgin forests, and with abusive forestry practices greatly limiting potential cutting areas, logging companies must adapt their methods to become more efficient and develop more sustainable practices. Their survival, along with the wood supply for a growing population, depends on preserving this vital resource.

However, commercial exploitation is not the only cause of deforestation. Human factors (such as burning for pasture and crop expansion, and urban development) and natural factors (like droughts, desert expansion, loss of groundwater, insects, fires, diseases, and typhoons) also contribute to forest loss. In certain parts of the world, particularly in the tropics, humid tropical forests cover what can be considered one of the greatest treasures: fertile land. These forests are often burned or cleared to facilitate access to and use of these lands. This practice frequently occurs when the perception of long-term subsistence needs is overshadowed by immediate short-term needs.

Not only does deforestation of biodiverse forests impact local and regional hydrological regimes, but the smoke from burning trees also pollutes the atmosphere, adding more CO<sub>2</sub> and contributing to the greenhouse effect. Monitoring forest health is essential for their conservation and survival, particularly in fragile environments where the loss of key species, such as mangroves along coastlines, can have devastating effects.

Monitoring forest health is essential for their conservation and survival. The deforestation of key species, such as mangroves in fragile coastal environments, the destruction of critical support trees or those harboring potentially harvestable species, and the loss of large biomes acting as carbon reservoirs have negative repercussions for society. Increasing efforts are being made to enforce laws and international protocols aimed at protecting these regions.

Forestry can greatly benefit from various international and domestic applications of remote sensing. Key applications include continuous development, biodiversity assessments, land tenure and cadastre management, deforestation monitoring, reforestation management, commercial cutting operations, mapping, coastal and watershed protection, and biophysical monitoring (wildlife habitat estimation).

Many developing countries have limited knowledge of their forest resources. Applications such as general forest cover mapping, monitoring coastal and watershed changes, tracking logging activities, and following up on regeneration, as well as mapping forest fires and burned areas, are services that Canadian and foreign agencies can offer in the international market using remote sensing as a source of information.

Among the applications of remote sensing in forestry are:

➤ **Reconnaissance**

**Mapping**

National forest or environmental agencies pursue objectives such as updating forest cover, monitoring resource depletion, and measuring the biophysical properties of forests. This includes discriminating forest cover types and agroforestry mapping.

➤ **Commercial**

**Forestry**

Forestry companies and resource management agencies place significant emphasis on inventory and mapping applications, such as gathering information on harvests, updating inventories for cutting requests, assessing forest types, vegetation density, and biomass measurements. This includes clear-cut mapping, regeneration assessment, fire-related deforestation, infrastructure mapping, forest inventories, biomass estimation, and species inventory.

➤ **Environmental monitoring**

Conservation managers are concerned with monitoring the quality, health, and diversity of the Earth's forests: "deforestation (Amazon rainforests, mangrove colonies)," "species inventory," "protection of watersheds (riparian buffers)," "coastal protection (mangrove forests)," "health and vitality of forests." Deforestation is a global problem with numerous implications. In industrialized Europe, pollution (acid rain, soot, and chemicals from industrial chimneys) has damaged a large part of the forests. In former Czechoslovakia, half of the forests have been destroyed or damaged by pollutants. Similar effects are felt in Germany, Poland, and even in Scandinavian countries. In tropical countries, precious forests have been destroyed to make way for arable land and pastures. This results in significant losses across Latin America (Central America, southern Mexico, Haiti), South America (Brazil), Africa, and Asia. In Haiti and Madagascar in particular, the results are catastrophic. The loss of forests exacerbates soil erosion and sedimentation of rivers, affecting navigation, fishing, wildlife habitats, drinking water reserves, as well as agricultural productivity and self-sufficiency. Sensitive estuarine environments are protected by mangrove forests that are cut down or lost to urban development and aquaculture, or damaged by pollutants or silt. Monitoring the health of these forests is a step toward protecting coastlines against erosion, degradation, and flooding of adjacent lands.

The loss of forests also affects the genetic diversity of species on Earth, which controls our intrinsic ability to adapt to changing conditions and the environment. The Amazon rainforest is home to about half of the planet's plant and animal species; their massive destruction can only reduce genetic potential and species diversity.

The rate and extent of deforestation, as well as the monitoring of regeneration, are key parameters measured by remote sensing methods.

#### 4.2. Agriculture

Terrestrial herbaceous vegetation is subject to several types of use. These types can be categorized as follows:

- a. Use for the production of grass and forage, necessary for livestock feed:
  - intensively,
  - extensively.
  
- b. Use for environmental conservation:
  - Protection perimeter for watersheds for drinking water capture,
  - Biological reserves for species (animal and plant),
  - Protection zones against erosion (wind and water);
  
- c. Use as an aesthetic value:
  - For aesthetic purposes,
  - For tourism-related purposes.

Depending on geographical areas, one type of use or another is often developed. In temperate regions of Western Europe, for example, there is a decrease in the use of permanent pastures for livestock, with a clear trend toward agricultural abandonment in disadvantaged areas. In this case, pastures may have more interest for their aesthetic value (contributing to the visual appeal of the landscape and reducing avalanche risk in mountainous areas) than for biomass production.

On the other hand, in semi-arid zones, where forage availability is somewhat limited, the biomass production function of herbaceous formations dominates all other types of use.

The management and planning of these herbaceous vegetation types and the conditions for using remote sensing will therefore be very different. However, the formations typically sought by managers and decision-makers include:

- Identification of plant communities;
- Assessment of areas;

- Evaluation of the quality of produced phytomass;
- Quantitative assessment;
- Assistance in predicting the dynamic evolution of plant communities and, in particular, the consequences of specific human uses or agricultural practices.

Remote sensing provides at least partial answers to all these questions, with varying levels of ease in implementation, speed in obtaining results, and varying degrees of precision and reliability (**Bonn & Rochon, 1996**).

### 4.3. Land cover and land use

Although the terms "land cover" and "land use" sound similar, they have very different definitions. Land cover refers to the physical cover on the ground, whether it is vegetation, infrastructure, water, bare soil, or other features. Identifying, mapping, and charting land cover is important for global monitoring studies, resource management, and planning activities. Identifying land cover establishes the baseline from which monitoring (and detection) of changes can occur and provides preliminary information for thematic maps.

Land use refers to how land is utilized, such as for recreation, wildlife habitat, or agriculture. The application of land use includes baseline mapping and the subsequent monitoring, as adequate information is necessary to know which areas of land correspond to which types of use, as well as to identify changes in use over the years. This knowledge will aid in the development of strategies to balance conflicting uses and pressures from urbanization. The loss and disruption of arable land, urbanization, and forest degradation are subjects that drive the development of land use studies.

It is therefore important to distinguish between land cover and land use, as well as the information we can derive from each. The properties measured by remote sensing relate to land cover, from which land use can be inferred using auxiliary data or prior knowledge.

The study of land cover and land use is multidisciplinary. Numerous and diverse participants are involved in such studies, including international wildlife conservation organizations, governmental research centers, and the forestry industry. Regional government agencies require inventories of land cover and monitoring of land use to fulfill their mandate as natural resource managers in their respective areas. In addition to facilitating sustainable land management, land cover and land use can be used for planning, monitoring and evaluating development, industrial activity, or land

claims. Long-term detection of changes in land cover can indicate a response to modifications in local or regional climatic conditions, which is the very basis of global monitoring.

Ongoing negotiations regarding land claims by Indigenous peoples have created a need for more accurate knowledge about these territories, both in terms of cartographic and thematic information. Resource managers working with resource extraction companies such as oil, timber, and mining are concerned about land cover and land use, just as local natural resource inventory agencies are. Changes in land cover are of interest to scientists, conservation managers, and municipal stakeholders who are keen to establish tax rates or map vegetation. Governments are also concerned about protecting natural resources and engage in public awareness activities regarding soil issues.

Here are some applications of remote sensing for land use:

- Natural resource management
- Wildlife habitat protection
- Baseline mapping for GIS data
- Urban expansion and development
- Planning routes and logistics for seismic exploration and resource extraction activities
- Delimiting the extent of damage (from tornadoes, floods, volcanoes, earthquakes, fires)
- Determining legal boundaries for property and tax assessment
- Target detection—identifying landing strips, roads, clearings, bridges, and land-water interfaces.

#### **4.4. Changes in land use (Rural/Urban)**

##### **❖ General Context**

As the Earth's population increases and national economies continue to move away from agriculture-based systems, cities are constantly expanding. Urban growth often occurs at the expense of agricultural land or productive forests, encroached upon by these irresistible pushes of urbanization. The growth of cities is indicative of industrialization development, and it generally has a negative impact on the environmental health of a region.

The transition from rural land use to urban use is monitored to estimate population growth, forecast and plan urban expansion, and track regions sensitive to certain environmental hazards.

The establishment of temporary shelters can be monitored, and the density and significance of a population can be estimated.

Analyzing changes in land use is essential to ensure that urban development does not encroach on valuable agricultural land and that agriculture expands in the most appropriate areas to avoid degradation due to urban proximity.

### ❖ Why remote sensing?

With multitemporal analyses, remote sensing provides a unique perspective on how cities develop. The key element for mapping changes in land use from rural to urban is the ability to distinguish between rural uses (agriculture, pastures, forests) and urban uses (residential, commercial, recreational). Remote sensing methods can be employed over large areas to classify land use types in a practical, economical, and repeatable manner.

### ❖ Data requirements

The detection and mapping of changes in land use must meet two requirements: high spatial resolution to obtain detailed information, and multispectral optical data to differentiate between various land use classes.

Operational sensors in the visible and infrared regions of the spectrum are the most useful data sources for analyzing land cover and use. While several urban features can be detected using radar imaging (due to high reflectivity), high-resolution optical data allow for finer distinctions in land cover and use, enabling more accurate identification of urban suburbs and transitional classes from urban to rural. Optical images acquired during winter months are also beneficial for delineating the boundary between urban and non-urban areas, as cities appear distinctly against smooth-textured snow-covered fields.

Radar sensors are also useful for mapping rural and urban applications due to their sensitivity to geometric shapes, allowing for the detection of anthropogenic elements such as buildings. The optimal geometric arrangement between the sensor and the urban area is a linear orientation, parallel to the sensor's movement and perpendicular to the incident energy received.

Generally, this type of application does not require a short processing and delivery time or a high acquisition frequency (Canadian Centre for Remote Sensing).

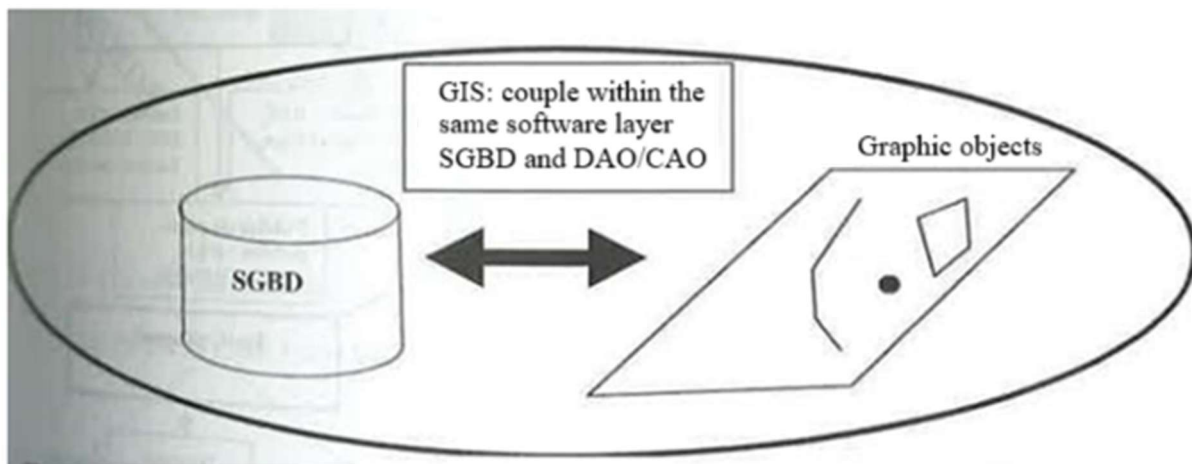
## Part 2: Geographic Information Systems (GIS)

### 1. Definition of a GIS

Geographic Information Systems (GIS) emerged from the intersection of:

- The management of graphic information, particularly computer-aided design (CAD) through software like AutoCAD, which provided a standard graphic data format (DXF) that many GIS incorporate into their practical data import modules.
- The management of databases using computer systems that organize data in tables and the relationships between them (e.g., ORACLE, ACCESS, DBASE).

The first GIS appeared in Canada and the USA around 1964-1965, when it became possible to establish a link between the geometry of objects (lines, points, and surfaces) and the information associated with them (**Pornon, 1990**).



**Figure 40: GIS layer (Pornon, 1990)**

In 1989, the French Society of Photogrammetry and Remote Sensing defined GIS as "a computer system that allows, from various sources, to gather and organize, manage, analyze, combine, develop, and present geographically located (georeferenced) information. The entire set of geographical information integrated into the GIS forms a geographic database."

Thus, GIS enables the management of a multitude of information types (satellite images, aerial photos, maps, numerical data, databases, etc.), allows for rapid updates, facilitates queries (both classic and spatial), applies topological rules, and generates new layers of information through these intersections (**Christophe Magdelaine / notre-planete.info, 2014**).

Spatially referenced data refers to any data that can be directly (e.g., a school, a road) or indirectly (e.g., an address, an owner) located on the Earth's surface.

## 2. Structure of geographic information

To transform a real-world object into spatially referenced data, the territory is broken down into thematic layers (relief, roads, buildings, etc.) structured within digital databases. The databases that feed into GIS must be georeferenced, meaning they share a common spatial reference framework known as a projection system (**Hammoum & Bouzida, 2010**).

## 3. Geographic information

Geographic information refers to any information related to a point or a set of points spatially referenced on the Earth's surface. It is of paramount importance for anyone managing a space or objects dispersed across a given area. The term spatial information encompasses diverse data such as the distribution of natural resources (soils, water, vegetation); the location of infrastructure (roads, buildings, various facility networks); and administrative and political boundaries.

The definition of each component—information system and geographic information—helps to clarify their scope:

- **Information system:** A set of interconnected components that collect information, process it, store it, and disseminate it to support decision-making and control within an organization.
- **Geographic information:** Information is considered geographic when it relates to one or more locations on the Earth's surface. This information is characterized by being localized, referenced, or geocoded.
  - **Geographic data** consists of two components: spatial data and attribute data. Here are a few examples illustrating the relationship between space and attribute:
    - A parcel and its number
    - The position of a point and its width
    - The location of a natural area and its type of vegetation

- **Spatial data:** These represent geographic objects associated with their location in the real world (localized data). Geographic objects are depicted on maps as points, lines, and polygons.
- **Attribute data:** These describe specific properties of geographic objects, such as parcel numbers, bridge widths, or types of vegetation.

## 4. Geographic data

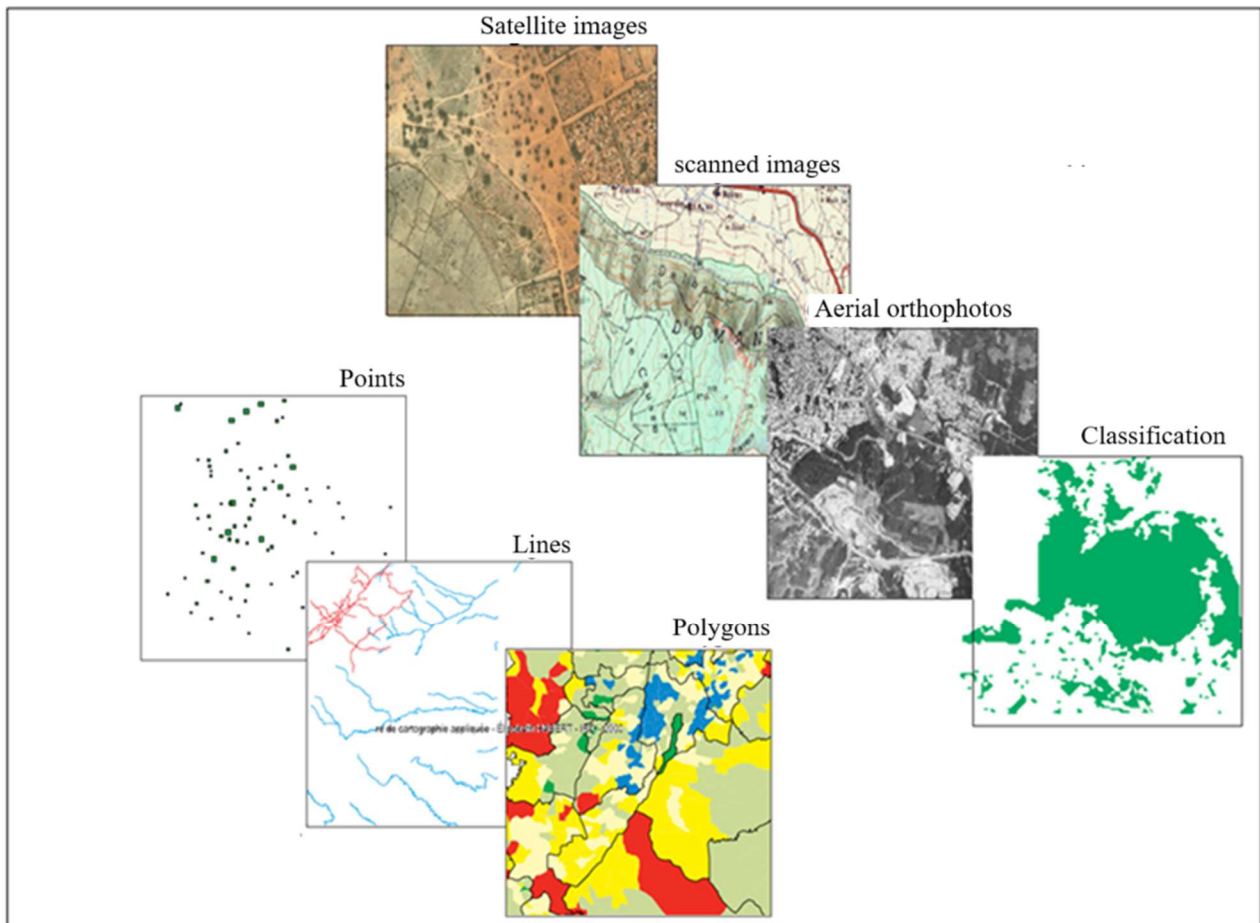
### 4.1. Raster data

Reality is decomposed into a regular rectangular grid, organized into rows and columns, forming elementary spatial units. This elementary spatial unit is called a pixel (Picture Element). The size of this pixel, measured in distance units, defines the spatial resolution of the image. Each cell in this grid has a gray intensity or a color. The juxtaposition of these points recreates the visual appearance of the map and each piece of information (**Minvielle & Souiah, 2003**).

### 4.2. Vector data

The boundaries of spatial objects are described through their elementary components, namely points, lines, and polygons. Each spatial object has an identifier that links it to an attribute table.

- **Points:** These define locations of separate elements for geographic phenomena too small to be represented by lines or areas that lack real surface, such as plotted points.
- **Lines:** These represent the shapes of geographic objects that are too narrow to be described by areas (e.g., streets or rivers) or linear objects that have length but no surface, like contour lines.
- **Polygons:** These represent the shape and location of homogeneous objects, such as countries, parcels, or soil types (fig. 41) (**Minvielle & Souiah, 2003**).



**Figure 41: Vector data**

Graphic data describe the location and shape of geographic objects, while alphanumeric data describe the nature and characteristics of spatial objects.

## 5. GIS models

The purpose of a GIS is to answer five fundamental questions:

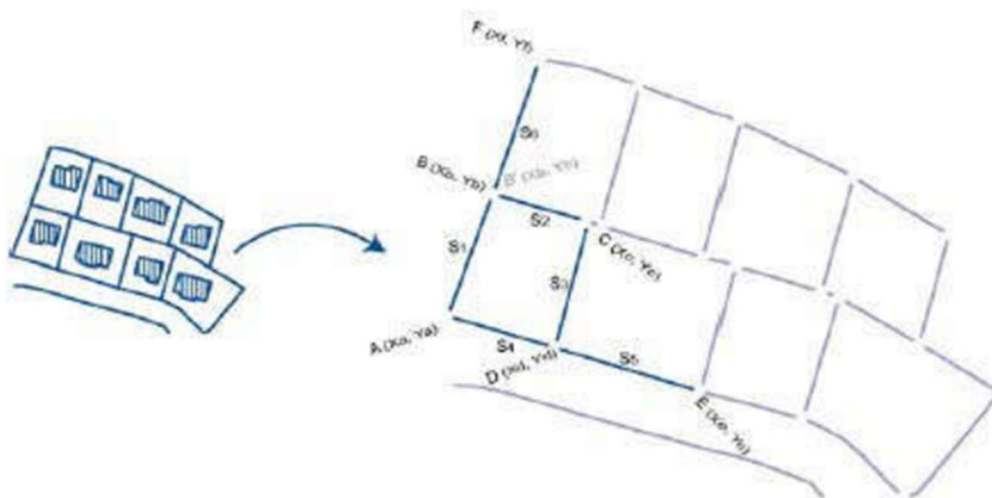
- **Where:** Where is the area I want to analyze?
- **What:** What is found at the analyzed location?
- **How:** How are the objects in this area distributed, and how do they interact with each other?
- **When:** Have there been any changes to the data at any point in time?
- **What if:** What would happen if a certain event occurred?

To address these questions, a method for storing geographic information has been developed. A model allows for analyzing reality and schematizing it to make the collected data usable. There are two models in GIS: the spaghetti model and the topological model.

### 5.1. Spaghetti model

The spaghetti model, or wireframe structure, involves storing basic geometric figures independently of one another (the data are described separately). This means that the various geometric elements, such as points, lines, and polygons, are treated as distinct entities without any inherent relationships to one another. This model is simple but can become complex and inefficient when representing intricate spatial relationships.

No relationships between the different segments are specified in the spaghetti model. As a result, there will be redundant information to link the data together. This type of structure is primarily used for visual representation of the data and makes spatial analysis very difficult. The lack of connectivity and inherent relationships limits the model's utility for complex analyses, as it does not effectively capture the spatial interactions between objects.

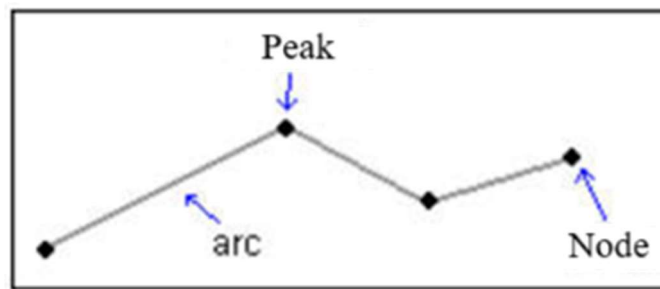


**Figure 42: Spaghetti model**

The image above represents a spaghetti model. To describe the image on the left in the database, each segment must be described. For instance, segment S1 has endpoints A and B, while segment S2 has endpoints B and C. Here, we see that to add two segments, point B must be entered twice (Minvielle & Souiah, 2003).

### 5.2. Topological model

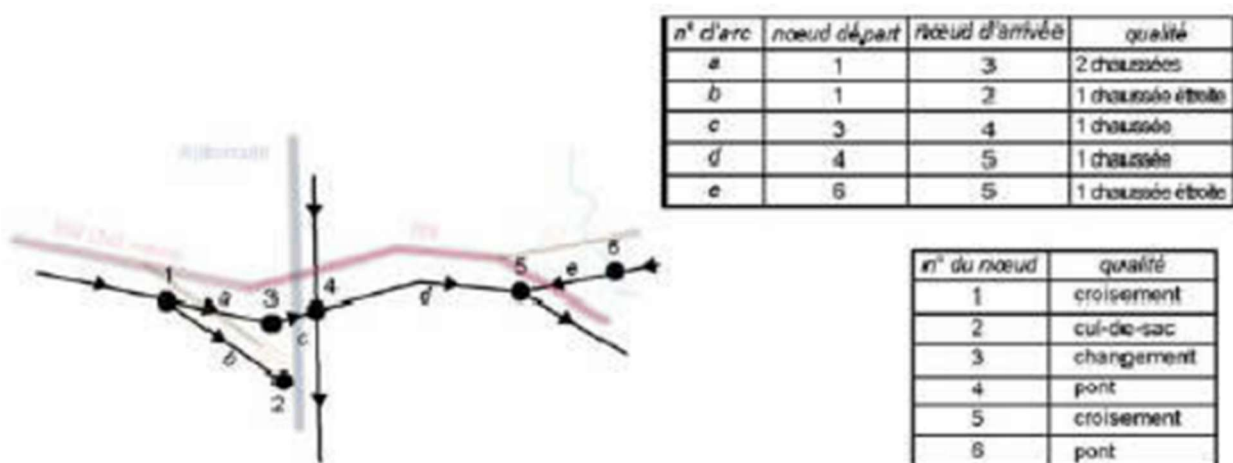
Topology refers to the expression of relationships between objects. Not all GIS software manages topology; in such cases, we refer to "object-based" GIS (or non-topological). Those that do manage topology (such as the ArcGIS suite from ESRI) identify all objects in relation to one another, capturing the relationships and connections among them. This includes recording the direction of data entry, allowing for a more meaningful representation of spatial relationships and enabling more complex spatial analyses. The topological model enhances data integrity and reduces redundancy, making it a powerful tool for geographic analysis.



**Figure 43: Topological model**

The topological model describes all relationships between segments and eliminates redundancy in information. While this may compromise display efficiency, these structures store data in a way that speeds up the execution of spatial queries.

The image below shows that each point is stored in a table with descriptive information. Additionally, another table connects these various points to create a complex set (Minvielle and Souiah, 2003). This approach allows for a more organized and efficient representation of geographic data, facilitating advanced spatial analysis and operations by leveraging the relationships between objects.



### Figure 44: Topological model

For example, vectors are referred to as arcs, intersection points as nodes, and intermediate points as vertices.

Topological rules connect these elements to each other: for instance, a dwelling is strictly contained within a cadastral parcel and does not intersect with a highway.

#### ❖ Advantages

- You can capture certain nodes to automatically close a polygon and remove dangling arcs.
- Results from the intersection of multiple layers can be recorded in a new layer that inherits all the geographic and attribute information from the original layers. There are several options for intersection (union, intersection, identity, etc.).
- Buffer zones can be created. This involves determining a fixed-distance area around spatial entities (e.g., protection zones, influence areas). This buffer is circular around isolated points, forms a corridor around an arc (line), and creates a buffer zone around a polygon.

#### ❖ Disadvantages

- The complexity of managing topological relationships can increase the computational load and require more sophisticated data management.
- Changes to one part of the topology can necessitate updates throughout the entire structure, which may complicate data editing and maintenance.
- Visualization may be less straightforward due to the emphasis on relationships rather than individual elements.

Overall, while the topological model offers significant advantages for spatial analysis and data integrity, it also comes with challenges that need to be managed effectively.

- If topological integrity is maintained, the information layers are reliable, making their use more rigorous.
- There is the possibility of Raster/Vector integration. A raster plan can be used passively (for visual overlay when presenting a plan), semi-passively (as a guide for digitizing), or actively by automatically enriching the vector database: this is Raster/Vector integration.

This approach focuses not just on the visual aspect of images, but also on the pixel values. You can determine the exact number of pixels within a polygon, as well as their average, minimum, or maximum values, or the most frequently occurring value, etc.

- It requires more time and rigor in the creation and updating of data.
- The application of topological rules may introduce new errors that will need to be managed.

## 6. Applications of GIS

A few years ago, the implementation of GIS seemed reserved for large organizations. Today, advancements in computing and the capabilities for management and analysis have led to the widespread use of GIS at all levels of governance.

Thus, GIS can be found in numerous fields, including:

- Land use planning and urbanism
- Agriculture
- Oil industry
- Natural risk prevention (floods, wildfires, pollution, etc.)
- Road infrastructure
- Public construction
- Water management

## 7. Metadata

Metadata is data that provides information about other data, enabling its relevant use. It allows users to:

- Understand the origin and nature of the data
- Comprehend its structure
- Know how to access the data and how to interpret it

Metadata plays a crucial role in ensuring that data can be effectively utilized, understood, and maintained within GIS systems.

- Knowing the data models and their management rules Example: cartographic projections, spatial accuracy.

## 8. Functions of a GIS

The literature in this field briefly defines the expected functions of a GIS by the "5 A's," which are: Abstraction, Acquisition, Archiving, Analysis, and Display.

### 8.1. Abstraction

This is the modeling of the real world from different perspectives. The construction of the conceptual data model allows for the modeling of the database by defining objects (classes of objects), their attributes, and their relationships. This step is necessary before any digitization, serving as the starting point for the creation of geographic databases and as a means of dialogue among the various stakeholders. The goal of modeling is to be understood by the widest audience possible.

The second step involves finding software capable of transcribing and "storing" the schema. Each software implicitly has a Conceptual Data Model. The important thing is the result; the software is just a tool. The GIS tool must be able to transcribe and store the modeling.

### 8.2. Acquisition

We can find information from national or international organizations that produce or sell data:

- Reference data: INCT (National Institute of Cartography and Remote Sensing), ANC (National Land Agency), INPS (National Institute of Planning and Statistics), CNTS (National Center for Spatial Techniques), Spot Image, etc.
- Thematic data: ANRH (National Agency for Water Resources), DGF (General Directorate of Forests).
- From local professionals, surveyor expert firms, state study offices, local communities (APC).

If the data does not exist in digital form, it is possible to create it oneself or through a service provider:

- **Digitization of the cadastre**
- **Topographic survey**

What are the acquisition techniques?

- **Acquisition from vector data:** The sources are either indirect (plans, photos, satellite images) or direct with field surveys. This acquisition is done using existing paper documents (maps, plans) through digitization using a digitizing tablet or by scanning the data displayed on the computer screen. Objects drawn on the plan are digitized into vector data. The drawback of this method is the transcription of errors due to the original medium (paper deformation, line thickness, etc.).
- If the data is scanned and geo-referenced, it is "raster" data.
- **Acquisition from photos:** From ortho-rectified scanned photos to vector data, this is one of the main sources for precise digitization over large areas. The accuracy of the data is related to the accuracy of the photo. This type of acquisition requires either field surveys or cross-referencing with other data to qualify the information; the photo is simply a collection of pixels.
- **Acquisition from satellite images:** Satellite imagery serves as the primary source of information for land use through remote sensing. Remote sensing encompasses the knowledge and techniques used to determine the physical and biological characteristics of objects through measurements taken at a distance, without physical contact with them.
- **Acquisition from the field:** Generally used for small-scale projects or as a complement to other techniques. GPS (Global Positioning System) is a positioning system on a global scale, utilizing a network of artificial satellites.

### 8.3. Archiving

**Management** Once acquired, the data must be stored and easily retrievable. This is one of the least visible functions for the user. It depends on the software architecture and whether it has an integrated relational or object-oriented Database Management System.

### The Work environment

We are no longer in the "storage space" but in the "work space." This refers to the space for project management (organization) as well as the software ergonomics (interface).

### 8.4. Analysis

The primary purpose of geographic information systems is not just to create maps or plans, nor solely to manage data, but to serve as a tool for geographic information.

- **Spatial analysis from semantics:** This involves a qualitative and/or quantitative description of a space using alphanumeric data stored within the geometric object or in an external database via a link. This analysis can be conducted through queries or calculations, often supported by cartography.
- **Geometric spatial analysis:** This analysis is based on the object's position, shape, and any existing relationships. The distance between objects is one of the basic functionalities of spatial analysis. Topology can be used when it exists. Data can be manipulated by cutting, joining, or excluding it.

### 8.5. Display

The purpose of display is to enable users to comprehend spatial phenomena, ensuring that the graphical representation adheres to cartographic principles. Display serves to communicate:

- On a computer during the development of a study
- On the internet, respecting constraints regarding weight, color, format, etc.
- On paper for work documents, reports, promotional materials (Hammoum and Bouzida, 2010).

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