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Pedagogical course support

Title :

REMOTE SENSING

By

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This course is intended for students enrolled in the Master's program in Risk Management and Civil Security. This course is prepared following the framework outlined by the Ministry of Scientific Education and Research titled "Harmonization of Academic Master's Training Offer" on page 30.

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For centuries, humans have been interested in documenting and mapping their world (Khorram et al., 2012). Although the field of cartography has made tremendous progress over the millennia, it was not until the 20th century, following the invention of the airplane and the refinement of cameras and photographic techniques, that humans had the ability to observe large geographic areas. Furthermore, since the launch of the first Earth observation satellites in the 1950s and 1960s, we have been able to examine our world and its changes from a truly global perspective. This has opened up a whole new dimension to our ability to observe, study, and monitor Earth's surfaces on a global and continuous scale. It has led to major developments in the field of remote sensing in scientific, commercial, technical, and national security realms (Elachi and Van Zyl, 2021).

The advent of satellites allows for the acquisition of detailed information about the Earth. Satellites in orbit (such as Landsat series data, Sentinel series data, Modis data, Meris data, etc.) provide information on surface vegetation cover and its seasonal variations, surface temperature, and climate change, cloud structure and dynamics on a global scale, water resources and aquatic pollution (Canadian Centre for Remote Sensing, 2015; Boris, 2012), disease monitoring (Tran et al., 2022), and surface morphological structures. The rapid and extensive coverage capability of satellite platforms enables the monitoring of rapidly evolving phenomena, especially in the atmosphere. The long-term and repetitive capability allows for the observation of seasonal, annual, and longer-term changes such as polar ice coverage, desert expansion, movement of land surfaces, subsidence, and tropical deforestation. Large-scale synoptic coverage allows for the observation and study of regional and continental features such as plate boundaries and mountain ranges.

These instruments, along with the data analysis techniques they collect, are constantly improving, making them not only more sensitive to changes but also more reliable for decision-makers.

This material is primarily intended for students in the Master's program in Risk Management and Civil Security. We will mainly cover fundamental concepts of remote sensing, different satellites, and satellite image processing. The work is supplemented by examples of remote sensing applications, including supervised land use classifications and extraction of hydrographic networks and watersheds in surface hydrology.

Historical overview

In his book titled "Fundamentals of Satellite Remote Sensing," Chuvieco (2016) extensively summarizes the evolution of remote sensing. According to the author, remote sensing has undergone significant advancement parallel to technological progress, especially in the fields of optics, sensor electronics, satellite platforms, transmission systems, and computerized data processing. These advancements have greatly expanded the quantity, quality, and diversity of data available for scientific research. The historical origins of remote sensing date back to the mid-19th century with the emergence of aerial photography. The first photographs were captured in France in 1839, and subsequent developments led to the use of aerial platforms for military reconnaissance purposes during the American Civil War in 1861.

By the late 1940s and early 1950s, improvements in navigation systems facilitated the emergence of the first space sensor devices. The launch of Sputnik by the Soviet Union in 1957 marked the beginning of a series of civilian and military missions exploring Earth and neighboring planets. In 1960, NASA launched the Television Infrared Observation Satellite (TIROS-1), which provided recurring images of Earth's cloud patterns, shedding light on atmospheric conditions and natural disasters.

Throughout the 1960s, manned missions such as Mercury and Apollo captured valuable images of Earth, demonstrating the scientific value of space exploration. In 1965, photography was officially integrated into space missions for geological and meteorological purposes. The introduction of digital technologies into remote sensing in the late 1960s paved the way for the Earth Resources Technology Satellite (ERTS-1), later renamed Landsat 1, launched in 1972. Landsat missions provided detailed, high-resolution, multispectral images of Earth's surface, facilitating a multitude of civilian applications.

In the 1980s, there was a growing interest in the development of global-scale space remote sensing systems, with countries like France, Japan, India, and European nations launching their own Earth observation satellites. By the late 1990s, the private sector played a significant role in advancing remote sensing capabilities, with the launch of commercial satellites such as IKONOS and QuickBird.

Recent trends include an increasing availability of satellite missions aimed at providing operational services, where remotely sensed data are regularly used for various applications, including weather forecasting, humanitarian activities, and disaster monitoring. The development of corrected reflectances and final products from raw data has facilitated the use of remotely sensed data even for non-experts. The distribution of data via the internet has also enabled near-real-time services, contributing to the growing utility of remote sensing in various domains.

Chapitre 1.

Remote sensing. Principle and basic concepts

1- Introduction

This chapter provides an in-depth analysis of remote sensing and its components. It commences with an exploration of the various definitions of remote sensing, shedding light on its emergence in the 1970s and the diverse interpretations that stem from it. Subsequently, it delineates the fundamental elements that constitute remote sensing. Among these essential components are electromagnetic radiation, which serves as the medium through which data are captured from space to Earth, and the electromagnetic spectrum, encompassing the full range of frequencies and wavelengths of radiation. Additionally, it addresses the atmospheric window, a region of the electromagnetic spectrum through which radiation can freely travel through Earth's atmosphere. This comprehensive presentation of the fundamentals of remote sensing lays the necessary groundwork for a thorough understanding of the applications and techniques employed in this field.

2- Definition of remote sensing

Compared to other data collection methods, remote sensing offers distinct advantages as it provides an overview of terrestrial phenomena, enabling users to discern patterns and relationships that are not apparent from the ground (Thenkabail, 2016). According to Li (2021), remote sensing is a comprehensive Earth observation technology that enables the collection, processing, and imaging of information from electromagnetic waves emitted and reflected by targets at long distances using various non-contact detection instruments, to achieve the detection and recognition of various ground objects. Elachi and Van Zyl (2021) define remote sensing as the acquisition of information about an object without physical contact. Information is acquired by detecting and measuring the changes that the object imposes on the surrounding field, whether it be an electromagnetic, acoustic, or potential field. It may involve an electromagnetic field emitted or reflected by the object, acoustic waves reflected or disturbed by the object, or disturbances in the surrounding gravitational or magnetic potential field due to the presence of the object. According to Tran et al. (2022), remote sensing is defined as the set of techniques used to collect information about objects remotely; specifically, Earth observation employs an instrument (the sensor) carried on a platform (satellite, aircraft, drone, etc.) to characterize the Earth's surface (continental surfaces, oceans, or the atmosphere). According to Campbell et al. (2023), the field of remote sensing has been defined on numerous occasions (see Table 1.1).

Table 1.1. Some definitions of remote sensing

Remote sensing has been defined in various ways, but essentially it is the art or science of obtaining information about an object without touching it (Fischer et al. 1976).

Remote sensing is the non-contact acquisition of physical data from an object (Lintz and Simonett 1976).

Imagery is acquired using a sensor other than (or in addition to) a conventional camera, through which a scene is recorded, for example by electronic scanning, using radiation outside the normal visual range of film and camera - microwave, radar, thermal, infrared, ultraviolet, as well as multispectral. Special techniques are applied to process and interpret remotely sensed imagery for the purpose of producing conventional maps, thematic maps, resource studies, etc. in the fields of agriculture, archaeology, forestry, geography, geology and so on (Société américaine de photogrammétrie).

Remote sensing is the observation of a target by a device separated from it by a certain distance (Barrett and Curtis 1976).

The term remote sensing, in its broadest sense, simply means "reconnaissance from a distance" (Colwell 1966).

Remote sensing, although not precisely defined, includes all methods for obtaining images or other forms of electromagnetic recordings of the Earth's surface from a distance, as well as image data processing, etc. Remote sensing, in its broadest sense, involves detecting and recording electromagnetic radiation from target areas within the field of view of the sensing instrument. This radiation may come directly from distinct elements of the target zone; it may be solar energy reflected by these elements; or it may be reflections of energy transmitted to the target zone by the sensor itself (White 1977).

Remote sensing" is the term currently used by a number of scientists for the study of distant objects (terrestrial, lunar and planetary surfaces and atmospheres, stellar and galactic phenomena, etc.). In its broadest sense... remote sensing refers to the combined effects of the use of modern sensors, data processing equipment, information theory and processing methodology, communications theory and devices, space and airborne vehicles, and the theory and practice of large-scale systems for the purpose of aerial or space-based surveys of the earth's surface (National Academy of Sciences 1970).

Remote sensing is the science of obtaining information about an object from measurements taken at a distance from the object, i.e. without coming into contact with it. The quantity most frequently measured in today's remote sensing systems is the electromagnetic energy emanating from the objects of interest, and while there are other possibilities (for example, seismic waves, sonic waves and gravitational force), our attention ... is focused on systems that measure electromagnetic energy (Swain and Davis 1978).

3- The advantages and disadvantages of remote sensing

3-1 Advantages of remote sensing

- (1) Remote sensing is said to be discrete when the sensor passively records the electromagnetic energy reflected or emitted by the observed phenomenon. This approach is crucial because passive remote sensing does not interfere with the object or area of interest, thus preserving their integrity.
- (2) Remote sensing devices are programmed to collect data in a methodical way. This systematic data collection eliminates the sampling biases that can be introduced in some in situ surveys, guaranteeing a more accurate and complete representation.
- (3) The science of remote sensing offers new data or fundamental scientific information such as geographical location, altitude or depth, temperature, water content, etc.
- (4) Information derived from remote sensing is now indispensable for the successful modelling of many natural processes (e.g. water supply estimation, eutrophication studies, non-point source pollution) and cultural processes (e.g. land use conversion on the outskirts of cities, water demand estimation, population projection, food security).

3-2 Disadvantages of remote sensing

- 1) Remote sensing is not a magic bullet providing all the information required for research in the physical, biological or social sciences. It is limited to providing relevant spatial, spectral and temporal data.
- 2) Powerful active remote sensing systems, such as LiDAR, RADAR and SONAR, emit their own radiation and can therefore be intrusive, impacting the phenomenon under study.
- 3) Human intervention in remote sensing data processing, such as specifying resolutions, calibrating sensors and selecting the right platform, can introduce errors and biases into the data obtained.
- 4) Remote sensing can be expensive, mainly due to the costs associated with the satellite programs needed to collect the data.

4- Principle of remote sensing

In most cases, remote sensing relies on the interaction between incident energy and target objects. The process of remote sensing using imaging systems comprises seven key stages (see Figure 1.1). These include the energy source, the earth's surface, the atmosphere, the sensor system, the receiving system, image processing and the users. It should be noted, however, that remote sensing can also involve transmitted energy and non-imaging sensors (Centre Canadien de Télédétection 2015).

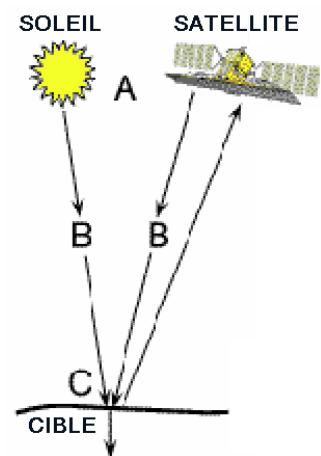


Figure 1.1. Remote sensing processes

4-1 Source of energy or illumination

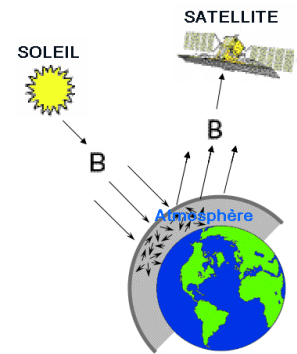
At the origin of any remote sensing process is necessarily an energy source to illuminate the target by emitting an electromagnetic wave. The sun is the main source of electromagnetic radiation used in passive optical remote sensing (Joseph and Jaganathan 2018). Nevertheless, Radar technology requires a transmitter to be onboard the satellite, in which case the satellite itself is the energy source.

It is also possible to measure the heat emanating from the surface of the target, in which case it is the target that is the source of energy.



4-2 Radiation and atmosphere

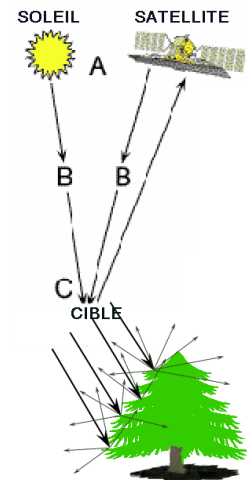
On its journey from the energy source to the target, radiation undergoes significant interactions with the atmosphere, creating important influences on its nature and composition. This first interaction can result in phenomena such as scattering, absorption and reflection, modifying the spectral distribution and intensity of the radiation. A second interaction occurs on the path between the target and the sensor. This stage of the journey again involves interactions with the atmosphere, but this time the specific characteristics of the target come into play. Reflection, thermal emission and other responses of the target to radiation can alter the spectral signature of the radiation as it returns to the sensor.



4-3 Interaction with the target

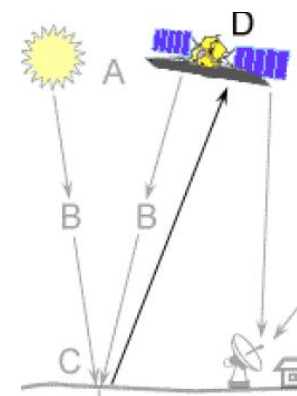
Once the energy from the source has reached the target, the interaction between this energy and the target surface becomes an essential aspect of the remote sensing process. The way in which this interaction manifests itself depends closely on the characteristics of the electromagnetic radiation and the intrinsic properties of the target surface.

The nature of the radiation, particularly its wavelength, plays a crucial role in how it interacts with the surface. Some materials exhibit high reflectance at certain wavelengths, while others can strongly absorb radiation at other wavelengths. These variations in reflectance and absorption create unique spectral signatures for different types of surfaces.



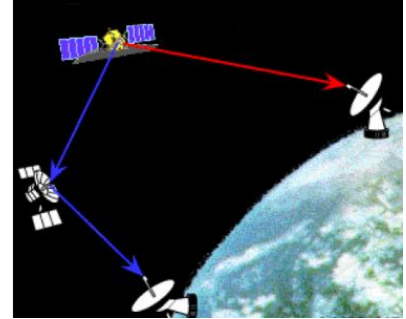
4-4 Sensor energy recording

After interacting with the target, either by scattering or emission, the resulting energy must be detected at a distance by a sensor that has no physical contact with the target. This crucial stage in the remote sensing process relies on instruments specially designed to capture signals emitted by the earth's surface. Sensors used in remote sensing are sensitive to different ranges of the electromagnetic spectrum, from radio waves to gamma rays. Each spectral range offers unique information about the target, enabling us to gather a variety of data on the composition, temperature, humidity and other characteristics of the surface observed.



4-5 Transmission, reception and processing

Once the energy has been captured by the remote sensor, the remote sensing process continues with the transmission of this information to a receiving station. This step is essential to convert the raw signals into understandable images, whether digital or photographic, enabling visual and analytical interpretation of the data collected.



The transmission of recorded energy from the sensor to the receiving station is usually carried out by electronic means. Sophisticated communication systems, such as satellites, satellite dishes or terrestrial networks, are used to transfer the collected data to processing centers.

4-6 Interpretation and analysis

After image processing at the receiving station, a crucial step in remote sensing is the visual and/or digital interpretation of these images. This phase aims to extract specific information about the observed target, in order to understand land surface features, temporal changes, and other parameters of interest.

Visual interpretation often involves direct examination of images by human experts, or the use of computer algorithms to extract information automatically.

4-7 Application

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

5- Electromagnetic radiation

An electromagnetic wave is a form of electromagnetic field motion. When this changing electromagnetic field propagates through space in the form of an electromagnetic oscillation, electromagnetic waves are formed. In fact, the electromagnetic oscillation propagates in different directions. This process of transmitting electromagnetic energy (including radiation, absorption, reflection and transmission) is called electromagnetic radiation (Li 2021).

Electromagnetic radiation (Figure 1.2) is composed of an electric field (E) and a magnetic field (M). The electric field varies in magnitude and is oriented perpendicular to the direction of radiation propagation.

The magnetic field is oriented perpendicular to the electric field. Both fields move at the speed of light (c).

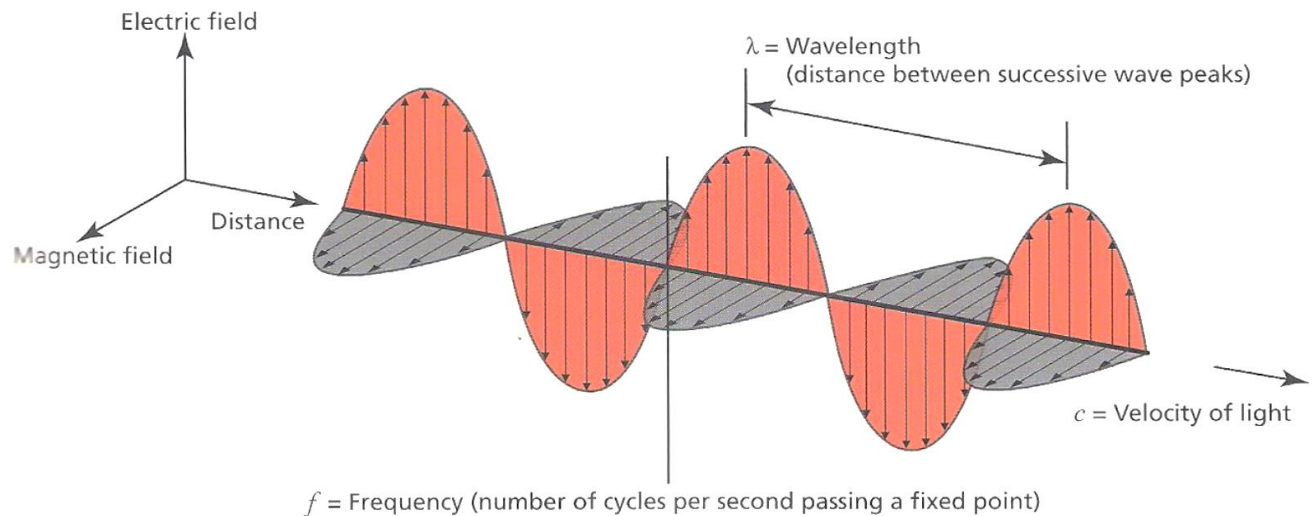


Figure 1.2. Electromagnetic radiation (Aronoff 2005)

To understand remote sensing, it's essential to understand the two components of electromagnetic radiation: wavelength and frequency. Wavelength is equivalent to the length of a wave cycle, which corresponds to the distance between two successive wave crests.

Wavelength is usually represented by the Greek letter lambda (λ), and is measured in meters or one of its submultiples such as nanometers (nm, 10^{-9} meters), micrometers (μm , 10^{-6} meters) or centimeters (cm, 10^{-2} meters).

Frequency represents the number of oscillations per unit of time. Frequency is normally measured in Hertz (Hz) (i.e. oscillations per second) or in multiples of Hertz.

The following formula illustrates the relationship between wavelength and frequency (Chuvieco 2016):

$$\lambda = \frac{v}{f}$$

λ is the wave length, v is the velocity, and f is the frequency.

Wavelength and frequency are therefore inversely proportional, i.e. the shorter the wavelength, the higher the frequency, and the longer the wavelength, the lower the frequency (Figure 1.3).

i) $F_1 = 2$ cycles per second = 2 hertz

ii) $F_2 = 4$ cycles per second = 4 hertz

iii) $F_3 = 1$ cycle per second = 1 hertz

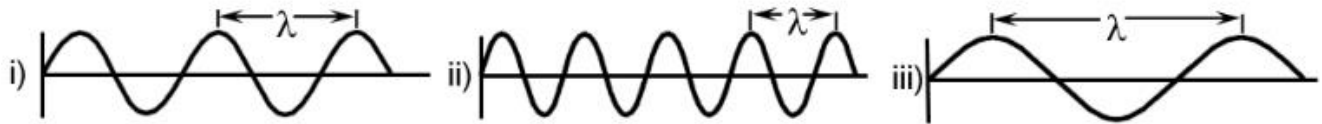


Figure 1.3. Characteristics of electromagnetic radiation

According to (Elachi and Van Zyl 2021) electromagnetic radiation is the means by which information is transmitted from an object to the sensor. Information is propagated by electromagnetic radiation at the speed of light from the source directly into free space, or indirectly by reflection, scattering and re-emission towards the sensor. The interaction of electromagnetic waves with natural surfaces and the atmosphere is highly dependent on wave frequency.

6- Electromagnetic spectrum

Electromagnetic radiation is defined as all energy traveling at the speed of light in a harmonic wave pattern. Visible light is only one type of electromagnetic radiation; other types include radio waves, infrared and gamma rays. Together, these make up the electromagnetic spectrum (Figure 1.4).

According to (Elachi and Van Zyl 2021), the main bands of the electromagnetic spectrum are:

The radio band covers the wavelength region greater than 10 cm (frequency lower than 3 GHz). This region is utilized by active radio sensors such as imaging radars, altimeters, and sounders, and to a lesser extent, by passive radiometers. The microwave band extends into the adjacent region, up to a wavelength of 1 mm (frequency of 300 GHz). In this region, most interactions are governed by molecular rotation, particularly at shorter wavelengths. This region is primarily used by microwave radiometers/spectrometers and radar systems.

The infrared band spans the spectral region from 1 mm to 0.7 μm. This region is sometimes subdivided into sub-regions called submillimeter, far-infrared, thermal infrared, and near-infrared. In this region,

both molecular rotation and vibration play significant roles. Imagers, spectrometers, radiometers, polarimeters, and lasers are employed in this region for remote sensing. The nearby visible region (0.7-0.4 μm) sees the onset of electronic energy levels becoming key. According to Khorram et al. (2012), visible light, representing only a small portion of the electromagnetic spectrum, has wavelengths ranging from approximately $3.9 \times 10^{-7} \text{ m}$ (violet) to $7.5 \times 10^{-7} \text{ m}$ (red), with corresponding frequencies ranging from 7.9×10^{14} to $4 \times 10^{14} \text{ Hz}$. (Note that visible wavelengths are commonly expressed in nanometers, where $1 \text{ nm} = 10^{-9} \text{ m}$, or in micrometers, where $1 \mu\text{m} = 10^{-6} \text{ m}$).

In the subsequent ultraviolet region (0.4 μm to 300 $\text{\AA}$), electronic energy levels predominantly drive the wave-matter interaction. Ultraviolet detectors have been primarily employed in studying planetary atmospheres or atmosphere-free surfaces due to gas opacity at these short wavelengths.

X-rays (300-0.3 $\text{\AA}$) and gamma rays (shorter than 0.3 $\text{\AA}$) have seen even less use due to atmospheric opacity. Their usage has been restricted to low-flying airborne platforms or the study of atmosphere-free planetary surfaces (e.g., the moon).

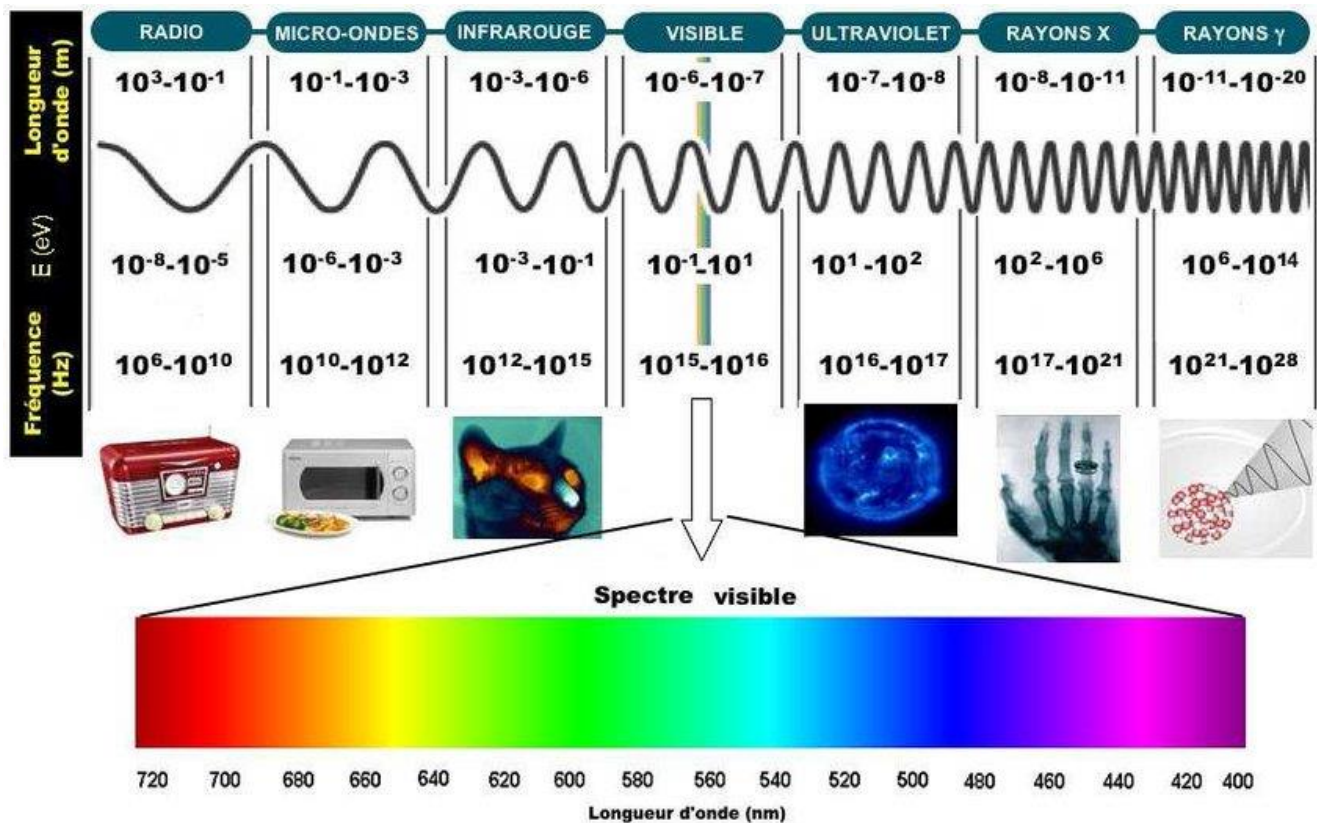


Figure 1.4. Electromagnetic spectrum

7- Interactions of electromagnetic radiation with the atmosphere and the earth's surface

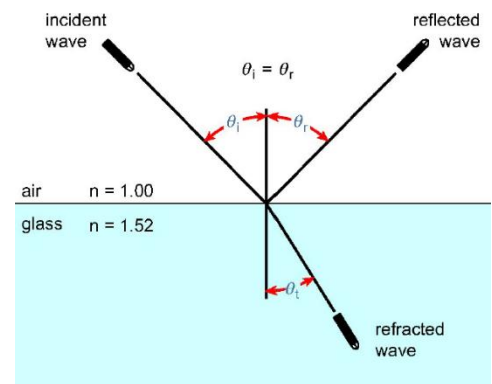
7-1 Interactions of electromagnetic radiation with the atmosphere

The interaction between electromagnetic radiation and the Earth's atmosphere can be considered to have three components (Knudby, 2021): (1) refraction, which alters the direction of propagation of the radiation field due to differences in density between outer space and the atmosphere; (2) scattering, which changes the direction of propagation of individual photons as they are absorbed and re-emitted by gases, aerosols, or other atmospheric constituents without changing wavelength; and (3) absorption, which converts photons into vibrations within a molecule, energy that is subsequently re-emitted in the form of one or more photons of longer wavelength.

7-1-1 Refraction

According to (Emery and Camps 2017) refraction is the bending of the direction of propagation of electromagnetic radiation as it travels between two media of different densities. This occurs when radiation arrives from space (density ≈ 0) and enters the atmosphere (density > 0).

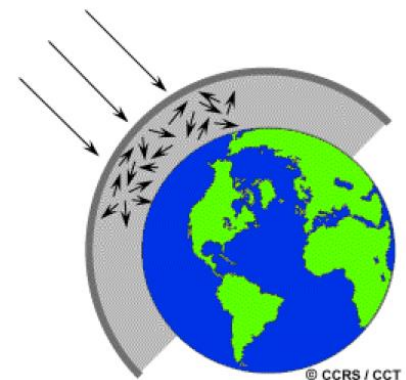
In remote sensing, atmospheric refraction can affect the geometric accuracy of images (Li 2021).



7-1-2 Scattering

Among the processes that influence electromagnetic radiation as it traverses the atmosphere is scattering (Knudby, 2021). Scattering occurs when a photon interacts with an object in the atmosphere, causing it to change direction. Depending on the size of the object with which the photon interacts, three types of scattering are distinguished:

(1) Rayleigh scattering occurs when the object is much smaller than the wavelength of the radiation. In the case of sunlight and the Earth's



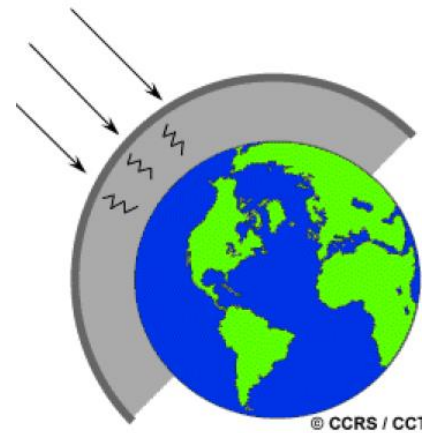
atmosphere, this means that Rayleigh scattering is caused by atmospheric gases such as N_2 , O_2 , CO_2 , etc.

(2) Mie scattering occurs when the size of the object is similar to the wavelength of the radiation, meaning it is caused by aerosols such as smoke and dust particles.

(3) Non-selective scattering occurs when particles (water droplets and large dust particles) are much larger than the wavelength of the radiation. We call this type of scattering "non-selective" because all wavelengths are scattered. (Centre Canadien de Télédétection 2015).

7-1-3 Absorption

According to Lillesand et al. (2015), atmospheric absorption results in an effective loss of energy for atmospheric constituents. This typically involves the absorption of energy at a given wavelength. The most efficient absorbers of solar radiation in this regard are water vapor, carbon dioxide, and ozone. As these gases tend to absorb electromagnetic energy in specific wavelength bands, they strongly influence the design of any remote sensing system. Wavelength ranges in which the atmosphere particularly well transmits energy are referred to as atmospheric windows.



For example, ozone absorbs ultraviolet rays, water vapor in the atmosphere absorbs much of the infrared radiation, carbon dioxide absorbs a lot of radiation in the thermal infrared portion, etc. (Canadian Center for Remote Sensing, 2015). The effects of water (H_2O), carbon dioxide (CO_2), oxygen (O_2), ozone (O_3), and nitrous oxide (N_2O) on the transmission of light through the atmosphere are summarized in Figure 1.5 (Jensen, 2014).

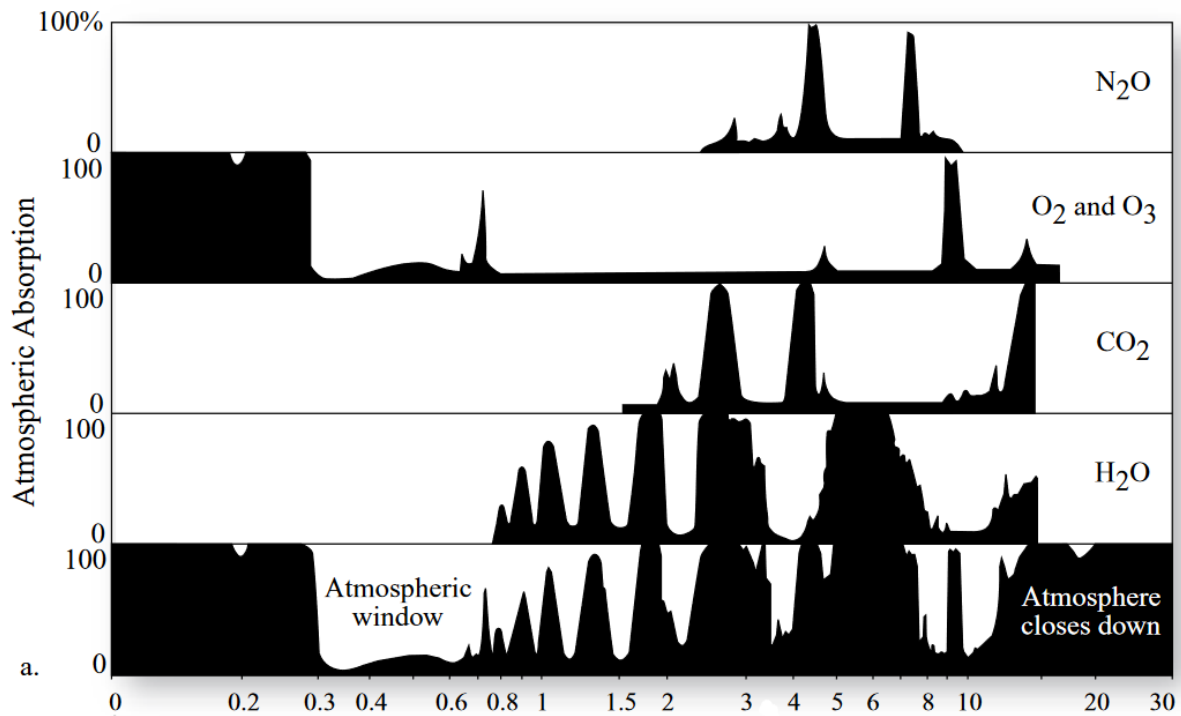


Figure 1.5. Absorption of incident solar radiation in the region of 0.1 to 30 μm

8- Interaction of electromagnetic radiation with the surface (spectral signature)

When electromagnetic radiation interacts with matter, the following interactions are possible (Canadian Center for Remote Sensing, 2015): it can be absorbed by the Earth's surface or it can be reflected back into space; specular and diffuse reflection (Figure 1.6). Remote sensing is primarily based on the detection and recording of reflected and emitted electromagnetic rays. Fundamentally, what makes remote sensing possible is that every object or material has particular emission and/or reflection properties, collectively known as its spectral signature or profile, which distinguish it from other objects and materials. In turn, remote sensing sensors are tailored to collect these "spectral" data.

For instance, water reflects a small amount of blue and green wavelengths (typically around 5 to 10% depending on turbidity), a lesser amount of red wavelengths, and almost nothing in the infrared wavelengths. Vegetation, on the other hand, reflects about half of all incoming infrared radiation, except for certain specific wavelengths that are effectively absorbed by liquid water in the leaves. These spectral signatures are usually depicted in graphs, with wavelengths on the x-axis and reflectance on the y-axis (Figure 6).

Spectral signatures are what allow us to differentiate between different materials on the Earth's surface when we look at a satellite image (Knudby, 2021). As shown in Figure 1.7, water has nearly zero reflectance at wavelengths greater than $0.7\ \mu\text{m}$, while both soil and green vegetation have reflectances of about 40% at $1.3\ \mu\text{m}$. Therefore, measuring the amount of radiation reflected by the Earth-Atmosphere system at $1.3\ \mu\text{m}$ will be particularly useful for distinguishing water from the two types of land surfaces. Similarly, measurements at wavelengths around $1.4\ \mu\text{m}$ (where liquid water in vegetation is a strong absorber) or $1.9\ \mu\text{m}$ (similarly) can be effective for distinguishing soil from green vegetation.

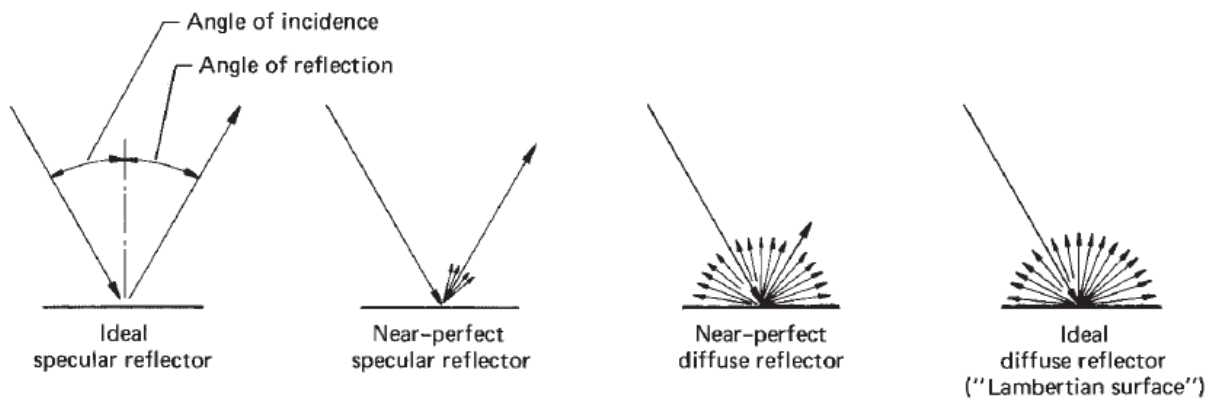


Figure 1.6. Specular or diffuse reflection (Lillesand et al. 2015)

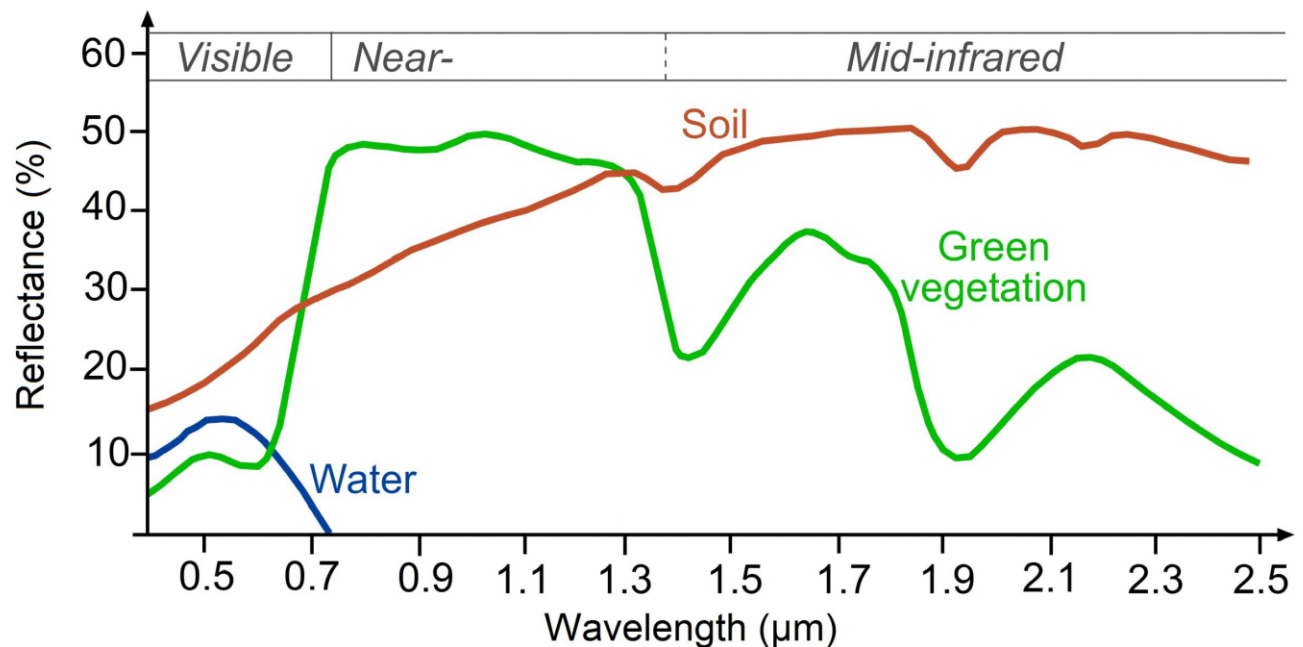


Figure 1.7. Spectral signatures of common types of earth surface materials (Knudby 2021)

8-1 Energy interaction in plants

While the reaction on smooth surfaces is straightforward, the interaction of energy in plants is more complex. A plant leaf consists of at least three layers (Figure 2.4): (1) Transparent epidermis, (2) Palisade mesophyll, which reflects green light and absorbs red light due to its chlorophyll content, and (3) Spongy mesophyll, which reflects near-infrared light (Konecny, 2014).

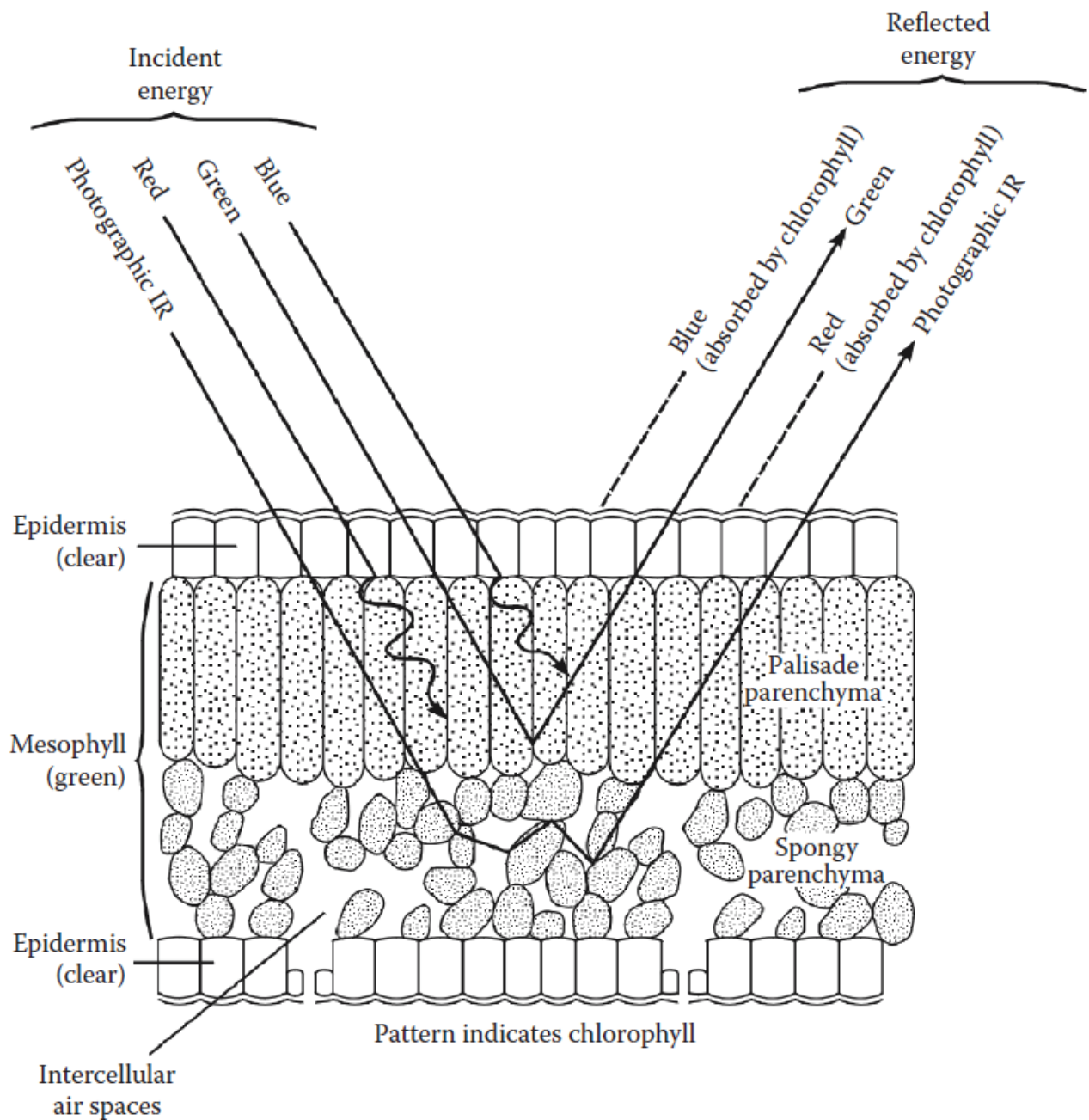


Figure 1.8. Energy interaction in plants (Konecny 2014)

9- Atmospheric window

The atmosphere has a significant influence on electromagnetic radiation (Emery and Camps, 2017). The Earth's atmosphere is by no means entirely transparent to electromagnetic radiation, as gases together form significant barriers to the transmission of electromagnetic radiation through the atmosphere (Campbell et al., 2023). According to Li (2021), solar radiation is reflected, absorbed, and scattered as it passes through the atmosphere, attenuating the intensity of the radiation. The band where atmospheric attenuation is lowest and transmittance is highest is called the atmospheric window. For a remote sensor, only the band with high transmittance can form a high-quality remote sensing image. The main atmospheric windows and currently used detection bands are presented in Figure 1.8:

- (1) 0.3-1.3 μm : This window includes a partial ultraviolet band (0.30-0.38 μm), the entire visible light band (0.40-0.76 μm), and a partial near-infrared band (0.76-1.3 μm), which is called the spectrum of reflection of terrestrial objects. The transmission factor of the window to electromagnetic wave is over 90%.
- (2) 1.5-1.8 μm and 2.0-3.5 μm : These two windows are near-infrared and short-wave infrared bands, still belonging to the spectrum of reflection of terrestrial objects, and their transmittances are close to 80%. Some bands of the near-infrared window have a good effect in distinguishing altered rocks, giving it great potential in geological remote sensing applications.
- (3) 3.5-5.5 μm : This window is called the mid-infrared band. The spectrum passing through this window can be either a ground object reflection spectrum or a ground object emission spectrum, which belongs to the range of mixed spectra.
- (4) 8-14 μm : This window is called the far-infrared (thermal) band and is classified in the spectrum of thermal radiation. Due to the influence of ozone, water vapor, and carbon dioxide, the transmittance in this band window is only 60 to 70%. As this band is most concentrated in thermal radiation energy at normal temperature, it is very useful for remote sensing.
- (5) 0.8-25 cm: This window is called the microwave window and belongs to the emission spectrum range. It is entirely transparent without interference from the atmosphere, and its transmission can reach 100%. It belongs to the all-weather remote sensing band.

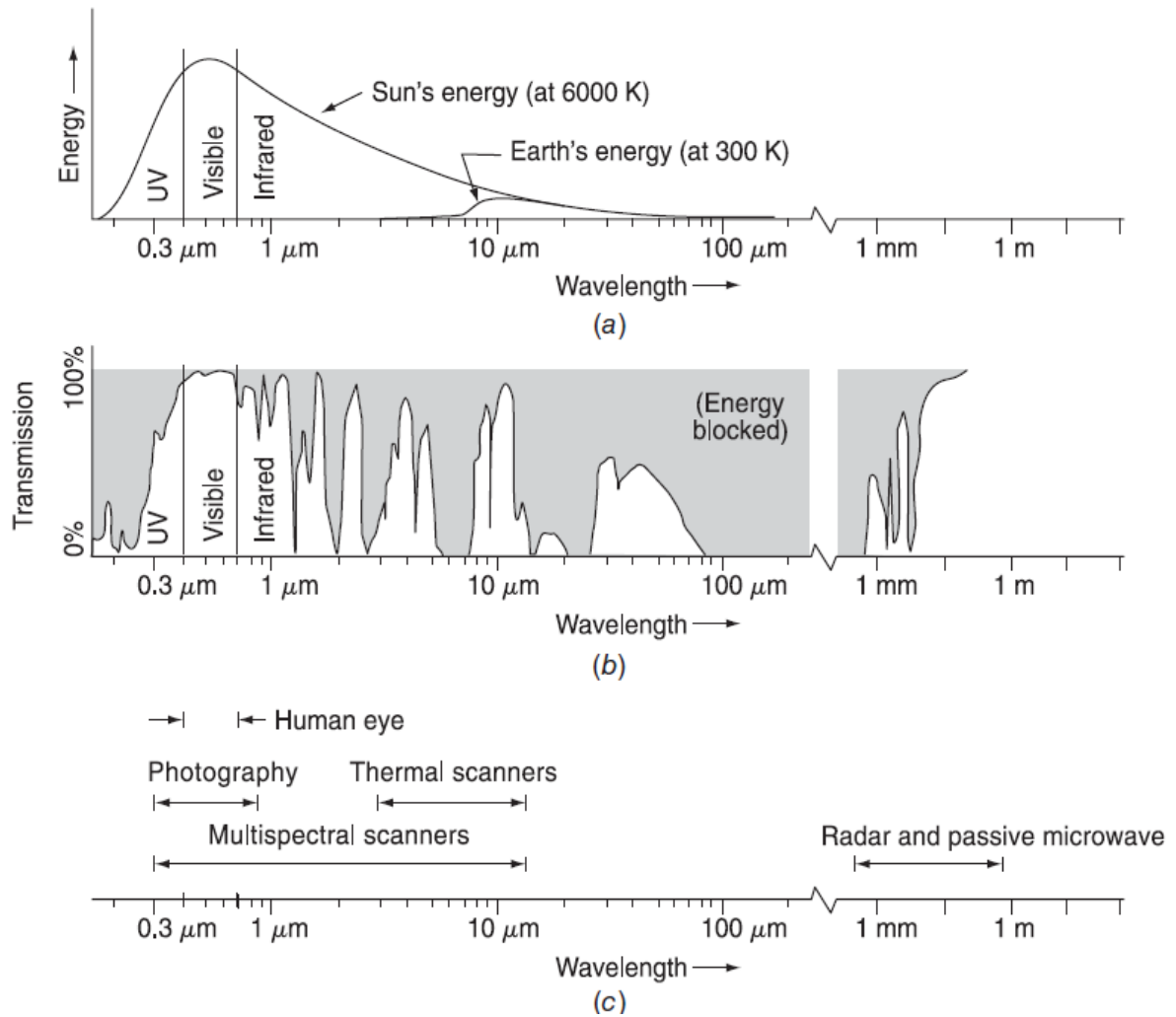


Figure 1.9. Main atmospheric windows and detection bands (Lillesand et al. 2015)

Chapitre 2.

Satellites and satellite images

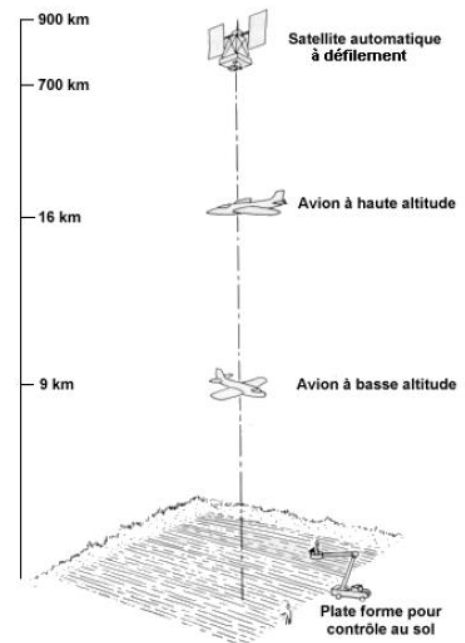
1- Introduction

This chapter provides an overview of the main remote sensing platforms, focusing on satellite characteristics. We explore their power source, whether passive or active, and their orbit, whether geostationary or sun-synchronous. By highlighting these key aspects, we will better understand the operation and use of satellites in data collection for remote sensing purposes. Finally, this chapter will conclude with a presentation of some of the most renowned satellites.

2- Remote sensing platforms

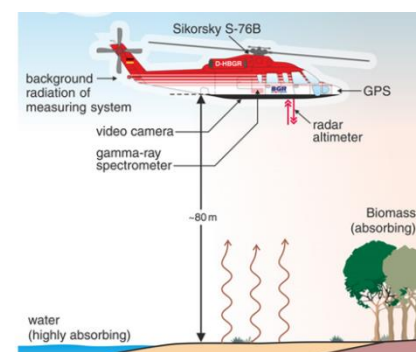
2-1 Platforms (vectors)

Remote sensing platforms refer to various vehicles carrying sensor systems that collect electromagnetic radiation used to form images of the Earth's surface. Depending on the distance from the ground, platforms include vehicles such as airplanes, helicopters, unmanned aerial systems (UAS), and satellites that enable control over altitude, orientation, trajectory, and synchronization necessary for acquiring useful images. These platforms vary significantly in terms of size, scope, maneuverability, cost, and altitude, and each has its advantages and disadvantages. (Campbell et al. 2023) ; (Liang and Wang 2020).



2-1-1 Helicopters

Helicopters offer specific capabilities to support remote sensing activities, including a unique ability to hover, fly laterally, and operate in confined environments, and they have the maneuverability needed to navigate complex flight plans. Helicopters can accommodate a wide range of remote sensing instruments. Larger models can be piloted with open cargo doors to provide unobstructed visibility on the sides, and they can also accommodate bulky equipment and instruments inside the cabin. They are well-suited for a variety of remote sensing missions due to their versatility and



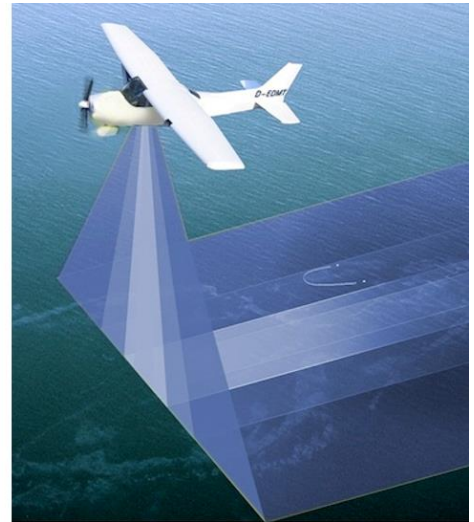
maneuverability, their ability to operate in restricted conditions such as wooded areas, rugged terrain, or other environments unsuitable for fixed-wing aircraft.

Helicopters are often used when maneuverability is crucial or low flight speeds are advantageous. They are, for example, utilized in rugged terrain for mapping and monitoring wildlife and environmental disasters, or in airspace where fixed-wing flight operations are impractical.

2-1-2 Fixed-wing aircraft

Fixed-wing aircraft possess numerous distinctive capabilities for remote sensing, including long endurance, precise navigation, the ability to accommodate various sensor systems, and the capacity to carry heavy payloads to support a variety of alternative remote sensing missions.

Remote sensing companies will carefully select aircraft models that meet the specific operational requirements of their business models regarding sensors, endurance, payload, and fuel economy. While some aircraft have been designed specifically for aerial surveying and observation, current systems are primarily based on specialized models of versatile aircraft adapted for aerial survey missions. The basic operating system of an optical sensor mounted on a fixed-wing aircraft is depicted in Figure 2.1.



2-1-3 Satellites

Satellites (artificial satellites of the Earth) are objects that orbit around another object, in this case, the Earth (Canadian Centre for Remote Sensing, 2015). These satellite platforms offer unique capabilities, including the ability to provide a synoptic perspective (observation of large areas in a single image), fine details, and systematic and repetitive coverage of the Earth's surface. These capabilities are well suited for maintaining an up-to-date global mapping infrastructure and monitoring changes in the many large-scale environmental issues facing the world today.



Satellite systems bring significant capabilities to the overall remote sensing mission by performing the following operations (Campbell et al., 2023): (1) Systematic collection according to established and repetitive schedules, (2) Using consistent data formats, (3) Providing global coverage capacity based on specificities, (4) Archiving data to provide resources for change detection, (5) Offering revisiting capability (the ability to observe the same region repetitively), (6) Providing a large customer base for remote sensing, and (7) Allowing regular acquisition of images of remote, hazardous, or inaccessible sites.

Satellite remote sensing systems also have limitations, including: (1) Substantial costs for development, manufacturing, and operation, (2) Long lead times for system development, (3) Challenges in recovery in case of system or equipment failure, and (4) Difficulty in responding to unexpected or rapidly evolving events for which images may be desired due to systematic coverage cycles.

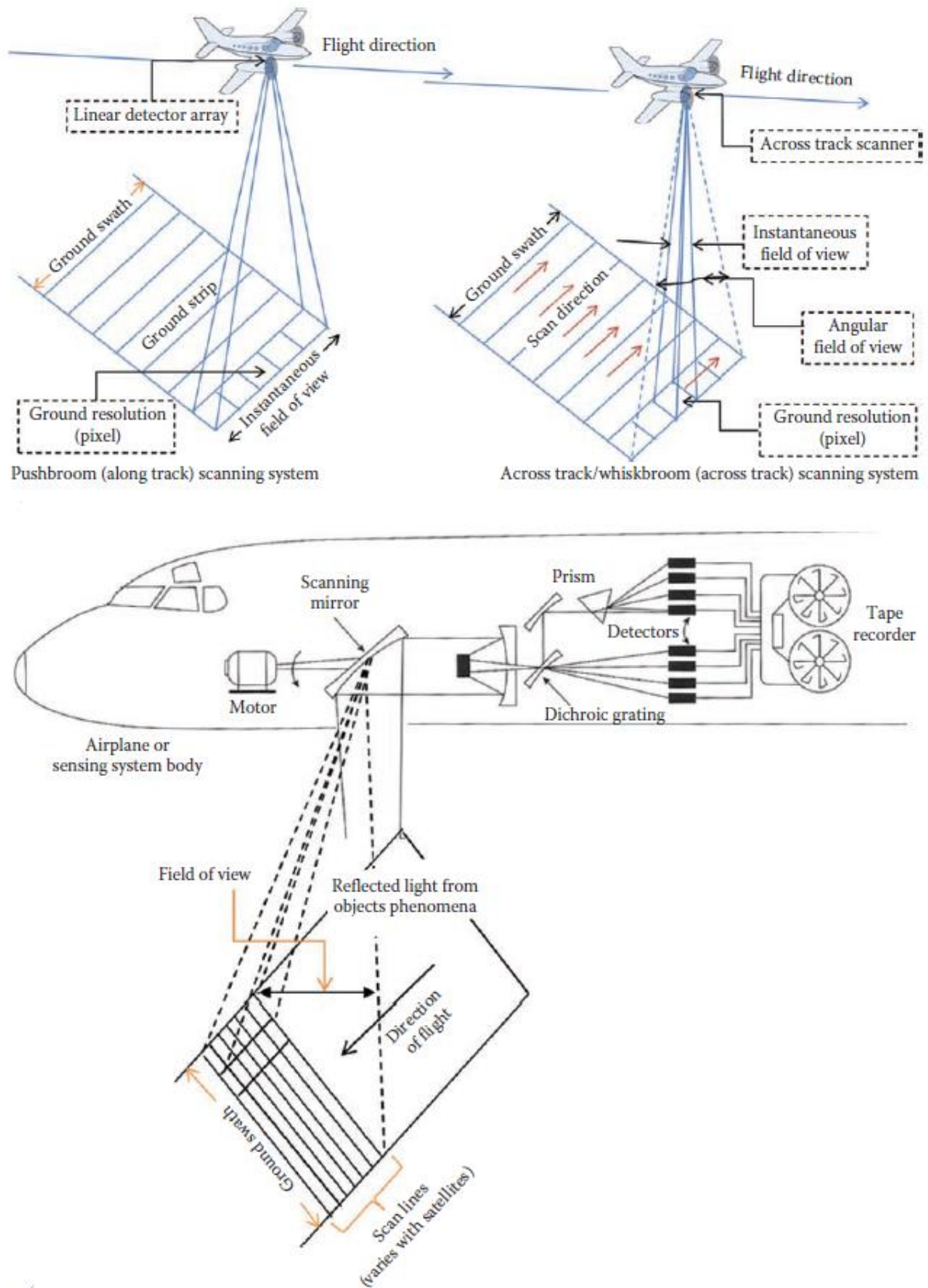
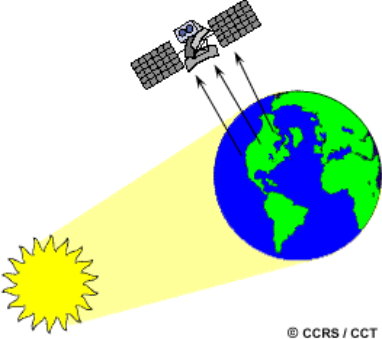
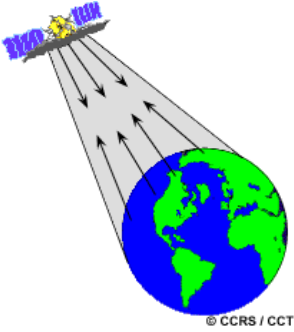


Figure 2.1. Basic operating system of an optical sensor mounted on a fixed-wing aircraft (Thenkabail 2016)

2-2 Passive or active remote sensing

The main difference between passive and active remote sensing lies in the way electromagnetic energy is emitted and received by the sensor. Table 2.1 shows some key distinctions (Richards 2013) ; (Campbell et al. 2023) ; (Centre Canadien de Télédétection 2015):

Table 2.1. Difference between passive and active detection

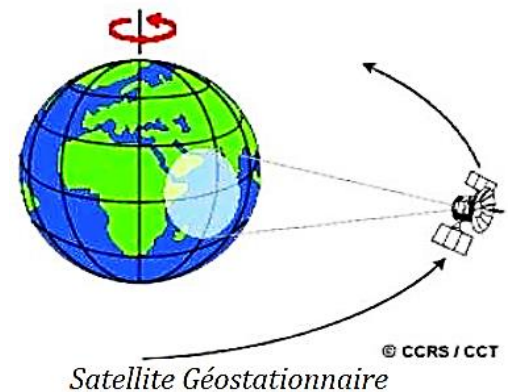
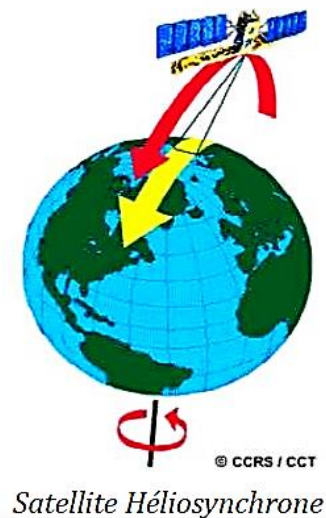
	Passive detection	Active detection
		
Energy emission	Passive sensors record the electromagnetic energy naturally emitted by the earth's surface. They measure reflected sunlight or thermal emission from the surface.	Active sensors actively transmit a signal, usually an electromagnetic wave, to the earth's surface. They then measure the signal reflected by the surface.
Energy source	The energy source comes from the sun or other natural sources. Collectors capture energy already present in the environment.	The energy source is integrated into the sensor itself. It emits an active signal to the earth's surface.
Use of daylight	Mainly used during the day when sunlight is available.	Can be used day and night, as it is not dependent on sunlight.
Atmospheric conditions	Sensitive to atmospheric conditions such as clouds, fog, etc.	Less sensitive to atmospheric conditions, as the energy source is emitted directly from the collector.
Typical applications	Optical imaging, vegetation detection, atmospheric observation.	Topographic mapping, ground deformation detection, environmental change monitoring.

The most widely used active remote sensing systems are the following (John R. Jensen 2014): (1) active microwave (RADAR), which is based on the transmission of long-wavelength microwaves (e.g., 3 to 25 cm) through the atmosphere, and then recording the amount of energy backscattered by the terrain. (2) LIDAR, which is based on the transmission of laser light of relatively short wavelength (e.g. 1040 nm) and the recording of the amount of light backscattered by the terrain. (3) SONAR, which is based on the transmission of sound waves through a water column and the recording of the amount of energy backscattered by the bottom or by objects located in the water column.

2-3 Geostationary and sun-synchronous satellites

Remote sensing imaging can be conducted from both satellite and aerial platforms. In many respects, their sensors exhibit similar characteristics, but differences in altitude and stability can lead to different image properties. According to Richards (2013), there are two main categories of satellite programs (Table 3):

(1) Geostationary orbit satellites (geostationary satellites) above the Earth's surface, typically associated with meteorological and climatological studies. According to Liang and Wang (2020), a geostationary satellite is in an orbit that can only be achieved at an altitude very close to 35,786 km and keeps the satellite fixed above a longitude of the equator. For ground observers, the satellite appears stationary at a fixed position in the sky. There are several hundred communication satellites and several weather satellites in this type of orbit.



(2) Heliosynchronous orbit satellites (heliosynchronous satellites) much closer to Earth, usually used for observations of the Earth's surface and oceanographic observations. In the case of heliosynchronous satellites, the orbital plane is designed to precede the Earth at the same speed as the sun appears to move across the Earth's surface. This way, the satellite acquires data at approximately the same local time on each orbit. Low Earth orbit satellites can also be used for meteorological studies. Despite differences in altitude, the wavelength bands used by geostationary satellites and low Earth orbit satellites for weather and Earth observation are very comparable. The main difference in the image data they provide generally

lies in the available spatial resolution. While data acquired for terrestrial resources have a pixel size of around 10 meters, those used for meteorological purposes (both at geostationary and lower altitudes) have a much larger pixel size, often around 1 kilometer.

According to Boiffin and Chartier (2019), geostationary satellites continuously observe the same area, unlike observation satellites, which may take 1 day to 1 month to revisit the target.

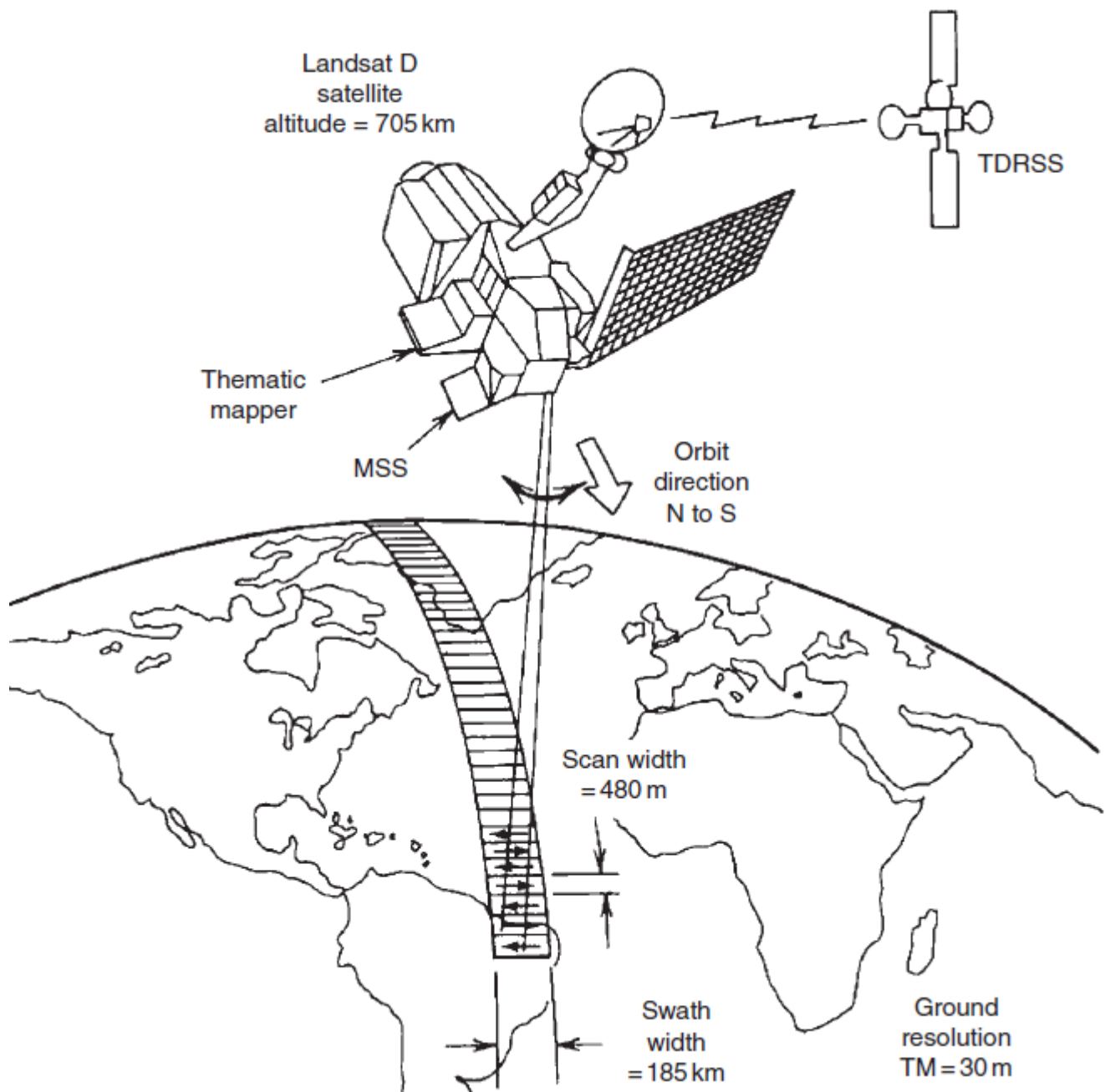


Figure 2.2. Example of a sun-synchronous satellite (Landsat)

Table 2.2. Example of geostationary and sun-synchronous satellites (Liang and Wang 2020) ; (Jaiswal and Bhatawdekar 2018)

Geostationary	sun-synchronous
<p>GOES (Geostationary Operational Environmental Satellites) : Operated by the U.S. National Oceanic and Atmospheric Administration (NOAA), these satellites provide continuous monitoring of weather conditions on the American continent.</p>	<p>Série Landsat : The Landsat program, managed by NASA and the US Geological Survey (USGS), consists of a series of Earth observation satellites in sun-synchronous orbit. They capture high-resolution images of the Earth's surface for applications such as land-use monitoring, agriculture and environmental assessments.</p>
<p>Himawari : Operated by the Japan Meteorological Agency, the Himawari satellites provide high-resolution images of the Asia-Pacific region for weather forecasting and meteorological research.</p>	<p>Sentinel-2 : part of the European Union's Copernicus program, Sentinel-2 satellites also operate in sun-synchronous orbit. They provide multispectral images of the Earth's land and coastal areas, contributing to applications such as agricultural monitoring, disaster management and land-use mapping.</p>
<p>Meteosat : Operated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), Meteosat satellites provide weather surveillance for Europe, Africa and parts of the Atlantic and Indian Oceans.</p>	<p>Terra : Terra is a NASA satellite launched in 1999 as part of the Earth Observation System (EOS). It operates in a sun-synchronous orbit and carries several instruments designed to monitor various aspects of the Earth's atmosphere, land and oceans, including measurements of aerosols, land surface temperature and vegetation.</p>
<p>INSAT (Indian National Satellite System) : Operated by the Indian Space Research Organization (ISRO), INSAT series satellites provide weather monitoring, telecommunications and broadcasting services on the Indian subcontinent.</p>	<p>Aqua : Also part of NASA's Earth Observation System, Aqua was launched in 2002 and orbits the Earth in a sun-synchronous orbit. It focuses on observing the Earth's water cycle, measuring precipitation, water vapor, clouds, sea ice and ocean surface temperature.</p>
<p>Fengyun : Operated by the Chinese Meteorological Administration, the Fengyun series of satellites provide weather monitoring and climate research for China and neighboring regions.</p>	<p>SPOT, ALOS, IKONOS, QuickBird, etc.</p>

2-4 Types of imaging systems

According to the manner in which the sensor acquires and records the incoming signal, imaging systems can be divided into three general categories (Elachi and Van Zyl, 2021): framing cameras, scanning systems, and pushbroom imagers.

A framing camera (Figure 2.3.a) captures a snapshot of an area on the surface, which is then projected by the camera's optics onto a film or two-dimensional array of detectors located in the camera's focal plane. Framing cameras are becoming increasingly common as detector arrays with more pixels become available. Framing cameras have the major advantage of offering excellent geometric fidelity since the entire image is acquired at once.

Scanning systems (Figure 2.3.b) use a scanning mirror that projects the image of a surface resolution element onto a single detector. To obtain an image, a cross-track scan is used to cover the imaged swath across the track. In some cases, a limited number of detectors are used so that each scan covers a set of cross-track lines instead of just one. In this case, the imaging system is known as a "whiskbroom" scanner. The platform's motion causes the imaged swath to move along the track. Images acquired with scanning systems generally have lower geometric fidelity than those acquired with framing cameras. Landsat instruments, such as MSS and TM, and ETM+, are examples of scanning systems.

Pushbroom imagers (Figure 2.3.c) eliminate the scanning mechanism and use a linear array of detectors to cover all the pixels in the cross-track dimension simultaneously. The dwell time of the detector on each surface pixel is thus much longer, resulting in much higher sensitivity and narrower spectral bandwidth. Cameras like SPOT and ASTER are examples of these systems. A pushbroom system can be considered as a framing camera whose image frame is long in the cross-track direction and much narrower in the along-track direction. Pushbroom sensors do not require a moving scanning mirror to acquire an image.

2-4-1 Difference between satellite and sensor

In remote sensing, a sensor and a satellite are two different but often interconnected elements in the data collection and transmission process. The sensor is the instrument that detects and measures various characteristics of the earth's surface or other objects at a distance. A satellite, on the other hand, is an object orbiting the earth equipped with sensors that can be used to collect information about the earth. In general, a sensor is the instrument that performs the measurement of the earth's characteristics, while a

satellite is the spacecraft that often carries these sensors and places them in orbit to enable remote data collection.

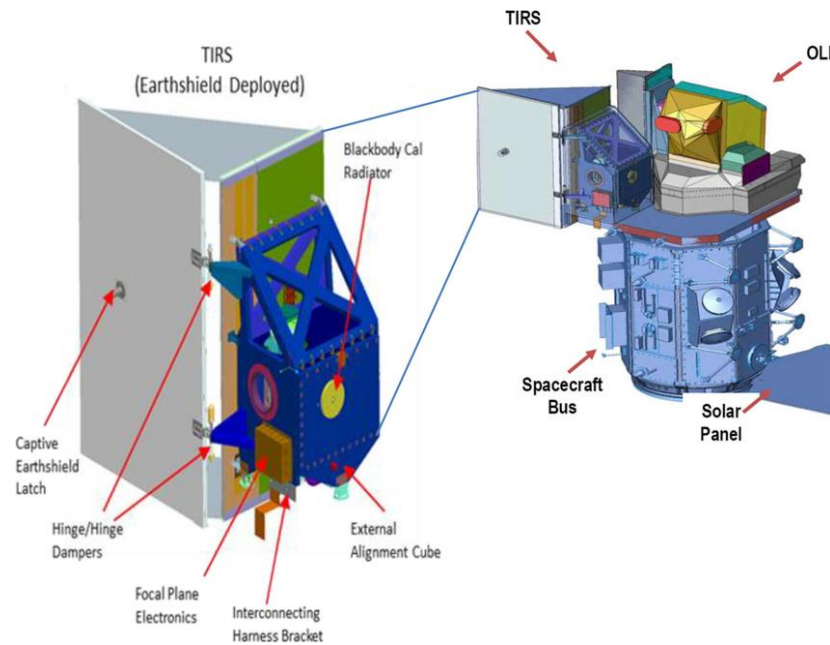


Figure 2.3. Difference between satellite and sensor (Landsat 8 satellite example)

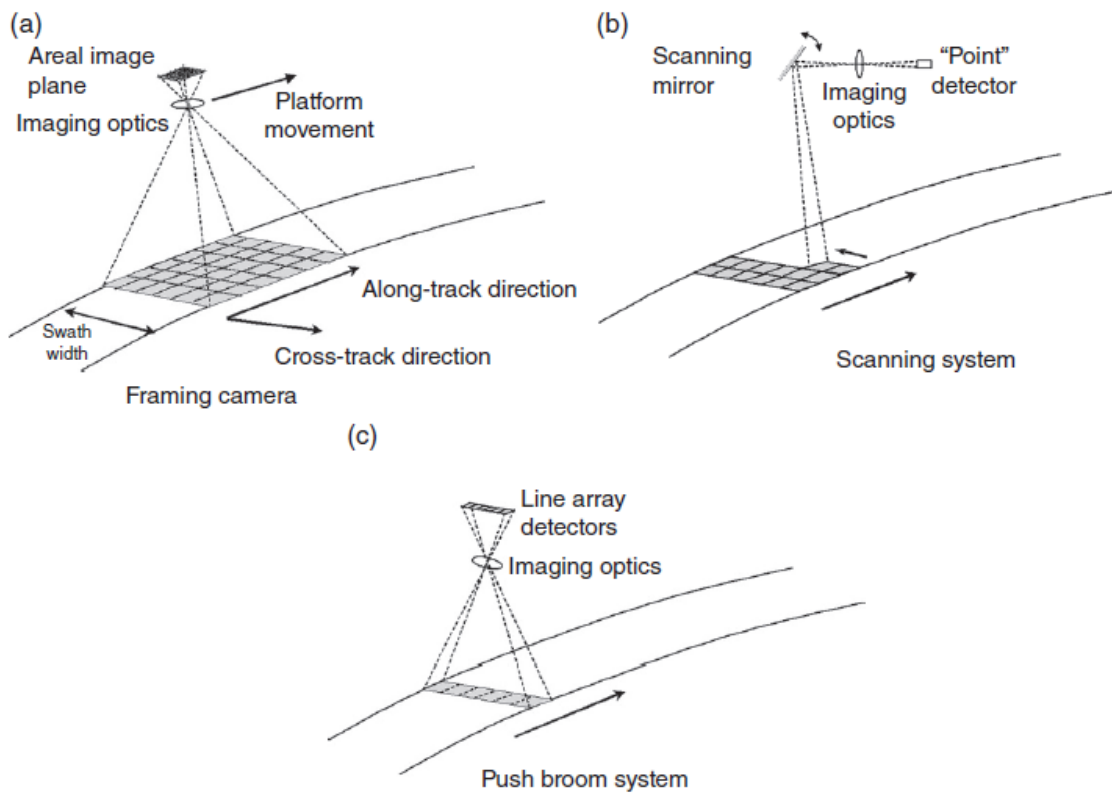


Figure 2.4. Different types of image sensor (Elachi and Van Zyl 2021)

3- Remote sensing satellites

(Tempfli et al. 2009) gave a summary of some of the recognized satellites:

3-1 SPOT

The SPOT (Système Pour l'Observation de la Terre) satellites belong to a consortium consisting of the French, Swedish, and Belgian governments. SPOT-1 was launched in 1986, marking the first operational linear CCD camera with cross-track viewing capability to be sent into space. At the time, its panchromatic spatial resolution of 10 meters was unprecedented in the field of civilian remote sensing. In March 1998, a significantly improved version of SPOT-4 was launched. Its HRVIR sensor features 4 bands instead of 3, and the VEGETATION instrument was added.



VEGETATION was designed for frequent (1 to 2 days) and precise monitoring of the Earth's land masses at a resolution of 1 kilometer.

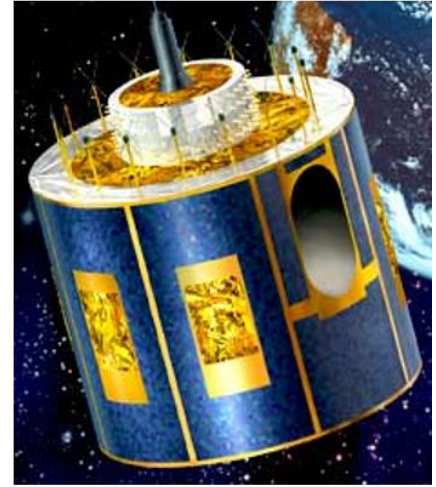
SPOT-5 was launched in May 2002. It differs from previous SPOT satellites by offering improved imaging resolution from its high-resolution visible and near-infrared sensors, as both twin instruments acquire multispectral images with a resolution of 10 meters.

Table 2.3. Characteristics of the SPOT-5 satellite

System	SPOT-5
Orbit	822 km, 98.7° inclination, sun-synchronous, 10:30 AM crossing, 26-day repeat cycle
Sensor	2× HRG (High Resolution Geometric) and HRS (High Resolution Stereoscopic)
Swath width	60 km
Off-nadir viewing	± 31° across-track
Revisit time	2–3 days (depending on latitude)
Spectral bands (μm)	0.50–0.59 (Green), 0.61–0.68 (Red), 0.78–0.89 (NIR), 1.58–1.75 (SWIR), 0.48–0.70 (PAN)
Spatial resolution	10 m, 5 m (PAN)

3-2 Meteosat-8

The first Meteosat satellite was placed in orbit in 1977. Meteosat satellites belong to the European organization Eumetsat. Meteosat-8, launched in August 2002, also known as MSG-1, is the first of the second-generation Meteosat satellites (MSG) and, compared to the first generation, it offers significant improvements in terms of spatial, spectral, radiometric, and temporal resolution.



In 2008, Meteosat-8 and Meteosat-9 satellites are in operation. The spectral bands of the SEVIRI sensor (Table 2.4) are chosen to observe phenomena relevant to meteorologists: a panchromatic band (PAN), bands in the mid-infrared, which provide information on water vapor in the atmosphere, and thermal bands (TIR). In the case of clouds, thermal data relate to the temperature at the top of the clouds, which is used for precipitation estimation and forecasting. In the presence of clouds, thermal data relate to the surface temperature of the land and sea and are used to detect thermal anomalies, such as forest fires or volcanic activity.

Table 2.4. Characteristics of the Meteosat-8 satellite

System	Meteosat-8
Orbit	Geo-stationary, 0° longitude
Sensor	SEVIRI (Spinning Enhanced VIS and IR Imager)
Swath width	Full Earth disc (FOV = 18°)
Off-nadir viewing	Not applicable
Revisit time	15 minutes
Spectral bands (μm)	0.5–0.9 (PAN), 0.6, 0.8 (VIS), 1.6 (NIR), 3.9, 6.2, 7.3, 8.7, 9.7 10.8, 12.0, 13.4 (TIR)
Spatial resolution	1 km (PAN), 3 km (all other bands)

3-3 Terra

The Earth Observing System (EOS) is the centerpiece of NASA's Earth science mission. The EOS AM-1 satellite, renamed Terra, is the flagship of the fleet and was launched in December 1999. It carries five remote sensing instruments, including the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The ASTER instrument (Table 2.5) is designed with three bands in the visible and near-infrared spectral range with a resolution of 15 m, six bands in the shortwave infrared with a resolution of 30 m, and five bands in the thermal infrared with a spatial resolution of 90 m. In addition to the Terra mission, NASA has developed two other significant satellites, Aqua and Aura. While Terra is primarily focused on land applications, Aqua focuses on water, and Aura focuses on trace gases in the atmosphere (particularly ozone). Aqua was launched in May 2002, and Aura was successfully placed into orbit in July 2004. Together, the satellites form a robust combination for Earth observation, complementing each other with their data. The satellites constitute the backbone of what NASA calls its "Earth Science Enterprise" (ESE).

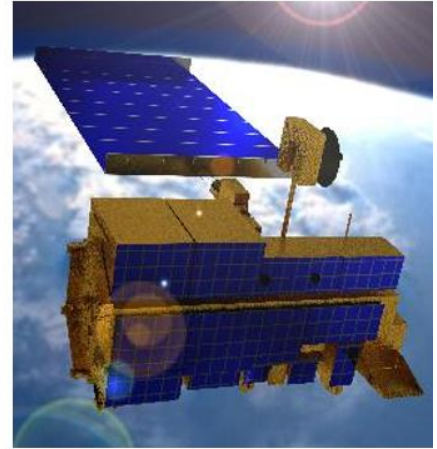


Table 2.5. Characteristics of the Terra ASTER satellite

System	Terra ASTER
Orbit	705 km, 98.2° inclination, sun-synchronous, 10:30 AM crossing, 16-day repeat cycle
Sensor	ASTER
Swath width	60 km
Off-nadir viewing	across-track $\pm 8.5^\circ$ SWIR and TIR $\pm 24^\circ$ VNIR along-track 27.7° backwards band 3B
Revisit time	5 days (VNIR)
Spectral bands (μm)	NIR 0.81 (3N nadir and 3B backward 27.7°), SWIR (4–9) 1.65, 2.17, 2.21, 2.26, 2.33, 2.40 TIR (bands 10–14) 8.3, 8.65, 9.10, 10.6, 11.3
Spatial resolution	15 m (VNIR), 30 m (SWIR), 90 m (TIR)

3-4 Landsat-9

The Landsat program is the oldest civilian Earth observation program. It began in 1972 with Landsat-1, which carried the Multispectral Scanner (MSS) sensor. In 1982, the MSS sensor was replaced by the Thematic Mapper (TM) sensor. Both MSS and TM are scanners. In April 1999, Landsat-7 was launched with the Enhanced Thematic Mapper Plus (ETM+) scanner. Today, only Landsat-8 and Landsat-9, launched respectively in February 2013 and September 2021, are operational.



Landsat-9 (Table 2.6) captures images in 11 different bands, including two thermal bands (Table 2.7). TIRS-2 is limited to a spatial resolution of 100 m. OLI-2 captures images in all bands with a spatial resolution of 30 m, except for the panchromatic band, which captures images with a spatial resolution of 15 m at nadir.

Table 2.6. Characteristics of the Landsat 9 satellite

System	Landsat 9
Orbit	705 km, 98.2 inclination, sun-synchronous, 10:00 AM crossing, 16-day repeat cycle
Sensor	OLI-2 ; TIRS-2
Swath width	185 km
Off-nadir viewing	No
Revisit time	16 days

Table 2.7. Spectral bands of the Landsat 9 satellite

Band Number	Description	Wavelength (μm)	Spatial resolution	Radiometric resolution (bits)
Band 1	Coastal/ Aerosol	0.43 – 0.45	30	12
Band 2	Visible blue	0.45 – 0.51	30	12
Band 3	Visible green	0.53 – 0.59	30	12
Band 4	Visible red	0.63 – 0.67	30	12
Band 5	Near infrared	0.85 – 0.87	30	12
Band 6	Short infrared	1.56 – 1.65	30	12
Band 7	Short infrared	2.10 – 2.29	30	12
Band 8	Panchromatic	0.50 – 0.67	15	12
Band 9	Cirrus	1.36 – 1.38	30	12
Band 10	Thermal infrared	10.60 – 11.19	100	12
Band 11	Thermal infrared	11.50 – 12.51	100	12

3-5 Ikonos

Ikonos was the first commercial "high-resolution satellite" to be launched into orbit. Ikonos is owned by GeoEye (a merger of Space Imaging and OrbImage), a United States-based Earth observation company. Other high-resolution commercial satellites include GeoEye-1 (OrbView-5, launched in 2008; the standard deviation of the panchromatic mode is 0.4 m), QuickBird (launched in 2001, owned by DigitalGlobe; the standard deviation of the panchromatic mode is 0.6 m), and EROS-A1 (launched in 2000). Ikonos was launched in September 1999, and regular data orders have been placed since March 2000.



The OSA sensor onboard Ikonos (Table 2.8) is based on the principle of the comb detector and can simultaneously capture panchromatic and multispectral images. In addition to the high spatial resolution of 1 m in panchromatic and 4 m in multispectral, it also has high radiometric resolution due to 11-bit quantization.

Table 2.8. Features of the IKONOS satellite

System	Ikonos
Orbit	681 km, 98.2° inclination, sun-synchronous, 10:30 AM crossing, 14-day repeat cycle
Sensor	Optical Sensor Assembly (OSA)
Swath width	11 km
Off-nadir viewing	$\pm 50^\circ$ omnidirectional
Revisit time	1–3 days
Spectral bands (μm)	0.45–0.52 (1), 0.52–0.60 (2), 0.63–0.69 (3), 0.76–0.90 (4), 0.45–0.90 (PAN)
Spatial resolution	1 m (PAN), 4 m (bands 1–4)

Chapitre 3.

Satellite data characteristics

1- Introduction

This chapter explores in depth the essential characteristics of satellite images. To begin with, we will define what an image is and examine its elementary component, the pixel, which represents the smallest unit of information in a digital image. Next, we'll highlight the different resolutions available in satellite images, including spatial, spectral and temporal resolution, highlighting their importance in various applications such as mapping, environmental monitoring and precision agriculture. Finally, we'll cover an overview of the different types of satellite images available, including multispectral images, which capture information across multiple spectral bands, hyper-spectral images, which offer finer spectral resolution, and the notion of color composition, which makes it possible to create more easily interpretable images by assigning colors to different spectral bands.

2- Images satellites

Satellite imagery can be seen as an extension of aerial photography, as satellite remote sensing relies on the same physical principles to acquire, interpret, and extract information content. Satellite images are taken at a higher altitude, allowing for coverage of a larger area of the Earth's surface at once, and importantly, satellite images are acquired by electronic scanners. Satellite sensors can generally detect and record a much wider range of electromagnetic radiation, from ultraviolet to microwave. Electromagnetic energy is electronically recorded as a table of numbers in digital format, resulting in digital images. In a digital image, individual elements of the image are called pixels. These are the smallest unit of information in a digital image and are easily visible in the image when magnified (Chuvieco 2016). Each pixel has an intensity value and a location address (positioning in the spatial dimension of reality) in the 2D array, representing the electromagnetic energy received at the precise location on the Earth's surface (Weng 2012).

Figure 3.1 illustrates pixels and how they compose digital images. The intensity value can have different ranges, depending on a sensor's sensitivity to changes in the magnitude of electromagnetic energy. In most cases, a zero value indicates no radiation is received at a given location, and the maximum recordable number of the sensor indicates the maximum level of detectable radiation. For example, if a satellite sensor sets the maximum level of detectable radiation to 255, it will have a range of 256 possible intensity levels in numeric digits. Thus, when a computer displays a digital image acquired by this sensor, 256 different brightness levels (i.e., from 0 to 255) can be utilized (Weng 2012).

Most often, satellite sensors are designed to record electromagnetic energy across multiple channels simultaneously. Each channel records a narrow range of wavelengths, sometimes referred to as a band. The digital image of each channel can be displayed in black and white on the computer, or we can combine and display three channels/bands of a digital image as a color image using the computer's three primary colors (blue, green, and red). In this case, the digital data of each channel is represented by one of the primary colors based on the relative brightness of each pixel in that channel.

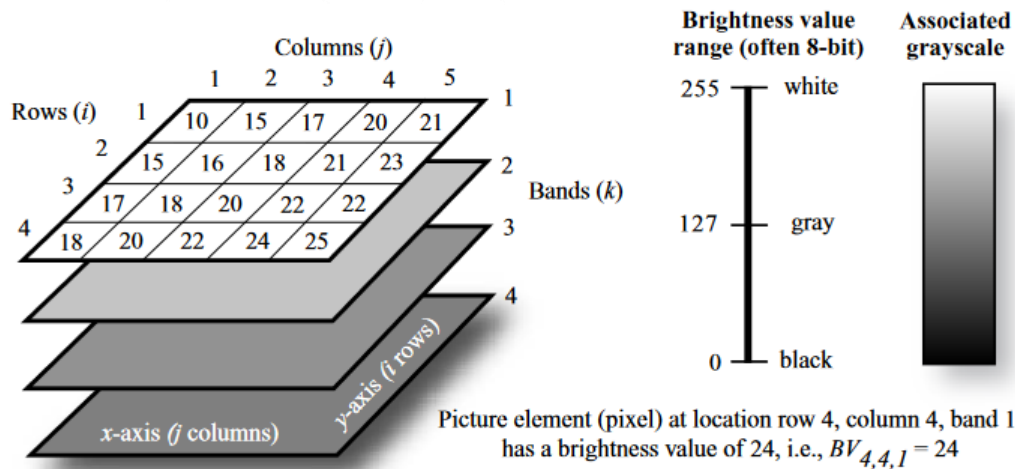


Figure 3.1. Principle of satellite imagery (Jensen 2014)

3- Satellite image characteristics

Various sensors continuously scan the Earth's surface to produce images. Each image is a matrix of pixels or image elements defined by columns and rows. The image data produced by different sensors of satellite systems exhibit unique characteristics related to sensor resolutions (spatial, spectral, radiometric, and temporal), swath width, types (multispectral, hyperspectral, etc.), and recording and exchange formats.

3-1 Resolutions

3-1-1 Spatial resolution

The spatial resolution (Figure 3.2) is a measure of the smallest object that can be resolved by the sensor, or the ground area imaged for the sensor's instantaneous field of view, or the linear dimension on the ground represented by each pixel (Liang and Wang, 2020). According to Aronoff (2005), spatial resolution is a measure of the detail fineness of an image. For digital images, it is the area captured by a

single pixel. Moreover, the simplest definition of spatial resolution is: the ability to distinguish two very close objects in an image (Sabins and Ellis, 2020).

According to Thenkabail (2016), the spatial resolution of the image mainly depends on the sensor's aperture and the platform altitude. The platform altitude is constrained by the sensor's platform class, i.e., whether it is spaceborne or airborne. The size of the sensor's aperture, especially for spaceborne systems, determines the cost of the remote sensing system; often, to reduce costs, the aperture size is larger, resulting in images with low spatial resolution.

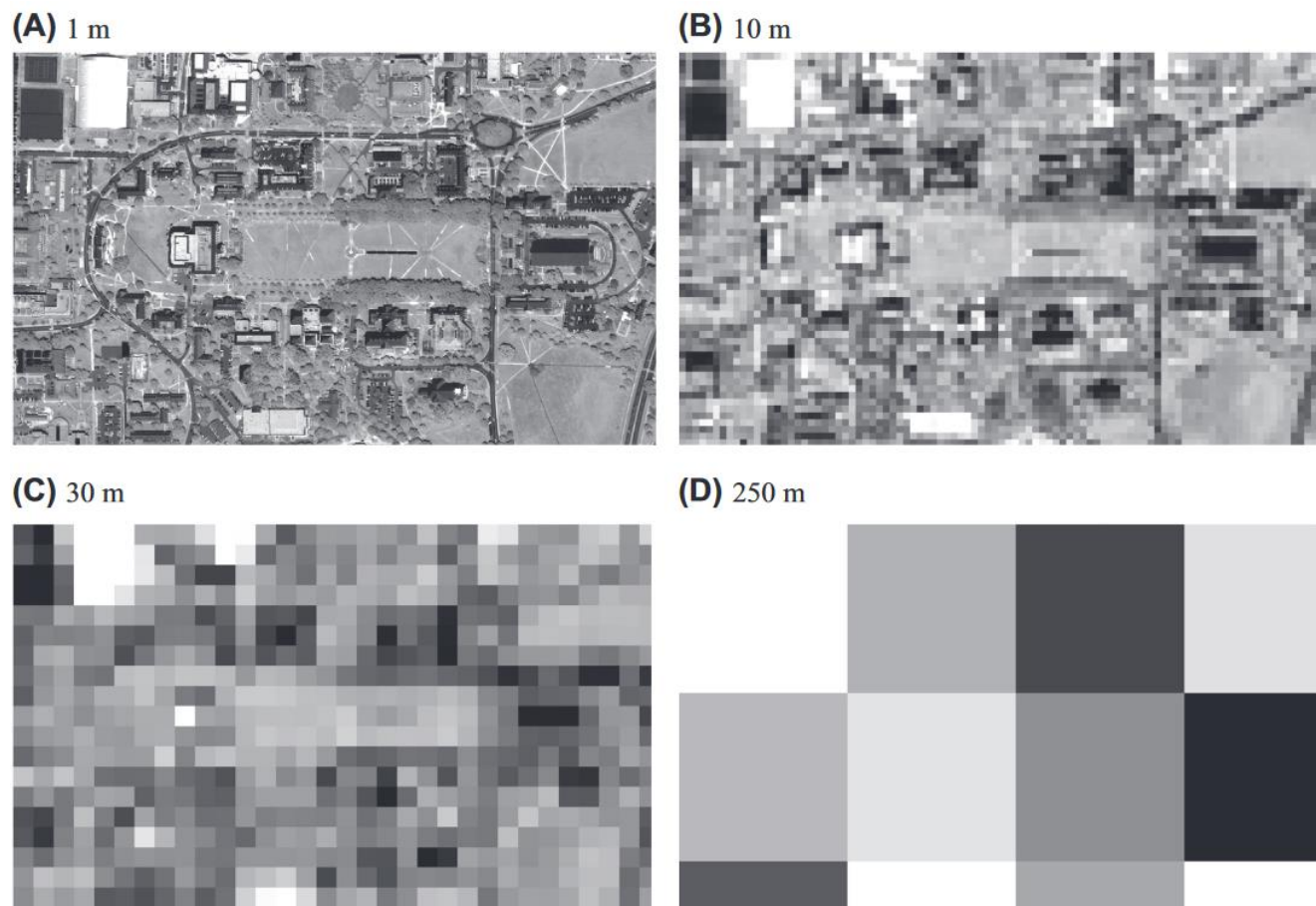


Figure 3.2. Example of four types of spatial resolution (Liang and Wang 2020)

3-1-2 Spectral resolution

Satellite sensors measure electromagnetic radiation across different parts of the electromagnetic spectrum. Spectral resolution (Figure 3.3) refers to the sensor's ability to resolve spectral features and bands into their distinct components in the electromagnetic radiation. It also describes the sensor's ability

to distinguish wavelength intervals in the EMS. Thus, in general, spectral resolution determines the number of bands a satellite sensor can detect (Thenkabail, 2016).

For example, the American Landsat sensor has higher spectral resolution than the French SPOT sensor. The MODIS sensor has high spectral resolution as it detects 36 wavelength regions of the EMS, whereas Landsat TM only detects 7 EMS regions. Hyperspectral systems typically feature hundreds of narrow spectral bands; for instance, Hyperion on the EO-1 satellite has 220 bands at a spatial resolution of 30 meters (Joseph and Jaganathan, 2018; Liang and Wang, 2020; Khorram et al., 2012).

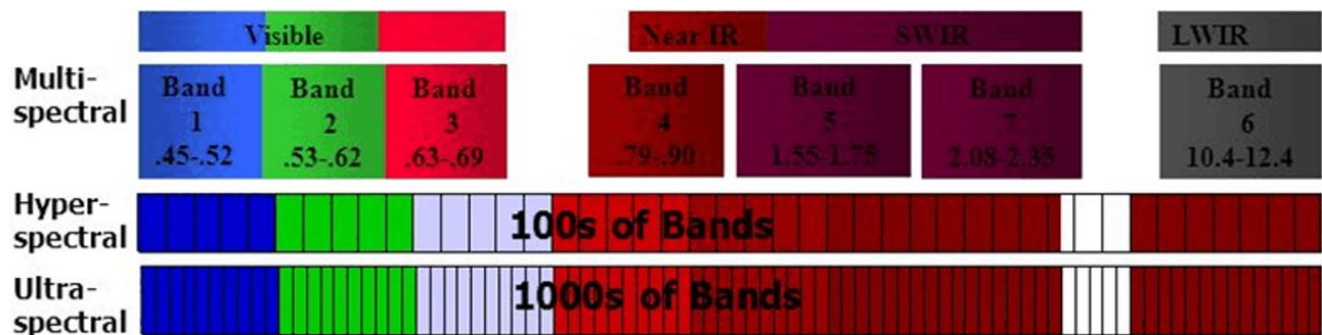


Figure 3.3. Example of spectral resolution

3-1-3 Radiometric resolution

Satellite sensors capture reflected energy from the Earth's surface, and the energy is quantified into a Digital Number (DN), where the value depends on the intensity of the detected energy (Thenkabail, 2016). The radiometric resolution of a remote sensing system describes its ability to recognize small differences in the electromagnetic spectrum. The finer the radiometric resolution of a sensor, the more sensitive it is to small differences in received energy intensity (Weng, 2012). Each quantity of energy measured in kilojoules is transformed into a digital count or radiometric values encoded in bits to facilitate information storage, typically ranging from 0 to 255 in most images, creating a range of 256 values. Therefore, higher numerical resolution leads to better thematic image quality.

As depicted in Figure 3.4, a sensor with low radiometric resolution (1 bit) can resolve incoming reflectance into two contrast levels, while sensors with higher radiometric resolution provide higher levels of energy quantification. These outcomes not only achieve better contrast on-screen but also facilitate numerical analysis of subtle differences in radiometry. The downside is the high volume of data and storage issues associated with high radiometric resolution imagery (Thenkabail, 2016).

Binary bit depth is typically expressed in the following grayscale ranges (Figure 3.5): 8 bits (0-255), 10 bits (0-1,023), 11 bits (0-2,047), 12 bits (0-4,095), and 16 bits (0-65,535).

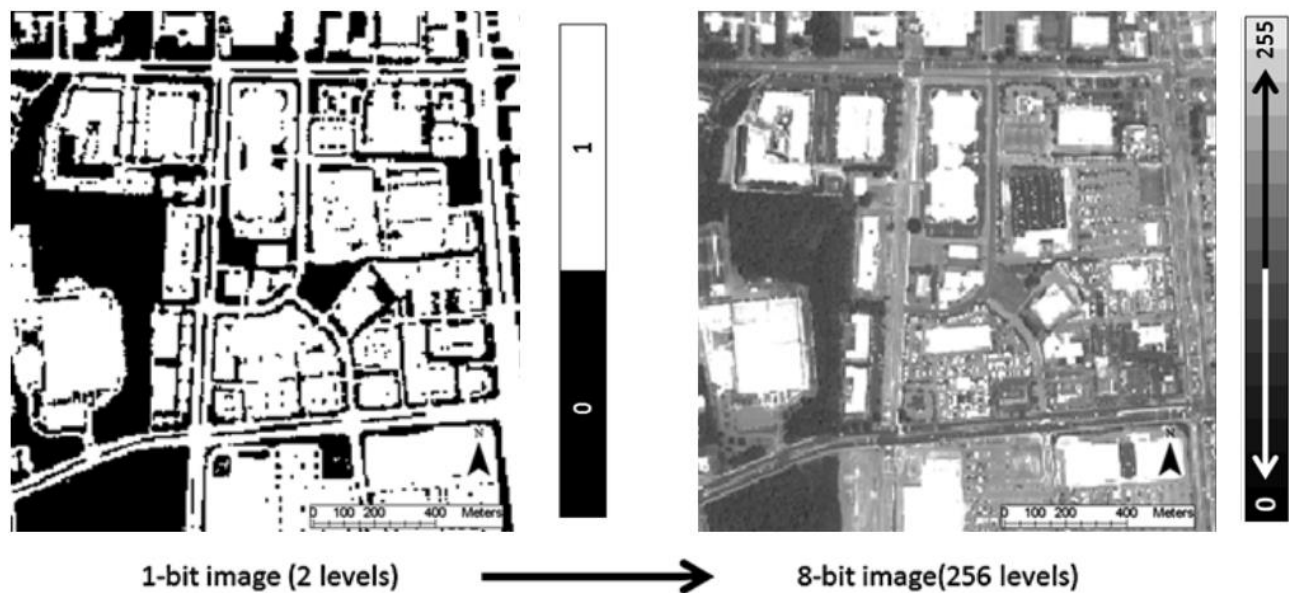


Figure 3.4. Example of two types of radiometric resolution (Khorram et al. 2012)

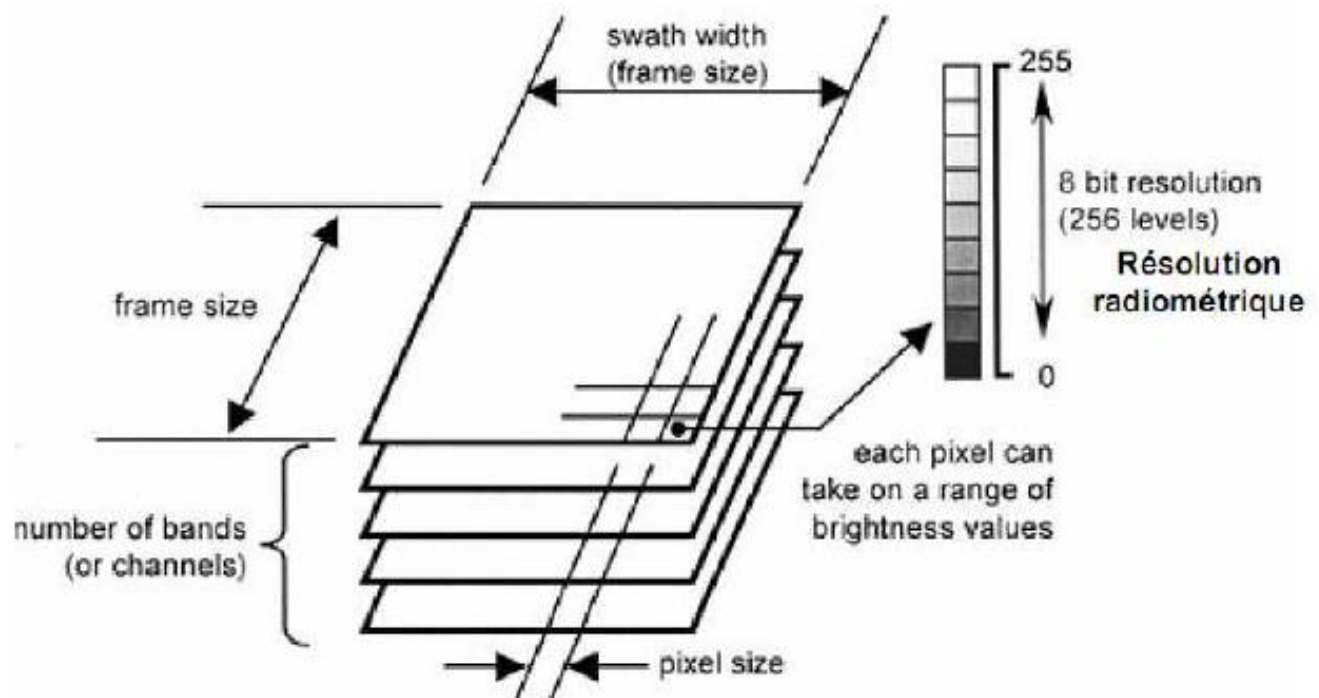


Figure 3.5. Notion of radiometric resolution

3-1-4 Temporal resolution

The time it takes a sensor to revisit a given geographic location is called temporal resolution (Lavender 2017). According to (Liang and Wang 2020) temporal resolution is a measure of the repetition cycle or frequency with which a sensor revisits the same part of the Earth's surface. Frequency characteristics are determined by the design of the satellite sensor and its orbit. Repeatability depends on orbit and swath characteristics. In general, the larger the swath, the higher the temporal resolution (Joseph and Jaganathan 2018). Table 3.1 shows the characteristics of some commonly used satellite sensors.

Table 3.1. Characteristics of some commonly used satellite sensors (Thenkabail 2016).

Sensor	Image Characteristics				Band Range (μm)
	Spatial (m)	Spectral (#)	Radiometric (bit)	Temporal (Days)	
<i>Coarse-resolution sensors</i>					
AVHRR	1000	4	11	Daily	0.58–0.68 0.725–1.1 5.55–3.95 10.30–10.95 10.95–11.65
MODIS	250; 500; 1000	36	12	Daily	0.62–0.67 0.84–0.876 0.459–0.479 0.545–0.565 1.23–1.25 1.63–1.65 2.11–2.16
<i>Multispectral sensors</i>					
Landsat 1, 2, 3 MSS	56 × 79	4	6	16	0.5–0.6 0.6–0.7 0.7–0.8 0.8–1.1
Landsat 4, 5 TM	30	7	8	16	0.45–0.52 0.52–0.60 0.63–0.69 0.76–0.90 1.55–1.74 10.4–12.5 2.08–2.35
Landsat 7 ETM+	30	8	8	16	0.45–0.52 0.52–0.60 0.63–0.69 0.50–0.75 0.75–0.90 10.4–12.5 1.55–1.75 0.52–0.90 (p)
Landsat 8	15; 30; 100	11	12	16	0.43–0.45 0.45–0.51 0.53–0.59 0.64–0.67 0.85–0.88 1.57–2.29 0.50–0.68 (p) 1.36–1.38 10.60–11.19 11.50–12.51
ASTER	15; 30; 90	15	8	16	0.52–0.63 0.63–0.69 0.76–0.86 1.60–1.70 2.145–2.185

					2.185–2.225
					2.235–2.285
					2.295–2.365
					2.360–2.430
					8.125–8.475
					8.475–8.825
					8.925–9.275
					10.25–10.95
					10.95–11.65
ALI	30	10	12	16	0.48–0.69 (p)
					0.433–0.453
					0.450–0.515
					0.425–0.605
					0.633–0.690
					0.775–0.805
					0.845–0.890
					1.200–1.300
					1.550–1.750
					2.080–2.350
SOPT-5	2.5–20	5	8	2–3	0.48–0.71 (p)
					0.5–0.59
					0.61–0.68
					0.78–0.89
					1.58–1.75
IRS-1A, IRS-1B	36; 73	4	8	22	0.45–0.52
					0.52–0.68
					0.62–0.68
					0.77–0.86
IRS-1C	5.8 (p); 23.5; 70.5 (B5)	5	8	24	0.50–0.75 (p)
					0.52–0.59
					0.62–0.68
					0.77–0.86
					1.55–1.70
IRS-P6 AWiFS	56	4	10	16	0.52–0.59
					0.62–0.68
					0.77–0.86
					1.55–1.70
IRS-P6 AWiFS	56	4	10	16	0.52–0.59
					0.62–0.68
					0.77–0.86
					1.55–1.70
JERS-1	18	8	8	44	0.52–0.60
					0.63–0.69
					0.76–0.86 (2 bands)
					1.60–1.71
					2.01–2.12
					2.13–2.25
					2.27–2.40
CBERS-2	20 (p)	5	8	26	0.51–0.73 (p)
CBERS-3B	20 (MS)				0.45–0.52
CBERS-3	5 (p)				0.52–0.59
CBERS-4	20 (MS)				0.63–0.69
					0.77–0.89

Hyperspectral sensor

Hyperion	30	196	16	16	196 effective calibrated bands VNIR (bands 8–57) 0.427–0.925 SWIR (band 79–224) 0.93–2.4
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Hyperspatial sensor

IKONOS	1–4	4	11	5	0.445–0.516 0.506–0.595 0.632–0.698 0.757–0.853
QuickBird	0.61–2.44	4	11	5	0.45–0.52 0.52–0.60 0.63–0.69 0.76–0.89
RESOURCESAT	5.8	3	10	24	0.52–0.59 0.62–0.68 0.77–0.86
RapidEye A–E	6.5	5	12	1–2	0.44–0.51 0.52–0.59 0.63–0.68 0.69–0.73 0.77–0.89
WorldView	0.55	1	11	1.7–5.9	0.45–0.51
FORMOSAT-2	2–8	5	11	Daily	0.45–0.52 0.52–0.60 0.63–0.69 0.76–0.9
KOMPSAT-2	1–4	5	10	3–28	0.45–0.9 (p) 0.45–0.52 0.52–0.60 0.63–0.69 0.76–0.9 0.5–0.9 (p)

3-1-5 Resolution compromise

Unfortunately, it is not always easy to obtain images with the exact spatial, spectral, and temporal resolution required (Chuvieco, 2016). According to Lavender (2017), compromises between different resolutions are often necessary due to technical constraints such as onboard memory and storage space, as well as satellite transmission capabilities to Earth. For instance, to achieve high spatial resolution, the sensor must have a small instantaneous field of view. This consequently reduces the amount of energy received by the sensor. A decrease in energy quantity leads to a decrease in radiometric resolution (the ability to discriminate differences in energy intensity). To increase the amount of energy reaching the sensor, and thereby the radiometric resolution, without reducing spatial resolution, the wavelength interval detected by a sensor channel must be widened. However, this reduces the sensor's spectral resolution.

3-2 Swath

Swath width refers to the width of the ground over which the satellite collects data in each orbit (Figure 3.6). The wider the swath, the greater the ground coverage; for example, MODIS can image the globe every 1-2 days because its swath is 2330 km, whereas Landsat 8 OLI has a swath of only 185 km and Landsat satellites therefore have an absolute revisit time of 16 days. Therefore, with a wide swath, a satellite can see more of the Earth in each orbit, reducing revisit time (Lavender 2017).

Table 3.2 shows the swath of some commonly used satellites.

Table 3.2. Swath of some commonly used satellites (Suratman 2023)

Satellite	Landsat TM	Sentinel 1	SPOT 1–5	MODIS	AVHRR
The swath (km)	185 × 185	80 x 80	60 × 60	2330 × 10	2400 × 6400
Satellite	IKONOS	QuickBird	ASTER	Hyperion	ALOS PALSAR 1, 2
The swath (km)	11 × 11	16.5 × 16.5	60 × 60	7.5 × 100	70 x 70

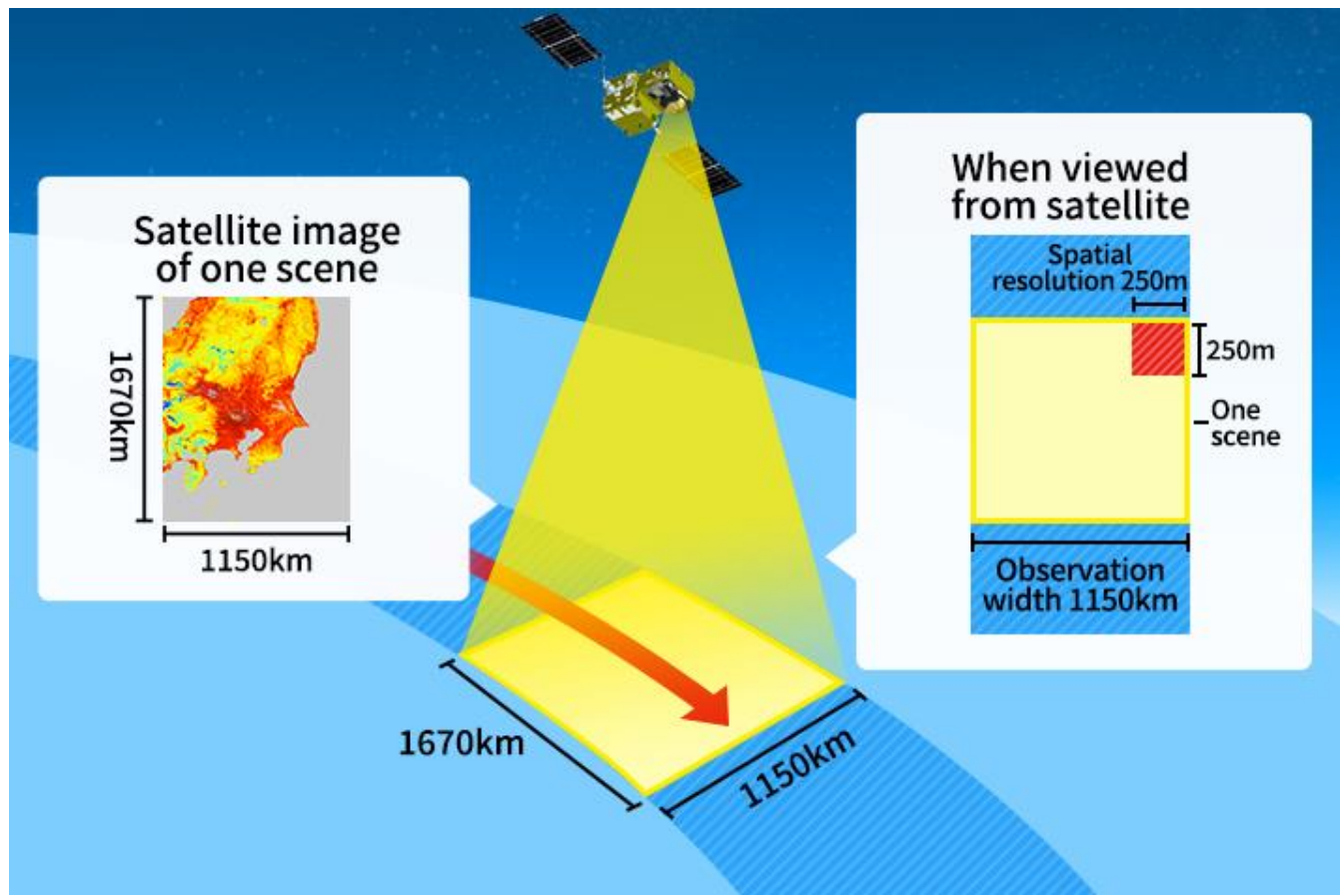


Figure 3.6. Swath concept (<https://earth.jaxa.jp/en/eo-knowledge/eosatellite-type/index.html>)

3-3 Formats

3-3-1 Recording formats

2-3-1-1 Band sequential (BSQ)

With multi-band digital data, the question arises of how to organize the data. In many cases, each data band is stored in a separate file or in a separate data block within the same file. This format is called Band Sequential (BSQ) format. It has the advantage of being simple, but it is often not the best choice for efficient data display and visualization because viewing even a small part of the image requires reading multiple data blocks from different "locations" on the computer's disk.

For example, to visualize a digital image in true color in BSQ format, with separate files used to store the red, green, and blue spectral bands, the computer must read data blocks from three locations on the storage media.

2-3-1-2 Band interleaved by line (BIL)

Another method of storing multi-band data uses the BIL (band interleaved by line) format. In this case, the image data file first contains one line of data from band 1, then the same line of data from band 2 and each subsequent band. This block of data, consisting of the first line of each band, is then followed by the second line of data from bands 1, 2, 3, and so on.

2-3-1-3 Band interleaved by pixel (BIP)

The third common data storage format is band-interleaved per pixel (BIP). This is perhaps the most widely used format for three-band images, such as those from most consumer digital cameras. In this format, the file contains the measurement of each band for the first pixel, then the measurement of each band for the next pixel, and so on.

The advantage of the BIL and BIP formats is that a computer can read and process data from small portions of the image much more quickly, because the data from all the spectral bands are stored closer together than in the BSQ format.

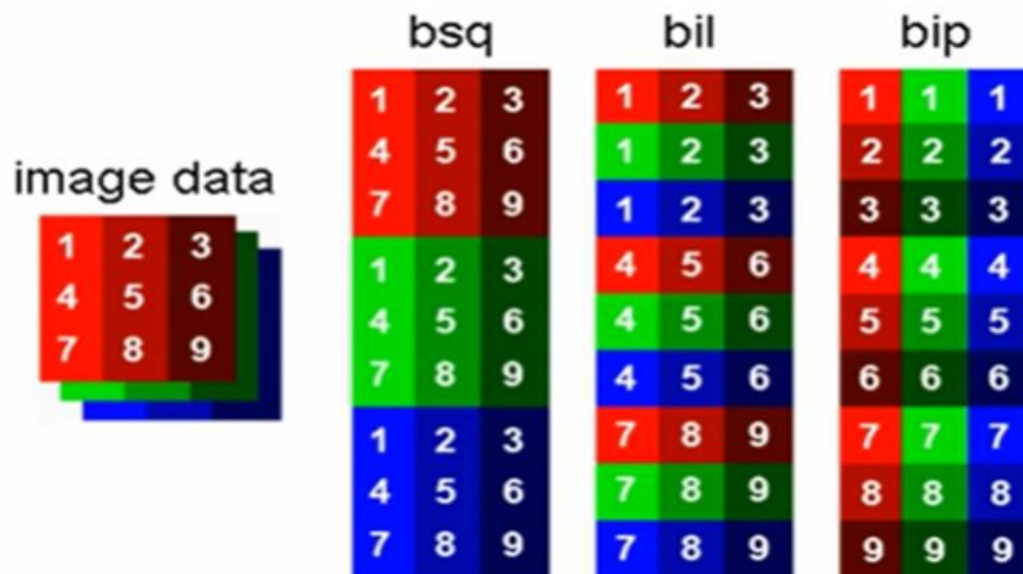


Figure 3.7. Different formats for recording remote sensing data

3-3-2 Exchange formats

The most widely 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 (Encapsuled PostScript). BMP (Bit Map).

3-4 Image types

Satellite images can be classified according to the number of spectral bands they capture (Figure 3.8).

3-4-1 Monochrome image

These images capture data in a single spectral band, usually in the visible or infrared spectrum. They are often used for basic applications such as topographic mapping. (Jensen 2014).

3-4-2 Multispectral images

Multispectral remote sensing systems record energy in several bands of the electromagnetic spectrum, offering better spectral resolution and enabling more detailed analysis of land surface features, such as soil composition, vegetation and water resources (Jensen 2014).

For example, the bandwidths of the four Landsat MSS bands are represented as follows: band 1 = 500 - 600 nm; band 2 = 600 - 700 nm; band 3 = 700 - 800 nm; and band 4 = 800 - 1,100 nm.

3-4-3 Hyper-spectral images

A hyper-spectral remote sensing instrument typically acquires data in hundreds of spectral bands. For example, the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) has 224 bands in the region between 400 and 2500 nm, spaced just 10 nm apart (Jensen 2014).

Hyper-spectral remote sensing involves the collection of data in several hundred bands used for applications such as mineral detection, land classification and water quality analysis.

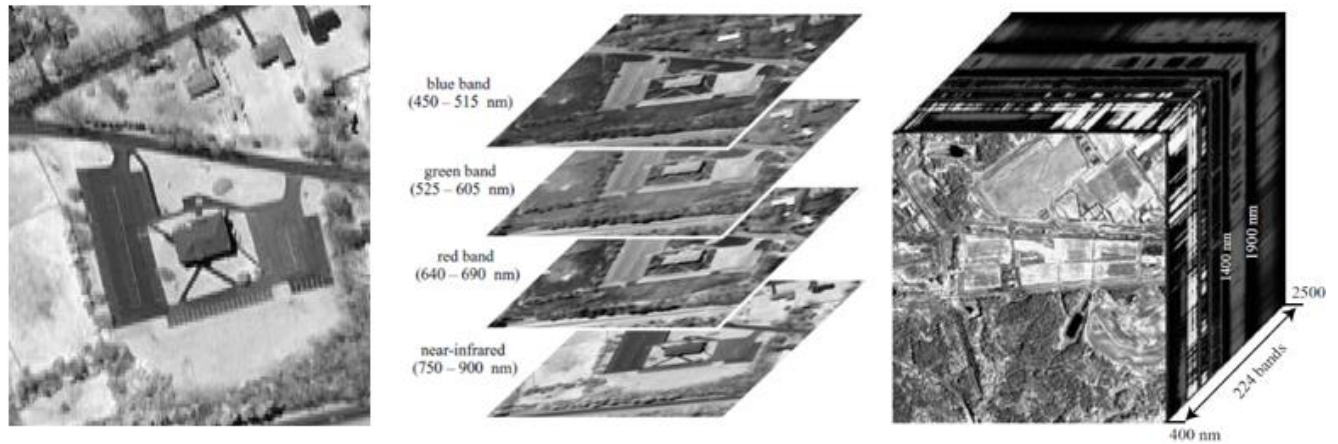


Figure 3.8. Image types, (left) Monochrome image, (center) Multispectral images, and (right) Hyperspectral images

4- Satellite image visualization

Visualizing a digital image on screen involves establishing a transition law between the scale of grid values (0 to 255) and a color table on the monitor.

4-1 Monochrome visualization

Monochrome visualization in remote sensing refers to the display of images obtained by sensors that record data in a single grayscale spectral band (Black & White).

4-2 Color visualization (color composition)

Before beginning an image classification procedure, it is often useful to generate color composites from different combinations of bands. A spacecraft (Landsat, SPOT, etc.) collects several bands of images in black and white, not in color. An interpreter can distinguish only 10 to 20 shades of gray, but may be able to distinguish many more colors. Color composite images help identify different features and facilitate interpretation. To display a color composite image on the screen, computers use light from the three primary colors (red, green, and blue), just like color televisions. The lights of the three colors can be combined in various proportions to produce different colors. A color composite image is generated by assigning each primary color to a distinct spectral band. Depending on the correspondence between the colors of composite images and the colors we see in nature, we can produce false color and true/natural color composite images.

The true/natural color composite consists of visualizing three channels taken in the visible spectrum by respectively assigning them the colors blue, green, and red according to the colorimetric principle of RGB additive synthesis (Figure 3.9.a). Overlaying the three channels but having the third channel taken in the near-infrared allows obtaining an image called false color composite (Figure 3.9.b).

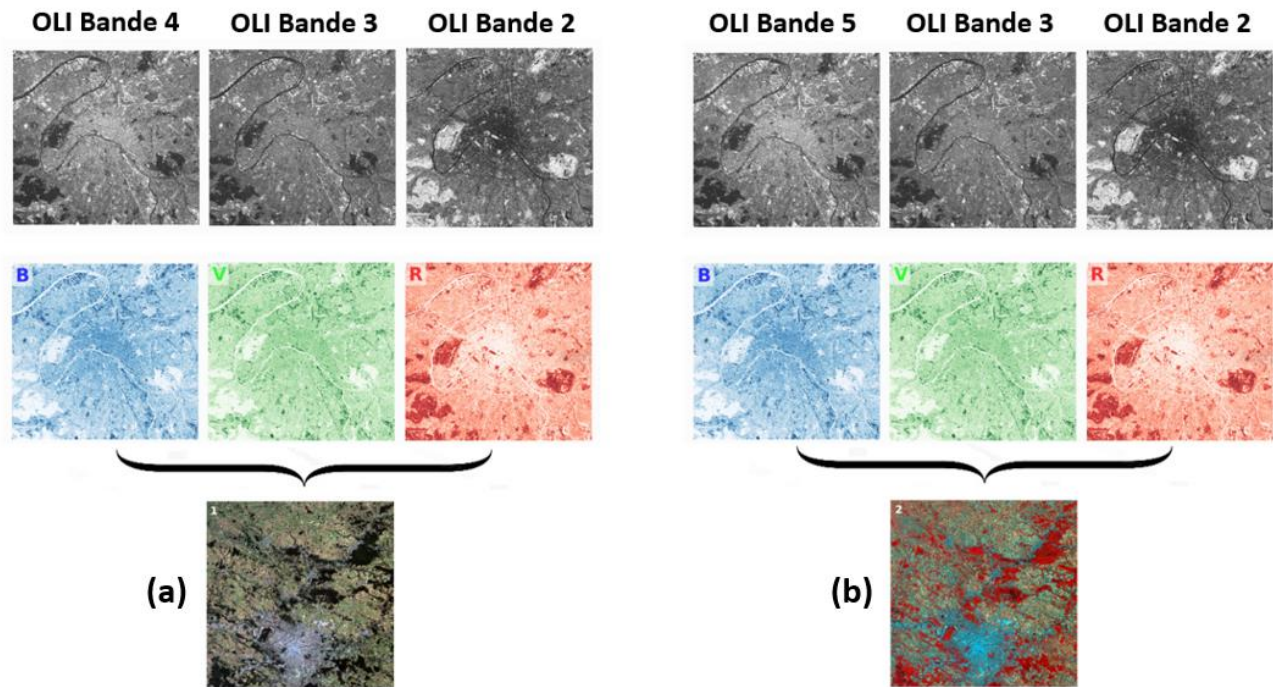


Figure 3.9. Color composition assembling the bands (a) Landsat 8_OLI 4-3-2 (true/natural color composite), and (b) Landsat 8_OLI 5-3-2 (false color composites) (Passy 2023)

Chapitre 4.

Satellite data processing

1- Introduction

Digital image analysis aims to detect, identify, measure and analyze features, objects, phenomena and processes from remotely sensed digital images, and uses computers to process digital images. In addition, before carrying out the main satellite image analysis (classification), it is often necessary to pre-process the digital images. Image pre-processing can include detection and restoration of bad lines, geometric rectification or image registration, radiometric calibration and atmospheric correction, as well as topographic correction. To facilitate interpretation and analysis, it may also be necessary to implement various image enhancements, such as contrast, spatial and spectral improvements (Weng 2012) ; (John R. Jensen 2014).

2- Image pre-processing

2-1 Geometric corrections

Geometric corrections are an important step in the preprocessing of images. Remote sensing images collected may contain systematic and non-systematic errors in terms of image geometry. Systematic errors can be caused by (1) scan obliquity (the ground swath is not normal to the ground track but is slightly oblique, producing transverse geometric distortion), (2) variance in mirror scan speed (the mirror scan speed is not constant, producing transverse geometric distortion), (3) platform speed, (4) Earth rotation, and (5) Earth surface curvature. Non-systematic errors occur when the sensor platform deviates from its normal altitude or when the terrain rises, resulting in changes in image scale.

Geometric correction corrects errors so that image elements are in their correct planimetric position (John R. Jensen 2014). According to (J R Jensen 2005), geometric correction can be Image-to-map rectification or Image-to-Image registration.

2-1-1 Image-to-map rectification

Image-to-map rectification is the process by which the geometry of an image is made planimetric. Whenever precise measurements of surface, direction, and distance are needed, image-to-map rectification is appropriate. However, it cannot eliminate all distortions caused by changes in topographic relief in the images. The image-to-map rectification process typically involves selecting the pixel

coordinates of Ground Control Points (GCPs) (row and column) along with their equivalents in map coordinates (e.g., meters north and east in a Universal Transverse Mercator map projection).

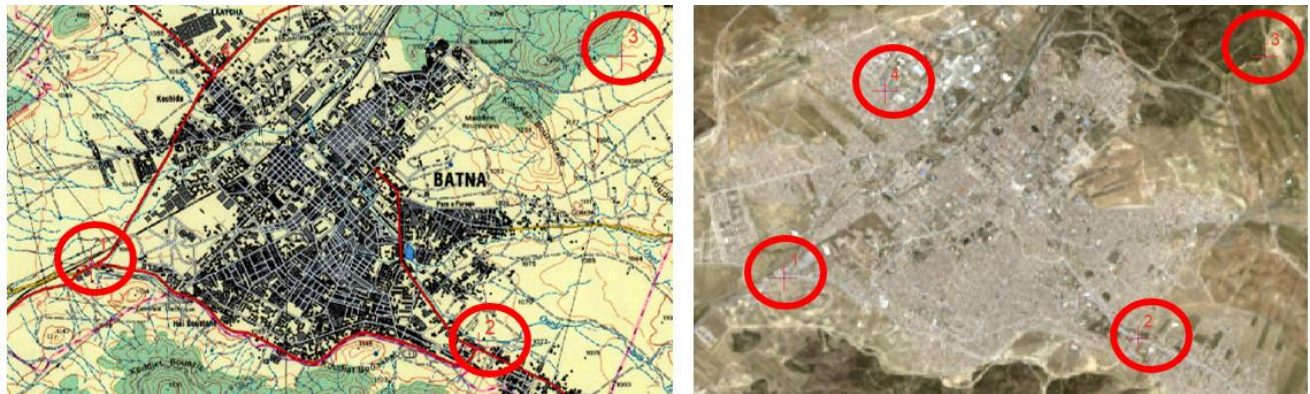


Figure 4.1. Example of an Image-to-map rectification (left) topographic map of the city of Batna 1995, scale 1/50000, UTM WGS 84 Z32N, (right) Landsat 8 OLI_TIRS image of the 4-3-2 color composition of the city of Batna, obtained on May 19, 2017

2-1-2 Image-to-Image registration

Image-to-image registration is the process of alignment by translation and rotation whereby two images of similar geometry and from the same geographical area are positioned in coincidence with each other so that corresponding features from the same area appear in the same place on the registered images. This type of geometric correction is used when it is not necessary to assign each pixel a unique x,y coordinate in a map projection.

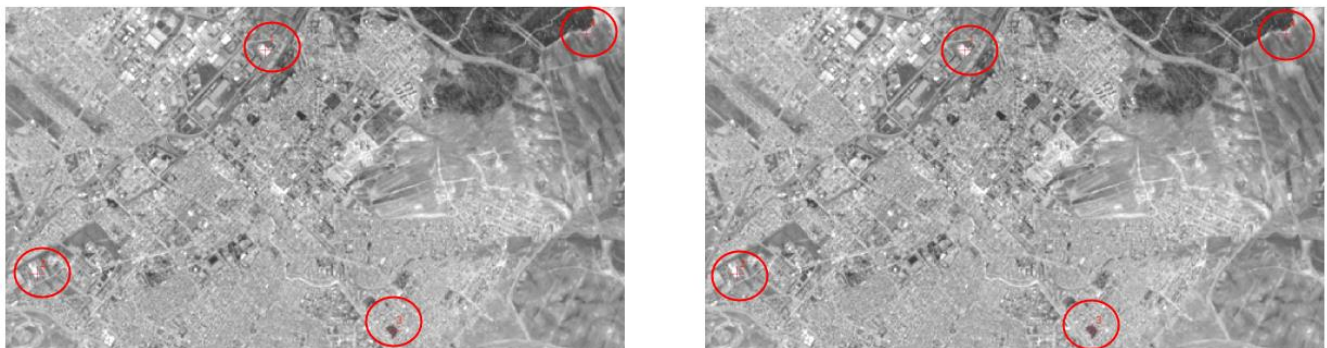


Figure 4.2: Example of an image-to-map rectification (left) Landsat OLI_TIRS band 8 image of the city of Batna, obtained on May 3, 2015, (right) Landsat OLI_TIRS band 8 image of the city of Batna, obtained on May 19, 2017

Overall, it is interesting to note that the same general principles of image processing are used for both image rectification and image registration. The difference is that in image-to-map rectification, the

reference is a map in a standard cartographic projection, whereas in image-to-image registration, the reference is another image.

2-2 Radiometric corrections

Remote sensing images may contain noise or errors introduced by the sensor system (electronic noise) or the environment (atmospheric scattering of light within the sensor's field of view) (John R. Jensen 2014). Radiometric corrections aim to reduce the influence of noise and facilitate the interpretation and analysis of images as well as quantitative measurements from remote sensing images (Weng 2012).

2-2-1 Image enhancement

Images can be digitally enhanced to identify subtle information in analog or digital imagery that might otherwise go unnoticed. Significant improvements have been made to our ability to stretch and filter data to enhance low- and high-frequency components, edges and texture in imagery (John R. Jensen 2014).

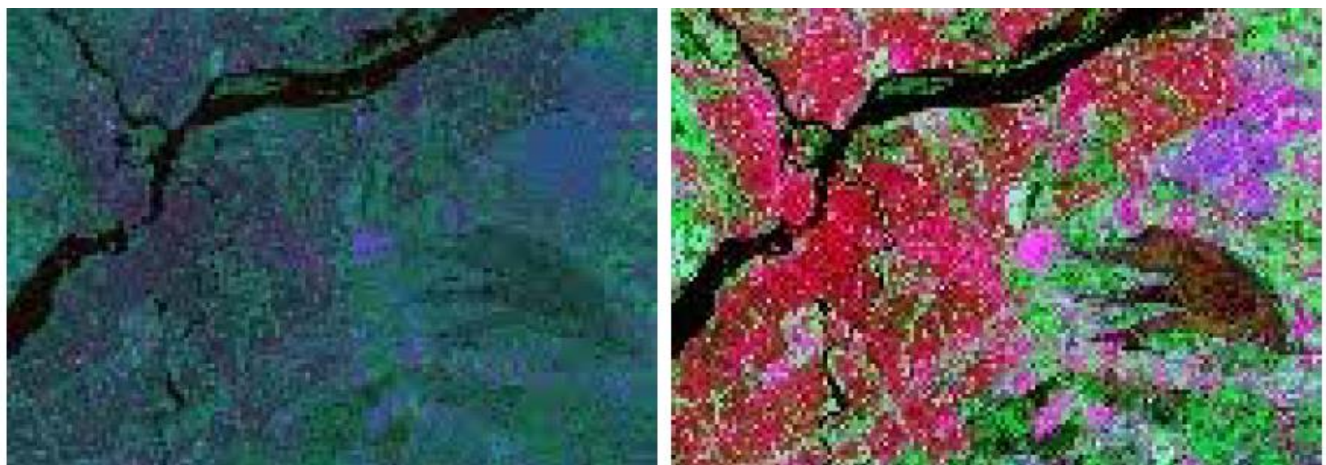


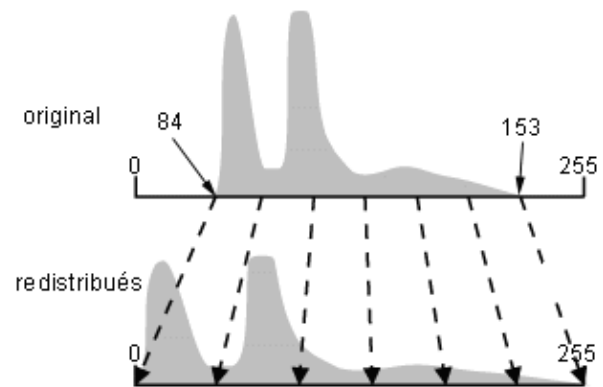
Figure 4.3. Example of how to enhance the appearance of a satellite image (Centre Canadien de Télédétection 2015)

2-2-1-1 Linear enhancement

To apply this method, we identify the minimum and maximum values on the histogram, and use a linear transformation to stretch these values over all available values.

Example

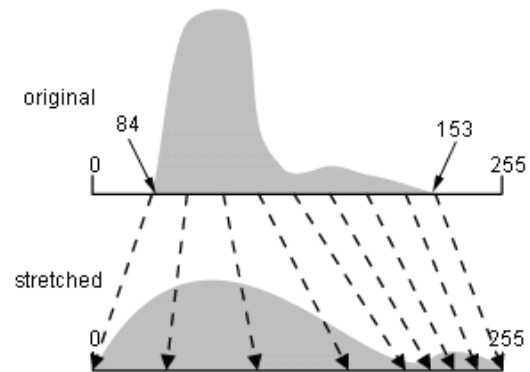
On the histogram of an image, the initial minimum value is 84 and the maximum value 153. These 70 levels occupy only a third of the 256 available values. Linear enhancement uniformly stretches this interval to use all values from 0 to 255.



This process enhances the contrast in the image by making lighter areas of the image lighter and darker areas darker. This facilitates visual interpretation.

2-2-1-2 Weighted enhancement

When the initial distribution is not uniform, linear enhancement is not always appropriate. In such cases, weighted histogram stretching can give good results. This method assigns a wider range of values to those parts of the histogram where intensity values have a higher frequency. In this way, the detail in these regions will be better enhanced than the detail in regions for which the frequency of intensity values in the histogram is lower.



Example

Let's suppose there's a river mouth in the image. The regions where there is water occupy numerical values in the range 40 to 76. To enhance the detail of the water, we could stretch this small portion of the histogram representing the water (40 to 76) over all available values (0 to 255). All other pixels with values greater than 76 will have a value of 255, and those with values less than 40 will have a value of 0. Details in other regions of the histogram will therefore be lost. However, detail on water will be greatly enhanced.

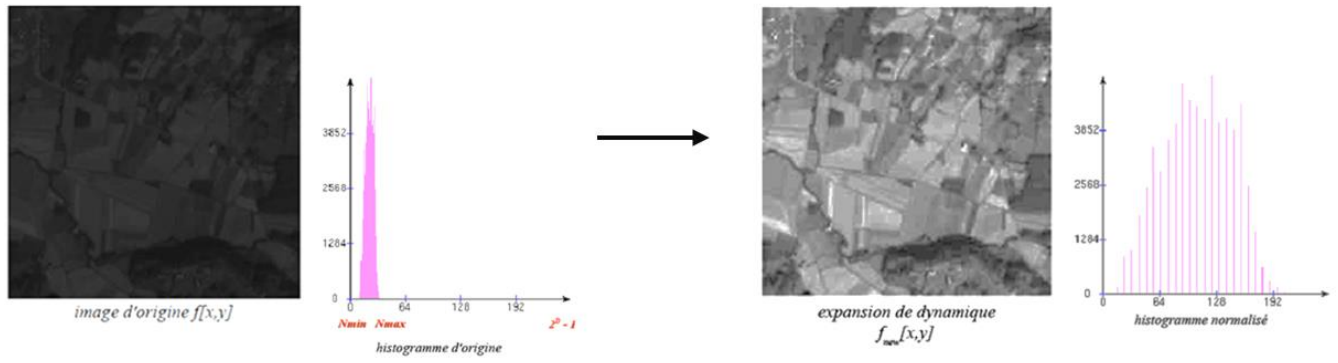


Figure 4.4. Example of linear enhancement

2-3 Atmospheric corrections

According to (Passy 2023), when we have an image in top-of-atmosphere reflectance (TOA), it can be useful to convert it to surface reflectance (TOC). This step is particularly important when monitoring the same region over time. Thanks to this correction, we can be sure that the changes observed over time represent surface changes and not changes in atmospheric conditions. This atmospheric correction can be carried out using various tools (e.g. ENVI 4.7's FLAASH module).

2-3-1 Top of Atmosphere (TOA) Reflectance

For example, Landsat data can be converted from digital number (DN) to TOA reflectance using reflectance rescaling coefficients and the following equation (Bendib et al. 2017):

$$\rho_{\lambda} = M_{\rho} x Q_{cal} + A_{\rho}$$

ρ_{λ} is the spectral reflectance; M_{ρ} is the band-specific multiplicative scaling factor obtained from the metadata; A_{ρ} is the band-specific additive scaling factor obtained from the metadata; Q_{cal} is the DN value for the quantized and calibrated standard product pixel of all bands.

2-3-2 Top of Canopy (TOC) Reflectance

Landsat data can be converted from digital number (DN) to TOC reflectance using the following equation (Bendib and Berghout 2023):

$$\rho = [\pi * (L_{\lambda} - L_p) * d^2] / [T_v * ((ESUN N_{\lambda} * \cos \theta_s * T_z) + E_{down})]$$

Where ρ is the spectral reflectance; L_λ is the spectral radiance at the sensor aperture (radiance at satellite level); L_p is the path radiance; d is the earth-sun distance in astronomical units (supplied with Landsat metadata); T_v is the atmospheric transmittance in the direction of observation; $ESUN N_\lambda$ is the mean exo-atmospheric solar irradiance; θ_s is the solar zenith angle in degrees, which is equal to $\theta_s = 90^\circ - \theta_e$ where θ_e is the sun's elevation; T_z is the atmospheric transmittance in the direction of illumination; E_{down} is the diffuse downward irradiance.

2-4 Ortho-rectification

In areas with large variations in altitude, images can be geometrically corrected to take into account the relief. This is achieved by using a digital elevation model, which further enhances the spatial accuracy of the images.

Recently, satellite images have been distributed under several processing levels. For each level of processing, the images are orthorectified.

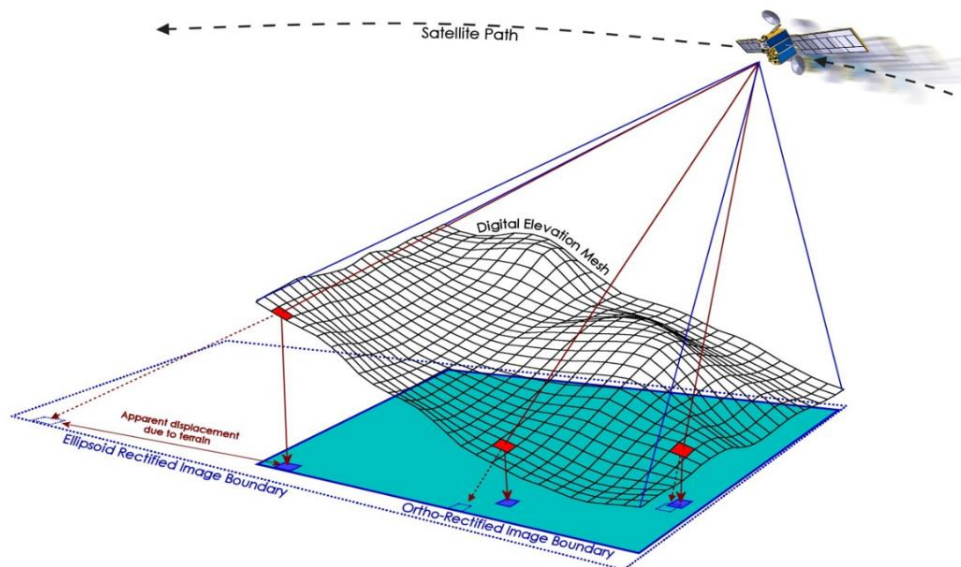


Figure 4.5. Ortho-rectification concept

2-5 Gap fill for ETM+ L7 sensor

On May 31, 2003, the Enhanced Thematic Mapper (ETM) sensor on Landsat 7 experienced a failure in the Scan Line Corrector (SLC). Since that date, all Landsat ETM images have exhibited wedge-shaped gaps on both sides of each scene, resulting in a data loss of approximately 22% (Center for Earth Observation 2024). Scaramuzza et al. (2004) developed a technique that can be used to fill in the gaps of

a scene with data from another Landsat scene. A linear transformation is applied to the "fill" image to adjust it based on the standard deviation and mean values of each band for each scene.

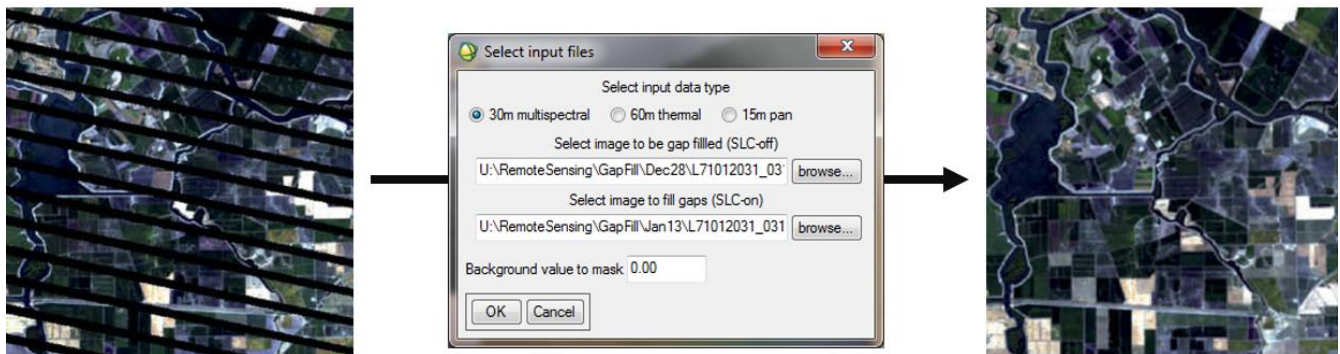


Figure 4.6. Filling the Landsat 7 ETM+ gaps under the landsat_gapfilld'Envi4.7 extension

2-6 Band Report

Sometimes, differences in brightness of identical surface materials are due to topographic slope and aspect, shadows, or seasonal variations in the angle of illumination and sunlight intensity. These conditions can hinder the ability of an interpreter or classification algorithm to correctly identify surface materials or land use in a remote sensing image. Band ratios can, in some cases, be applied to mitigate the effects of these environmental conditions (John R. Jensen 2014).

By definition, band ratios involve operations between different channels, consisting of dividing an image from one channel by the image from another channel. Some subtle details in the raw channels may appear in the resulting image. It is not possible to create a color composite with all 6 channels at once, but with ratio processing, a color composite can be created with the 3 resulting ratios (pseudo-channels), each corresponding to two channels. This is the significant advantage of this processing technique.

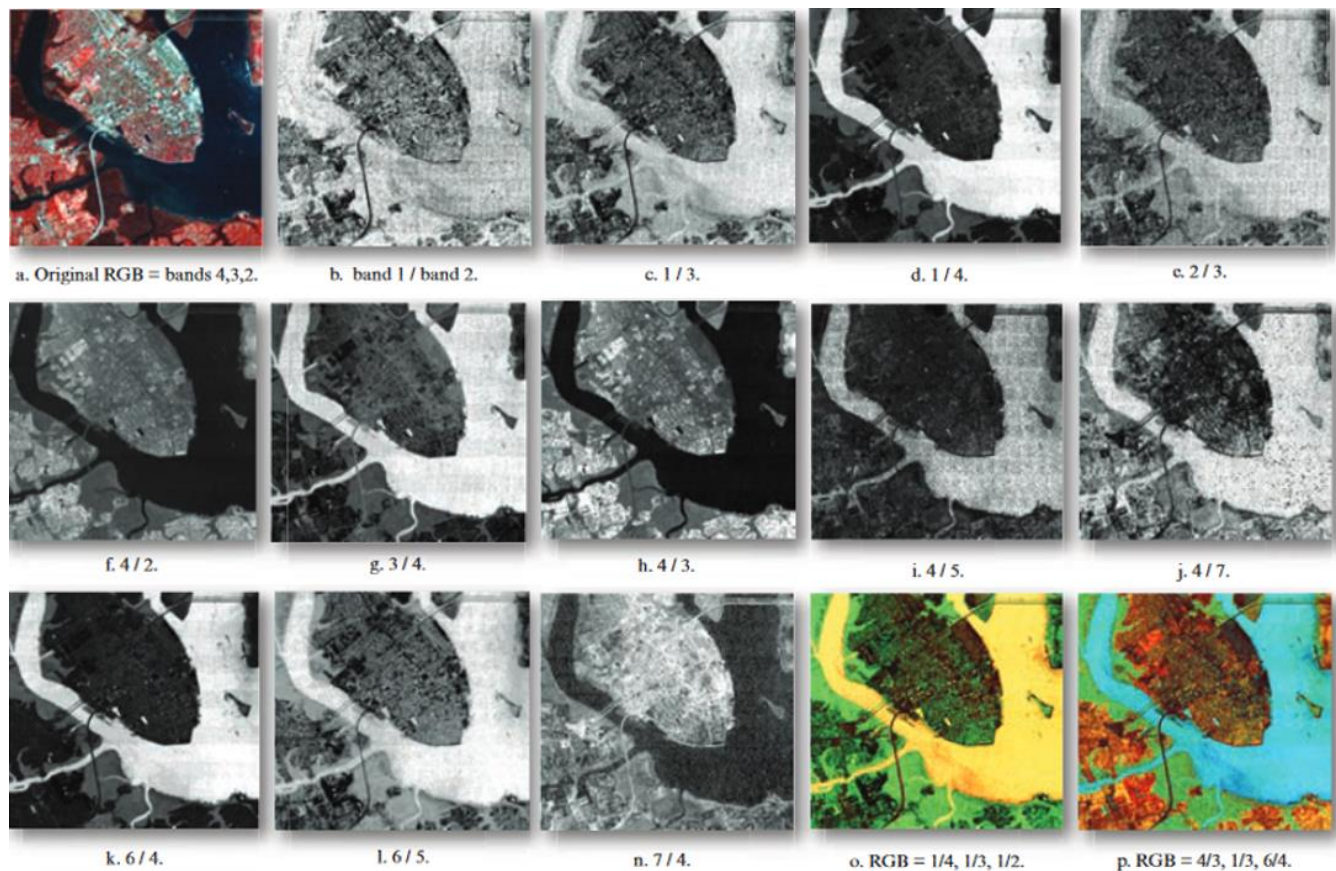


Figure 4.7. The ratio between the different Landsat TM bands (John R. Jensen 2014)

2-7 Spatial filtering

Spatial filtering is digital processing used for image enhancement by highlighting or removing specific image features based on their spatial frequency.

According to (Centre Canadien de Télédétection 2015), the method involves moving a "window" a few pixels in size (e.g.: 3 by 3, 5 by 5, etc.) above each pixel in the image. We then apply mathematical processing using the values of the pixels below the window, and replace the value of the central pixel with the result obtained. The window is moved along the columns and rows of the image, one pixel at a time, repeating the calculation until the entire image has been filtered. By modifying the calculation performed within the window, it is possible to enhance or suppress different types of features present in an image. Widely used filters include low-pass and high-pass.

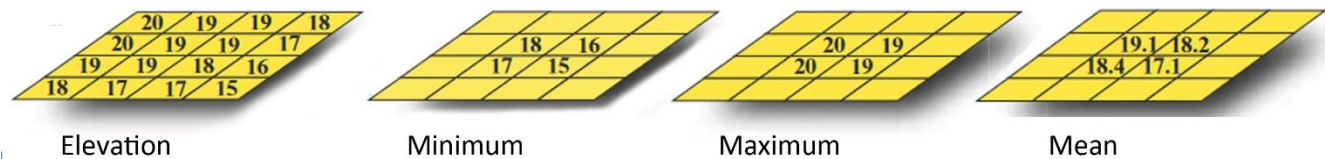


Figure 4.8. Neighborhood operations applied to a single raster dataset using a 3*3 spatial displacement window (John R. Jensen 2016)

2-7-1 Low-pass filter

A low-pass filter reduces or smooths the spatial contrast of an image by minimizing the spatial variability of the numerical values (DN) of each pixel within the filter window, thereby adjusting the DN of the central pixel to be more similar to its neighboring pixels. Visually, the filtered image appears more diffuse (blurry) because edge transitions are softened by the filtering operations (Chuvieco 2016). Low-pass filters are also used to reduce the spatial variability of certain land cover classes as a preliminary step to classification. The goal is to mitigate "image noise" produced in highly heterogeneous areas compared to the sensor's spatial resolution.



Figure 4.9. Low-pass filter (from left to right: original image, 3×3 filtered image and 9×9 filtered image)

2-7-2 High-pass filter

The goal of a high-pass filter is to preserve the local contrast of the image by retaining high-frequency variations. These filters enhance the spatial contrast between neighboring pixels and are therefore very useful for highlighting linear changes, such as roads, agricultural fields, and geological faults (Chuvieco 2016).

The simplest method to obtain a high-pass filter is by subtracting the original image from a low-pass filtered image.



Figure 4.10. High-pass filter (from left to right: original image, 3×3 filtered image and 9×9 filtered image)

2-8 Data fusion (Pan-Sharpening)

Data fusion, also known as pan-sharpening, is a remote sensing technique that combines lower spatial resolution multispectral images with a high spatial resolution panchromatic image, to create a single high spatial resolution multispectral image.

The pan-sharpening process improves the spatial resolution of multispectral images while preserving their spectral information. This results in more detailed and accurate images, which are useful for many applications such as mapping, environmental monitoring, natural resource management and land change analysis. (Khorram et al. 2012) ; (Aronoff 2005).



Figure 4.11. Pan-sharpening process, (left) L8 OLI_TIRS 4-3-2 color composition (30m), (right) L8 OLI_TIRS 4-3-2 color composition merged with Panchromatic 8 band (15m)

2-9 Image mosaic

High spatial resolution images typically cover a smaller area per image (Aronoff 2005). According to (Joseph and Jaganathan 2018), two or more satellite images with overlapping areas can be assembled to generate an image covering a larger geographic area, a process known as image mosaicking.

In summary, image mosaicking in remote sensing involves combining multiple images obtained from remote sensing sensors to create a single, larger, and coherent image. This technique is often used for mapping large land areas or monitoring environmental changes on a large scale.

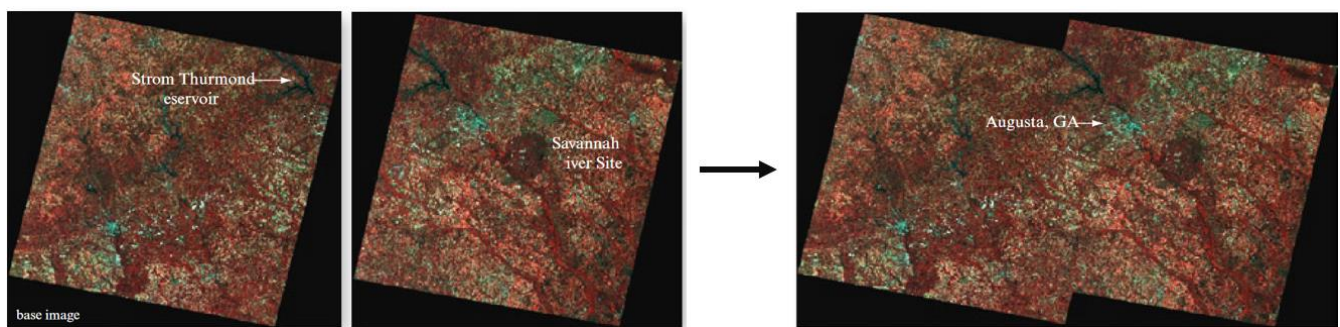


Figure 4.12. Mosaicking process of two Landsat 7 ETM+ bands

2-10 Indexes

Passive optical imaging, with its spectral richness, enables the study of material characteristics observed by remote sensing systems. By leveraging the optical properties of various surface types, it is possible to develop a range of indices used in specific application domains, such as vegetation monitoring, water property analysis, cloud detection, and urban structure description (Tupin et al., 2014).

2-10-1 Normalized Difference Vegetation Index (NDVI)

NDVI data are used as input in crop growth models and climate change models (Tempfli et al. 2009). According to, (Tupin et al. 2014), NDVI is highly informative in sparse cover, but tends to saturate in the presence of thick vegetation cover. It is given by the following formula:

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

Where Red and NIR denote spectral reflectance measurements acquired in the red (visible) and near-infrared regions, respectively.

Mathematically, values should be between -1 and +1. In practice, the absence of vegetation on bare ground generally results in a value close to zero, while areas of dense vegetation have values close to +1.



Figure 4.13. Normalized Difference Vegetation Index (NDVI)

2-10-2 Bare Soil Index (BSI)

The Bare Soil Index (BSI) is a numerical indicator that combines blue, red, near-infrared and short-wave infrared spectral bands to capture soil variations. These spectral bands are used in a standardized way. The red and short-wave infrared spectral bands are used to quantify soil mineral composition, while the blue and near infrared spectral bands are used to highlight the presence of vegetation.

BSI can be used in a wide range of remote sensing applications, such as soil mapping, crop identification (in combination with NDVI), etc.

$$BSI = \frac{(MIR + R) - (PIR + B)}{(MIR + R) + (PIR + B)}$$

Where MIR is the mid-infrared band, R is the red band, PIR is the near-infrared band and B is the blue band.

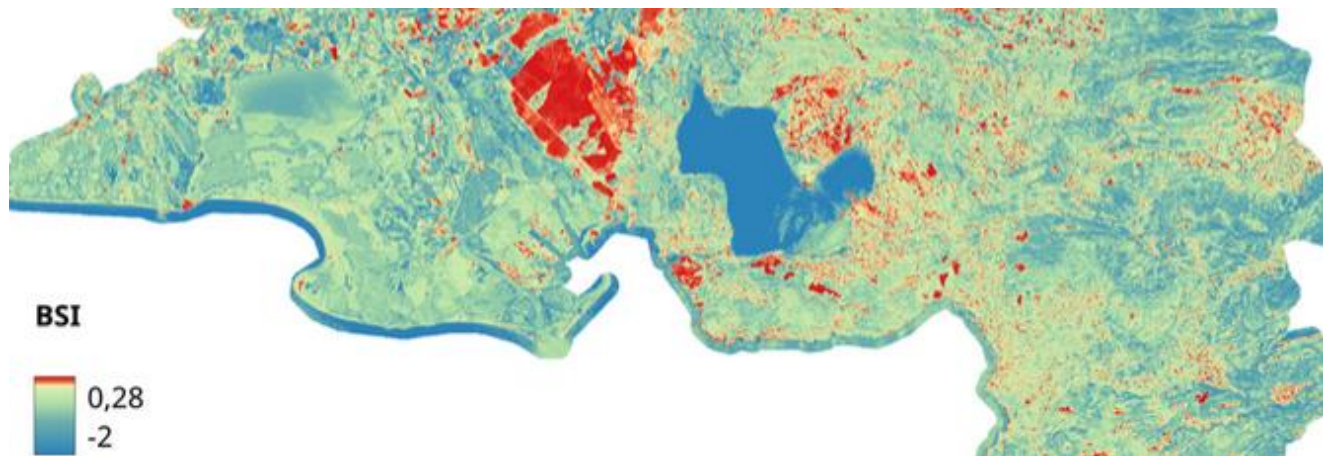


Figure 4.14. Bare Soil Index (BSI)

2-10-3 Modified Normalized Difference Water Index (MNDWI)

The Modified Normalized Difference Water Index (MNDWI) uses green and SWIR bands to highlight open water features. It also diminishes the characteristics of built-up areas, which are often correlated with open water in other indices.

$$\text{MNDWI} = \frac{G - \text{MIR}}{G + \text{MIR}}$$

Where G corresponds to the Green band and MIR to the Mid-Infrared band.

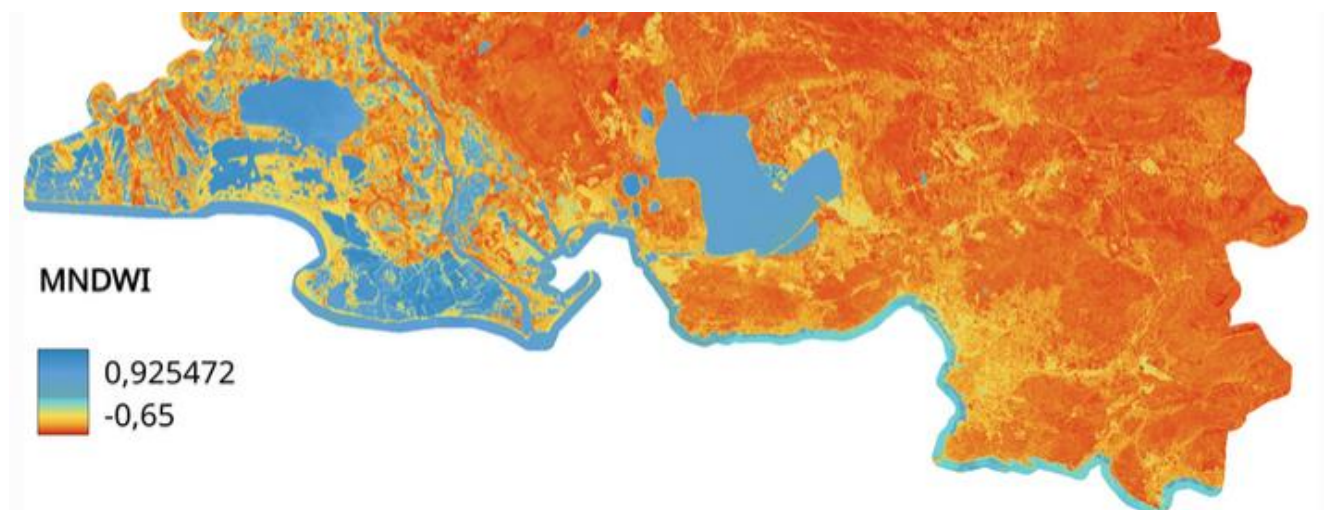


Figure 4.15. Modified Normalized Difference Water Index (MNDWI)

The essential indices are summarized in tables 4.2, 4.2, and 4.3 :

Table 4.1. Extract of some vegetation indices (Towers et al. 2019)

Index	Formula	Features
NDVI—Normalized difference vegetation index	$(\text{NIR} - \text{R}) / (\text{NIR} + \text{R})$	Robust but insensitive at high leaf area index (LAI) values
RVI—Ratio vegetation index	NIR / R	Sensitive over a broad range
WDRVI—Wide dynamic range veg. index [6]	$(\alpha \text{NIR} - \text{R}) / (\alpha \text{NIR} + \text{R})$	Sensitive at high LAI
MSAVI—Modified soil-adjusted vegetation index [24]	$(\text{NIR} - \text{R}) / (\text{NIR} + \text{R} + \text{L})(1 + \text{L})^{(1)}$	Corrects influence of soil and provides a variable value for L
MSAVI ₂ —Second modified soil-adjusted vegetation index [24]	$\frac{1}{2} \left[2(\text{NIR} + 1) - \sqrt{2(\text{NIR} + 1)^2 - 8(\text{NIR} - \text{R})} \right]$	Corrects influence of soil and provides and does not require L ⁽¹⁾
PVI —Perpendicular vegetation index [23]	$\sqrt{(\text{Rs} - \text{Rv})^2 + (\text{NIRv} - \text{Rs})^2}^{(2)}$	Affected by atmospheric attenuation and soil dampness
CI _{rededge} —Red edge chlorophyll index [25]	$\frac{\text{NIR}}{\text{RE}} - 1$	Sensitive in corn, good gross primary productivity estimator
SAVI ₂ —Soil-adjusted vegetation index 2 [35]	$\frac{\text{NIR}}{\text{R} + \frac{\text{b}}{\text{a}}}^{(3)}$	Sensitive in corn, good gross primary productivity estimator

Table 4.2: Extract of some built-up indices (Ettehadi Osgouei et al. 2019)

Index Name	Index ID	Bands Used	Formula	Application
Normalized difference built-up index	NDBI	SWIR and NIR	$\frac{\text{SWIR} - \text{NIR}}{\text{SWIR} + \text{NIR}}$	Automatically mapping urban areas
Built-up index	BUI	SWIR, NIR and Red	$\text{NDBI} - \text{NDVI}$	Mapping urban built-up areas
Built-up area extraction index	BAEI	Red, Green and SWIR	$\frac{\text{Red} + \text{L}}{\text{Green} + \text{SWIR}}$ $\text{L} = 0.3$	Extraction of built-up area
New built-up index	NBI	Red, NIR and SWIR	$\frac{\text{SWIR} \times \text{Red}}{\text{NIR}}$	Automating the process of mapping residential areas
Vegetation index built-up index	VIBI	Red, NIR and SWIR	$\frac{\text{NDVI}}{\text{NDVI} + \text{NDBI}}$	Segmenting urban areas
Index-based built-up index	IBI	Red, Green, NIR and SWIR	$\frac{\text{NDBI} - (\text{SAVI} + \text{MNDWI})/2}{\text{NDBI} + (\text{SAVI} + \text{MNDWI})/2}$	Enhancing the built-up land feature while effectively suppressing background noise
Urban index	UI	NIR and SWIR	$\left(\frac{\text{SWIR} - \text{NIR}}{\text{SWIR} + \text{NIR}} + 1.0 \right) \times 100$	Evaluating urbanization
Bare soil index	BSI	Red, Blue, NIR and SWIR	$\frac{(\text{SWIR} + \text{R}) - (\text{NIR} + \text{B})}{(\text{SWIR} + \text{R}) + (\text{NIR} + \text{B})}$	Enhancing bare soil areas, fallow lands

Table 4.3. Extract of some water indices (Ogilvie et al. 2018)

Normalised Difference Water Index (McFeeters, 1996)	$NDWI = \frac{Green - NIR}{Green + NIR}$
Modified NDWI (Xu, 2006)	$MNDWI = \frac{Green - SWIR}{Green + SWIR}$
Automated Water Extraction Index (Feyisa et al., 2014)	$AWEI_{nsh} = 4 \cdot (Green - SWIR_1) - (0.25 \cdot NIR_4 + 2.75 \cdot SWIR_2)$
Normalised Difference Turbidity Index (Lacaux et al., 2007)	$NDTI = \frac{Red - Green}{Red + Green}$

3- Image processing

Once the preprocessing stage is completed, multispectral satellite images are then ready for classification. During classification, each pixel in an image is assigned to a specific category from a set of categories of interest, such as land cover types. The classification process is typically based on the pixel values (i.e., their spectral values) in each image band.

One of the main objectives of the classification process is to convert the original spectral data, which are variable and may exhibit relatively complex relationships among multiple image bands, into a simple thematic map (typically a land cover map) that is easily understandable by end users.

Classification systems involve one of two types of classification: supervised or unsupervised. Although supervised and unsupervised classification techniques have the same ultimate goal, they follow fundamentally different conceptual strategies. In brief, supervised classification relies on an analyst (i.e., a human interpreter of the image) to identify training sites (or signatures) that represent each of the classes in the chosen classification scheme. Unsupervised classification involves minimal input from the analyst before the classification process. The bulk of the work is done by an iterative computational process that assigns pixels in an image to particular clusters, which represent natural groupings of pixels exhibiting spectral similarities across all image bands.

3-1 Unsupervised classification

Unsupervised clustering methods (Figure 4.8) involve limited initial input from the analyst, as a computer algorithm determines the most appropriate clusters from the image data. Nevertheless, the analyst will probably need to make certain decisions to guide the clustering algorithm, such as the desired number of output groups, the number of iterations and the statistical threshold values used to separate the groups.

Although many classification methods exist, the two most widely used techniques for unsupervised classification of multispectral images are the K-means technique and the iterative self-organizing data analysis technique (ISODATA).

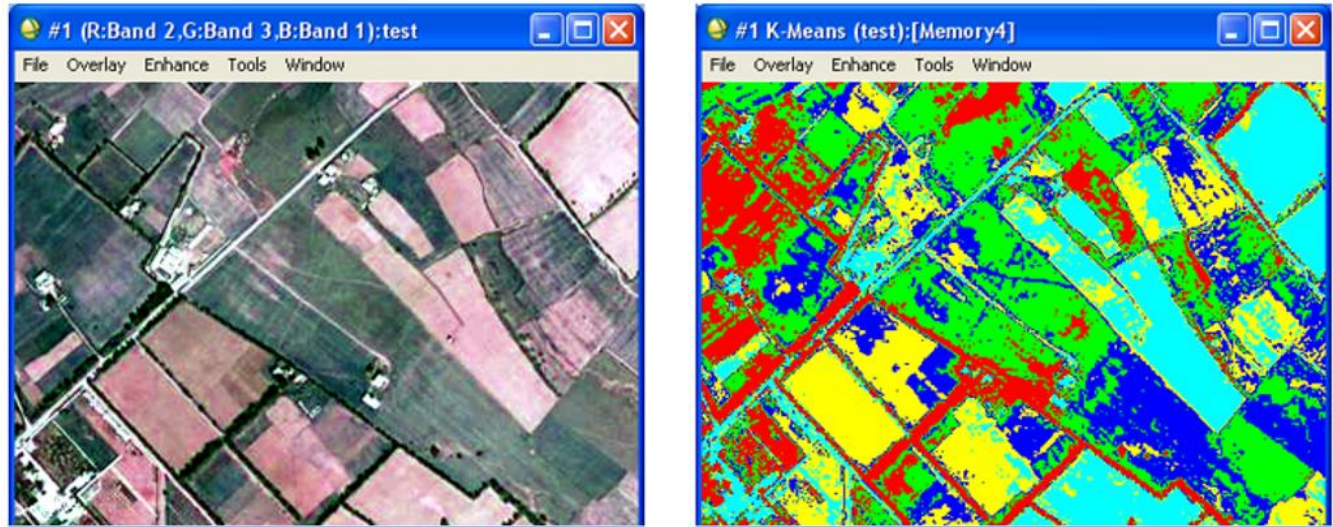


Figure 4.16. Unsupervised K-Means classification

3-2 Supervised classification

The concept behind supervised classification is that the image analyst provides the computer with certain information (training areas) to calibrate a classification algorithm (Knudby 2021). The training areas selected by an analyst during the initial phase of a supervised classification project are used to establish the relationships between the classes of interest and the spectral data in the image. To identify and delineate candidate sites, the analyst will typically rely on auxiliary data sources, such as field visits.

Firstly, the number of training sites should be at least three times greater than the number of categories of interest. Training areas should be selected to represent the spectral distribution of each category of interest as comprehensively as possible and should be distributed randomly or systematically across the entire image area. Lastly, each training site should be as homogeneous as possible, meaning that the group of pixels within a training site should have similar spectral values.

Among the widely used algorithms in supervised classification are the minimum distance, parallelepiped, maximum likelihood, support vector machine (SVM), etc.

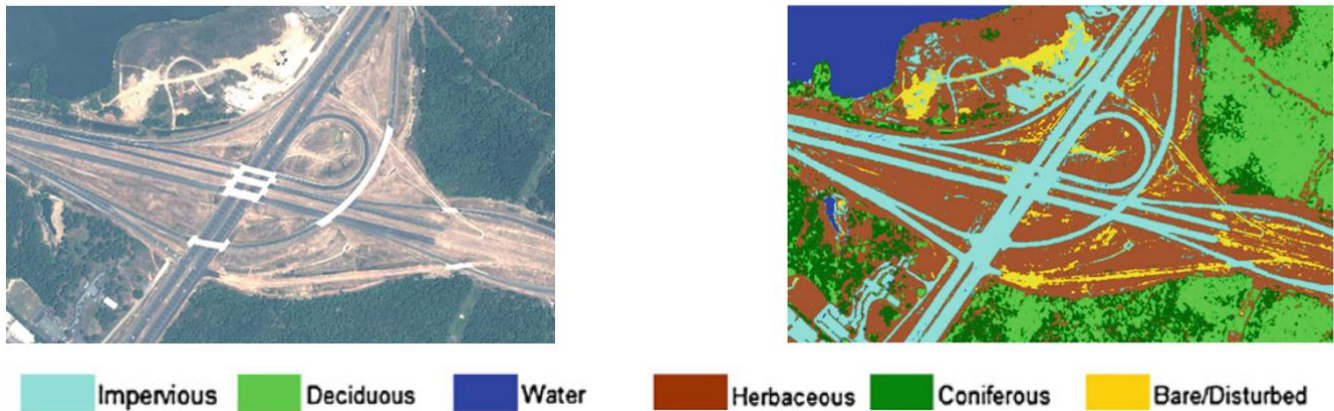


Figure 4.17. Results of a supervised classification using the maximum likelihood algorithm (Right), compared with a true-color composite image of the target area (Left)

4- Data post-processing

4-1 Accuracy assessment

Accuracy assessment has been a key element in remote sensing (Khorram et al. 2012). Without assessing the accuracy of classified data, the reliability of results is called into question. The most commonly used procedure for accuracy assessment is confusion matrix analysis. A confusion matrix can be constructed from results based on reference data (for example, data collected on the ground or from an image with much higher spatial resolution) on one side of a table, and results based on the classified image on the other side of the table.

From a confusion matrix, it is possible to calculate a battery of quantitative indicators providing information on the quality of a classification. Some indicators provide information on the quality of the classification class by class, while others provide information on the overall quality of the classification. For the following examples, we will use the confusion matrix shown in figure 4.18.

V_Classified	1	2	3	4	5	6	7	Total
1	2308	210	0	0	0	0	0	2518
2	0	5921	116	0	0	20	0	6057
3	0	348	533	0	0	1	4	886
4	0	0	0	8305	680	0	249	9234
5	0	0	0	845	3893	1	993	5732
6	0	114	11	0	0	8000	507	8632
7	0	0	0	0	214	48	4793	5055
Total	2308	6593	660	9150	4787	8070	6546	38114

Figure 4.18. Confusion matrix for supervised classification

4-1-1 User quality and errors of omission

For each class, user's accuracy is calculated by dividing the number of correctly classified pixels by the total number of pixels in the class in the total column.

$$\text{User accuracy} = \frac{\text{Number of correctly classified pixels in each category}}{\text{Total number of classified pixels in that category (the column total)}} \times 100$$

For example, here, the user quality of class 2 is 97.75% (i.e. 5921/6057).

This user quality is equivalent to answering the question: "If I go to a place on your map that has been classified as 2, what is the probability that this place is actually 2 in the field? This user quality minus 1 is also called Error of Omission (1 - User Quality).

4-1-2 Producer quality and error per commission

Producer's accuracy is calculated for each class by dividing the number of correctly classified pixels by the total number of pixels in the class in the total line.

$$\text{Producer accuracy} = \frac{\text{Number of correctly classified pixels in each category}}{\text{Total number of classified pixels in that category (the line total)}} \times 100$$

For example, here, the production quality of class 2 is 89.81% (i.e. 5921/6593).

This producer quality is equivalent to answering the question: "What is the probability that an area actually classified as 2 in the field will be classified as 2 on your map? This Producer Quality minus 1 is also called Commission Error (1 - Producer Quality).

4-1-3 Overall accuracy

Overall accuracy is expressed as a percentage and provides information on the overall quality of the classification. It is calculated by dividing the sum of well-classified pixels by the total sum of pixels.

$$\text{Overall accuracy} = \frac{\text{Number of correctly classified pixels (diagonal)}}{\text{Total number of reference pixels}} \times 100$$

For example, here the overall accuracy is 88.56% (i.e. 2308+5921+533+8305+3893+8000/4793/38114).

4-1-4 Kappa Index

The Kappa index, calculated for all classes, also provides information on the overall quality of the classification. Its calculation takes into account the fact that some pixels may be well classified at random. This index varies between $-\infty$ and 1. The closer the Kappa is to 1, the better the classification.

$$\text{Kappa coefficient} = \frac{(\text{TS} \times \text{TCS}) - \sum(\text{column total} \times \text{raw total})}{(\text{TS}^2) - \sum(\text{column total} \times \text{raw total})} \times 100$$

Several applications have been developed to quickly calculate the Kappa coefficient, including (<http://vassarstats.net/kappa.html>)

Chapitre 5.

Some practical work

1- Practical work 1: Downloading satellite images

Downloading satellite images is the fundamental first step in carrying out any remote sensing analysis, providing a solid foundation for the subsequent stages of data processing and interpretation. To this end, NASA's official USGS website (<https://earthexplorer.usgs.gov/>) offers a wide selection of satellite images from various missions, including Landsat, Sentinel and MODIS, covering a wide range of spatial, spectral and temporal resolutions. These data are essential for remote sensing analysis and supervised classification, as they provide an accurate, up-to-date overview of the earth's surface.

Once on the USGS website, you can access a user-friendly interface to search, view and download the satellite images you require (Figure 5.1).

However, before starting to download images, it is essential to create an account on the site by clicking on Login then Create New Account.

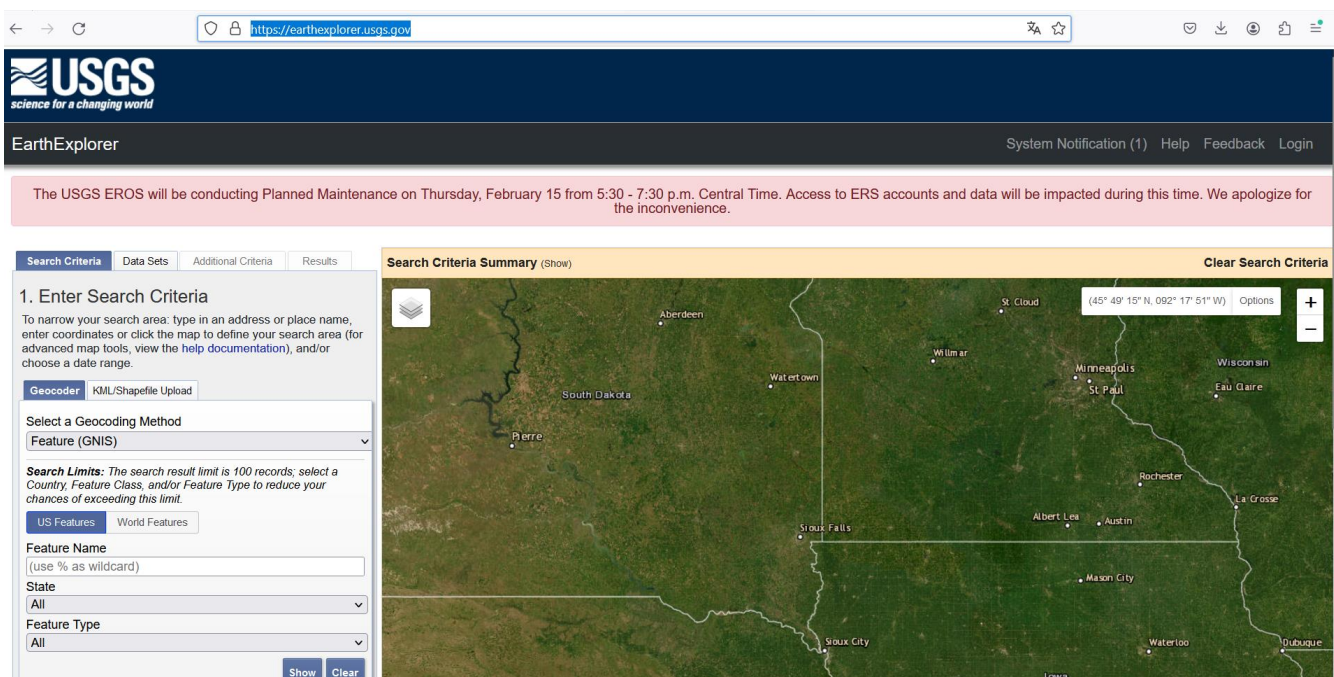


Figure 5.1. The main interface of the official USGS website

Once registered on the site, users can specify criteria such as geographical area of interest, acquisition date, sensor type and cloud cover to find the images most suited to their needs (Figure 5.2). Once selected,

images can be downloaded free of charge in various formats compatible with image processing and remote sensing software (Figure 5.3).

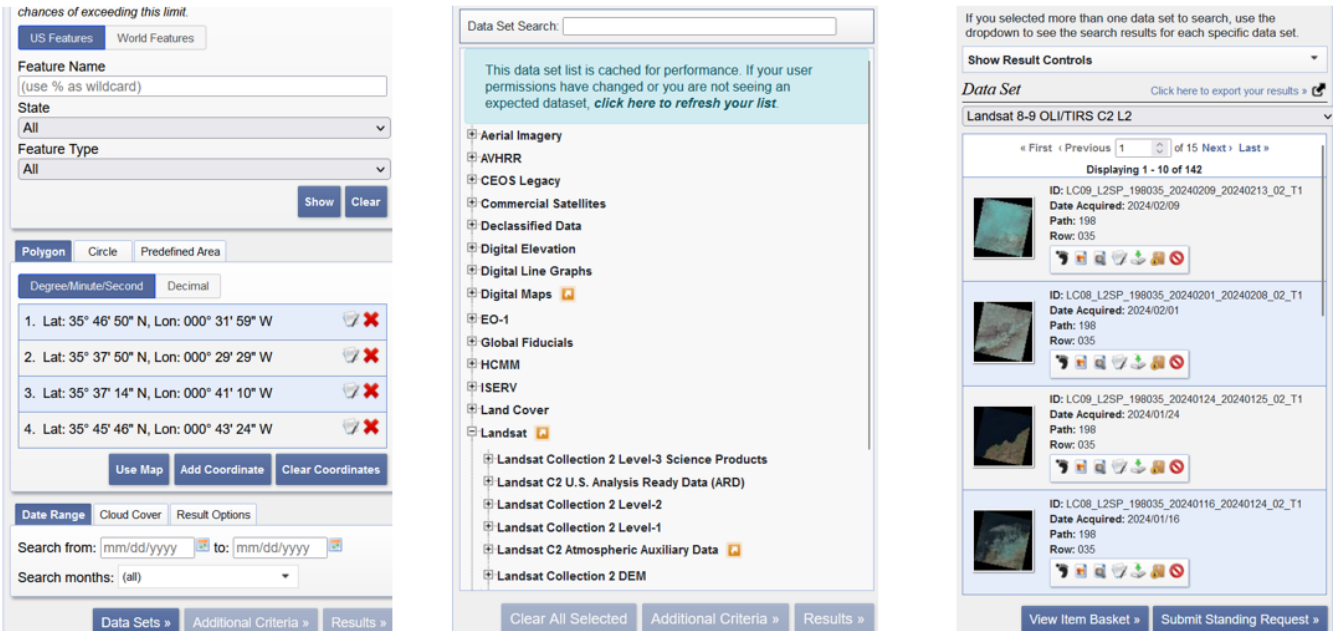


Figure 5.2. Specifying criteria before downloading satellite images

It should be noted that the availability of satellite images can vary according to mission, geographical area and acquisition date. It is therefore important to select the most relevant data to guarantee the accuracy and reliability of future analyses.

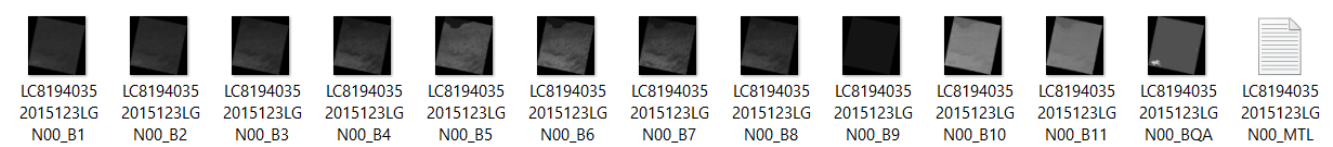


Figure 5.3. Extract of a Landsat 8 satellite image with the 11 suitable bands

The following support (<https://www.youtube.com/watch?v=j6PsBL8kPUo>) is an excellent example of how to download satellite images.

2- Practical work 2: Preparing data for classification

2-1 Applying Clip to data

Before starting the satellite image classification process, it is essential to clip the image. This essential step consists in delimiting and extracting only the study area, thus focusing the analysis on the targeted zone and minimizing the size of the data to be processed.

Selecting only the study area considerably reduces the amount of data to be manipulated, which has several significant advantages. Firstly, this allows for saving time and computational resources, as only relevant information is processed, speeding up the analysis and classification process. What's more, limiting data size makes it easier to store, manipulate and share images, which is particularly useful in cases where storage space is limited or when working with less powerful computer systems.

To do this, we first draw a rectangle using ArcGIS' Drawing functionality (Figure 5.4).

The second step is to execute the Clip using the Image Analysis function (Figure 5.5).

The software then slices the satellite image based on the drawn rectangle (Figure 5.6).

Once this step has been completed, it's time to save the strips. To do this:

Right-click (on the desired band) ----- Data ----- Export Data

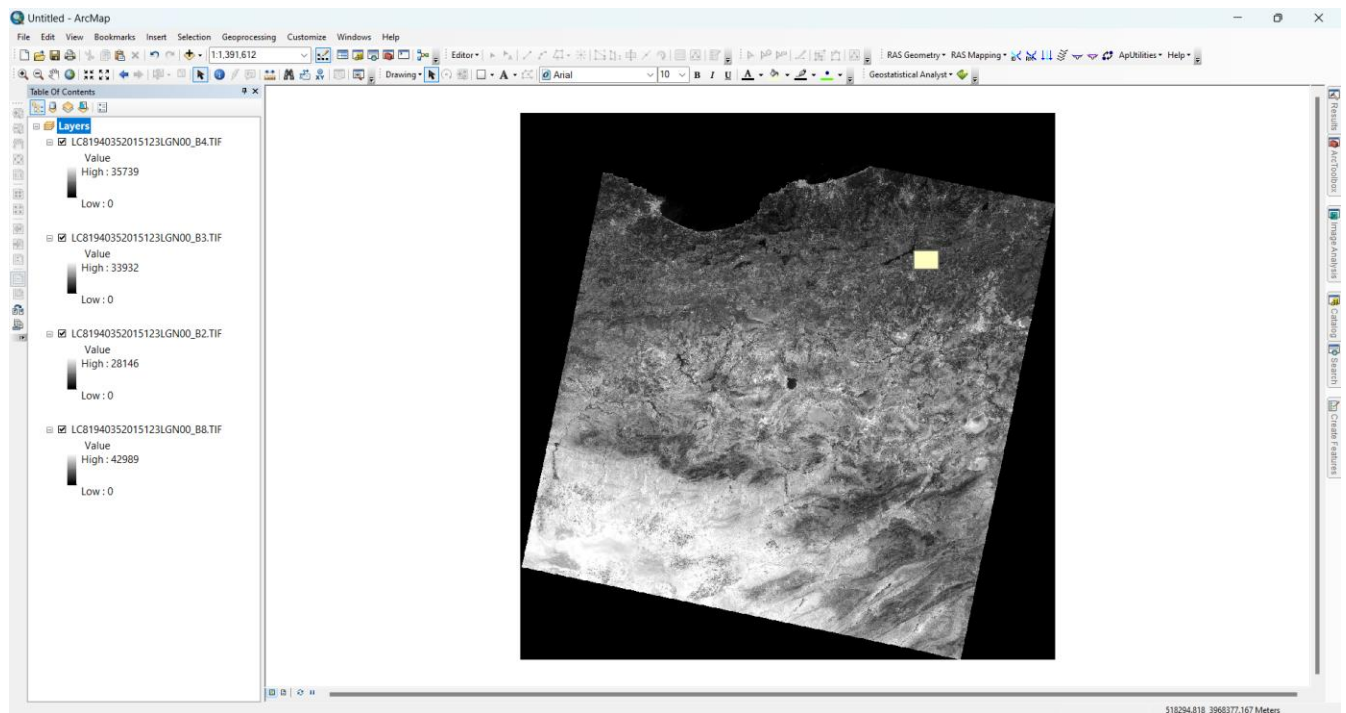


Figure 5.4. Data size limited by a rectangle expressing the study area

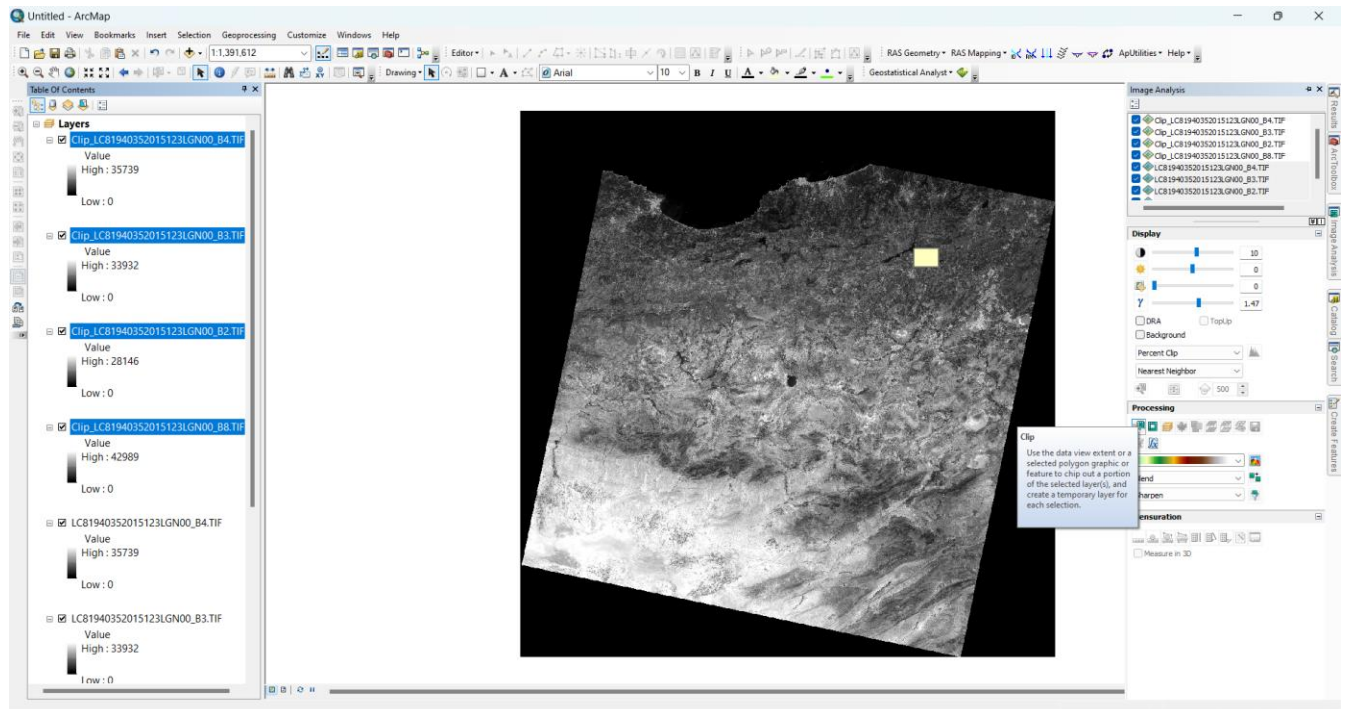


Figure 5.5. Clip functionality in ArcGIS

Observation

If the study area is an administrative Shapfile, we apply the mask extraction in this case:

Arc Toolbox ----- Spatial Analyst tools ----- Extraction ----- Extract by Mask

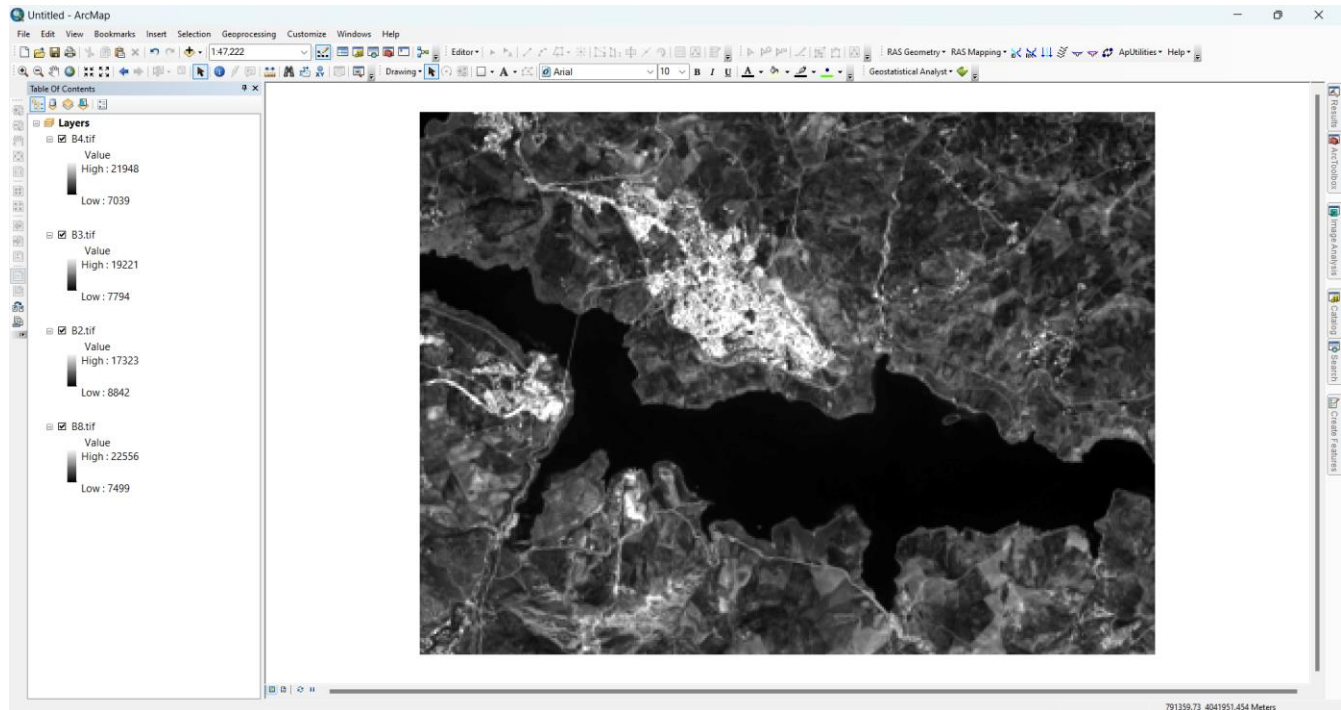


Figure 5.6. Final result of the Clip process in ArcGIS

2-2 Application of color composition

Once the study area has been selected and clipped, the second step is to create a color composite. In this example, the true/natural color composite consists of visualizing three channels taken from the visible spectrum, and assigning them the colors blue (band 4), green (band 3) and red (band 2) respectively.

This step involves running Composite Bands using the Image Analysis function.

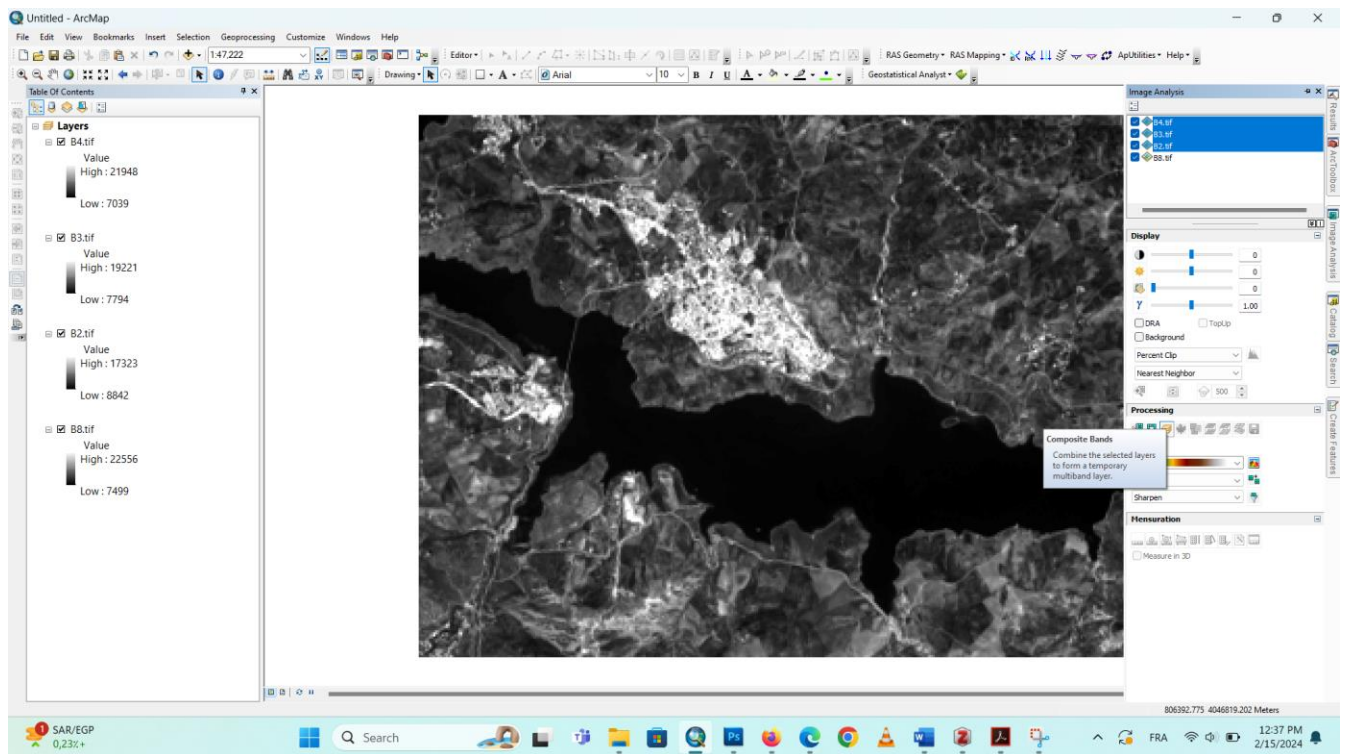


Figure 5.7. True/natural color composite production process

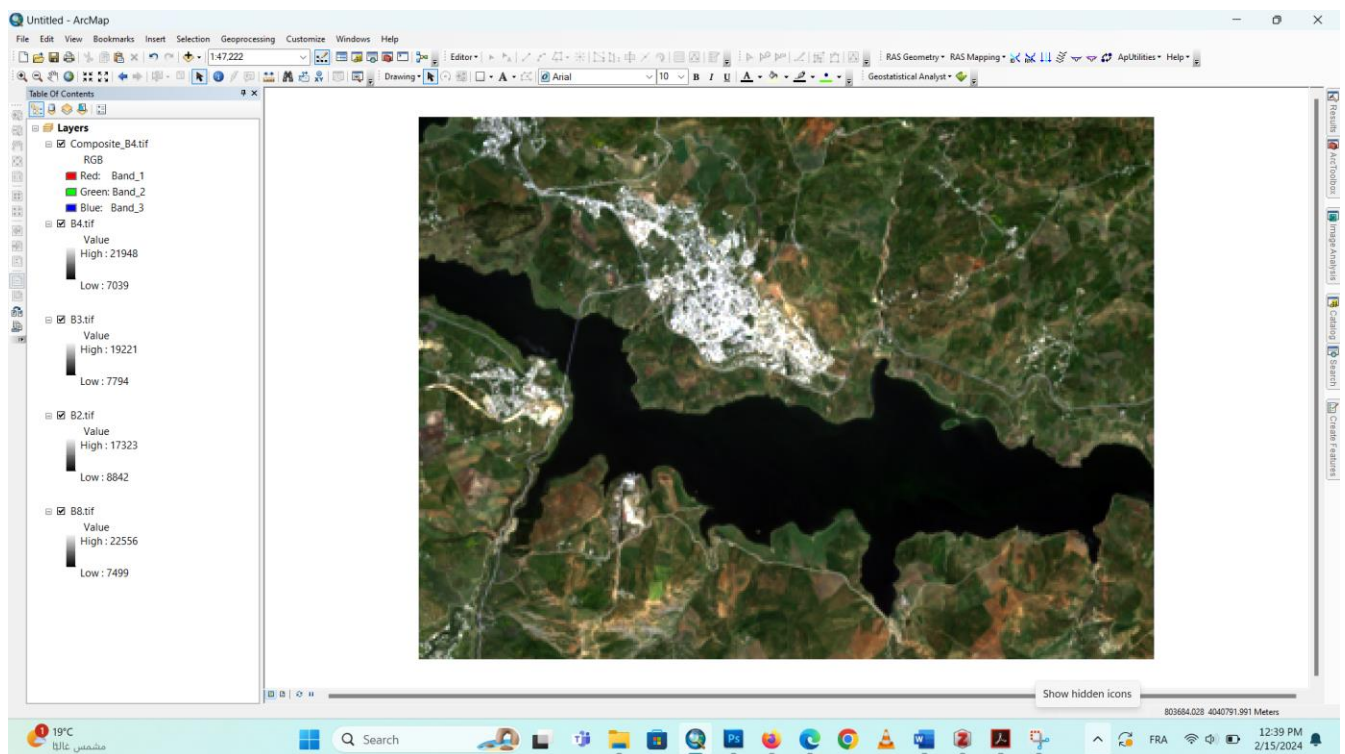


Figure 5.8. Result of 4-3-2 color composition

2-3 Data fusion (Pan-Sharpening)

Before starting supervised classification, it is important to increase the spatial resolution of the image. The aim is to make it easier to identify spatial features (land cover), which in turn enables training areas to be selected efficiently. The method involves using the 15m spatial resolution of the panchromatic band (band 8) to increase the spatial resolution of the multispectral image from 30m to 15m.

To do :

Arc Toolbox ----- Data Management Tools ----- Raster ----- Raster Processing ----- Create Pan-Sharpended Raster Dataset (Figure 2.6)

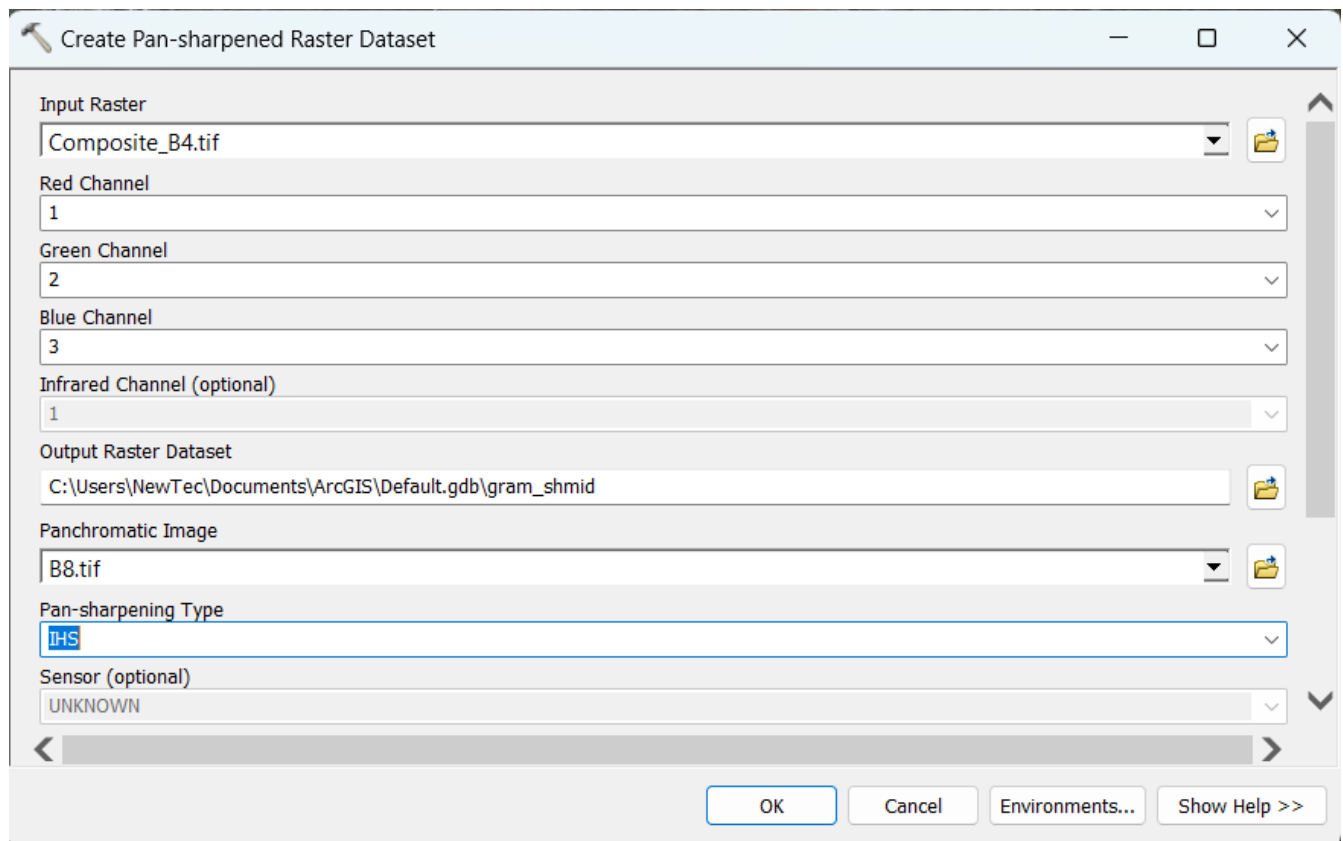


Figure 5.9. Processus de pan-sharpening sous ArcGIS

Several algorithms can be used (Gram-Schmidt, IHS, ESRI, BROVEY, Simple-mean). The optimal result can be achieved using the IHS algorithm (Figure 2.7).

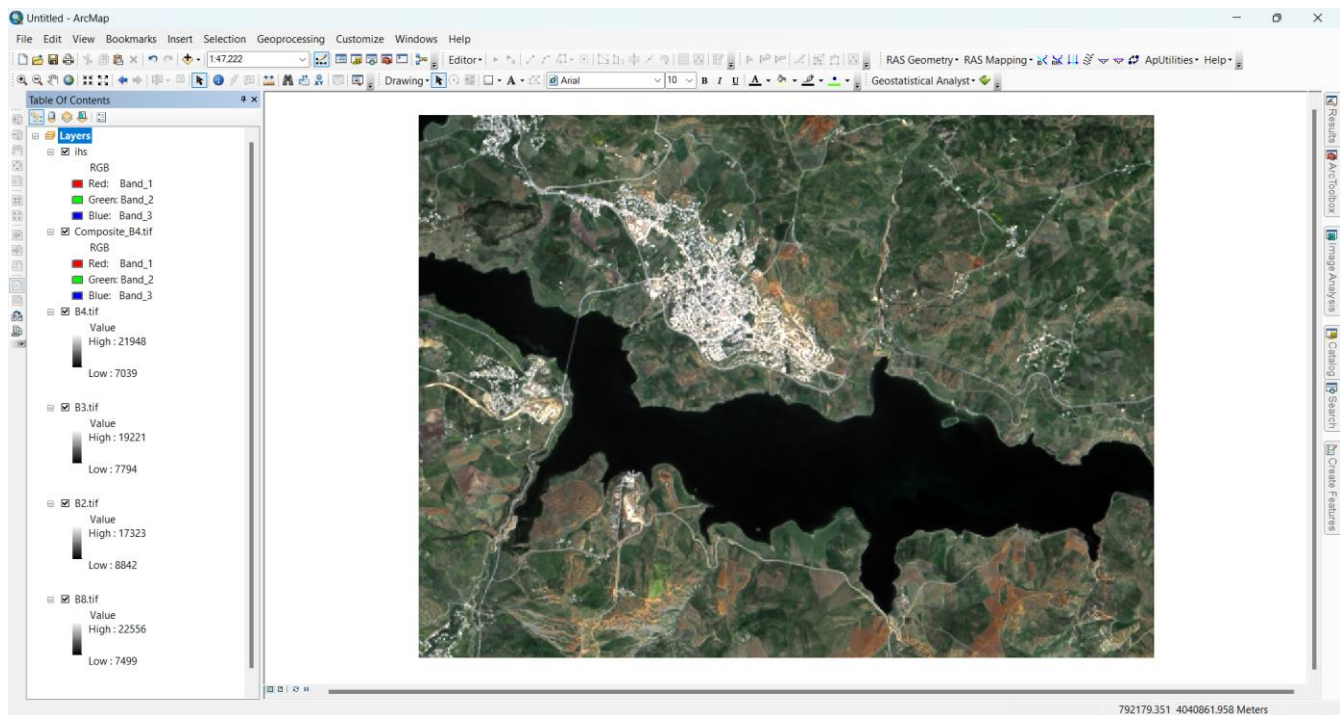


Figure 5.10. Result of pan-sharpening process (multispectral image with 15m spatial resolution)

3- Practical work 3: Application of supervised image classification

3-1 Selecting training areas and applying classification

Thanks to its Image Classification functionality, ArcGIS is a powerful software package for developing supervised classifications of satellite images. Once data preparation (Clip, Pan-Sharpening, etc.) has been completed, it is now possible to begin the classification process. The first step is to select the training areas (Region of interest). To do this, simply draw a set of polygons using the Draw Polygon function. Once the polygons have been drawn for each class (water surface, for example), we apply a polygon merge using the Merge Training Samples function. This collects all polygons into a single class (Figure 3.1).

For best results, it should be noted that the training areas should be selected randomly over the entire image area. Once complete, the training areas are saved.

The next step is to create a signature file. To do this, simply use the Create a signature file function.

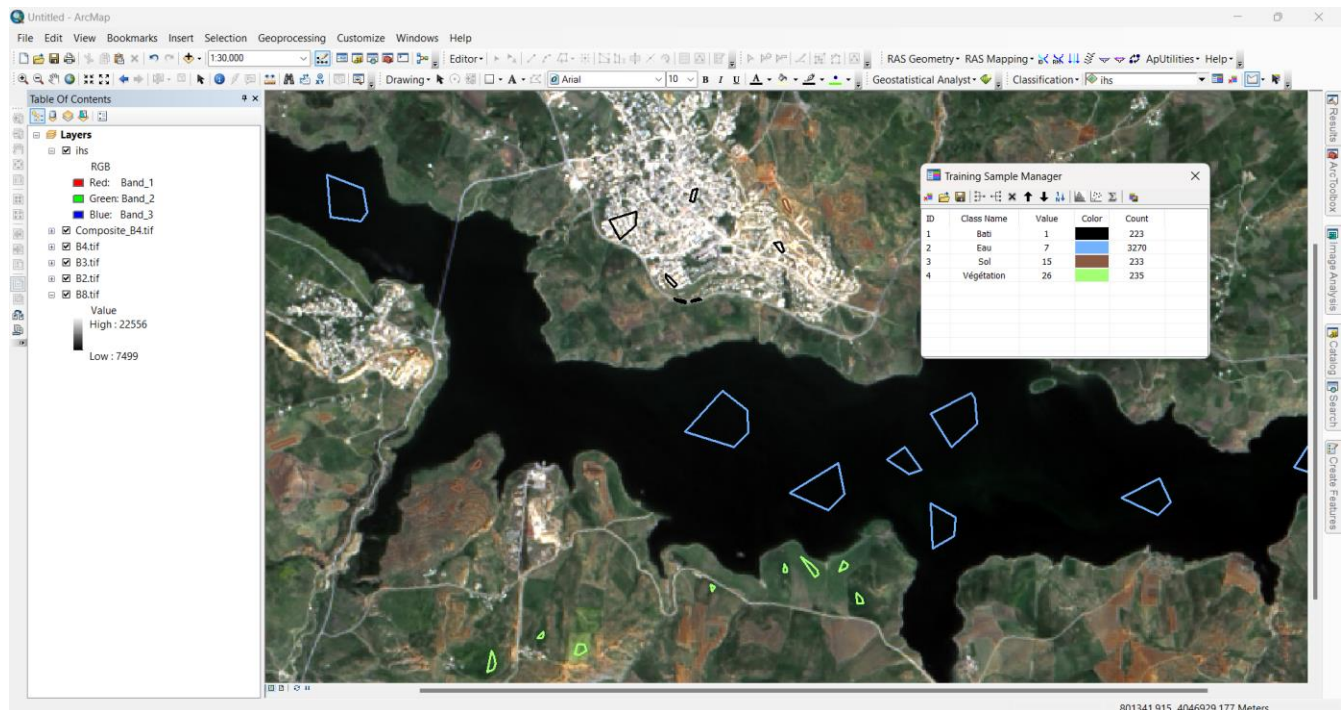


Figure 5.11. Training area selection process

To start the classification, select the Maximum Likelihood classifier from the toolbar and enter the necessary data. The results are shown in figure 3.2.

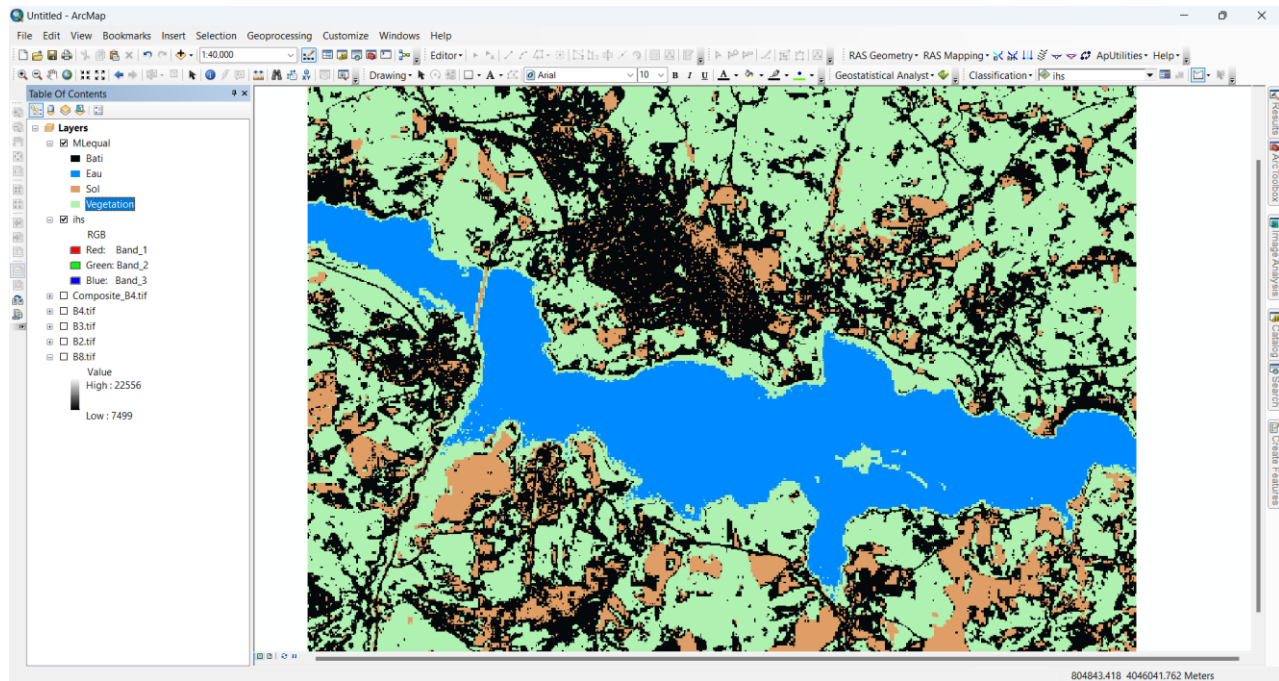


Figure 5.12. Maximum Likelihood supervised classification result

3-2 Improved classification quality (smoothing and aggregation)

The first step is to apply the Majority Filter. To do this:

Arc Toolbox ----- Spatial Analyst Tools ----- Generalization ----- Majority Filter

The second step is to apply Boundary Clean. To do this:

Arc Toolbox ----- Spatial Analyst Tools ----- Generalization ----- Boundary Clean

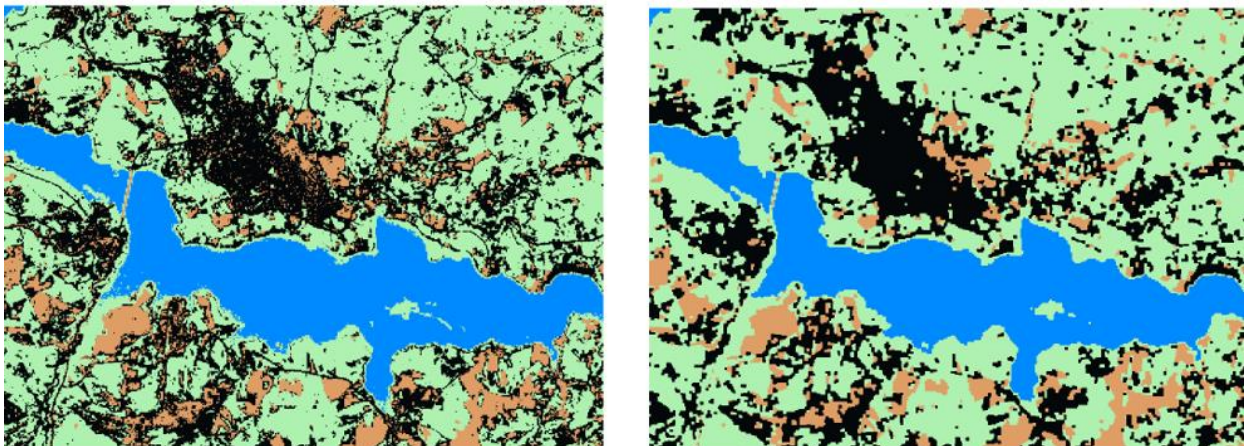


Figure 5.13. Result of majority filtering (left) and border cleaning (right)

The next step is to apply a Region Group. To do this :

Arc Toolbox ----- Spatial Analyst Tools ----- Generalization ----- Region Group

The next step is to apply a Set Null to eliminate classes smaller than 50 pixels.

To do this : Arc Toolbox ----- Spatial Analyst Tools ----- Conditional ----- Set Null

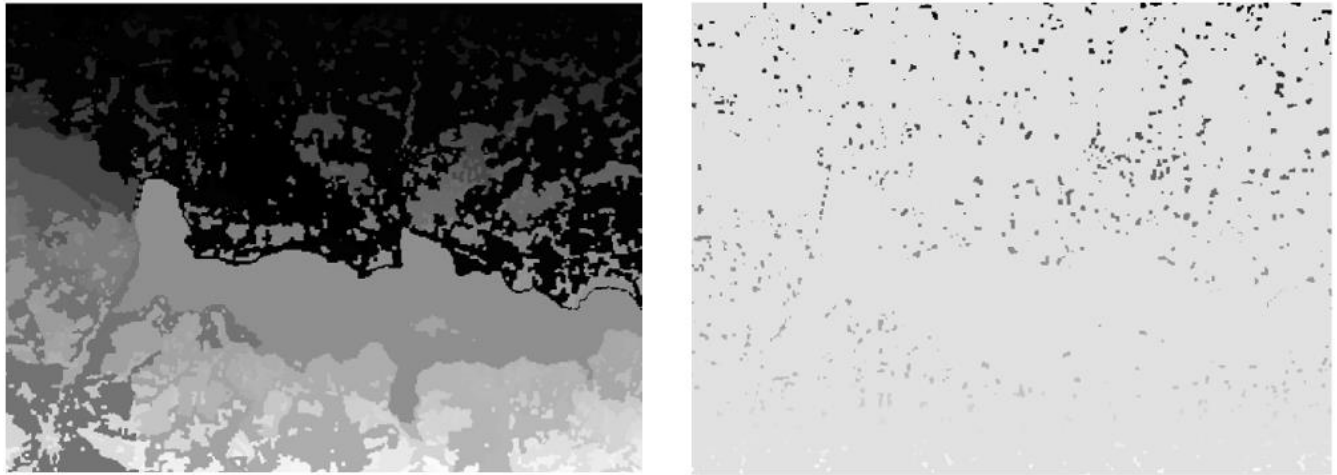


Figure 5.14. Result of applying the region group (left) and Set Null (right)

The final step is to apply a Nibble. To do :

Arc Toolbox ----- Spatial Analyst Tools ----- Generalization ----- Nibble

3-3 Assessment of classification accuracy

The method consists in comparing the image obtained by classification with a very high-resolution image from Google Earth or with samples taken in the field.

To do this, we first need to create a shapfile of the sampling points in Arc Catalog:

Arc Catalog ----- Right clic ----- New ----- Shapfile

Specify name, type and reference system. Points are then drawn over the entire study area.

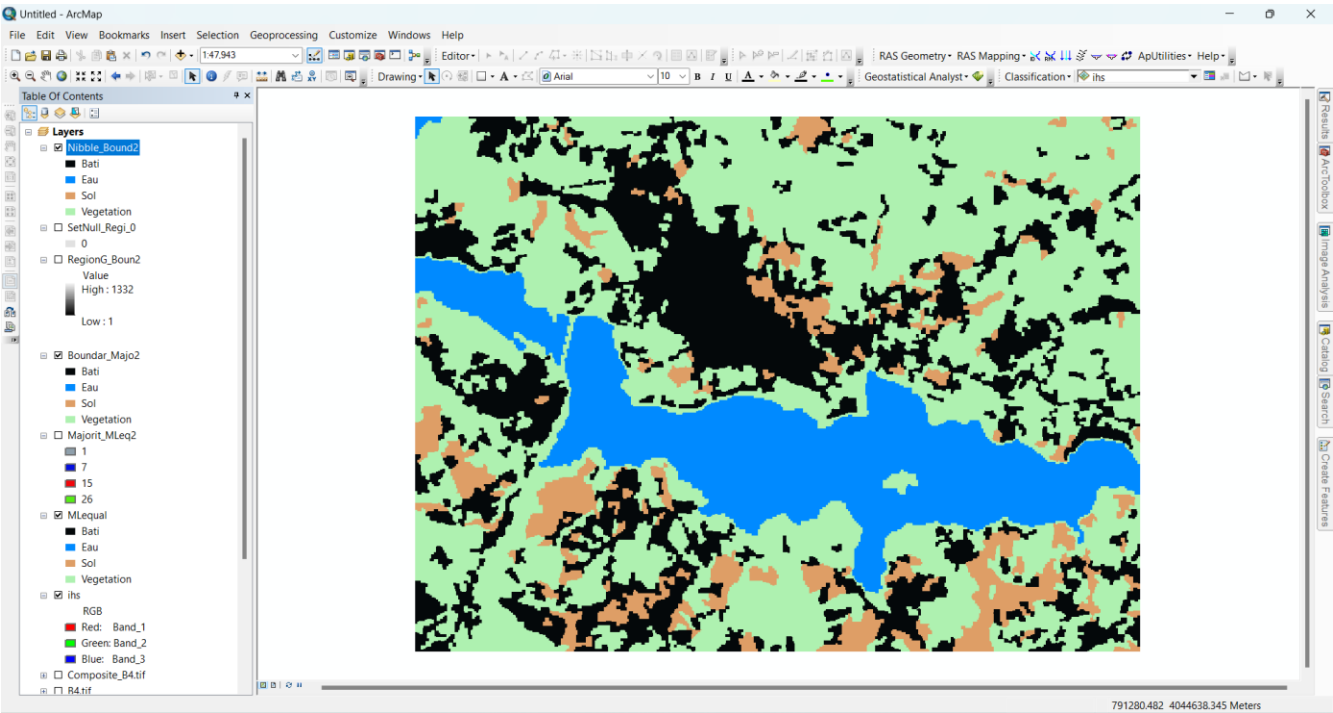


Figure 5.15. Final result of the aggregation and smoothing process

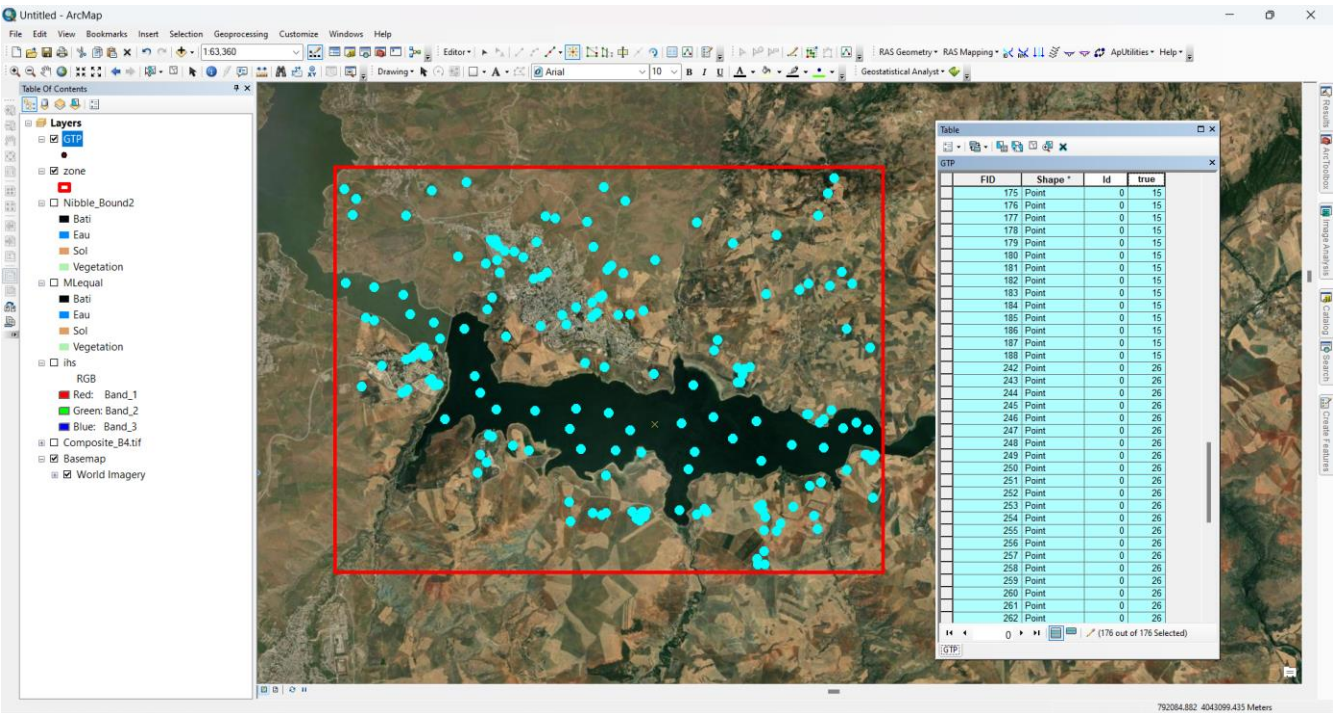


Figure 5.16. Capturing the truth of the terrain with a very high-resolution ArcGIS image

The next step is to compare the points obtained by classification with the points obtained by Google Earth. To do this, we use the Extract Values To Points feature.

Arc Toolbox ----- Spatial Analyst Tools ----- Extraction ----- Extract Values To Points

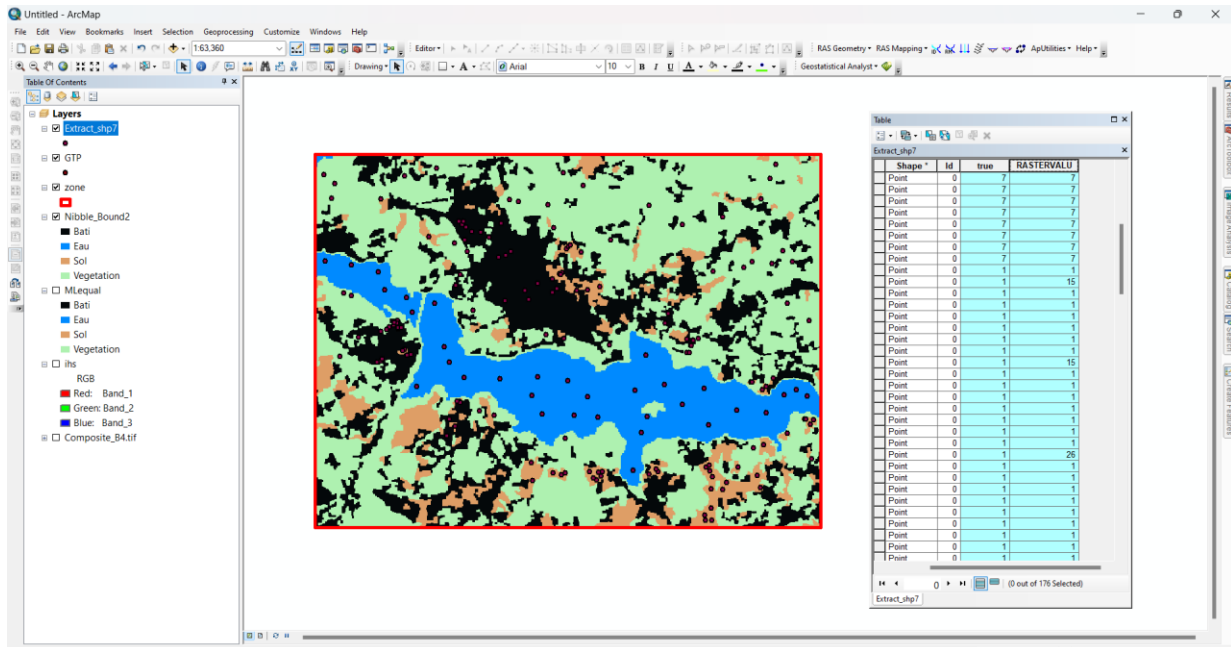


Figure 5.17. Process of extracting values through spatial analysis

The next step is frequency analysis

Arc Toolbox ----- Analysis Tools ----- Statistics ----- Frequency

The next step is to extract the cross-table

Arc Toolbox ----- Data Management Tools ----- Table ----- Pivot Table

	OBJECTID *	RASTERVALU	true1	true15	true26	true7
▶	1	1	29	5	7	0
	2	7	0	0	1	32
	3	15	4	48	4	0
	4	26	3	0	43	0

Figure 5.18. Matrix of well and poorly classified pixels

Class 1 is buildings, class 2 is water, class 15 is soil, and class 26 is vegetation.

Using Excel software, it's easy to calculate the accuracy (Figure 5.19)

	Bâti	Eau	Sol	Végétation	Total	Producer accuracy
Bâti	29	0	5	7	41	0.71
Eau	0	32	0	1	33	0.97
Sol	4	0	48	4	56	0.86
Végétation	3	0	0	43	46	0.93
Total	36	32	53	55	176	
User accuracy	0.81	1.00	0.91	0.78		

total accurate	152	
Overall accuracy	0.86	(29+32+48+43)/176
Kappa coefficient	0.81	

Figure 5.19. Calculation of classification accuracy

3-3-1 Overall accuracy

$$\begin{aligned}
 \text{Overall accuracy} &= \frac{\text{Number of correctly classified pixels (diagonal)}}{\text{Total number of reference pixels}} \times 100 \\
 &= \frac{(29 + 32 + 48 + 43)}{176} \times 100 = 86.36\%
 \end{aligned}$$

3-3-2 Kappa Index

$$\text{Kappa coefficient} = \frac{(TS \times TCS) - \sum(\text{column total} \times \text{row total})}{(TS^2) - \sum(\text{column total} \times \text{row total})} \times 100 = 81.59\%$$

4- Practical work 4: Application of remote sensing to surface hydrology

The present practical work is dedicated to the extraction of the hydrographic network and the watershed. To this end, a digital terrain model is downloaded and applied.

4-1 Correction of data imperfections (Fill)

ArcToolBox ----- Spatial Analyst Tools ----- Hydrology ----- Fill

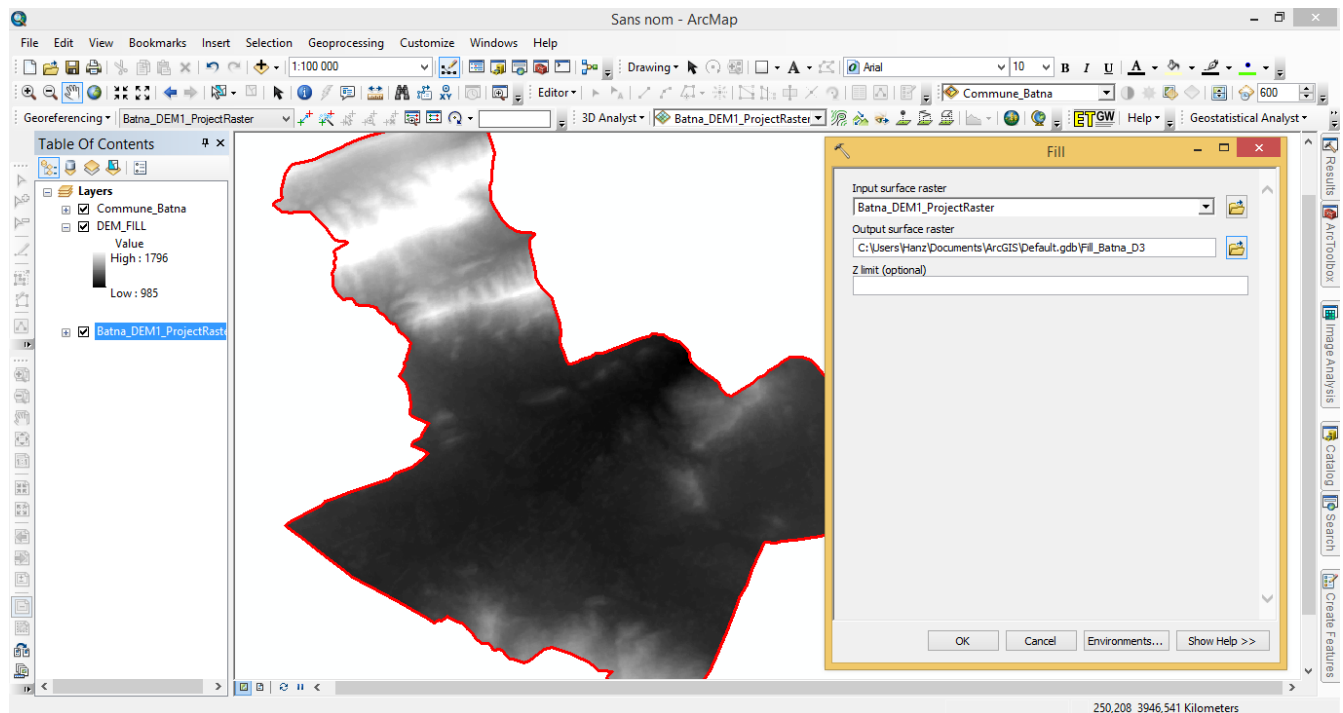


Figure 5.20. Correction of digital terrain models using the FILL function

4-2 Extraction of Flow Direction

ArcToolBox ----- Spatial Analyst Tools ----- Hydrology ----- Flow Direction

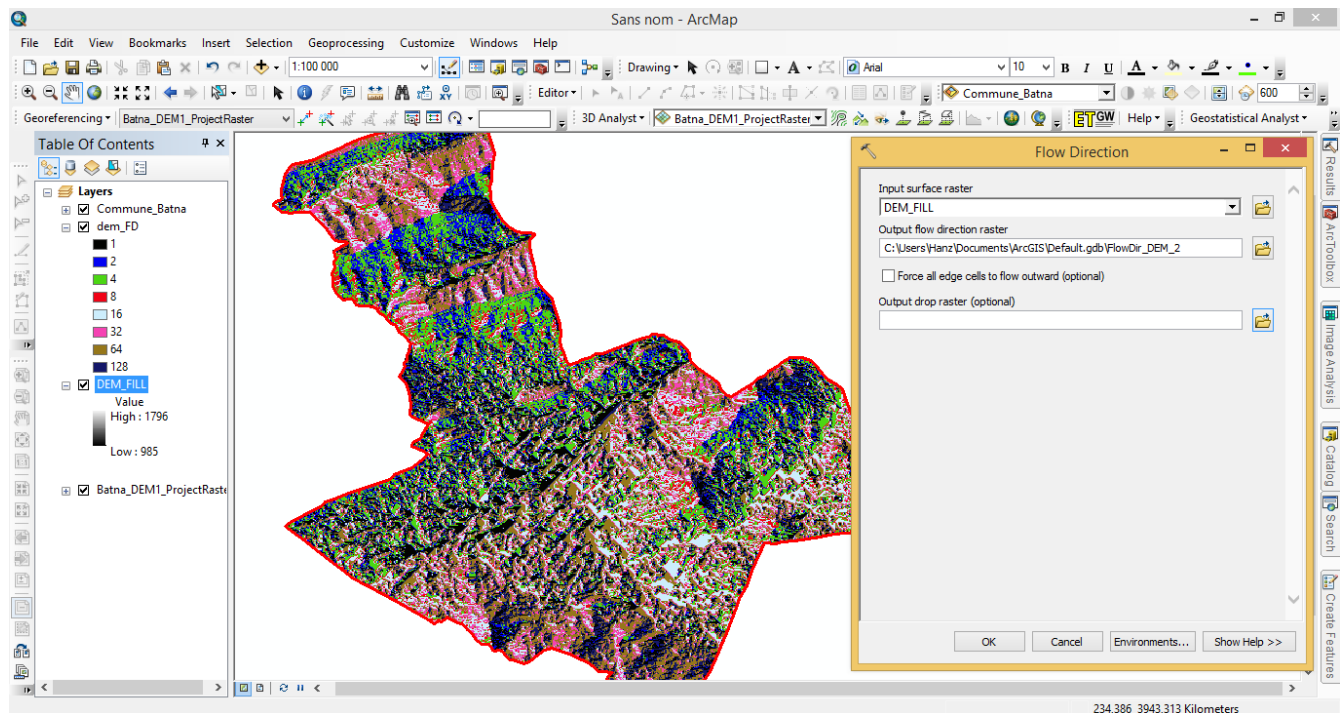


Figure 5.21. Flow direction extraction result

4-3 Extraction of Flow Accumulation

ArcToolBox ----- Spatial Analyst Tools ----- Hydrology ----- Flow Accumulation

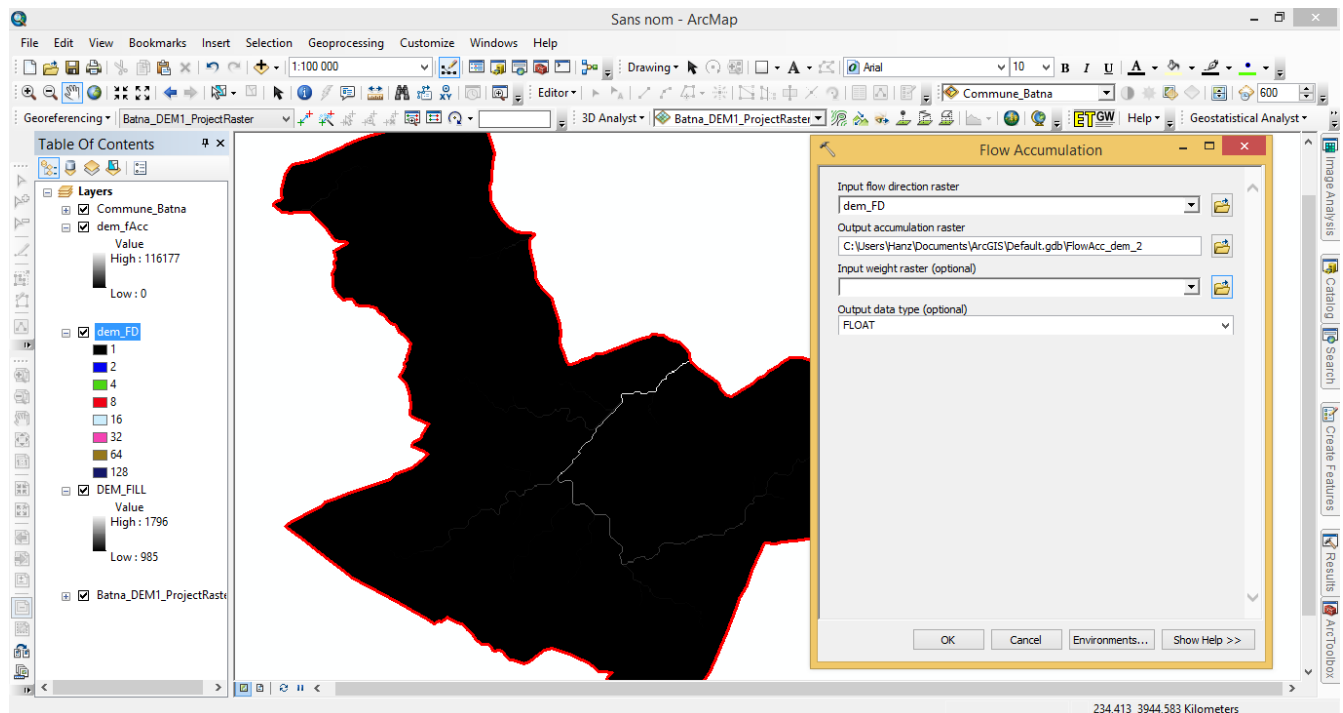


Figure 5.22. Flux accumulation extraction result

4-4 Conditional

The Con feature is used to determine the density of the hydrographic network. In our case, density 200 is adequate.

ArcToolBox ----- Spatial Analyst Tools ----- Conditional ----- Con

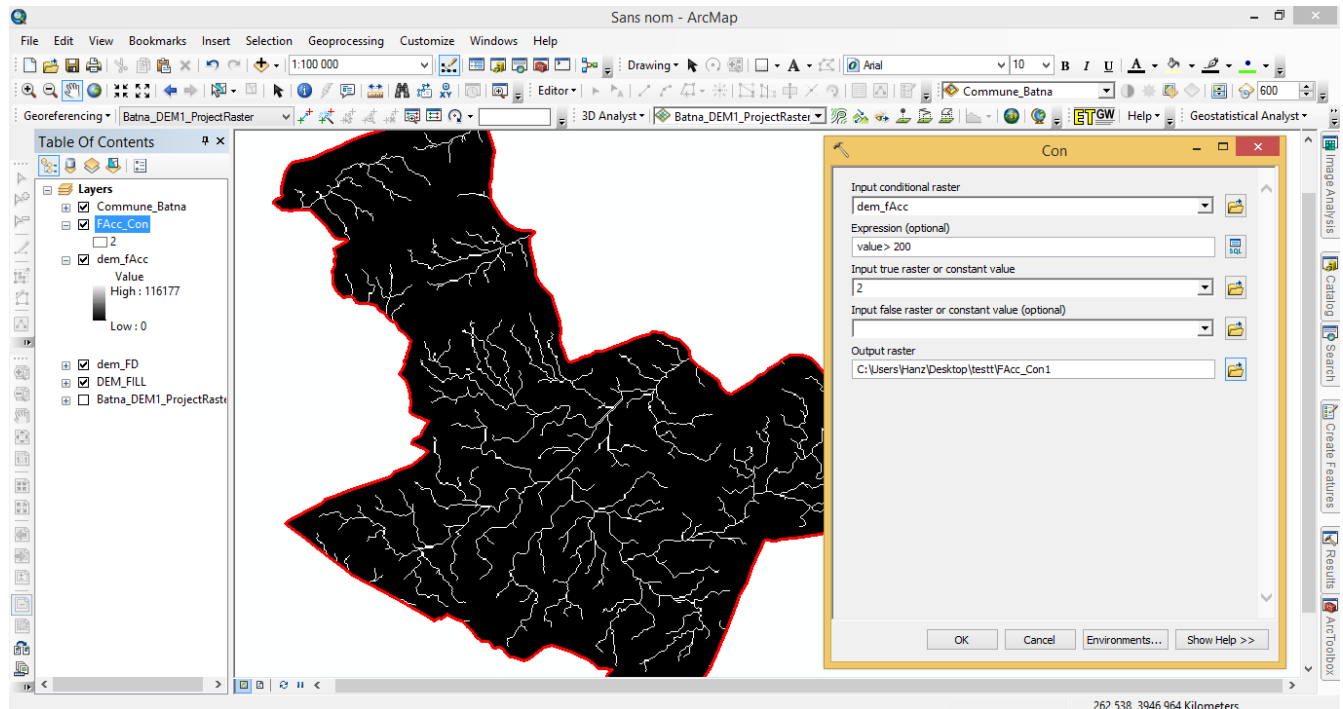


Figure 5.23. Application of the Value > 200 condition

4-5 Stream to Feature conversation application

ArcToolBox ----- Spatial Analyst Tools ----- Hydrology ----- Stream to Feature

4-6 Watershed (watershed delimitation)

Before delimiting the boundaries of the watershed, we must first create a point representing an outlet.

In ArcCatalog Clic Droit ----- New ----- Shapfile ----- Point ----- Ok

ArcToolBox ----- Spatial Analyst Tools ----- Hydrology ----- Watershed

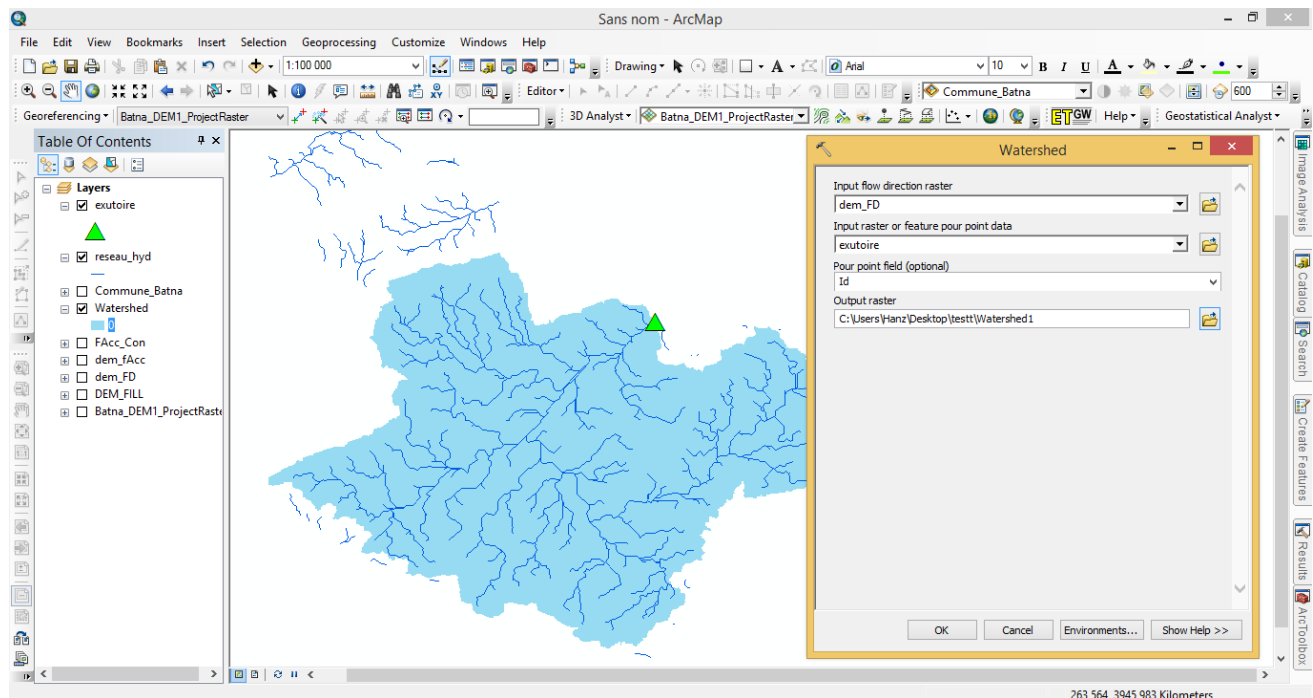


Figure 5.24. Watershed delimitation

Once the watershed has been defined, the next step is to convert it into a polygon. To do this:

ArcToolBox ----- Conversion Tools ----- From Raster ----- Raster to Polygone

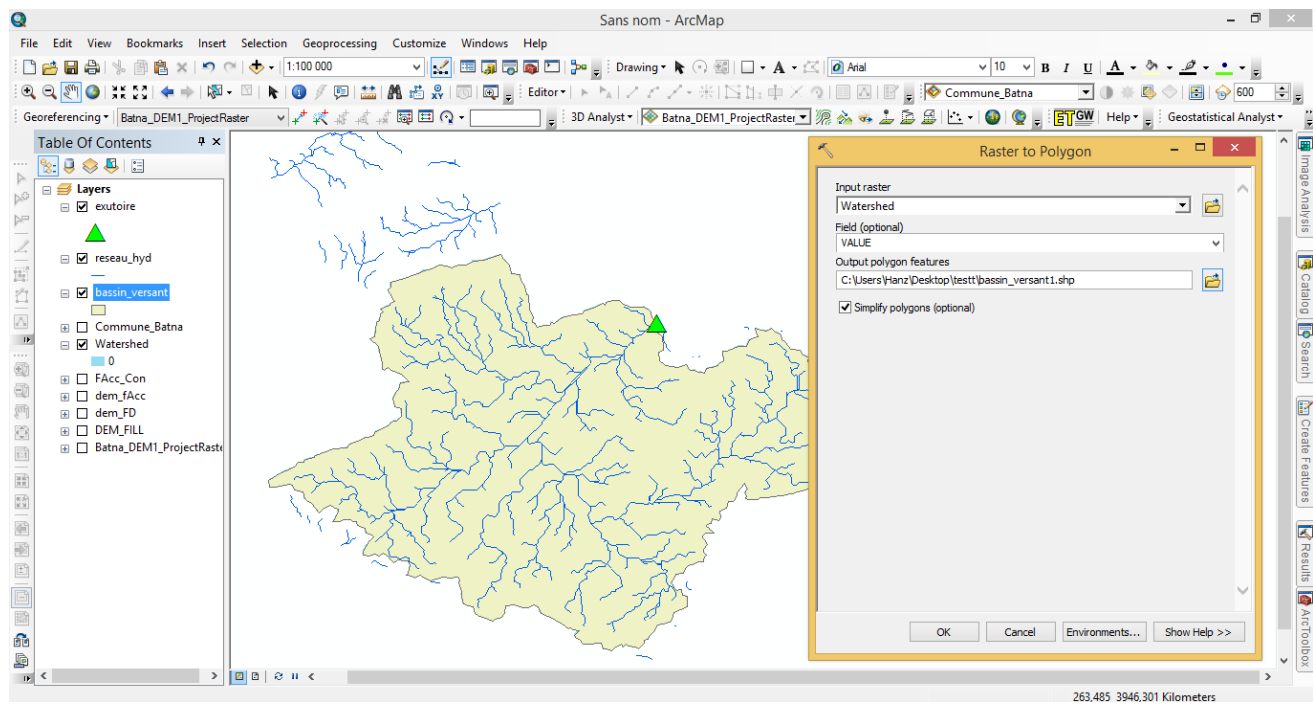


Figure 5.25. Watershed polygon conversation result

4-7 Stream Order (Classification of talwegs)

ArcToolBox ----- Spatial Analyst Tools ----- Hydrology ----- Stream Order

Une fois l'ordre des talwegs est effectué, une seconde étape consiste à convertir le réseau en polyligne.

ArcToolBox ----- Conversion Tools ----- From Raster ----- Raster to Poline

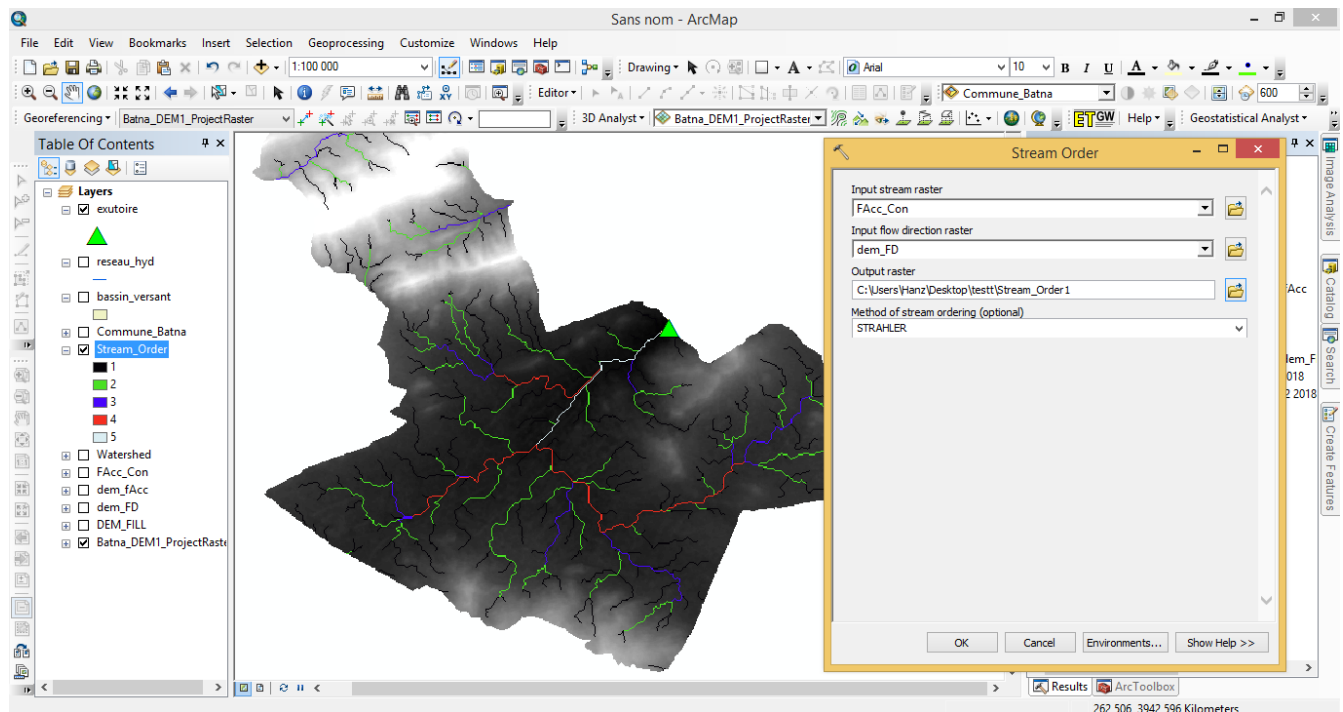


Figure 5.26. Schumm method for river network classification

The final step consists in making a cut (Clip) between the watershed and the hydrographic network, to make: Geoprocessing ----- Clip

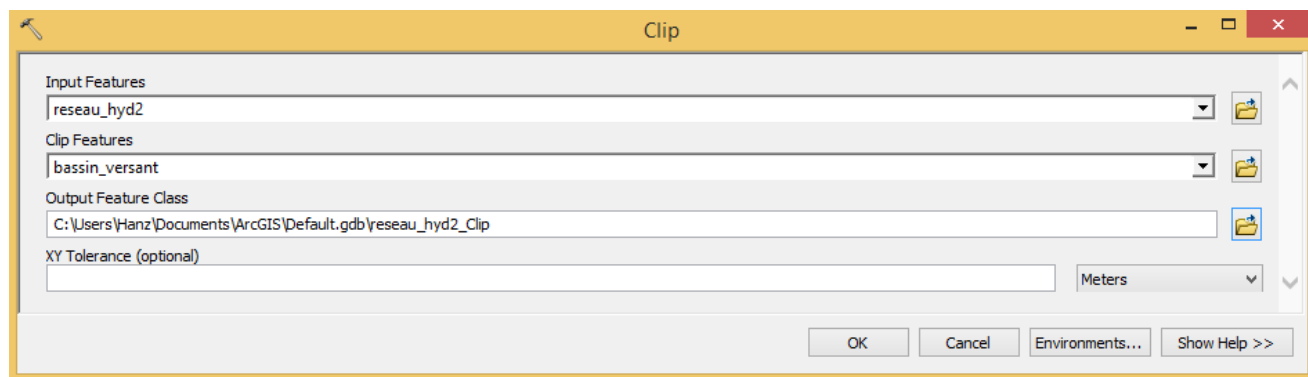


Figure 5.27. Clip process of the hydrographic network using the basin as a reference

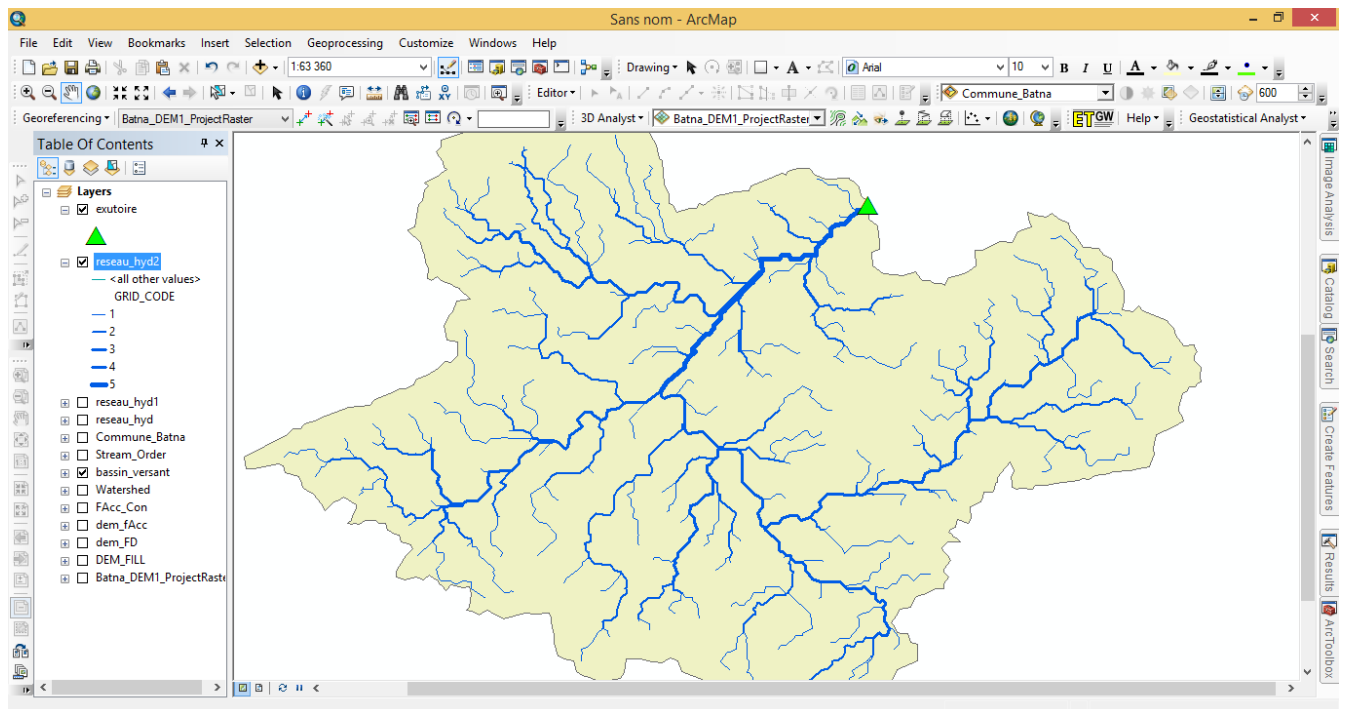


Figure 5.28. Final result of hydrographic network extraction and watershed delineation

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