QUICK REFERENCE GUIDE
on
Remote Sensing

Regional Remote Sensing Centre-North
National Remote Sensing Centre, ISRO

Quick Reference Guide

On

Remote Sensing

Regional Remote Sensing Centre-North

National Remote Sensing Centre

Indian Space Research Organisation

भारत सरकार
अन्तरिक्ष विभाग
राष्ट्रीय सुदूर संवेदन केन्द्र
बालानगर, हैदराबाद-500 037, तेलंगाना, भारत
टेलिफोन : +91 40 23884001 / 04

Government of India
Department of Space
National Remote Sensing Centre
Balanagar, Hyderabad-500 037, Telangana, India
Telephone: +91 40 23884001 / 04

डॉ. प्रकाश चौहान / Dr. Prakash Chauhan
उत्कृष्ट वैज्ञानिक & निदेशक
Outstanding Scientist & Director

Foreword

National Remote Sensing Centre (NRSC) is one of the primary centres of Indian Space Research Organisation (ISRO), Department of Space (DOS) for developing remote sensing applications, establishing ground stations for receiving satellite data and generating high-quality satellite data and aerial data products. Regional Remote Sensing Centres (RRSC) are part of NRSC supporting various remote sensing tasks specific to their regions at the national level.

In today's rapidly evolving technological landscape, remote sensing has become an indispensable tool for observing, understanding, and managing our world. From environmental monitoring and disaster response to urban planning and agriculture, remote sensing technologies provide critical insights that were once beyond our reach.

This Quick Reference Guide on Remote Sensing, meticulously prepared by RRSC-North, serves as a comprehensive and accessible resource for students, researchers, and professionals.

I am confident that this reference guide will serve as a valuable resource, equipping readers with the knowledge and skills necessary to leverage Remote Sensing technology in their respective fields. It is my hope that this guide will serve as a valuable tool in your exploration and application of this dynamic field, equipping you with the knowledge to navigate and leverage remote sensing effectively.

September 17, 2024

(Prakash Chauhan)

भारत सरकार
अंतरिक्ष विभाग
भारतीय अंतरिक्ष अनुसंधान संगठन
राष्ट्रीय सुदूर संवेदन केंद्र
प्लॉट सं. 7, प्लानिंग एरिया सेंटर, जे.बी. टीटो मार्ग
सादिक नगर, नई दिल्ली 110 049

Government of India
Department of Space
Indian Space Research Organisation
National Remote Sensing Centre
Plot No. 7, Planning Area Centre, J.B. Tito Marg
Sadiq Nagar, New Delhi 110 049

डॉ. एस. के. श्रीवास्तव
मुख्य महाप्रबंधक (क्षेत्रीय केंद्र)
Dr. S. K. Srivastav
Chief General Manager (Regional Centres)

दूरभाष/ Telephone: 011-26400754
ईमेल/ Email: cgm@nrsc.gov.in
sksrivastav@nrsc.gov.in

From The Chief General Manager's Desk

National Remote Sensing Centre (NRSC) has five Regional Remote Sensing Centres (RRSCs) spread across the country. These centres are involved in addressing the local and regional issues using space and geospatial technology and also actively participate in capacity building as well as outreach activities in their respective regions. RRSC-North, located at New Delhi, caters to the needs of users in the Northern states of India viz. Delhi, Himachal Pradesh, Jammu & Kashmir, Uttar Pradesh and Uttarakhand. RRSC-North also organises training programmes and workshops on topics related to remote sensing, geographic information systems, digital image processing and their applications for government officials, academia and students.

I am extremely happy that RRSC-North has prepared a "Quick Reference Guide on Remote Sensing." Basic concepts of Remote Sensing are covered in a crisp and lucid manner in this compilation. I am sure that this reference guide will be helpful for the beginners to get familiar with the concepts of Remote Sensing in a short time.

एस. के. श्रीवास्तव

S. K. Srivastav
Chief General Manager (Regional Centres)
NRSC

भारत सरकार
अंतरिक्ष विभाग
भारतीय अंतरिक्ष अनुसंधान संगठन
राष्ट्रीय सुदूर संवेदन केंद्र
क्षेत्रीय सुदूर संवेदन केंद्र – उत्तर
प्लॉट सं.7, प्लानिंग एरिया सेंटर, जे.बी. टीटो मार्ग
सादिक नगर, नई दिल्ली 110 049

Government of India
Department of Space
Indian Space Research Organisation
National Remote Sensing Centre
Regional Remote Sensing Centre- North
Plot No. 7, Planning Area Centre, J.B. Tito Marg
Sadiq Nagar, New Delhi 110049

डॉ. समीर सरन
उप महाप्रबंधक, क्षेत्रीय सुदूर संवेदन केंद्र - उत्तर
Dr. Sameer Saran
Deputy General Manager, Regional Remote Sensing Centre- North

दूरभाष/ Telephone: 011-26400746
ईमेल/ Email: sameer_s@nrsc.gov.in
gmrc_n@nrsc.gov.in

About the Book

Reference guide on Remote Sensing provides a thorough understanding of key concepts and practical applications of Remote Sensing. It begins with an Introduction to Remote Sensing, covering the basic principles of data collection using electromagnetic wavelengths. It explains energy-matter interactions, distinguishing passive from active sensing, and highlights various applications.

It explores Remote Sensing Platforms, Sensors & Instruments, including satellites, drones, and ground-based systems, discussing their suitability for various data collection needs. It details different sensors—optical, radar, microwave, and thermal—outlining their capabilities and limitations. The chapter on Image Acquisition and Data Processing covers essential steps in converting raw data into usable information.

Advanced topics include Microwave Remote Sensing, which uses radar to penetrate clouds and vegetation, and Hyperspectral Remote Sensing, which captures detailed spectral data for land cover and mineral analysis. Thermal Remote Sensing and LiDAR are also explored, focusing on 3D terrain modelling and tree height estimation.

The study material will be helpful for understanding the Remote Sensing concepts in an easier and lucid manner for the benefit of the beginners in the field of Remote Sensing.

समीर सरन

Sameer Saran
Deputy General Manager,
RRSC-North, NRSC

Index

Chapter 1

Introduction to Remote Sensing

1.1. Background

Remote sensing refers to the process in which some device or sensor records information on any property of objects and phenomena without being in physical contact with the object and phenomena. By definition, Remote sensing is the science of measuring, detecting and monitoring the physical properties of a target object/area without coming in direct contact with the target, usually by measuring the reflected or emitted radiation at a distance (Lillesand and Keifer, 1987, Joseph 1996, and Jensen, 2000, & 2005). The human eye also works on the same principle in which observations and recording of objects are done by being in physical contact with the objects. The human eye responds to light in a minute portion of the total energy received and responded to by the object's surface. In remote sensing, the reaction is a much more comprehensive range of radiations reflected/absorbed/transmitted by the objects and primarily involves an object surface, recording sensor, and reflected energy or information. There are different stages in remote sensing to understand the concept of remote sensing.

1.2. Electromagnetic Spectrum

Remote sensing relies fundamentally on the distribution of energy across the electromagnetic spectrum. This encompasses the entire range of electromagnetic radiation, from radio waves to gamma rays, each characterized by distinct wavelengths and frequencies, despite all electromagnetic waves traveling at the speed of light in a vacuum; they exhibit a broad spectrum of frequencies, wavelengths, and photon energies. This spectrum includes numerous subranges, often termed portions, such as visible light and ultraviolet radiation. Each portion is distinguished by unique characteristics in emission, transmission, absorption, and practical applications. Boundaries between these contiguous portions are not rigidly defined, leading to overlapping ranges. Figure 1.1 shows the Electromagnetic (EM) spectrum.

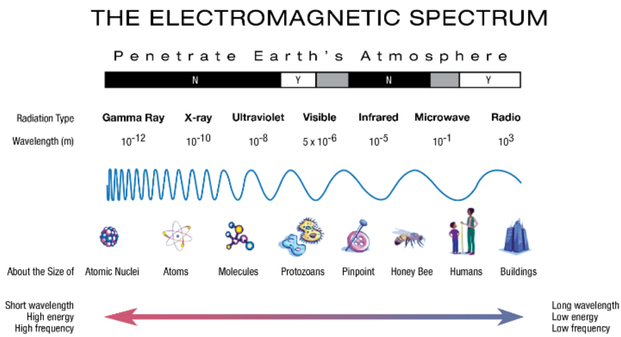


Figure 1.1: Diagram of Electromagnetic Spectrum (*Source: https://mynasadata.larc.nasa.gov/basicpage/electromagnetic-spectrum-diagram*)

Visible region is from 380 to 750 nanometers (nm) and is categorized into three primary intervals: blue, green, and red wavelength bands. These intervals, or bands, are distinguished based on their distinct characteristics within the electromagnetic spectrum. Additionally, terms like "channel" or "red channel" are sometimes used interchangeably to refer to specific wavelength bands, such as the red channel. The human eye senses visible light. It detects and interprets wavelengths in the visible spectrum, allowing us to perceive colors ranging from violet to red. This ability enables us to see and interpret our surroundings based on the light reflected from objects.

Adjacent to visible light, on its shorter wavelength side, lies Ultraviolet (UV) radiation from 10 to 380 nanometers (nm) while on its longer wavelength side are Near Infrared (NIR) and Thermal Infrared (TIR) wavelengths. The NIR wavelength region is sometimes referred to as Very Near Infrared (VNIR) and includes the Shortwave Infrared (SWIR) region (1400 to 3000 nm). The boundary between reflected and emitted infrared typically occurs around 3 micrometers (µm). Most of the optical sensors like multispectral and hyperspectral works in visible and infrared region.

Further along the longer wavelength side of the electromagnetic spectrum lie microwaves, extensively employed in radar systems. These microwaves enable observation of the Earth's surface day and night, supporting remote sensing applications that involve measuring reflected signals for various purposes, such as weather monitoring and Earth observation. Table 1 outlines the ranges, descriptions, and typical applications for each region of the electromagnetic spectrum. Each region offers unique capabilities that are utilized across various scientific, industrial, and practical fields.

Table 1: Different spectral regions used in remote sensing

Region	Wavelength Range	Description
Ultraviolet (UV)	10 nm - 380 nm	Shorter wavelengths than visible light, not visible to the human eye.
Visible Light	380 nm - 750 nm	Spectrum visible to the human eye, includes colors from violet to red.
Near Infrared (NIR)	750 nm - 1400 nm	Just beyond visible spectrum, useful for vegetation, mineralogy and material analysis.
Shortwave Infrared (SWIR)	1400 nm - 3000 nm	Extends further into infrared, useful for moisture detection, mineralogy and penetration.
Midwave Infrared (MWIR)	3 µm - 5 µm	Mid-range infrared wavelengths, sensitive to heat emissions.
Longwave Infrared (LWIR)	8 µm - 14 µm	Longer infrared wavelengths, used for thermal imaging and heat detection.
Far Infrared (FIR)	15 µm - 1000 µm	Farther infrared wavelengths, important for remote sensing of colder objects.
Microwave	1 mm - 1 m	Longer wavelengths than infrared, used for penetrating clouds and ground imaging.
Radio	1 m - kilometres	Longest wavelengths, used for communication and radar applications.

1.3. Stages in Remote Sensing

Human eyes and photographic systems are sensitive to a small portion of the total energy radiated by the Earth's surface objects. Advanced sensors now have the capability to capture a much broader range of wavelengths of radiation emitted or reflected by any surface. Photographic systems operate on similar principles to human vision, observing and recording objects on the Earth's surface. Remote sensing systems consist of sensors that capture electromagnetic radiation emitted or reflected from various objects and surfaces. These sensors then convert this radiation into numerical data stored in a format compatible with computers. This stored data then further processed and transformed into an image using specialized software on a computer. Remote sensing process is depicted in figure 1.2 and involves elements mentioned below:

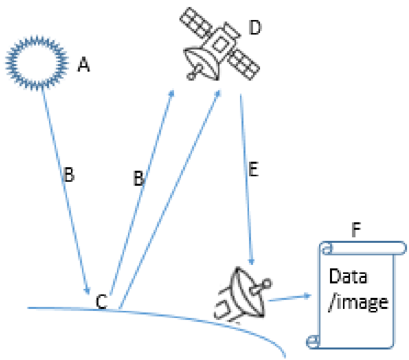


Figure 1.2: Major stages of the remote sensing process

- Source of energy (A)
- Propagation of energy through the atmosphere (B)
- Interaction of EM radiation with the object (C)
- Recording of the EM radiation by sensor onboard satellite (D)
- Transmission, reception, and processing of the recorded data (E)
- Analysis and interpretation of the processed data (F)

1.4. Types of Remote Sensing

Remote sensing systems are classified into two main groups based on their technical approach (Figure 1.3). Passive remote sensing systems detect and measure existing radiation, such as solar radiation reflected from the Earth's surface like the optical sensors in visible and infrared region. During night-time, no sunlight is available for reflection. However, naturally emitted energy, like thermal infrared radiation, can be detected both during the day and night, provided the emitted energy levels are sufficient for detection and recording. Example of passive remote sensing include different types of radiometers and spectrometers.

In contrast, active remote sensing systems emit radiation towards the object under study and then measure the amount of radiation reflected back from the object. Active sensors offer several advantages, including the capability to gather data irrespective of day, night, or seasonal conditions. These sensors can operate in wavelengths that are not adequately supplied by sunlight, such as microwaves, and allow for precise control over target illumination. However, using active systems necessitates generating a significant amount of energy to effectively illuminate targets. Radar, Sonar (Sound navigation and ranging) and LiDAR (Light Detection and Ranging) systems uses their own source of light and are examples of active remote sensing.

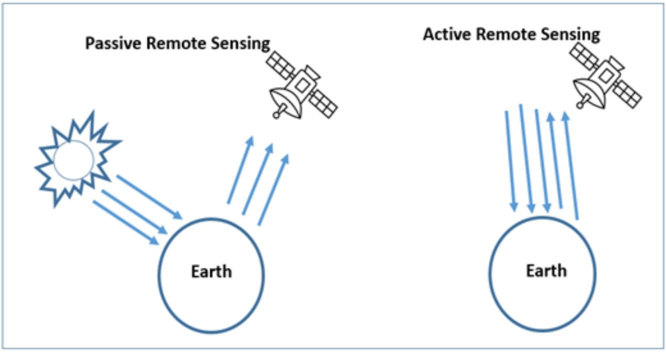


Figure 1.3: Passive Remote Sensing and Active Remote Sensing.

1.5. Interaction of energy and propagation through the Atmosphere

The interacted energy with the objects on the Earth's surface leads to transmitted, absorbed, or reflected from the target (Figure 1.4). Due to the various compositions of objects, the responses from the target vary depending on the different regions of the spectrum. The reflectance from the target object varies for diverse natural targets as a function of wavelength. The energy reflected from the objects passes through the atmosphere, and certain waves are absorbed, scattered, or reflected by atmospheric substances like water vapor, hydrogen, and carbon dioxide. Hence, the energy is either absorbed, transmitted, or reflected by atmospheric molecules; some waves have wavelengths that can pass through the atmosphere unhindered, but some energy waves are left unrecorded by the sensor. The sensor will receive and record the energy provided.

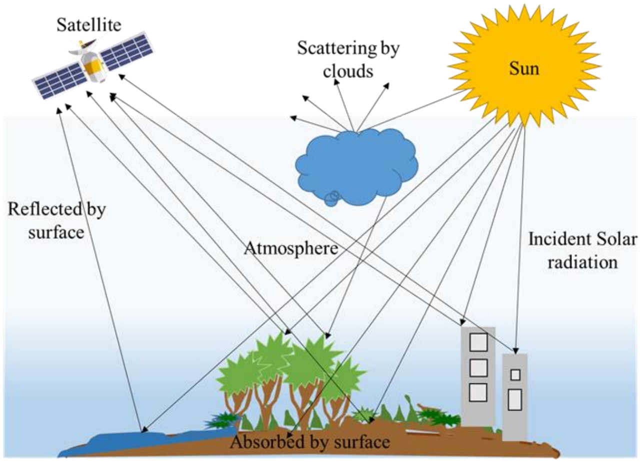


Figure 1.4: Interaction of electromagnetic energy with earth's surface.

In the Earth's atmosphere, incoming radiation interacts primarily through two processes: atmospheric scattering and absorption. Scattering occurs when particles of varying sizes in the atmosphere redirect radiation, causing diffusion. Meanwhile, absorption results in the atmosphere consuming a portion of incoming energy, which is subsequently re-emitted as heat. These processes are largely dictated by atmospheric conditions, including particle sizes, and the nature of incoming radiation, particularly its wavelength.

Types of scattering:

There are three main types of scattering-

- **Rayleigh scattering** is also called molecular scattering and happens when the effective diameter of atmospheric particles, such as oxygen and nitrogen molecules, is much smaller (typically less than 0.1 times) than the wavelength of the incoming electromagnetic radiation. During this process, atoms or molecules absorb and then re-emit the radiation, causing the scattering and is responsible for the blue color of the sky.
- **Mie Scattering** also known as non-molecular or aerosol scattering occurs when the size of atmospheric particles is comparable to the wavelength of the incident energy. Dust, smoke, and aerosols (0.1 to 10 micrometers particle size) mostly cause this scattering. Mie scattering affects longer wavelengths and results in a greater amount of scatter compared to Rayleigh scattering.
- **Nonselective scattering** happens when atmospheric particles are significantly larger than the wavelength of the incoming radiation. It is termed "nonselective" because it scatters all wavelengths of light equally. Consequently, water droplets and ice crystals in clouds and fog scatter all visible light wavelengths equally, making clouds appear white.

The energy recorded by the sensor is captured in the form of digital numbers, which are then transformed into scientifically usable quantities through extensive digital processing. This processed data is converted into meaningful information and is subsequently used for various applications, such as environmental monitoring, resource management, disaster response, geology, agriculture, weather monitoring and urban planning. The ability to interpret and analyze this data accurately is crucial for making informed decisions in these fields.

Despite absorption and scattering by the atmosphere, there exist specific regions where electromagnetic radiation can penetrate effectively, making them completely transparent for remote sensing. These regions are known as atmospheric windows. Dominant atmospheric windows are found in the visible and radio frequency regions, facilitating effective remote sensing. In contrast, X-rays and ultraviolet (UV) wavelengths are strongly absorbed, rendering remote sensing impractical in these regions. Figure 1.5 depicts the transmission of electromagnetic (EM) radiation across different wavelength regions, highlighting absorption zones caused by atmospheric gases such as CO2, O2, H2O, O3, and others. It also illustrates the locations of atmospheric windows where EM radiation can pass through with minimal absorption.

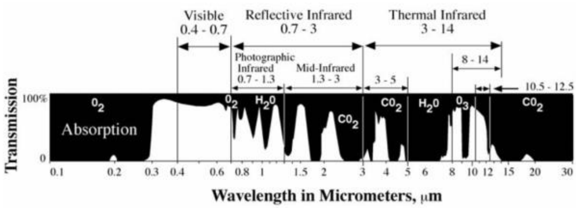


Figure 1.5: Atmospheric windows - wavelength regions where electromagnetic radiation penetrates the Earth's atmosphere. Atmospheric gases such as CO2 and O2 are responsible for absorbing sunlight at specific wavelengths. (Source- Alavipanah et al., 2010).

1.6. Energy Interaction with the Earth's surface

Electromagnetic (EM) radiation interacts with surfaces and materials in several fundamental ways: absorption, transmission, and reflection (Figure1.6).

1. **Absorption**: When EM radiation encounters a material, some of its energy can be absorbed into the material itself. This absorbed energy may be converted into heat or other forms of energy depending on the material's properties.
2. **Transmission**: EM radiation can pass through certain materials without being absorbed. The degree to which radiation is transmitted depends on the material's transparency or opacity to specific wavelengths. Materials that are transparent in certain wavelengths allow radiation to pass through largely unchanged.
3. **Reflection**: EM radiation can also bounce off surfaces without being absorbed or transmitted. The angle and intensity of reflection depend on the nature of the surface: smooth surfaces typically reflect more specularly (like a mirror), while rough surfaces scatter the radiation in multiple directions (diffuse reflection).

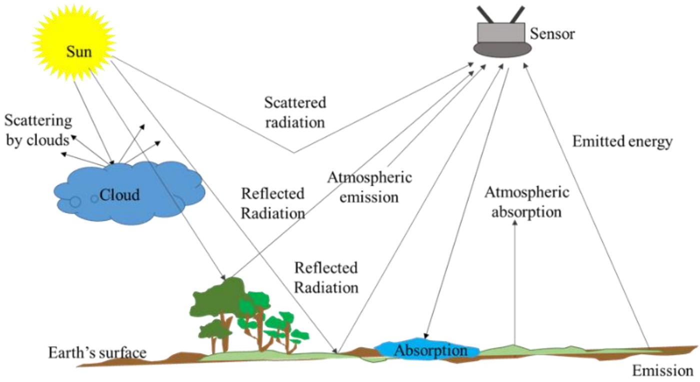


Figure 1.6: Energy interaction with the Earth's surface via absorption, reflection and emission.

1.7. Spectral Regions of Recorded Energy

The energy reflected from the Earth's surface forms the basis of optical remote sensing, as it varies with different objects across different wavelength regions. The measurement of reflected solar radiation across different wavelengths, known as spectral reflectance and forms the basis of identification of various objects. Figure 1.7 illustrates the spectral reflectance patterns of various typical objects.

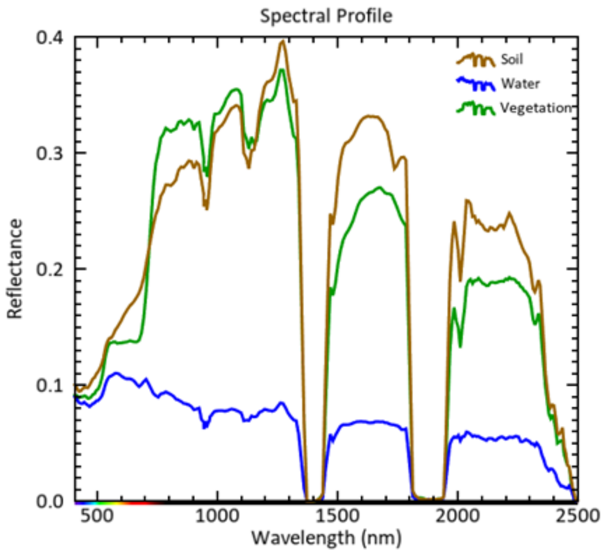


Figure 1.7: Spectral reflectance curves of soil, water and vegetation showing differences in reflectance patterns.

The spectral reflectance curves shows that water has less reflectance as compared to soil and vegetation. Water absorbs maximum radiation within the visible spectrum and reflection is less in NIR whereas beyond 1.2 µm, all radiation is absorbed (Encyclopaedia of Inland Waters, 2022). Clear water still exhibits reflectance in the blue-green region, but the presence of sediments, suspended material, and algae significantly alters the spectral response curve. These spectral properties of water are utilized for studying water quality, mapping of potential fishing zones and many other applications.

The spectral reflectance of soil is primarily determined by its characteristics, including organic matter content, clay minerals, iron oxide content, soluble salts, soil texture, and moisture content (Ben-Dor et al., 1999). Soils spectra typically show absorption bands in SWIR region due to its composition and presence of mineral and iron oxides (Diwedi, 2017). Absorption features around 1.4 µm and 1.9 µm is due to water present in the soil. Moisture content in soil largely affects reflectance, with wet soils showing lower reflectance than dry ones.

Vegetation exhibits a unique reflectance curve with low reflectance in the visible spectrum due to chlorophyll absorption, and high reflectance in the NIR region due to cell wall and spongy inner structure of leaf tissue (Roy, 1989). This distinctive pattern includes a notable slope around 0.7 µm (the red-edge region), similar to the influence of water observed in soils' NIR region. The absorption in the red region and the high reflectance in the near-infrared (NIR) wavelength are fundamental to the Normalized Difference Vegetation Index (NDVI), which is widely utilized for crop mapping purposes (Acker et al., 2014).

1.8. Sensor Resolution

The sensor resolution is the capability of the sensor to identify the object, and it depends on sensor data, which varies on the satellite's orbit and sensor configuration. Depending on the satellite's orbit and sensor configuration, resolution can change. For any dataset, there are four different resolution forms to consider- radiometric, spatial, spectral, and temporal.

1.8.1. Spatial Resolution

The sensor's spatial resolution refers to the smallest ground item it can resolve in terms of size. It is the capability of the sensor to distinguish or differentiate two closely spaced objects. A single number of the image represents the length of the square depicted on the ground by each pixel. The possibility of identifying smaller objects increases with increasing spatial resolution (Figure 1.8).

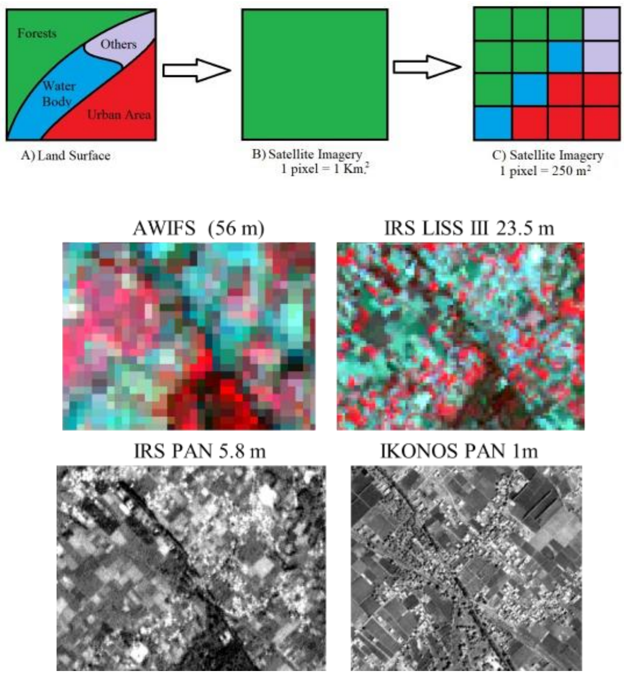


Figure 1.8: (a) Spatial Resolution of an image. and (b). Spatial resolution of different satellite images. (Source- https://pangeography.com/types-of-resolution-in-remote-sensing/).

1.8.2. Spectral Resolution

The sensor's recording power in different electromagnetic spectrum bands is spectral resolution. Multi-spectral images are generated using a device that disperses radiation the sensor receives and records in specific spectral ranges.

1.8.3. Radiometric Resolution

The ability of the sensor to detect incoming electromagnetic radiation to discriminate between two targets is known as radiometric resolution. It represents the highest number of bits that can be utilized to separate the captured energy. The higher the radiometric, the smaller the differences captured between the targets.

1.8.4. Temporal Resolution

The frequency at which a satellite or sensor captures an image of a specific ground target is known as temporal resolution. It refers to the ability of the sensor to capture the same objects on Earth's surface. The more the temporal resolution, the more frequent images of the same objects in the exact location on the earth's surface can be obtained.

1.9. Applications of remote sensing

Remote sensing has a wide array of applications across various fields, significantly enhancing our ability to monitor, manage, and understand the Earth's systems. In agriculture, remote sensing is used to monitor crop health, estimate yields, and manage irrigation. By analyzing satellite imagery, farmers can detect stress in crops early, optimize resource use, and improve food production efficiency. In environmental monitoring, remote sensing plays a crucial role in tracking deforestation, land degradation, and changes in ecosystems. It aids in assessing the impacts of climate change by providing data on glacier retreat, sea-level rise, and shifting weather patterns.

Urban planning and development also benefit from remote sensing, which provides detailed maps and data to support infrastructure development, zoning, and sustainable urban growth. In disaster management, remote sensing is invaluable for assessing damage from natural disasters like earthquakes, hurricanes, and floods. It enables rapid response and recovery efforts by providing real-time information on affected areas.

Remote sensing is essential in hydrology for monitoring water quality, managing water resources, and predicting floods and droughts. Additionally, it supports mineral and oil exploration by identifying geological formations and potential resource deposits. In the field of meteorology, remote sensing provides critical data for weather forecasting, climate modelling, and studying atmospheric phenomena.

In geology, remote sensing is instrumental in mapping geological features, identifying mineral deposits, and studying Earth's surface processes. It allows geologists to analyze rock formations, detect faults and fractures, and understand the geological history of an area. Remote sensing data helps in the exploration of natural resources and in assessing geological hazards such as landslides and volcanic activity.

Overall, remote sensing is a powerful tool that offers comprehensive insights and data, driving advancements in science, resource management, and policy-making, ultimately contributing to more informed and effective decision-making processes.

The next step is to interpret and analyse the data visually or digitally to extract useful information. In Chapter 3, the data processing is discussed in detail.

1.10. Conclusion

This chapter started with a basic introduction to remote sensing and the electromagnetic spectrum. The different stages of remote sensing were explained. The types of remote sensing and the interaction of energy and propagation through the atmosphere were briefly described. To better understand the concept of remote sensing, it is essential to understand the behaviour of different objects, such as water, soil, and vegetation, in various spectral regions, and briefly discussed. Sensor resolution was described, and significant remote sensing applications were also mentioned. In remote sensing, the next step is to interpret and analyze the data visually or digitally to extract useful information. The next chapter will provide the Remote sensing platform, sensors, and instruments, and Chapter 3 discusses the data processing and analysis in detail.

Overall, remote sensing is a powerful tool that offers comprehensive insights and data, driving advancements in science, resource management, and policy-making, ultimately contributing to more informed and effective decision-making processes.

Chapter 2

Remote Sensing Platforms, Sensors & Instruments

2.1. Introduction

Remote sensing platforms, sensors, and instruments have evolved significantly since their inception in the early 19^{th} century, with aerial photography for landscape mapping. A major advancement came with the launch of the Landsat satellites in the 1970s, which provided regular, high-resolution images of the Earth's surface. This breakthrough marked the beginning of rapid progress in remote sensing technology, leading to ongoing innovations in sensors and platforms that cater to diverse needs and challenges. Instrumented satellites and aircraft play a crucial role in assessing atmospheric conditions and surface features, including temperature and reflectivity.

In the upcoming chapter, we will thoroughly examine remote sensing platforms, sensors, and instruments. We will cover the various platforms utilized for data acquisition, including satellites, aircraft, and drones. Additionally, we will explore the different types of sensors used in remote sensing, such as optical, radar, and thermal infrared sensors. Finally, we will discuss the instruments and technologies involved in processing and analyzing the data collected through remote sensing.

2.2. Remote Sensing Platforms

2.2.1. Ground-Based Platforms

Terrestrial Laser Scanning (TLS)

Terrestrial Laser Scanning (TLS) is a state-of-the-art technology in ground-based remote sensing that revolutionizes spatial data capture and analysis. TLS emits laser pulses that bounce off objects and return to the sensor, allowing it to measure distances with high accuracy. This process creates a dense point cloud, offering a detailed 3D representation of the scene.

TLS has wide-ranging applications: it provides precise architectural data for building mapping, allows archaeologists to document historical sites without disturbance, and delivers critical measurements for engineering projects, ensuring accuracy and reliability. Its versatility and precision make TLS an essential tool across various fields.

Ground-Penetrating Radar (GPR)

Ground-Penetrating Radar (GPR) is a powerful ground-based remote sensing tool for subsurface exploration. It works by sending electromagnetic waves into the ground, which reflect off different materials and return to the surface. Analyzing these reflected signals generates detailed images of subsurface features, such as buried objects, pipelines, and geological formations. GPR is versatile and valuable in several fields: it maps geological structures, locates buried infrastructure like water and sewer lines, and uncovers artifacts and structures in archaeological investigations. Its ability to reveal hidden elements without invasive methods makes GPR essential for various practical and investigative purposes.

2.3. Airborne Platforms

2.3.1. Unmanned Aerial Vehicles (UAVs)

Unmanned Aerial Vehicles (UAVs) have transformed data collection with their versatility and dynamic capabilities. They come in two main types: fixed-wing UAVs, which are efficient for long-range flights and stable over large areas, and rotary-wing UAVs (drones), which can hover and maneuver, making them ideal for detailed inspections and close-range observations. UAVs can be equipped with various payloads to meet specific needs. Common payloads include high-resolution cameras (multispectral, hyperspectral, and thermal infrared) for capturing detailed surface images, and LiDAR systems for precise topographic mapping.

UAV applications are extensive: in precision agriculture, they monitor crop health and soil conditions; in disaster response, they assess damage and support rescue efforts; and in environmental monitoring, they track deforestation, wildlife, and water quality. UAVs' flexibility and effectiveness make them invaluable for diverse data collection and analysis tasks.

2.3.2. Aircraft

In airborne remote sensing, aircraft provide essential capabilities that complement and extend those of UAVs. They are typically categorized into fixed-wing and rotary-wing types. Fixed-wing aircraft, similar to traditional planes, excel in long-range missions and covering large areas due to their efficiency and endurance. Rotary-wing aircraft, like helicopters, offer superior maneuverability and are ideal for detailed inspections and localized surveys thanks to their hovering and precise movement capabilities.

Aircraft can carry various payloads to meet different remote sensing needs. Synthetic Aperture Radar (SAR) is a key sensor, capable of penetrating cloud cover to provide high-resolution imagery regardless of weather conditions. Hyperspectral sensors, when mounted on aircraft, collect data across many wavelengths, facilitating comprehensive analysis for tasks like land use mapping and environmental monitoring. Aircraft are used for diverse applications: they assist in land use mapping by identifying and classifying land cover types, support environmental monitoring by studying climate change, assessing water quality, and tracking deforestation, and provide critical data for urban planning and environmental management. Their advanced sensors and operational versatility make aircraft invaluable in remote sensing.

2.4. Spaceborne Platforms

Satellites represent a pivotal component of spaceborne remote sensing, offering a unique vantage point of observing and collecting data about the Earth's surface. These satellites orbit Earth at various altitudes, each orbit providing distinct advantages depending on the mission's objectives and requirements.

2.4.1. Satellite Orbits

One of the most common orbits is Low Earth Orbit (LEO), where satellites operate at altitudes ranging from approximately 160 to 2,000 kilometers above Earth. Satellites in LEO are renowned for their ability to capture high-resolution imagery due to their proximity to the Earth's surface. This orbit is particularly beneficial for applications requiring frequent updates, such as weather forecasting and disaster monitoring. The closer proximity also allows for more detailed and timely data collection.

In contrast, Geostationary Orbit (GEO) positions satellites at a much higher altitude of about 35,786 kilometers. This specific altitude allows satellites to remain fixed relative to a particular point on Earth's surface. The stationary nature of GEO satellites makes them exceptionally suited for continuous monitoring of specific regions, and they are heavily utilized for communication, meteorological and broadcasting services (Figure 2.1). This stable position ensures that they can provide consistent data and maintain a constant line of sight to their target area.

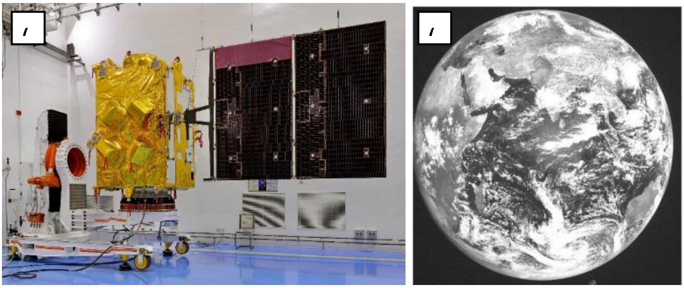


Figure 2.1. a) INSAT-3DR satellite in clean room with solar panel deployed and b) first image from INSAT-3DR in visible band from geostationary orbit. Source: GSLV- F05 Gallery (isro.gov.in)

Medium Earth Orbit (MEO) serves as an intermediary between the lower altitudes of LEO and the higher elevations of GEO. Satellites in MEO orbit at altitudes between LEO and GEO, providing a balance between the detailed coverage of LEO satellites and the broader, global view offered by GEO satellites. MEO satellites are commonly used for navigation, communication, and scientific research. Their position allows them to support a range of applications, including global positioning systems (GPS) and data relay.

Satellite remote sensing has extensive applications: it maps land cover, tracks deforestation, and observes sea ice changes for global monitoring; aids climate change research by measuring sea level rise and studying the climate system; and supports disaster management with early warnings, damage assessment, and real-time data for relief efforts. These capabilities are vital for environmental management, scientific research, and disaster response.

2.4.2. Satellite Payloads

Satellites in spaceborne remote sensing are equipped with an array of sophisticated sensors designed to capture and analyze data about the Earth's surface and atmosphere. The payload options for these satellites are diverse, catering to various observational needs and scientific objectives. Optical sensors are key payloads in remote sensing, including multispectral, hyperspectral, and panchromatic cameras. Radar sensors, such as Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR), are crucial for generating high-resolution imagery under any weather conditions. Further details about these are presented in the following section.

2.5. Remote Sensing Sensors

2.5.1. Optical Sensors

Panchromatic Sensors

Panchromatic sensors are key tools in optical remote sensing, known for their capability to capture high-resolution black-and-white images across a broad spectrum of visible light (Figure 2.2). Unlike multispectral sensors, which separate light into distinct bands, panchromatic sensors capture the entire visible range without division, resulting in exceptionally sharp imagery with high spatial resolution.

The applications of panchromatic imagery are diverse and significant. For high-resolution mapping, panchromatic sensors are vital in creating detailed maps of urban areas, infrastructure, and natural landscapes, providing accurate spatial representations. Additionally, image fusion combines panchromatic images with multispectral data, enhancing the overall image quality by integrating the fine details of panchromatic imagery with the spectral information from multispectral sensors.

Multispectral Sensors

Multispectral sensors are crucial in optical remote sensing, capturing data across multiple discrete spectral bands, including visible light, near-infrared, and shortwave infrared. By measuring reflectance across these bands, they distinguish objects and substances based on their unique spectral signatures.

Multispectral imagery has broad applications. In land cover classification, these sensors identify and map various land types, such as forests, agricultural fields, and urban areas, aiding in environmental management and urban planning. For vegetation monitoring, multispectral sensors assess plant health, calculate vegetation indices, and track crop growth, supporting agricultural management and ecological studies. In water quality assessment, they detect pollution, measure water depth, and monitor algal blooms, contributing to better water resource management. In mineral exploration, multispectral sensors help identify mineral deposits by their spectral signatures, assisting in resource discovery and extraction.

Hyperspectral Sensors

Hyperspectral sensors represent a major advancement in optical remote sensing, capturing images across hundreds or thousands of narrow, contiguous spectral bands. Unlike multispectral sensors, which use a few broad bands, hyperspectral sensors provide a detailed spectral profile for each pixel, enabling precise material identification and classification based on unique spectral reflectance properties.

These sensors have a wide range of applications. In mineral identification, hyperspectral sensors detect and map minerals and rocks by analyzing their specific spectral signatures, which is essential for geological surveys and mining. In precision agriculture, they monitor crop health, assess soil conditions, and optimize farming practices with detailed data on plant and soil properties. Environmental monitoring benefits from hyperspectral imagery by studying vegetation stress, detecting pollution, and monitoring water quality, providing valuable insights into ecosystem health and environmental changes.

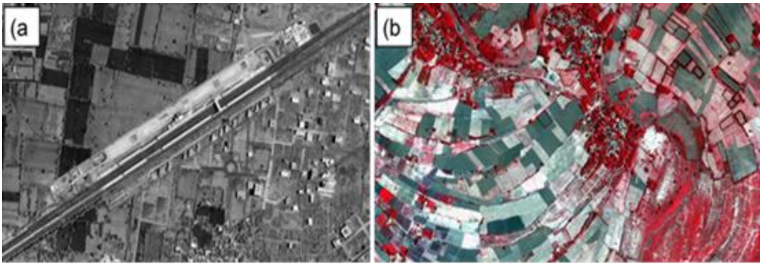


Figure 2.2. a) Panchromatic imagery of New Railway Station, Kishangarh, Rajasthan and b) Multispectral data over Bhidaurya, Uttar Pradesh from the Cartosat 2 series satellites.

2.6. Radar Sensors

Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar (SAR) is a radar technology used in remote sensing to create high-resolution images of the Earth's surface. SAR works by transmitting microwave pulses towards the Earth and capturing the reflected signals. By leveraging the movement of the sensor, whether on an aircraft or satellite, SAR synthesizes a large aperture, which enhances image resolution. This technique allows SAR to produce detailed imagery regardless of weather conditions or time of day, bypassing limitations such as cloud cover or darkness.

SAR is used for various applications. It enables all-weather imaging, providing surface imagery under any atmospheric conditions, crucial for ongoing monitoring. In sea ice monitoring, SAR maps the extent, thickness, and movement of sea ice, aiding climate studies and maritime navigation. For land use mapping, it identifies and classifies land cover types, improving resource management and planning. In disaster response, SAR assesses damage from events like hurricanes and earthquakes, offering vital information for emergency response and recovery.

Interferometric Synthetic Aperture Radar (InSAR)

Interferometric Synthetic Aperture Radar (InSAR) advances the capabilities of traditional SAR by using two SAR images taken from slightly different positions to create an interferogram that reveals phase differences. This technique allows for precise measurement of surface elevation and detection of ground deformation. InSAR is utilized for several important applications. It helps to generate highly accurate digital elevation models, providing detailed topographic maps of the Earth's surface. It is also essential for monitoring ground deformation, detecting subsidence, uplift, and other movements. Additionally, InSAR is used in volcano monitoring to track volcanic activity and anticipate eruptions, as well as in earthquake monitoring to assess seismic hazards and analyze post-earthquake surface changes.

2.7. Remote Sensing Instruments

2.7.1. LiDAR (Light Detection and Ranging)

LiDAR systems operate by emitting laser pulses towards the Earth's surface and measuring the time it takes for the pulses to return. By analyzing the time of flight, LiDAR calculates the distance to the target, creating a detailed 3D point cloud of the environment. LiDAR is utilized across various fields with significant applications. In topographic mapping, it provides highly accurate digital elevation models (DEMs) of the Earth's surface. For forest height measurement, LiDAR estimates tree height and biomass, aiding in forest management and ecological studies. In urban planning, LiDAR helps assess infrastructure, map buildings, and analyze land use patterns. Additionally, archaeological surveys use LiDAR to detect buried structures and artifacts, enhancing archaeological research and site discovery.

2.7.2. Thermal Infrared Sensors

Thermal infrared sensors function by detecting and measuring the infrared radiation emitted by objects, which correlates with their temperature. This capability allows these sensors to detect and map heat sources across various environments.

The applications of thermal infrared sensors are broad and impactful. They are used in heat detection to identify and locate heat sources, such as fires, hot spots, and thermal anomalies. In wildfire monitoring, these sensors track wildfires, assess fire intensity, and observe fire behaviour. For urban heat island studies, thermal infrared sensors help identify and map areas of elevated temperatures within cities.

2.8. Other Instruments

2.8.1. Spectrometers

Spectrometers operate by measuring the intensity of light across a range of wavelengths, allowing them to analyze the spectral composition of materials and identify different substances based on their unique spectral signatures. This capability has a wide range of applications on both Earth and the Moon. On Earth, spectrometers are used for mineral identification by detecting and mapping various minerals and rocks through their spectral properties. They also play a crucial role in environmental monitoring, assessing water quality, detecting pollutants, and evaluating vegetation health by examining spectral characteristics.

In space exploration, spectrometers, such as those on the Chandrayaan-3 mission, extend these capabilities to the lunar surface. The Chandrayaan-3 spectrometer is designed to analyze the Moon’s surface composition by measuring reflected light, helping to identify lunar minerals and providing valuable insights into the Moon's geology and history. This data is essential for understanding lunar materials and evaluating potential resources for future missions (Figure 2.3 a).

2.8.2. GNSS Receivers

Global Navigation Satellite Systems (GNSS) receivers, including GPS, GLONASS, Galileo, and India's Navigation with Indian Constellation (NavIC), operate by receiving signals from multiple satellites to determine precise locations on the Earth's surface. By triangulating the positions of these satellites, GNSS receivers can accurately pinpoint their location. NavIC, established by ISRO, complements other GNSS systems with its constellation of seven satellites: three in geostationary orbits and four in inclined geosynchronous orbits. Together with a network of ground stations, NavIC meets national positioning, navigation, and timing requirements.

GNSS receivers are integral to various applications, especially when used alongside remote sensing data. They are essential for georeferencing imagery, which involves assigning geographic coordinates to remote sensing data for accurate spatial alignment. Additionally, GNSS receivers are used to monitor ground deformation, tracking changes such as subsidence or uplift, which is critical for understanding and managing geological and environmental processes.

2.8.3. Radiometers

Radiometers measure the intensity of electromagnetic radiation emitted or reflected by objects. By analyzing this radiation, radiometers can determine the temperature of objects or study their physical properties. Radiometers are applied in several key areas. They are used for temperature measurement, determining the temperature of the Earth's surface, atmosphere, and oceans. In climate monitoring, radiometers study the Earth's radiation balance and detect changes in climate patterns. They also play a crucial role in remote sensing of the atmosphere, measuring atmospheric parameters such as temperature, humidity, and ozone concentration, which are vital for understanding and predicting atmospheric conditions.

Figure 2.3. a) Alpha Particle X-Ray Spectrometer onboard the Chandrayaan 3 Pragyaan Rover used to derive the chemical mineralogical composition of the moon. b) Vegetation measurements using Terrestrial laser scanning (TLS) instrument at field.

2.9. Conclusion

In this chapter, we have delved into the diverse platforms, sensors, and instruments that constitute the field of remote sensing. We began by exploring the different types of platforms, including ground-based, airborne, and spaceborne systems, each offering distinct advantages for data collection. We then examined a broad array of sensors, such as optical, radar, and thermal infrared sensors, each with specialized capabilities tailored to specific applications. The field of remote sensing is rapidly advancing, with ongoing innovations in technology leading to the development of new platforms, sensors, and instruments. These advancements are enhancing our ability to acquire more accurate and detailed information about the Earth's surface. As technology progresses, we anticipate even more ground breaking applications in areas such as agriculture, urban planning, environmental monitoring, and disaster management.

Chapter 3

Image acquisition and data processing

3.1. Introduction

Image acquisition in remote sensing and digital processing is the first step in which the physical phenomenon converts into a digital representation. As mentioned in Chapter 1, the reflected energy propagates through the atmosphere after the interaction between the energy source and the object. This electromagnetic propagated energy is reflected, absorbed, or transmitted by the object. This energy captured or recorded by sensors is converted into an analog or digital data. In analog imagery, traditional methods of capturing and representing visual information are used to record in a continuous, physical form.

Meanwhile, in digital images, visual information is captured, stored, and processed in a digital format. The scope of this chapter refers to only the digital form. This digital data can be a matrix that further needs analysis to extract useful information for different applications. There are essential steps that need to be taken to extract useful information. The details of digital data, including basic details of digital data, data formats, band combinations, image pre-processing, image display, and analysis, are briefly discussed in this chapter. The image processing software primarily used is also described at the end of the chapter.

3.2. Image Acquisition

The process of obtaining digital images involves capturing digital image data from different sources for later analysis, interpretation, and processing. Different sensors capture different electromagnetic spectrum ranges, such as visible light, infrared light, and ultraviolet light. Ground devices are installed to capture the sensor-recorded energy and provide the data to users. For example, the Department of Space (DoS) and ISRO establish, maintain, and service ground systems required for space technology for national and international users. National Remote Sensing Centre (NRSC), ISRO, is committed to providing satellite images from Indian and foreign remote sensing satellites. NRSC can acquire data pertaining to any part of the globe. Figure 3.1 depicts an example of the ground infrastructure of New Space India Limited (NSIL), DoS. NRSC has established and operationalized a unique Cal-Val facility in the IMGEOS complex at Shadnagar Hyderabad to enable the calibration needs of Optical and microwave sensors.

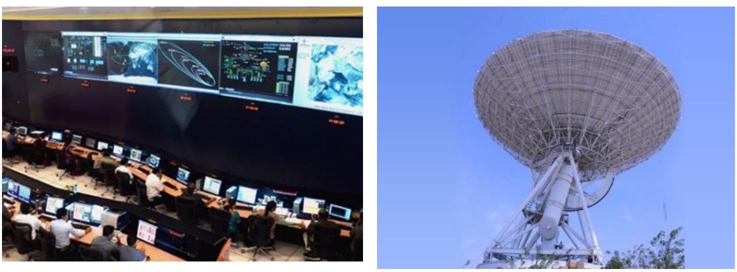


Figure 3.1: Ground Infrastructure for space-based need (*Source: https://www.nsilindia.co.in)*

3.3. Digital Image

A digital image is a visual depiction of an object or a scene using a collection of divided cells (pixels) arranged in a specific grid and containing quantized values or digit-based values of the average intensity of the targeted object or scene. After the creation of modern computers, the advantages of digitizing data for convenient processing have been recognized. Essentially, digital refers to any form of data/information/signal representation in quantized form or digits. Digital images are a matrix of pixels, where each pixel is a tiny element that carries information about the color and intensity of a specific point in the image. The major components of digital images are as follows:

3.3.1. Pixel

Each pixel in a digital image holds numerical data to depict its colour and brightness. The quantity of pixels determines a digital image's resolution, usually expressed as width x height (for example, 1920 x 1080 pixels).

3.3.2. Color Models

Digital images commonly use the RGB color model, especially for screens and web applications. The colors in this model are produced by blending different levels of red, green, and blue light. Other color models include CMYK (Cyan, Magenta, Yellow, black). Models are also used for intuitive color manipulation, especially in image editing applications.

3.3.3. Bit Depth

The bit depth refers to the number of bits used to depict the color of each pixel. Standard bit depths include 8-bit (which represents 256 colors per channel), 16-bit (which represents 65,536 colors per channel), and 24-bit (which represents 16.7 million colors). Greater bit depths enable a more significant number of color variations and finer intensity gradations.

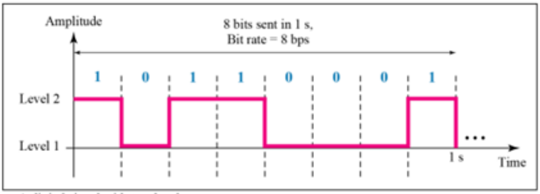
3.3.4. Image formats

The format of a digital image determines how data is stored and compressed. Standard formats include JPEG, PNG, TIFF, GIF, and BMP. The chosen image format impacts the image format's quality, compression, and compatibility. JPEG, for instance, is preferred for photographs because of its lossy compression, whereas PNG allows for lossless compression and transparency.

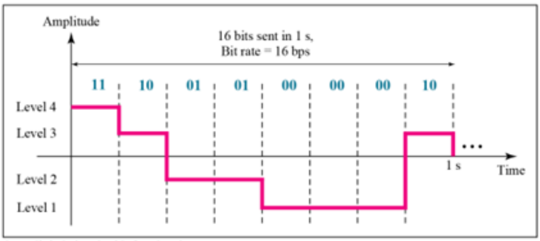
3.4. Digital Data

3.4.1. Conversion of energy to digital form of data

Digital data can be stored in binary form 0 or represented as a digital signal. For example, one can be encoded as a positive voltage and 0 as a zero voltage. For more than two storage levels, digital data must be stored in more than 1 bit for each level. If a digital signal has eight levels, the number of bits required per level will be $\log_2 8$, i.e., 3. Bit rate is used to describe digital signals. The bit rate refers to the bits used in 1 second and expressed in bits per second (bps). For example, in figure 3.2, a digital signal shows two and four levels. In each case, bps is different from 8bps and 16bps. The bit length is the product of propagation speed and bit duration. Digital data can be transmitted using various approaches, such as baseband or broadband transmission (modulation). Data must be pre-processed before extracting helpful information from different remote sensing applications. For more details on digital image processing, readers may refer to Kenneth, 1996; Gonzalez 2001 & 2008.



a. A digital signal with two levels



b. A digital signal with four levels

Figure 3.2: Digital data stored in different levels *Source:https://www.uobabylon.edu.iq/eprints/publication_1_25921_1562.pdf*).

3.4.2. Band Combinations: Multi-spectral imagery

Multi-spectral imagery refers to collecting and processing data from multiple wavelengths of light across the electromagnetic spectrum. This technology captures information from various bands beyond the visible spectrum, including infrared, ultraviolet, and others. In a multispectral remote sensing image, this reflectance pattern, also known as a spectral signature, is utilized to identify targets. Any object's and condition's spectral signature comprises a set of reflectance and emittance values in various spectral bands. Indirectly or directly, this results in identifying an object and its state.

Satellite images are acquired, and an actual color composite image is generated using the data in different bands such as visible (Blue, Red, Green) and infrared (Near Infrared and Shortwave infrared). The image data captured in the red, green, and blue spectral regions must be mapped to the processor's respective red, green, and blue memory. When images captured in multiple bands are displayed in image planes different from their own, it creates a false color composite (FCC). The FCC image is generated by storing the infrared in the red, red, green, and green in the blue memory. Vegetation, which absorbs most green and red radiation but reflects about half of the incident infrared energy, appears as red shades in the image. Urban areas appear gray as they reflect equal amounts of near-infrared (NIR), red (R), and green (G) radiation. For more understanding, there is a need to know about the spectral sensitivity and responses of the different objects.

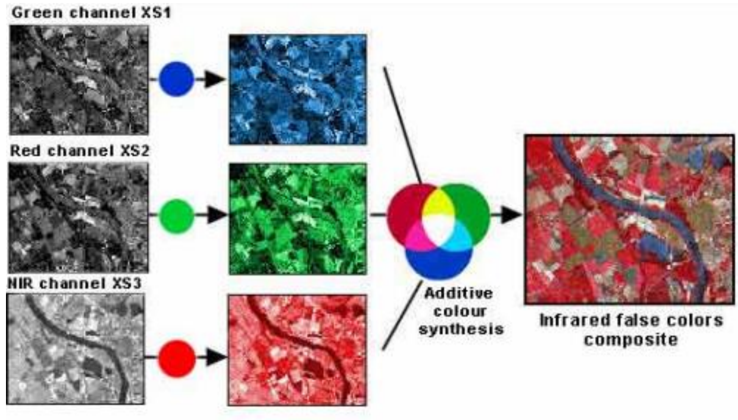


Figure 3.3: Example of False Color Composite Image, (*Source https://jogamayadevicollege.ac.in/uploads/1586347159.pdf*).

3.5. Spectral Sensitivity and Responses

Spectral sensitivity refers to the ability of the sensor device to respond in different wavelengths of the electromagnetic spectrum. The imaging device may be the human eye as well as the camera. This response determines which colors and features of a scene are captured with greater or lesser accuracy. It depends on wavelength, ability to reproduce colors and sensor types. Each object behaves differently concerning wavelength; the spectral response curve represents the spectral behavior of various objects as per different wavelengths and sensor abilities.

The spectral responses of the various objects need to be understood to understand better the behavior of different target objects concerning the electromagnetic spectrum. Figure 3.1 depicts the spectral behaviour of diverse natural targets as a function of wavelength. The plant leaves absorb the blue and red wavelengths of sunlight, whereas the green light is reflected in the visible region (0.4–0.8 µm) (Campbell, 1996). The interior mesophyll structure of leaves reflects near-infrared (NIR) radiation (0.8-2.5 µm), whereas leaf pigments primarily reflect visible radiation. Because leaf pigments reflect green wavelengths in the spectrum while other visible wavelengths are absorbed, leaves can be seen as green in human eyes.

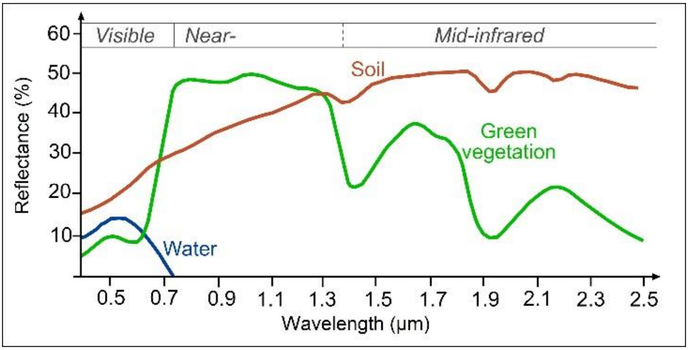


Figure 3.4: Spectral Signatures of Vegetation, soil and water *(Source: https://seos-project.eu/classification/classification-c01-p05.html).*

Additionally, certain parts of the NIR radiation that are invisible to the human eye are reflected, transmitted, and absorbed by components in plants. The reflected NIR radiation can be measured and sensed by sensors, which allows the study of vegetation. A healthier plant will reflect more NIR light than one with less chlorophyll. Thus, the health and production of a plant can be determined by examining its spectrum for absorption and reflection in visible and NIR wavelengths. In the visible region, the reflectance of the leaf is lower than the soil, whereas in the NIR region, the reflectance of the leaf is higher than the soil (Joseph, 1996). Hence, this helps to explain the utility of agricultural application and crop identification.

3.6. Image Interpretation and Analysis

3.6.1. Visual Interpretation

In remote sensing, visual interpretation provides the basic idea about satellite imagery before extracting useful information using processing techniques. The primary characteristics are tone, color, texture, size, shape, pattern, and association. Remote sensing data is received in different forms, such as optical (visible, infrared) and, microwave and LiDAR data. Data is captured in various spatial, spectral, radiometric, and temporal resolutions. An example of Sentinel-2 data is shown in Figure 3.5 in false color composite image. In this satellite image, features such as built up, Plantation, water bodies, transportation, and agricultural cropland may be identified by visual interpretation. In this pattern, color interpretation, texture, and shape are the significant features of discrimination. Vegetation might appear bright red, built up is cyan color tone, the water body is a dark color, plantation is in dark red tone, and transportation also visually clearly observed.

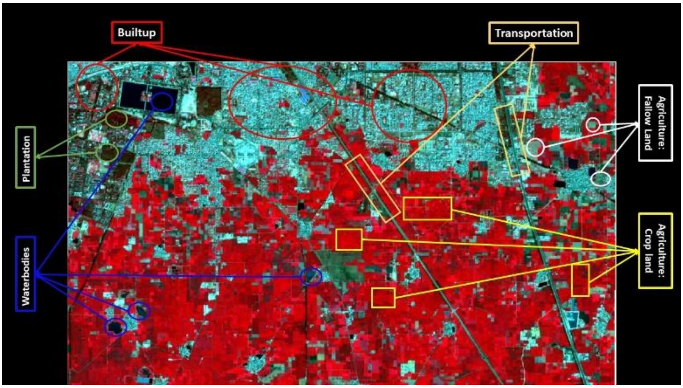


Figure 3.5: Visual Interpretation of False Color Composite image, Sentinel-2 (10 Mar 2023)

3.6.2. Image Processing, and Analysis

Image processing is the essential step after receiving the satellite data. There is a need to interpret the imagery, first visually and then by performing analysis. There are different formats and levels for which satellite data can be acquired for various applications. The various spectral band combinations need to be understood and processed to interpret the satellite imagery. Specialized software used for this purpose which is called digital image processing. The basic steps of digital image processing are as follows:

Image Correction or Restoration

The geometry and brightness values of the pixels in the image data captured by sensors on a satellite or aircraft need to be corrected. These inaccuracies are addressed with the aid of appropriate mathematical models-definite or statistical models.

Image enhancement

Image enhancement is the process of altering an image by changing the brightness values of the pixels to increase its visual effect. When using image enhancement techniques, the new brightness value for a pixel is derived either from its current value or from the brightness values of a group of adjacent pixels.

Image transformation

Due to the multi-spectral nature of image data, it is possible to spectrally transform the data to a new set of image bands or components to make some information more obvious or of preserving the image's essential information content (for a particular application) with a smaller number of transformed dimensions. The additional components' pixel values are connected to the existing spectral bands using a linear procedure.

Image Pre-processing

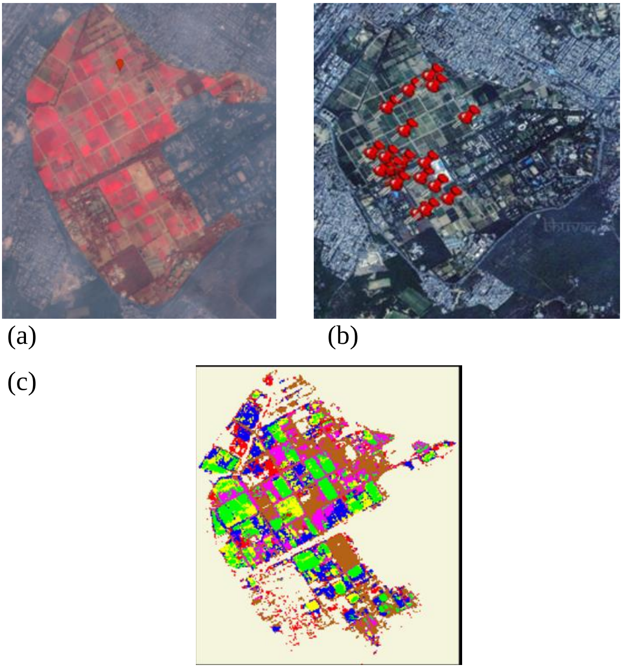
The essential steps of image pre-processing are rectification, restoration, as well as image enhancement. In image rectification, images are adjusted to remove distortions caused by sensor characteristics and terrain relief. By applying sensor models and ground control points, images are transformed to align spatially with other datasets and accurately represent the Earth's surface. Through image rectification and geometric correction, we obtain reliable and georeferenced images that form the foundation for diverse geospatial analyses and applications.

Image classification

Image classification is an essential step in image analysis, which categorizes every pixel of an image into different land cover categories or themes. This step analyzes each pixel's spectral signature in other wavelength bands, providing unique characteristics corresponding to each object. Similar spectral signatures are grouped, and separate spectral signatures are determined to identify the unique characteristics of each pixel.

There are two types of classification methods: Unsupervised and Supervised. In unsupervised classification, pixels are classified based on different spectral signatures with prior knowledge of the signatures of various features. Unsupervised classification techniques refer to the algorithm that can make clusters iteratively based on similar characteristics such as mean, standard deviation, covariance matrices, etc. These clusters may be defined and assigned to a specific class. So, clustering and assigning to the particular class are the significant steps in this technique. Many clustering algorithms, such as k-means and ISODATA, do not require training data sets.

In supervised classification, training signatures must be generated based on the spectral signatures for different objects corresponding to the ground truth data. Then, it classifies images based on the various signatures of varying land features. In supervised classification techniques, maximum likelihood classification (MLC) and rule-based hierarchical classification are the most popular methods. In the MLC method, the likelihood function must be maximized for a normal distribution (Zivot, 2009). Another approach is popularized, in which more than one method can be combined, and results will be generated, is called the hybrid approach. An example of image classification for optical data (Sentinel-2) using the MLC method is shown in figure 3.6. Ground truth data was used for training signature generation, and satellite image is classified using MLC method.



(a) (b)

(c)

Figure 3.6: IARI Pusa, New Delhi (a) FCC image, Sentinel-2, Feb 2016, (b) Ground Truth data and (c) Classified Image using MLC method.

3.7. Accuracy Assessment

Accuracy assessment is essential in comparing estimated values with actual results to determine the differences. In image classification, the estimates are the assigned classes for each pixel based on the spectral signature of each corresponding object. The reference points or actual values are much needed to generate the spectral signatures and validate the classified data. These actual reference values are known as ground truth data. The ground truth data will be collected corresponding to the remote sensing data acquisition date, considering factors such as date of sowing, transplanting, crop grown, soil condition, competitive crop, and field size to generate an accurate spectral signature from the image. Classification accuracy constructs an error matrix, a confusion matrix, or a contingency table to represent accuracy. Firstly, a matrix is formed using reference pixels and classified pixels in rows and columns (Srivastava.et al., 2022). Various classification accuracy measures can be derived from the error matrix using basic descriptive statistics. The major components are briefed below:

1) **Producer's accuracy** refers to likelihood that specific features on the ground is classified correctly. It is calculated by dividing the total number of pixels sampled for this category by the number of correctly identified pixels in each category (column total).

2) **User's accuracy:** It deals with the likelihood that a pixel on a map labelled as a specific class actually belongs to that class. It is calculated by dividing the number of pixels correctly classified by the overall number of pixels correctly identified in this category.

3) **Overall accuracy:** Displays the overall classification accuracy. It is calculated by dividing the total number of pixels that were successfully identified by the total number of pixels that served as references. This measure's limitation is that it does not provide information on how accurately various classes are categorised. The omission and commission accuracy depends on the producer and user accuracy, two commonly used measurements of class accuracy.

4) **Kappa coefficient:** The Kappa metric measures how much better the classification performed compared to the probability of randomly assigning pixels to their right groups and accounts for chance agreement in the categorization.

$$k = \frac{p_o - p_e}{1 - p_e} = 1 - \frac{1 - p_o}{1 - p_e}$$

where p_0 = relative observed agreement among raters, p_e = the hypothetical probability of chance agreement.

3.8. Image processing software

Image processing software analyses digital images obtained from satellites, drones, or airborne sensors. There is a need to do image pre-processing steps. These, image processing software will be helpful in pre-processing, image analysis, and classifying the images. Accuracy assessment is an essential step in image analysis, as described above. These software tools assist in processing, analysing, and accuracy assessment for multispectral and hyperspectral images to extract valuable information about the Earth's surface. Below are several essential software packages commonly utilized in remote sensing.

Table 3.1: Major Image Processing Software used in RS data analysis*

Software	Features	Open-source /Priced	Source/Reference
ENVI	Advanced tools for RS data analysis	Priced	https://www.nv5geospatialsoftware.com/Products/ENVI
ERDAS IMAGINE	Advanced features for RS data analysis	Priced	https://hexagon.com/products/erdas-imagine
QGIS	GIS Software also support image analysis	Open-source	https://www.qgis.org/
SNAP	Specialized for microwave data	Open-source	https://step.esa.int/main/download/snap-download/
GEE	Cloud-based platform for large scale RS data analysis	Open-source	https://earthengine.google.com/
GDAL	Library for reading and writing raster and vector geospatial data	Open-source	https://gdal.org

OTB	Library for RS data anaylsis	Open-source	https://www.orfeo-toolbox.org/
PolSARpro	Specialized for polarimetric synthetic aperture radar data	Open-source	https://earth.esa.int/eogateway/tools/polsarpro
IGiS	Remote sensing and GIS mapping and analysis	Priced	https://www.sgligis.com/

GEE-Google Earth Engine, GDAL-Geospatial Data Abstraction Library, OTB-Orfeo Toolbox, RS-Remote Sensing

**This is only indicative list for image processing software. Many more software are used for RS data analysis.*

3.9. Conclusion

This chapter starts with image acquisition, digital image and data, band combinations, multi-spectral imagery, spectral sensitivity, and responses, and image interpretation and analysis are discussed briefly. An accuracy assessment is also discussed, and major image processing software is listed. As technology rapidly changes, cloud-based platforms' use has increased drastically in the last decade. This chapter broadly explains satellite image acquisition, spectral responses, and image analysis, from processing steps to classification and accuracy assessment.

Chapter 4

Microwave Remote Sensing

4.1. Fundamentals of Microwave Remote Sensing

Microwave remote sensing involves the transmission and reception of microwave radiation. This radiation is characterized by its wavelength and frequency. Microwaves have longer wavelengths and lower frequencies compared to visible light. This property allows it to penetrate various materials and provide information about subsurface features.

The electromagnetic spectrum consists of waves of varying wavelengths and frequencies. The microwave portion of the spectrum lies between the infrared and radio wave regions, typically in the wavelength range from 1 millimeter to 1 meter. In terms of frequency, this corresponds to a range of 300 GHz to 300 MHz.

Microwave remote sensing is divided into two broad categories:

- Active remote sensing, which involves sensors that emit microwave radiation and measure the backscatter (e.g., radar).
- Passive remote sensing, which measures the natural microwave radiation emitted by objects (e.g., radiometers).

4.1.1. Active Microwave Remote Sensing

Active microwave remote sensing, commonly referred to as radar (Radio Detection and Ranging), is based on the transmission of electromagnetic waves by a sensor, followed by the reception of the reflected signals from the Earth's surface or atmosphere. Radar operates by analyzing the time delay, strength, and phase shift of the returned signal.

There are different types of radar systems used in microwave remote sensing:

- Imaging radar (such as Synthetic Aperture Radar, or SAR)
- Non-imaging radar (such as altimeters and scatterometers)

Active microwave remote sensing systems are particularly useful for applications that require high spatial resolution and the ability to penetrate atmospheric obstructions like clouds and rain.

4.1.2. Passive Microwave Remote Sensing

Unlike active sensors, passive microwave sensors do not emit any energy; instead, they detect the natural thermal emission from objects. All objects emit microwave radiation based on their temperature and physical properties, which is why passive microwave sensors are often used to monitor parameters such as soil moisture, sea surface temperature, and atmospheric humidity. As natural microwave emissions are relatively weak, passive microwave sensors require very sensitive equipment.

These sensors are commonly used in meteorology, climatology, and hydrology.

4.2. Principles of Microwave Remote Sensing

4.2.1. Wavelength and Penetration

Microwaves lie between infrared and radio waves and are typically divided into several frequency bands, such as L-band, C-band, X-band, and Ku-band. Each of these bands is suited for different applications in Earth observation, depending on their ability to penetrate the atmosphere and interact with the surface (Figure 4.1).

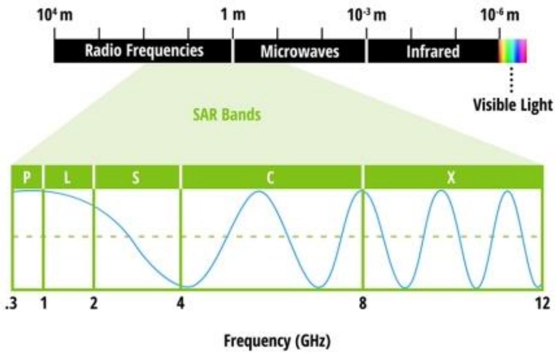


Figure 4.1: The position of microwaves within the electromagnetic spectrum. (Source: https://earthdata.nasa.gov/learn/what-is-sar).

P-Band (0.3-1 GHz): P-band offers the deepest penetration among microwave bands, making it ideal for subsurface imaging and forestry applications, such as estimating biomass and monitoring forest structure.

L-Band (1-2 GHz): Ideal for vegetation and soil moisture studies due to deeper penetration.

S-Band (2-4 GHz): This band is used for weather radar and some low-resolution Synthetic Aperture Radar (SAR) applications. Its moderate wavelength is effective for monitoring precipitation, sea ice, and coastal zones.

C-Band (4-8 GHz): Commonly used for SAR applications like monitoring ice sheets and floods.

X-Band (8-12 GHz): High-resolution imaging for urban and infrastructure mapping.

Microwave signals are also capable of penetrating soils to varying depths depending on the moisture content and texture (Figure 4.2). This property is particularly useful in geophysical studies, agriculture, and hydrological applications.

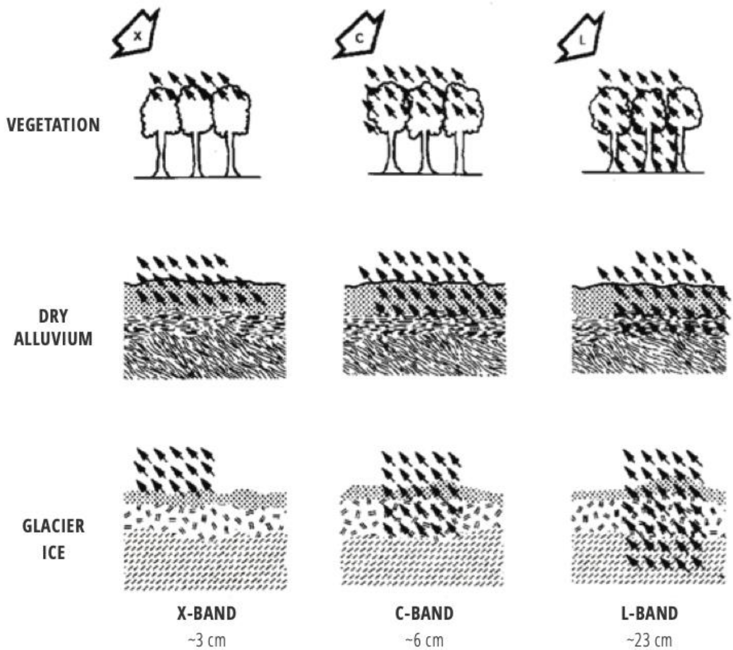


Figure 4.2: Microwave Penetration depends on the wavelength (Meyer 2019).

4.3. Surface Interaction

When microwave radiation interacts with matter, it can be scattered, reflected, or absorbed. The specific interaction depends on the properties of the material and the frequency of the microwave radiation.

- **Scattering**: When microwave energy encounters particles or surface structures, it is dispersed in different directions. Scattering can be either *specular* (mirror-like) or *diffuse* (random).

- **Reflection**: The return of a microwave signal from a surface or object, particularly when it is smooth relative to the wavelength.

- **Absorption**: A portion of the microwave energy may be absorbed by the material, converting it into heat. The level of absorption depends on the material's dielectric properties, which are influenced by factors like moisture content.

The scattering, reflection, and absorption mechanisms of microwaves are influenced by several factors:

- **Dielectric properties:** The dielectric properties of a material, including its permittivity and conductivity, determine how it interacts with microwaves.

- **Surface roughness:** The roughness of a surface affects the amount of scattering that occurs.

- **Geometry:** The geometry of objects can influence the direction of reflected and scattered microwaves.

4.4. Polarization

Microwaves have both amplitude and polarization properties. Polarization refers to the orientation of the electric field vector of a microwave wave. In microwave remote sensing, polarization can be used to extract information about the target's properties. Different polarization states can be used to enhance the contrast between different types of surfaces (Figure 4.3).

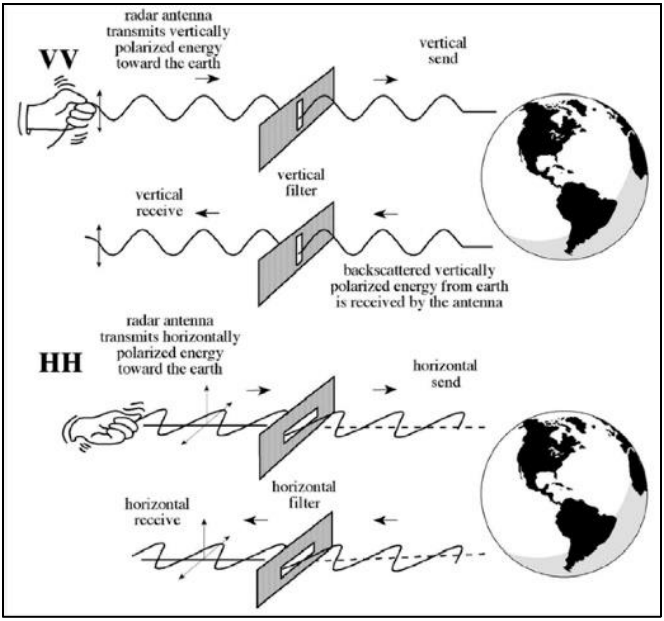


Figure 4.3: Polarization explanation using the slit experiment.

Polarization refers to the orientation of the electric field vector of a microwave wave, different type of polarizations is:

- **Horizontal polarization:** The electric field vector is parallel to the Earth's surface.
- **Vertical polarization:** The electric field vector is perpendicular to the Earth's surface.
- **Dual polarization:** Both horizontal and vertical polarizations are used to obtain more information.

Most microwave sensors, particularly radars, are capable of transmitting and receiving signals in different polarizations, which can provide additional information about the surface properties. For example:

- **VV (Vertical Transmit, Vertical Receive):** Often used for detecting smooth surfaces like water bodies.
- **HH (Horizontal Transmit, Horizontal Receive):** More effective for rough surfaces, such as forests or urban areas.
- **VH (Vertical Transmit, Horizontal Receive):** Cross-polarized data can reveal additional structural information about targets, useful for identifying vegetation or man-made structures.

By understanding the principles of microwave interaction and polarization, scientists can interpret microwave remote sensing data and extract valuable information about the Earth's surface.

4.5. Active Microwave Remote Sensing Systems

4.5.1. Synthetic Aperture Radar (SAR)

SAR is one of the most advanced radar imaging systems used in remote sensing. SAR systems produce high-resolution images of the Earth's surface by transmitting microwave pulses and recording the returned signal over time. By simulating a larger antenna (aperture) using the motion of the satellite or aircraft, SAR achieves fine spatial resolution even from long distances (Figure 4.4).

4.4.1.1 Why is it called "Synthetic"?

The term "synthetic" in SAR refers to the creation of a virtual antenna that is much larger than the physical antenna. This is achieved by moving the antenna during data acquisition.

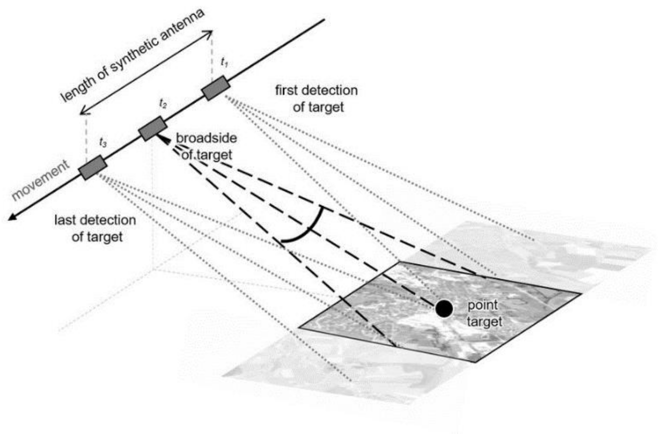


Figure 4.4: Synthetic Aperture of the Antenna is due to the relative motion of target and sensor (Jensen 2007).

As the antenna moves, it collects data from different perspectives, effectively creating a larger aperture. The processing algorithms then combine these data points to synthesize a virtual antenna, resulting in higher resolution images.

4.5.2. Types of Resolutions in SAR

SAR Image offers two primary types of resolution and have a geometry of acquisition as shown in figure 4.5.

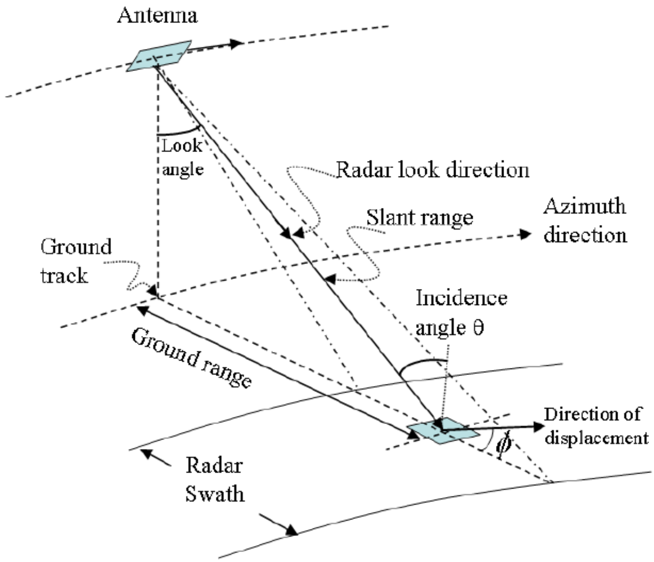


Figure 4.5: Geometry of SAR acquisition

- **Range Resolution:** This refers to the ability to distinguish between targets that are located at different distances from the radar. Range resolution is directly related to the bandwidth of the transmitted signal.

- **Azimuth Resolution:** This refers to the ability to distinguish between targets that are located at different angles from the radar. Azimuth resolution is determined by the synthetic aperture length.

4.5.3. Types of SAR Acquisitions

SAR systems can be operated in various modes (Figure 4.6), each with its own advantages and applications:

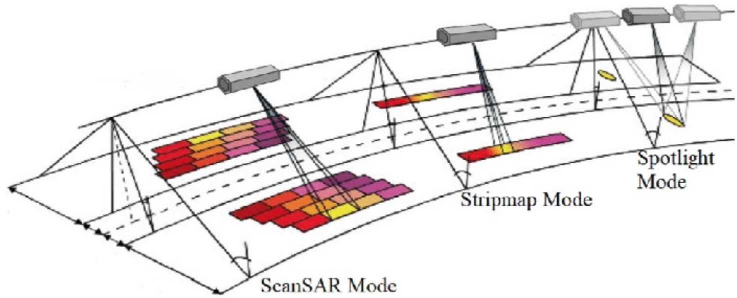


Figure 4.6: Different Modes of SAR acquisition. (Source: http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10382/570_read-431/)

- **Stripmap Mode**: This is the most common SAR mode, where the radar antenna remains pointed perpendicular to the flight path. Stripmap mode provides high azimuth resolution but limited swath width.

- **Spotlight Mode:** In spotlight mode, the radar antenna is continuously steered to focus on a specific target. This mode provides extremely high resolution but limited coverage.

- **ScanSAR Mode:** ScanSAR mode combines the advantages of stripmap and spotlight modes. The antenna is electronically scanned to cover a wider swath, while maintaining high azimuth resolution for specific targets within the swath.

- **Interferometric SAR (InSAR):** InSAR uses two SAR antennas to acquire data simultaneously. By comparing the phase differences between the two images, InSAR can measure surface deformation, such as subsidence or uplift (Figure 4.7).

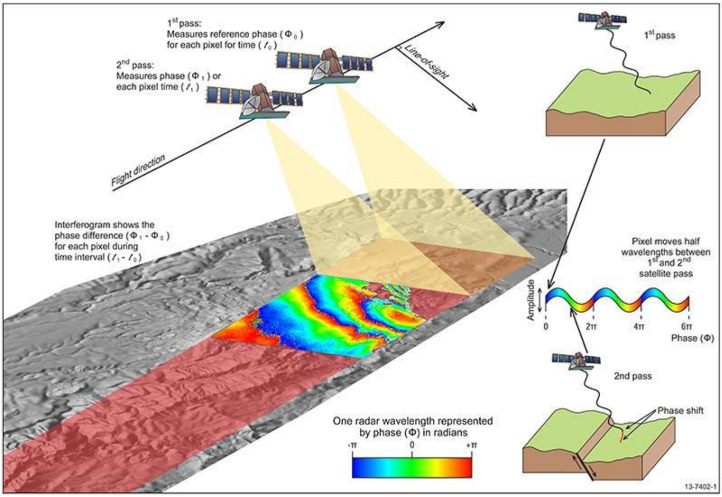


Figure 4.7: Interferometric SAR used for study of land deformation (Source: https://www.ga.gov.au).

- **Polarimetric SAR:** Polarimetric SAR transmits and receives signals with different polarizations (e.g., horizontal, vertical, circular). This allows for the discrimination of different surface types based on their scattering properties.

4.6. Scatterometers

Scatterometers are non-imaging radar systems designed to measure the amount of microwave energy scattered back to the sensor from the Earth's surface. These systems are primarily used to measure **surface wind speeds over oceans**, as the interaction between microwaves and the rough ocean surface can reveal the wind's influence on wave patterns.

4.7. Radar Altimeters

Radar altimeters measure the distance between the satellite and the Earth's surface by timing the travel of microwave pulses. These instruments are critical for determining **sea surface heights**, monitoring ocean circulation, and mapping ice sheet elevations.

4.8. Passive Microwave Remote Sensing Systems

4.8.1. Microwave Radiometers

Microwave radiometers detect natural emissions of microwave radiation from the Earth's surface and atmosphere. The intensity of this radiation is related to the temperature and physical properties of the emitting objects. Radiometers are used in:

- Soil moisture estimation
- Sea surface temperature and salinity measurements
- Monitoring snow and ice coverage
- Atmospheric studies, including measuring water vapor and cloud liquid water content

4.9. Applications of Passive Microwave Remote Sensing

Passive microwave sensors are widely used in climatology, hydrology, and environmental monitoring. Their ability to monitor soil moisture and vegetation conditions makes them essential for agricultural forecasting and drought assessments. Additionally, they play a significant role in polar studies, tracking sea ice extent and melting processes.

4.10. Applications of Active Microwave Remote Sensing

4.10.1. Agriculture and Soil Moisture Monitoring

Microwave remote sensing, particularly through the use of SAR and radiometers, allows for accurate monitoring of soil moisture levels, which is critical for agricultural productivity. By detecting variations in dielectric properties of wet and dry soils, microwave sensors help assess drought conditions, irrigation needs, and crop health.

4.10.2. Forest and Vegetation Monitoring

Forests and vegetation canopies can be penetrated by longer-wavelength microwaves, enabling radar systems to observe biomass, forest structure, and deforestation rates. In forestry, SAR data is often used to estimate tree height, density, and overall biomass, providing valuable information for carbon cycle studies and sustainable forest management.

4.10.3. Hydrology and Flood Monitoring

Microwave sensors play a crucial role in hydrological applications such as flood detection and water resource management. The ability of microwaves to penetrate clouds and provide data in all weather conditions makes SAR systems ideal for monitoring floods, river dynamics, and changes in water bodies (Figure 4.8).

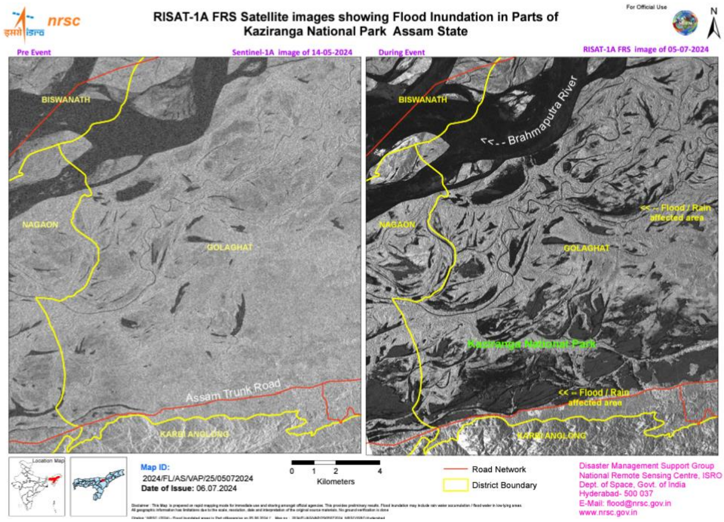


Figure 4.8: EOS 4 (RISAT) data of flood affected area in Assam (Source: https://ndem.nrsc.gov.in).

4.10.4. Oceanography

In oceanographic studies, radar altimeters and scatterometers are used to measure sea surface heights, wave patterns, and wind speeds. These measurements are vital for understanding ocean circulation, predicting weather patterns like El Niño, and monitoring sea level rise due to climate change.

4.10.5. Cryosphere Studies

Microwave remote sensing has revolutionized the study of the cryosphere (Earth's frozen regions) (Figure 4.9). SAR and radiometers are extensively used to monitor snow cover, ice sheets, glaciers, and sea ice. These observations are critical for understanding climate change impacts, particularly in the polar regions, where warming temperatures are leading to ice melt and rising sea levels.

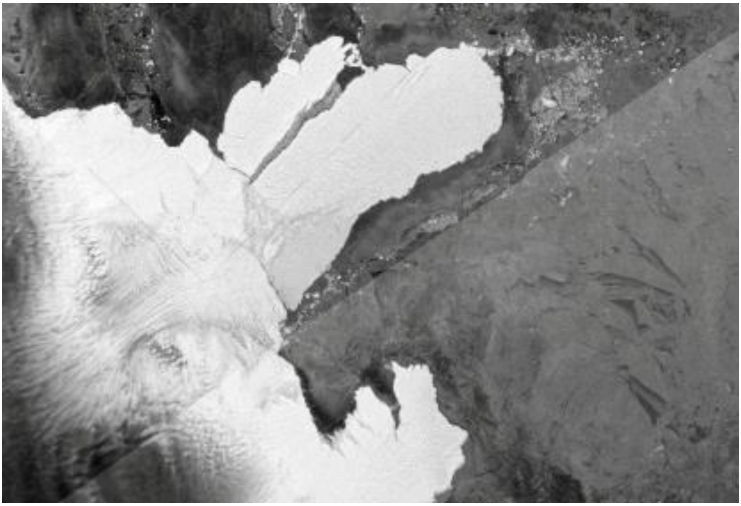


Figure 4.9: Sentinel 1 data of Antarctica for Sea Ice Monitoring (Source: https://www.esa.int).

4.10.6. Urban Applications

Microwave remote sensing is increasingly being used in urban areas for mapping, infrastructure monitoring, and land use classification. SAR data, in particular, is useful in detecting buildings, roads, and other human-made structures. It also aids in monitoring subsidence and land deformation in cities, which is important for planning and risk management.

4.10.7. Disaster Management

Microwave remote sensing is indispensable in disaster management, particularly during events like hurricanes, floods, earthquakes, and landslides. The ability of microwave systems to capture data in cloudy or stormy conditions allows for real-time monitoring of disaster zones and facilitates timely responses.

4.11. Conclusion

Microwave remote sensing is a powerful tool for observing the Earth's surface and atmosphere, offering unique capabilities that complement other types of remote sensing. Its ability to penetrate clouds, vegetation, and soils, combined with all-weather, day-and-night observation capabilities, makes it essential for a wide range of applications, from agriculture and hydrology to disaster management and urban planning. As technology advances, microwave remote sensing is set to play an even more significant role in Earth observation and planetary exploration, contributing to a deeper understanding of our world and its dynamic processes.

Chapter 5

Hyperspectral Image Analysis

5.1. Introduction

Hyperspectral remote sensing involves collecting and analyzing data from a range of electromagnetic wavelengths in order to extract information about objects on the Earth's surface or any other planetary surface (Camps-Valls et al., 2011; Goetz et al., 1985; Richard and Jia, 2006). This data is typically collected by sensors on airborne or spaceborne platforms, which measure the radiance or energy reflected or emitted by the objects being studied. By analysing the unique spectral signatures of different objects, hyperspectral remote sensing can be used to identify and map different types of vegetation, minerals, water bodies, and other features of interest. This technique is widely used in variety of fields such as agriculture, environmental monitoring, geology, food technology and archaeology, among others.

Hyperspectral imaging, also termed imaging spectroscopy, the sensor acquires a spectral vector with hundreds or thousands of elements from every pixel in a given scene which make it possible to derive a continuous spectrum for each image cell. The result is the so-called hyperspectral image (HSI) or are also termed hyperspectral data cubes and can be interpreted as a stack of images representing the radiance in each respective band or wavelength interval, as shown in the illustration below (Figure 5.1).

Multispectral remote sensors such as the Landsat, Thematic Mapper, IKONOS, IRS LISS II, LISS III and Sentinel 2, SPOT XS on the other hand produce images, with a few relatively broad wavelength bands. One of the major limitations of the multispectral data is that the sensors operate in broad wavelength bands thus limiting the amount of spectral information available.

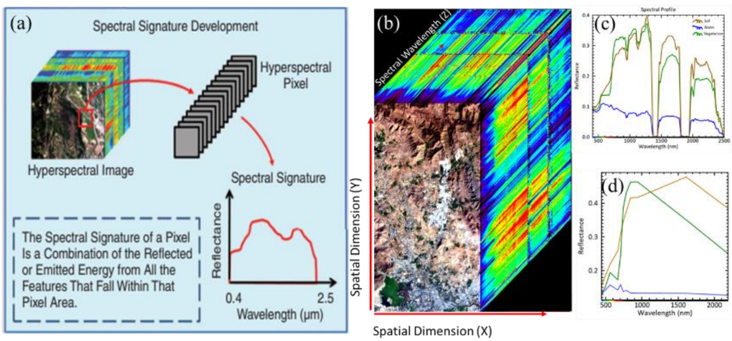


Figure 5.1(a): Concept of hyperspectral image (adopted from 10.1109/MGRS.2013.2244672) and spectral signature. (b). EO-1 Hyperion 3D spectral cube of Udaipur in a natural color composite (c) shows the spectral signatures of vegetation, soil, and water extracted to demonstrate their differences in spectral properties in hyperspectral data (d) same spectral response from multispectral data (Sentinel-2).

5.2. Hyperspectral Datasets

NASA's Earth Observing-1 (EO-1) Hyperion instrument was launched in the year 2000, created for exploiting the space-borne hyperspectral imaging capabilities and was the first hyperspectral sensor to provide a continuous information in terms of spectral profile across the broad electromagnetic spectrum ranging from 400 nm to

2500 nm. Hyperion has total 242 spectral channels with 30 m spatial resolution with. Examples of other hyperspectral sensors two airborne (HYDICE and AVIRIS) and five spaceborne are listed in Table 5.1.

Hyperspectral images contain a wealth of data, but interpretation requires great understanding of the properties of ground materials we are trying to measure, and how they relate to the measurements actually made by the hyperspectral sensor. Hyperspectral images require removal of atmospheric, and terrain effects, after which the image spectra can be compared with field or laboratory reflectance spectra in order to recognize and map surface materials. Therefore, pre-processing plays a critical role in hyperspectral image analysis and should be considered an essential step in any scientific analysis.

Table 5.1: Hyperspectral sensors

PARAMETER	AVIRIS	HYDICE	CHRIS	PRISMA	HyspIRI	EnMAP	HYPERION
Altitude (km)	20	1.6	556	614	626	653	705
Spatial Resolution (m)	20	0.75	36	5-30	60	30	30
Spectral resolution (nm)	20	7-14	1.3–12	10	4-12	6.5–10	10
Spectral Coverage (μm)	0.4–2.5	0.4–2.5	0.4–2.5	0.4–2.5	0.38–2.5 & 7.5–12	0.4–2.5	0.4–2.5
Number of bands	224	210	63	238	217	228	220

5.3. Pre-processing of Hyperspectral Data

Hyperspectral sensors typically provide images in raw digital numbers (DN), which represent the measured radiance values at the sensor. To convert these raw digital numbers into surface reflectance values, a number of corrections and calibrations must be applied.

Firstly, radiometric calibration is performed to convert the raw digital numbers into at-sensor or top-of-atmosphere (TOA) radiance values, which account for the sensor characteristics. This involves using the sensor's characteristic gain and offset values to convert the raw digital numbers into radiance values.

Next, for meaningful measure of radiance at the Earth's surface, the atmospheric interferences must be removed from the data. This process is called "atmospheric correction". As sunlight passes through the atmosphere, it gets partially absorbed and scattered, which can influence the spectral values measured by the sensor. To correct for this, various atmospheric correction algorithms are used to estimate the atmospheric conditions and remove their influence on the spectral values.

Finally, geometric and surface corrections are applied to account for the effects of illumination, viewing angle, and the surface's structural and optical properties. This involves correcting for things like shadows, topography, and surface orientation, as well as accounting for differences in reflectance due to the surface properties such as vegetation, water, and soil. Overall, these corrections and calibrations are necessary to convert the raw digital numbers into useful surface reflectance values that can be used for advanced information extraction techniques such as classification and feature extraction. Figure 5.2 shows the entire process of radiometric correction.

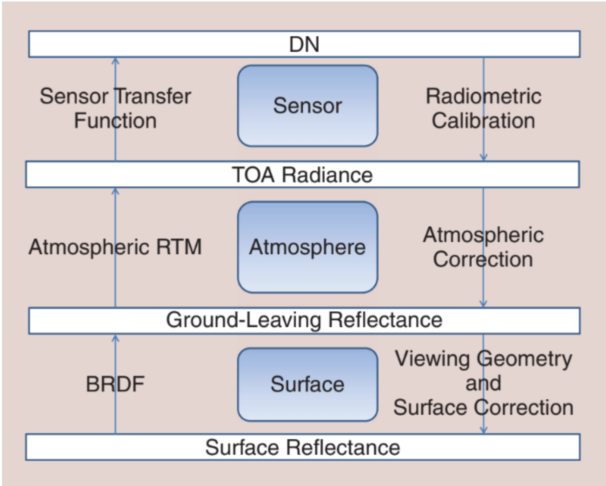


Figure 5.2: Steps of conversion of DN values to Surface Reflectance (Source: DOI: 10.1109/MGRS.2013.2244672).

Step 1. Conversion of DN to spectral radiance

This step requires information on the gain and bias of the sensor in each band (Figure 5.3). The transformation is based on a calibration curve of DN to radiance. The calibration is carried out before the sensor is launched. Since the accuracy of the sensor changes over time, re-calibration of the sensor is carried out periodically and gain and offset values are provided with the satellite data. The gain and bias values for each band are calculated from the lower (Lmin) and upper (Lmax) limits of the post-calibration spectral radiance range.

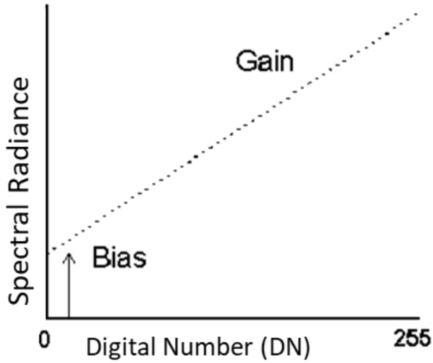


Figure 5.3: Calibration curve of Sensor. Gain represents the gradient and Bias defines the spectral radiance of the sensor for a DN of zero.

The formula to convert DN to radiance using gain and bias values is:

$L_\lambda = gain * DN + bias$ (Eq. 5.1)

units: mW cm^{-2} $ster^{-1}$ μm^{-1}

Where:

L_λ is the cell value as radiance

DN is the cell value digital number

gain is the gain value for a specific band

bias is the bias value for a specific band

Gain can be calculated using the equation –

$$\text{Gain} = \frac{\text{Lmax} - \text{Lmin}}{255} \quad \text{(Eq. 5.2)}$$

Step 2. **Conversion of spectral radiance to reflectance**

The apparent reflectance, which for satellite images is termed Top of the atmospheric reflectance, ρ, defined as the ratio of measured radiance, L, to the solar irradiance incident at the top of the atmosphere and is expressed as a decimal fraction between 0 and 1**.**

$$\frac{\pi * L * d^2}{ESUN * \cos(SZ)} \quad \text{(Eq. 5.3)}$$

ρ = unitless reflectance (ranges 0-1)

π = 3.141593

L = Spectral radiance at sensor aperture in mW cm^{-2} $ster^{-1}$ μm^{-1}

d^2 = the square of the Earth-Sun distance in astronomical units = (1 - 0.01674 cos(0.9856 (JD-4)))2 where JD is the Julian Day (day number of the year) of the image acquisition.

ESUN = Mean solar atmospheric irradiance in mW cm^{-2} μm^{-1}.

SZ = sun zenith angle in radians when the scene was recorded.

Step 3. **Removal of atmospheric effects due to absorption and scattering**

Atmospheric correction techniques can be divided into two categories which are absolute (empirical) and relative atmospheric corrections (Van der Meer, 1999) and are explained in the next section.

5.4. Absolute Atmospheric Correction Techniques

In this method, a prior knowledge of the surface characteristics and atmospheric model is not required. This method corrects the image data for scattering and absorption of water vapor, mixed gases and topographic effects (AIG, 2001). Radiative transfer codes (i.e. LOWTRAN - Low-resolution propagation model and MODTRAN-MODerate resolution atmospheric TRANsmission) use scattering and transmission properties of the atmosphere, the difference between the radiation leaving the earth and the radiation received at sensor and can model the scattering effects in the atmosphere (Van der Meer, 1999). MODTRAN is designed to model the atmospheric propagation of electromagnetic radiation from visible to far infrared region with a spectral resolution of 100 µm. It is licensed to U.S. Air Force and core modules are written in FORTRAN code. These codes are modelled for different types of atmosphere models and can work for a large number of atmosphere types intended for calculation of atmospheric radiance spectrum on a pixel-by-pixel basis.

Different atmospheric correction modules are available –

- *Atmospheric CORrection (ACORN) (Goetz, et. al., 2002),*
- *ATmospheric CORrection (ATCOR2 and ATCOR 3),*
- *Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH))*

For Hyperion images, FLAASH is commonly used for atmospheric correction. FLAASH is developed by Air Force Research Laboratory, Space Vehicles Directorate (AFRL/VS) and is based on physics-based algorithm from the MODTRAN4 radiative transfer code (Felde et. al., 2003). FLAASH is designed to eliminate atmospheric effects caused by molecular and particulate scattering and absorption from the radiance at the sensor and to obtain reflectance at the surface. FLAASH uses a standard equation of spectral radiance at a sensor pixel (L) that applies to solar wavelength range and flat Lambertian materials. FLAASH is available in ENVI software and is widely used by scientific community for atmospheric corrections (ENVI Manual, 2005).

5.5. Relative Atmospheric Correction Techniques

Relative atmospheric correction method uses directly image brightness values and reflectance value of pixels are computed relatively to each other (Van der Meer, 1999). There is no need to a prior knowledge of the surface characteristics and atmospheric model in this method. Four different methods which are commonly used are:

- *Logarithmic residuals*
- *Flat field correction*
- *Internal Average Relative Reflectance Correction*
- *Empirical Line Correction.*
- *QUick Atmospheric Correction- QUAC*

Logarithmic residuals, or shortly log residuals correction accounts for the illumination, reflectance, topographic factors. In this method, original radiance value of individual wavelength is divided by geometric mean of all channels and then, the logarithm of the resultant data computed.

Flat Field Correction approach assumes that there is an area in the scene that has spectrally neutral reflectance which has little variation with wavelength. The mean spectrum of the "flat field" is then used for the derivation of relative reflectance spectra of other pixels in the scene.

IARR correction allows the calibration when no sensor information is available (Kruse, 1988). This technique involves using the average reference spectrum of an entire image to divide the radiance spectrum of each pixel in the image, resulting in the relative reflectance spectrum for each pixel. This method sometimes produces wrong interpretation as spectral features (Van der Meer, 1999). Both the IAR approach and the "flat field" approach do not need any field measurements of reflectance spectra of surface targets and are Scene-Based Empirical Approaches.

The **Empirical Line Method (ELM)** requires the selection and characterization of two or more calibration targets (at least one bright and one dark target) with known reflectance values, which are used to derive a linear regression equation (i.e., the empirical line) for each spectral band to derive the gain and offset curves. These gain and offset curves are then applied to the whole image for the derivation of surface reflectance for the entire scene. This method produces reflectance spectra that are most comparable to laboratory-based reflectance spectra.

Quick Atmospheric Correction (QUAC) derives the atmospheric compensation parameters directly using the pixel spectra of the scene (Figure 5.4). The approach is based on the finding mean spectrum of a collection of diverse material spectra, such as the endmember spectra in a scene, is essentially invariant from scene to scene. It allows the retrieval of reasonably accurate reflectance spectra even without proper sensor radiometric or wavelength calibration, or when the solar illumination intensity is unknown. This method works very faster than first-principles methods, making it potentially suitable for real-time applications.

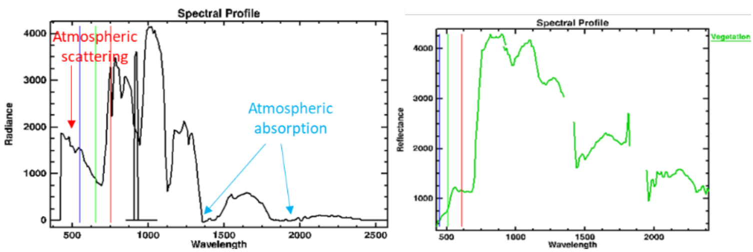


Figure 5.4: An example of atmospheric correction processing for Hyperion, showing several at-sensor pixel spectra (left) and the corresponding atmospherically corrected surface reflectance spectra (right) using QUAC. At 1400 and 1900 nm regions atmospheric attenuation is strong, it is not possible to correct these regions.

Other important pre-processing steps involved in Hyperspectral image analysis involves - Bad band removal i.e., removing the bands with no information, and destriping.

5.6. Bad band removal

Different ground objects are characterized by different spectral characteristics forming the physical basis for target detection or mapping. Band combinations of hyperspectral data play an important role while detecting or separating one specific target. One particular band combination may work for one target but for different targets, those informative band combinations may differ, and even for the same target, the informative band combination will vary when the background changes. However, certain bands in the datasets that provides little information to detect any target in the scene and have a low SNR value are considered as Bad Bands. The number and locations of bad bands will change in different scene and the regions of study.

In the case of Hyperion, which has 242 bands, bands 1 to 7 and 225 to 242 have zero values and are not useful. Additionally, bands 58 to 76 fall in the overlap region of the two spectrometers and have higher noise levels, making them bad bands as well. Therefore, for Hyperion dataset only 196 bands out of 242 are considered as good bands. The water vapour absorption bands 120 to 132 (1346 nm to 1467 nm), bands 165-182 (1800 to 1971 nm) and bands 221 (above 2356) and higher also needs to be eliminated. Example of bad bands is shown in

Figure 5.5. The list of bad bands of Hyperion data is listed in Table 5.2.

Table 5.2: List of bands which are eliminated from Hyperion data including the water absorption bands.

Bands	**Description**
1 to 7	Not Illuminated
58 to 78	Overlap Region
120 to 132	Water Vapour Absorption Band
165 to 182	Water Vapour Absorption Band
185 to 187	Identified by Hyperion Bad Band List
221 to 224	Water Vapour Absorption Band

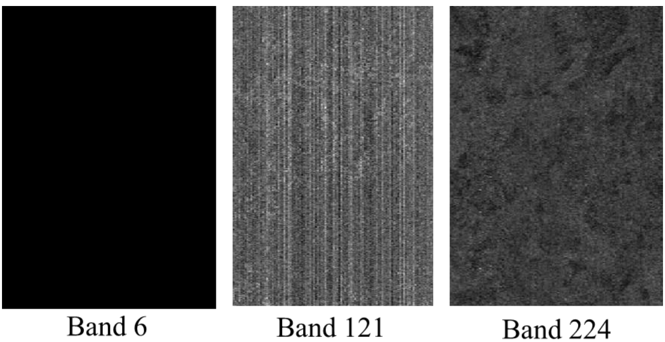


Figure 5.5: Example of bad bands in Hyperion data.

5.7. Destriping

Hyperspectral data sets often affected by striping artifacts, i.e., intensity variations that are functions of the column or row of an image i.e., intensity variations that are functions of the column or row of an image. These artifacts may be caused by a variety of effects involving the sensor or viewing conditions and may be oriented along either the along-track (scan) direction or the cross-track direction (Kruse., 1988). These stripes and the corrupted pixels are referred to as abnormal pixels. Along-track striping is more common which is caused by drift in the radiometric responses of detector array elements or problems in the readout electronics. Vertical stripes occur if one detector of an array (in either the VNIR or SWIR arrays) has a slightly modified or unbalanced response from that of its neighbours or from its normal condition (Figure 5.6 and 5.7). If the difference of this response is persistent, the effect can be reduced or eliminated by “fine tuning” the calibrations which are normally different for each detector array. The striping may occur in most channels to some degree but are often pronounced in the SWIR and in channels with low SNR.

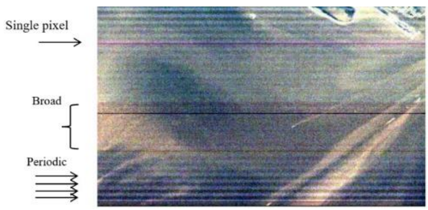


Figure 5.6: Striping in a Hyperion image FCC RGB = (468, 447, 427) nm. The image is rotated so that the scan direction is from left to right. Source: https://doi.org/10.1117/12.2014317.

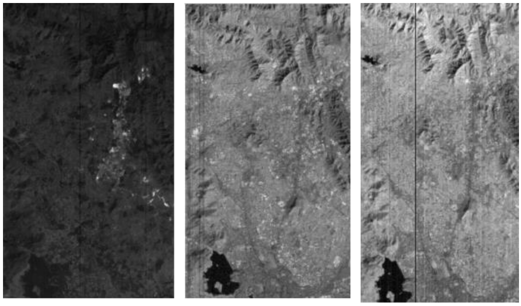


Figure 5.7: Examples of Vertical Striping in a Hyperion bands of Udaipur Scene.

Due to high resolution of the images, the particular pixels do not hold much information compared to the whole image. During de-striping, the values of abnormal pixels or bad columns are approximated to an average or average mean and standard deviation of the neighbouring set of pixels.

In order to perform segmentation and classification on hyperspectral data sets, it is essential to pre-process the images to ensure accurate spectral profiles and expected pixel values. This typically involves applying various techniques such as spectral calibration, atmospheric correction, noise reduction, and radiometric calibration to prepare the image data for analysis. The complete processing of the hyperspectral data is summarized in the Figure 5.8.

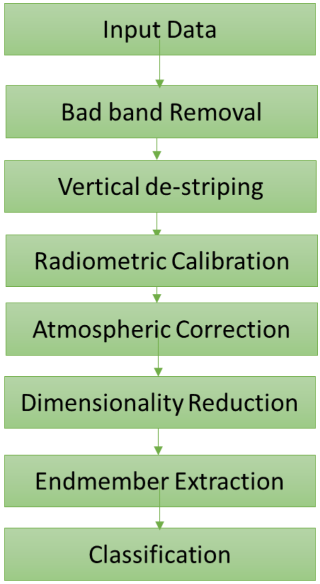


Figure 5.8: Processing chain of the hyperspectral data.

5.8. Dimensionality Reduction

Hyperspectral images typically comprise hundreds of bands that offer high spatial and spectral information. However, the large size of these images can present significant constraints in terms of data handling and processing. To facilitate more concise and meaningful interpretation, it may be necessary to reduce the dimensionality of the image without sacrificing any information. The dimensionality reduction can be achieved either by feature selection and second one by feature extraction. Feature extraction methods involve creating a new subset of features by selecting or combining existing information within the feature space. On the other hand, feature selection involves analyzing a subset of features that are chosen from the original set of features. This is achieved by using dimensionality reduction algorithms such as Principal Component Analysis (PCA) and Minimum Noise Fraction (MNF) (Green et al., 1988; Lee et al., 1990).

PCA is one of the best methods for feature extraction for dimensionality reduction. PCA transform multidimensional image data into a new, uncorrelated co-ordinate system or vector space and produces a space in which the data have maximum variance along its first axis, the next largest variance along a second mutually orthogonal axis and so on. In PCA, the images are ordered based on the eigenvalues in decreasing order of variance. This means that the image with the highest variance is assigned the first principal component, followed by the second highest variance for the second component, and so on, until all components are determined. Useful PCA images then selected based on the eigen values or visual interpretation. However, sometimes even the lower-order PC's may contain valuable information. Figure 5.9 shows the PCA images derived from Hyperion data showing the majority of the variability is accounted for in the first few PCA bands and that the remaining bands contains noise. Comparing PC1 to PC9 in Figure 5.9 shows that each PC is different from all the others (because all are decorrelated) The use of PCA band combinations proves to be highly effective in distinguishing between different surface materials highlighted with various colors as in Figure 5.9 (extreme right).

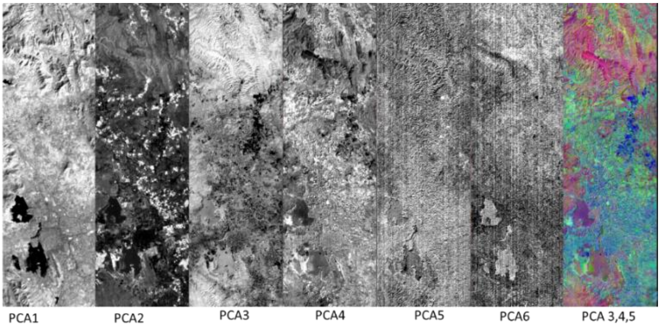


Figure 5.9: PCA components of Hyperion image over Udaipur showing the increase the noise component from the PCA 1 to PCA 6 and discrimination of different surface materials in PCA RGB combination.

Minimum Noise Fraction (MNF) is two-tiered component transformation used to identify the number of bands of image data, segregate the noise in the data, and reduce the computational demand for further processing (Green et. al., 1988). Minimum noise fraction (MNF) transform is a linear transform performed in two separate steps. In the first step, the noise covariance matrix is used to decorrelate and rescale the noise in the data, known as noise whitening. The second step involves performing a standard Principal Component Analysis (PCA) transform on the noise-whitened data to obtain the MNF components. The MNF is an eigenvector procedure based on the covariance structure of the noise in the image data set unlike PCA and is much more effective in creating a set of images ordered according to image quality. Figure 5.10 shows the first six MNF band of the Hyperion data cube showing how the information is decreasing and nosie component is increasing towards the higher components. The first ten bands are found to be free from salt and pepper effect (Figure 5.10). As can be seen in Figure 5.10, eigen values approach to value of 2 beyond the first 20 MNF bands are considered suitable and noise free for classification. Beyond MNF band 20, the eigen value distribution is nearly becomes constant as being parallel to the horizontal axis.

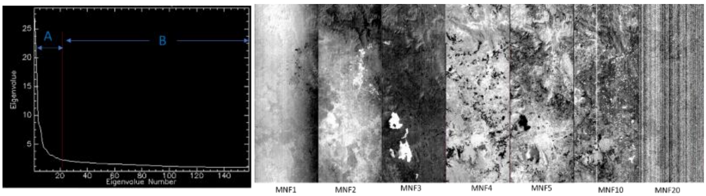


Figure 5.10 (left): Graphical representation of the eigen values versus eigen numbers for the Hyperion Udaipur image. A region shows high eigen indicating image data and B region shows low eigen values indicating possible noise. (Right) MNF transform output channels for the Hyperion data cube showing steadily increase in the noise level.

5.9. Endmembers Extraction

End members are considered as the purest pixels in an imaged scene (Keshava and Mustard, 2002). Spectral unmixing is often performed to unmix the mixed pixels components in hyperspectral image, into their respective endmembers and abundances. The abundance fractions represent the proportion of each endmember that contributes to the mixed pixel spectrum. The Pixel Purity Index (PPI) algorithm is used to extract purest spectral signature from the data cube (Boardman et al., 1995). The end members spectra are further used to find the different classes present in the whole image. The accuracy of this spectral profile totally depends on the per-processing corrections applied on the image. Figure 5.11 (left) shows the PPI output with pure pixels in 10000 iterations which are used as the candidate points. Figure 5.11 (middle) shows n-D visualizer which is used to locate, identify, and cluster the purest pixels and the most extreme spectral responses (endmembers) in a dataset in n-dimensional space (ENVI User's Guide, 2001). Different pixels classes are marked in different colors and the reflectance spectra is extracted (Figure 5.11, right) which represent pure pixels endmembers vegetation, water and soil class. These end members are utilized further for classification of image.

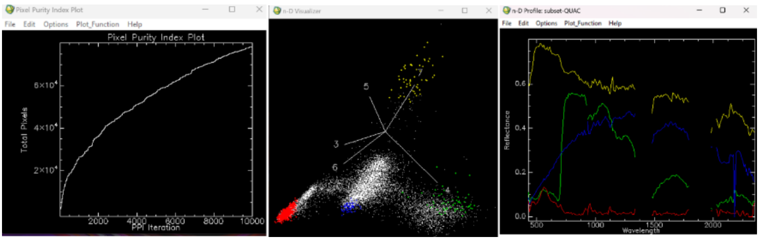


Figure 5.11: PPI output showing number of pure pixels extracted (left), n-D visualizer used to locate pure pixels (middle), and pure pixels endmember extracted (right).

5.10. Classification

Classification is identified as the Information extraction technique based on the spectral reflectance properties of the study scene by performing certain spectral analysis algorithms (Pignatti et al., 2009) It is based on grouping pixels of similar characteristics together in an image where the spectral pattern present within the data for each pixel is used as the numerical basis for classification. Classification of hyperspectral images has been a very active area of research in recent years. The goal of classification is to assign a unique label to each pixel vector based on given a set of observations (i.e., pixel vectors in a hyperspectral image).

There are two main approaches used in hyperspectral classification: Supervised and Unsupervised based on the usage of the training datasets. Most common approaches for identification or classification of hyperspectral data are Spectral Angle Mapper, Spectral feature Fitting, Maximum likelihood (ML) methods, Neural Networks architectures (Zhong and Zhang, 2012), Support Vector Machine (SVM) (Melgani and Bruzzone, 2004), Bayesian approach (Mohamed and Farag, 2005) as well as Kernel methods (Camps-Valls et al., 2006).

5.10.1. Supervised Classification

This method relies on a set of training samples for different classes of interest provided by the user. The entire image will be classified into the desired categories based on the training samples. This resultant accuracy is high as it incorporates the user's domain knowledge. However, this classification requires more time and effort to collect the training samples (Zhang and Li, 2014).. The user first selects the classes of interest, which correspond to information classes. The algorithm will evaluate the similarity of the known to unknown pixels and assign unknown identity pixels to the class that has the highest likelihood of being a member.

Spectral Angle Mapper - SAM is a supervised classification algorithm, which utilizes spectral angular information for the classification of hyperspectral data (Kruse et al., 1993). In this classification, each pixel in a hyperspectral image is represented as an n-dimensional vector, where n equals the number of spectral bands. The algorithm measures similarity of a target spectrum to a reference spectrum by calculating spectral angles between them. The variation in the angle between the image spectra and the endmember spectra is used as the measure of discrimination. A smaller angle represents a closer match to the reference spectrum. Pixels further away than a specified maximum angle threshold (in radians) are not classified (Figure 5.12).

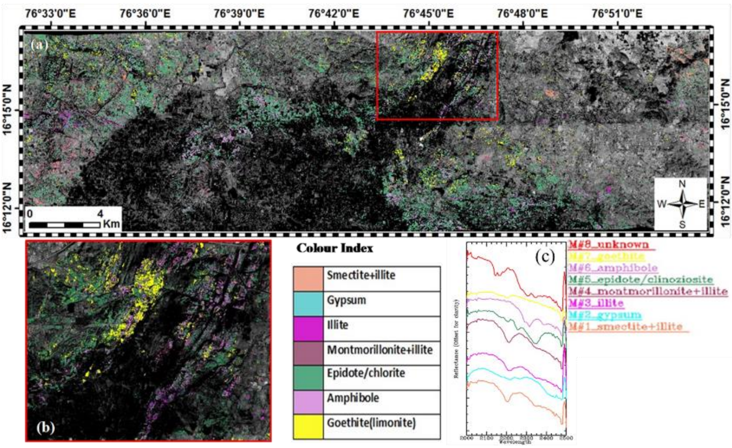


Figure 5.12: (a) SAM classification image of the part of Hutti-Maski area, Karnataka India using AVIRIS-NG data (b) Close view of the mineralised zone (c). Reflectance spectra of endmembers selected using n-D visualizer.

Spectral Feature Fitting (SFF) - Spectral feature fitting (SFF) algorithm works with the continuum removed image and library spectrum. The algorithm compares the continuum removed mage spectra with the reference spectral library spectra and operates the least square fitting. The identification of best fitting material depends on spectral features of reference and done by comparing the correlation coefficient of fits (Boardman & Kruse, 1994). Continuum removed image spectra can be derived by dividing the original spectrum of every pixel in the original image by the continuum curve.

$$Scr = \frac{S}{C} \quad \text{(Eq. 5.4)}$$

Where, Scr = Continuum removed spectra, S = Original Spectra, C = Continuum curve

Minimum distance classifier (MDC) is based on the distance of pixels in the feature space as a classification basis. MDC works on the basic assumption of the similarity measure that is if the feature differences between the two modes are below a set threshold, the two modes are said to be similar. The similar feature points (same class) are clustered in the feature space. The mean vector is then determined by these feature points and used as the center of the category. The dispersion of surrounding points is described by the covariance matrix Points are similarly measured with each category. It uses distance as the main basis for measuring the similarity of samples. There are many forms of distance calculation, including Ming's distance, Mahalanobis distance, absolute value distance, Euclidean distance, Che's distance, and Barth's distance.

Maximum Likelihood Classifier (MLC) is based on the Bayesian criterion and is form of nonlinear classification method. The statistical feature values of each type of training samples are calculated during classification by establish a classification discriminant function. The discriminant function is then used to find the probability that each pixel in the hyperspectral remote sensing image belongs to various types, and will be used to classify the test sample into the category with the highest probability. The pixels are classified only after selecting a probability threshold. Each pixel is assigned to the class that has the highest probability (that is, the maximum likelihood). If the highest probability is smaller than a threshold you specify, the pixel remains unclassified. Other Supervised algorithm commonly used are Neural Network Classification, Support Vector Machine algorithm.

5.10.2. Unsupervised classification algorithms

Hyperspectral datasets come with curse of high dimensionality. To overcome this difficulty, feature extraction methods are used to reduce the dimensionality by selecting the prominent features. In unsupervised methods, pixels with similar spectral characteristics (means, standard deviations, etc.) are automatically grouped into unique clusters according to some statistically determined criteria. Unsupervised classification methods do not require any prior knowledge to train the data. The familiar unsupervised methods are principal component analysis (PCA), independent component analysis (ICA), K-Means, ISODATA, and Hierarchical Clustering.

K-means: K-Means Clustering is a centroid based algorithm which groups the unlabelled dataset into different clusters by iteratively updating the cluster centroids and assigning pixels to the closest one. The clusters are associated with a centroid and the algorithm works on minimizing the sum of distances between the data point and their corresponding cluster. Here K defines the number of pre-defined clusters that need to be created in the process. It allows us to cluster the data into different groups and a convenient way to discover the categories of groups in the unlabelled dataset on its own without the need for any training.

ISODATA (Iterative Self-Organizing Data Analysis Technique) is one of the most utilized methods in unsupervised classification and is an extension of K-Means algorithm. It is an iterative clustering method that allows for cluster merging and splitting based on user-defined parameters, making it more flexible than K-means. In ISODATA, the number of clusters selects automatically and normally assumes that each class obeys a multivariate normal distribution. The algorithm assigns arbitrary cluster centers and the cluster means and covariance are calculated. The pixels are subsequently classified into the nearest cluster. New cluster means and covariances are calculated based on all the pixels within that cluster, and this process is repeated for several iterations until the change between iterations is considered 'sufficiently low'. The modification can be quantified in two ways: either by measuring the distance the cluster mean has changed from one iteration to the next, or by calculating the percentage of pixels that have changed between iterations.

5.11. Spectral unmixing

Spectral unmixing refers to separation of the pixel spectra from a hyperspectral image into a collection of constituent spectra, or spectral signatures, known as endmembers and a set of fractional abundances, one set per pixel. These endmembers represent the pure materials present in the image and the set of abundances, or simply abundances, at each pixel represent the percentage of each endmember that is present in the pixel (Bioucas-Dias et al., 2012). Unmixing algorithms operate based on the anticipated type of mixing. which can be linear or non-linear mixing. In linear mixing, the measured reflectance spectrum is a weighted average of the material spectra and the relative amount of each material is represented by the associated weight. As shown in Figure 5.13, the reflecting surface is considered similar to a checkerboard mixture, and there is no multiple scattering between components. In this case, there exists a linear relationship between the fractional abundance of the substances comprising the area being imaged and the spectra in the reflected radiation (Keshava and Mustard, 2002). Linear unmixing model is either geometrical- or statistical based.

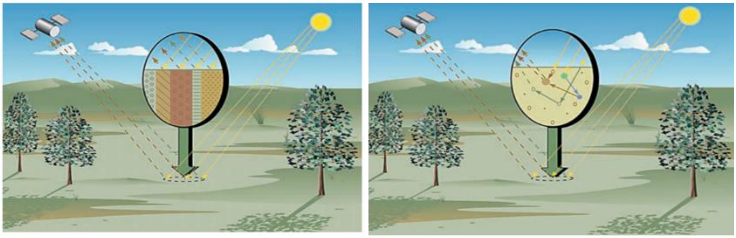


Figure 5.13: Illustration of linear mixing where incident solar radiation reflects from surface through a single bounce and surface consists of distinct endmembers (left); nonlinear mixing where incident solar radiation encounters an intimate mixture that induces multiple bounces (right). Source – Keshava and Mustard, 2002.

Conversely, nonlinear mixing is usually due to physical interactions (classical, or multi-layered, level or at a microscopic, or intimate, level) between the light scattered by multiple materials in the scene (Bioucas-Dias et al., 2012) (Figure 5.14). Classical level mixing occurs due to scattering of light from one or more objects, is reflected off additional objects, before getting measured by hyperspectral imager. Non-linear mixing is generally explained by intimate or multilayer model as given by Borel and Gerstl (1994). Figure 5.14 illustrates two non-linear mixing scenarios: intimate mixture, in which the materials are in close proximity; a multi-layered scene, where there are multiple interactions among the scatterers at the different layers.

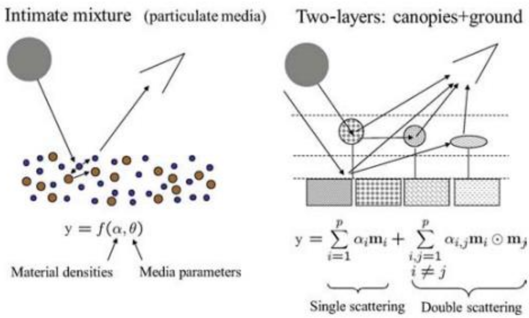


Figure 5.14: Non-linear mixing models: intimate mixture (left); multi-layered scene (right). (Source: http://dx.doi.org/10.1109/JSTARS.2012.2194696).

Unmixing processing steps typically involve atmospheric correction, dimensionality reduction, and unmixing. This can be achieved through endmember determination plus inversion, or by utilizing sparse regression or sparse coding approaches. The key to linear unmixing is to determine spectral endmembers that capture the spectral variability present in a given scene. Various algorithms can be employed to derive these endmembers, utilizing criteria such as field knowledge, ratios, or PCA. The results of spectral unmixing, including endmember spectra and abundance estimates, form the foundation of hyperspectral image classification routines used to identify the material composition of mixtures. Unmixing is another significant research topic in hyperspectral processing, particularly in addressing the subpixel target detection problem.

5.12. Conclusion

In conclusion, hyperspectral image analysis is a powerful tool for understanding and interpreting complex data sets. Given the numerous applications in fields such as agriculture, environmental monitoring, and mineral exploration, it is crucial to ensure accurate and reliable hyperspectral data analysis. The interpretation of hyperspectral data can provide valuable insights and inform decision-making processes in a range of industries. However, without proper data processing and analysis, the resulting information may be incomplete, inaccurate, or even misleading. Therefore, it is essential to employ rigorous analytical techniques and expertise in the interpretation of hyperspectral data to ensure its effective use in various applications. By using sophisticated algorithms and mathematical models, hyperspectral image analysis can extract valuable information from the spectral data collected by remote sensing devices.

However, the analysis of hyperspectral data can be challenging due to its high dimensionality and noise. Therefore, it requires expertise in signal processing, statistical analysis, and machine learning techniques. Moreover, the interpretation of results obtained from hyperspectral data analysis requires a deep understanding of the physical processes that govern the observed spectral signatures.

Chapter 6

Thermal Remote Sensing

6.1. Introduction

Thermal remote sensing deals with the acquisition, processing, and interpretation of data from the thermal infrared (TIR) region of the electromagnetic (EM) spectrum. In thermal remote sensing, radiation emitted by the target's surface is measured by satellite sensors. The infrared portion of the electromagnetic spectrum typically ranges from 0.7 to 1,000 µm and is separated into different subranges, as shown in figure 6.1. The region from 0.7 – 1.3 µm is visible near-infrared (VNIR) region, the 1.3– 3 µm region is shortwave infrared (SWIR), and the 3-14 µm region is known as the longwave or thermal infrared region (Sabins, 1997, Tempfli et al., 2009). The near-infrared and shortwave infrared sensors measure reflected infrared light, while the sensors working in longwave or thermal infrared measure emitted energy. In the thermal infrared region, 3 to 5 µm and 8-14 µm regions are the most effective atmospheric windows. However, 3-5 µm region is more challenging due to interference from solar reflection in daytime imagery. Therefore, the 8-14 µm window is widely utilized for thermal remote sensing applications.

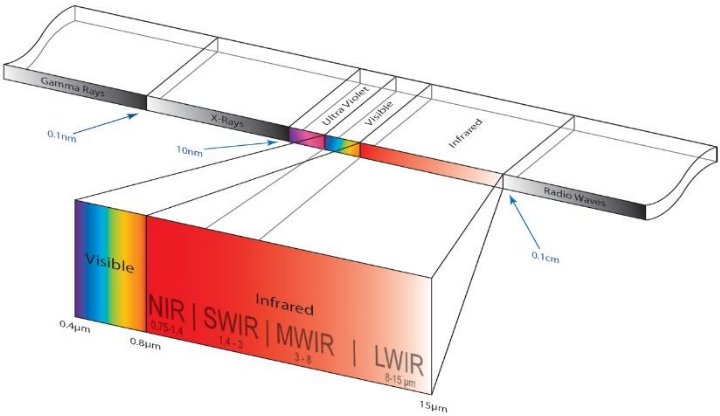


Figure 6.1: EM spectrum showing thermal infrared region.

6.2. Importance of Thermal Remote Sensing

Thermal remote sensing is based on the infrared radiation emitted by objects, which corresponds to their temperature. Unlike optical sensors, thermal sensors can operate day and night, making them highly versatile. TIR is based on the fundamental principle that all objects with a temperature above absolute zero emit thermal radiation, which is utilized to measure temperature variations in different objects, even when they are not directly visible. The importance of thermal remote sensing lies in its ability to

1. **Detect Temperature Variations**: It can monitor surface temperatures of land, water bodies, vegetation, and even buildings due to difference in the emission patterns, which is critical for various scientific and practical applications.

2. Provide All-Day Coverage: Thermal remote sensing not depend on sunlight; thermal sensors can work any time of the day or night.

3. Observe Hidden Features: It can detect features that might not be visible in optical imagery, such as heat leaks in buildings, subsurface geothermal activity, or soil moisture.

6.3. Principles of Thermal Radiation

6.3.1. Blackbody Radiation Concept

A blackbody is an idealized object that absorbs all incident electromagnetic radiation, regardless of wavelength, and emits radiation at maximum efficiency for a given temperature. The concept of blackbody radiation is essential in understanding how real objects emit thermal radiation. Real-world objects, however, are not perfect blackbodies; they emit less radiation than a blackbody at the same temperature. The radiation emitted by a blackbody is described by Planck's law, which defines the spectral distribution of radiation as a function of temperature and wavelength (Jensen, 2007). Figure 6.2 illustrates Plank's law showing blackbody curves for the Sun with Temperature around 6000 K and Earth with temperature around 300 K, respectively. The curves show the variation of radiation emitted by Sun and Earth's surface with respect to the different wavelength regions (Sabins, 1997).

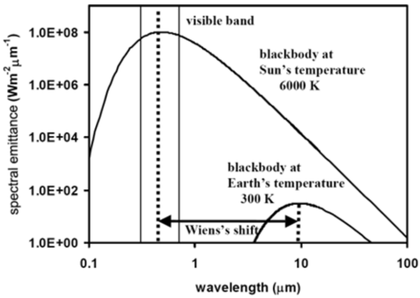


Figure 6.2: Plank's law for blackbodies like Sun (6000 K) and Earth (300 K). (Source: Tempfli et al., 2009).

6.3.2. Stefan-Boltzmann Law

The Stefan-Boltzmann law states that the total energy radiated per unit surface area of a blackbody is proportional to the fourth power of its absolute temperature. Mathematically, this is expressed as:

$E = \sigma T^4$ (Eq. 6.1)

where:

E is the total energy radiated per unit area,

T is the absolute temperature (in Kelvin),

σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/m^2K^4$).

This law is crucial for thermal remote sensing because it allows for the calculation of the energy emitted by objects based on their temperature, providing a direct relationship between temperature and radiated energy.

6.3.3. Wien's Displacement Law

Wien's Displacement Law relates the temperature of an object to the wavelength at which it emits the most radiation. As an object's temperature increases, the peak of its emitted radiation shifts to shorter wavelengths and mathematically expressed as:

$$\lambda_{max} = \frac{b}{T} \text{ (Eq. 6.2)}$$

Where λ_{max} is the wavelength of maximum emission,

T is the absolute temperature in Kelvin,

b is Wien's displacement constant (2.897×10^{-3} mK).

Figure 6.2 explains the Wein's displacement law with the blackbody curves of Sun and Earth. Wien's law helps explain why hotter objects like Sun emit more radiation in shorter wavelengths (such as visible light), while cooler objects like Earth emit radiation primarily in the thermal infrared region, which is crucial in thermal remote sensing.

6.3.4. Kirchhoff's Law of Thermal Radiation

Kirchhoff's law of thermal radiation states that for an object in thermal equilibrium, its emissivity (the efficiency of radiation emission) is equal to its absorptivity (the efficiency of radiation absorption). In other words, good absorbers of radiation are also good emitters. For real-world objects, emissivity values range from 0 to 1, where a blackbody has an emissivity of 1, and a perfect reflector has an emissivity of 0. Emissivity is given by the ratio of the radiation emitted by a real object to the radiation emitted by a perfect blackbody at the same temperature (Sabins, 1997):

$$\epsilon = \frac{M_{\lambda,T}}{M^B_{\lambda,T}} \text{ (Eq. 6.3)}$$

Where $M_{\lambda,T}$ = radiant emittance of real body at given temperature

and $M^B_{\lambda,T}$ = radiant emittance of black body at given temperature

This principle is important in thermal remote sensing because the radiation emitted by a surface is directly related to the emission, which must be accounted for when interpreting temperature from thermal imagery. By understanding an object's emissivity, we can more accurately derive its temperature from the radiation it emits. All selectively radiating objects have emissivity values that range between 0 and less than 1, and these values vary depending on the wavelength of the energy being analyzed. A graybody is an object that has a constant emissivity less than 1 across all wavelengths. Table 6.1 shows the emissivity values for common materials.

Material	Average Emissivity over 8-14 µm
Clear water	0.98 - 0.99
Healthy green vegetation	0.96 - 0.99
Dry vegetation	0.88 - 0.94
Asphaltic concrete	0.94 - 0.97
Basaltic rock	0.92 - 0.96
Granitic rock	0.83 - 0.87
Dry mineral soil	0.92 - 0.96
Polished metals	**0.06 - 0.21**

Source: Lillesand et al. (2008)

Table 6.1 Emissivity values for common materials

Emissivity of a surface is dependent on various factors such as material composition, surface roughness, temperature, and wavelength of the radiation. Polished metals typically have low emissivity (closer to 0), meaning they reflect more radiation and emit less. Natural surfaces like soil, water, and vegetation often have high emissivity (closer to 1), meaning they absorb and emit more radiation. Materials like distilled water exhibit emissivities near 1 (around 0.99) within the 8 to 14 μm wavelength range, while highly reflective materials like polished aluminum (0.08) and stainless steel (0.16) have much lower emissivity values. Two materials on the ground may have the same actual kinetic temperature but show different apparent temperatures when measured by a thermal radiometer due to differences in their emissivities (Snyder et al., 1998). Several factors can influence an object's emissivity, including:

- **Color**: Dark-colored materials generally absorb and emit more energy (i.e., they have higher emissivity) compared to lighter-colored materials, which tend to reflect more incoming energy.
- **Surface Roughness**: A rougher surface increases the effective surface area exposed to incoming radiation, enhancing the material's ability to absorb and re-emit energy, especially if the roughness is significant compared to the wavelength of the incident energy.

Other factors like moisture content, degree of soil compaction, field-of-view/resolution, wavelength also affect emissivity.

6.3.5. Kinetic Temperature vs. Radiant Temperature

The electromagnetic energy emitted by an object is called **radiant flux**, measured in watts. The amount of radiant flux is directly related to the object's **radiant temperature** (Trad). Typically, there is a strong positive correlation between an object's **true kinetic temperature** (Tkin) and the radiant flux it emits. This allows us to use **radiometers** from a distance to measure an object's radiant temperature, which closely aligns with its kinetic temperature. This principle forms the basis of **thermal infrared remote sensing**.

The relation between true kinetic temperature of objects and radiant temperature is given as

$$T_{rad} = \varepsilon^{1/4} T_{kin} \text{ (Eq. 6.4)}$$

T_{rad} = Radiant Temperature

T_{kin} = Kinetic Temperature

Thermal remote sensing measures the energy emitted by an object, referred to as **radiant temperature**, also known as **brightness temperature** or **apparent temperature**. Any object with a temperature above absolute zero (0 K) emits electromagnetic energy (Sabins, 1997). In everyday terms, **temperature** usually refers to **kinetic temperature** (or physical temperature), which is caused by the motion of molecules within the object. Kinetic temperature, also called **true temperature**, can be measured using conventional instruments like thermometers, in Fahrenheit (°F), Celsius (°C), or Kelvin (K) (Jensen, 2007). Because of the strong connection between an object's **true kinetic temperature** and **radiant temperature**, remote sensing tools like radiometers can measure radiant temperature and provide an estimate of the object's kinetic temperature (Kahle & Alley, 1992).

6.4. Interaction of thermal radiation with Earth's surface

Figure 6.3 illustrates difference between energy transmission in visible and thermal infrared region. Earth's surface absorbs sunlight, heats up, and re-emits energy in the form of longwave infrared radiation. In visible region, solar energy is primarily reflected by the Earth's surface. This reflectance is used in remote sensing to identify different surface features such as vegetation, water, and urban areas, as all surfaces reflect visible light differently. In thermal infrared region (Longwave, the Earth's surface emits radiation in the form of heat.

This emission is based on the surface temperature and is used to detect temperature variations across different surfaces like land and water. The intensity of this emission varies depending on the surface temperature, and it helps measure temperature differences between land and water.

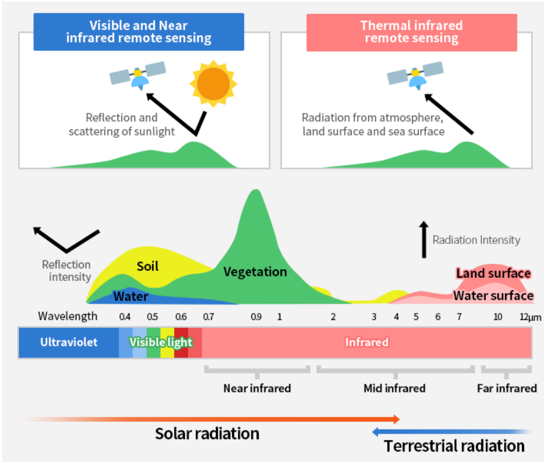


Figure 6.3 Illustration showing difference between visible and thermal infrared energy transmission. (Source: https://earth.jaxa.jp/en/eo-knowledge/remote-sensing/index.html).

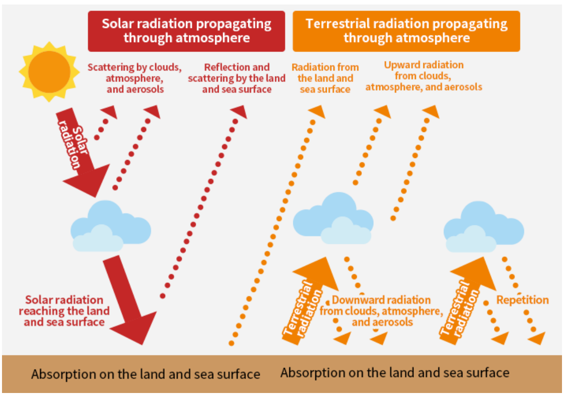


Figure 6.4: Interaction of thermal radiation radiative transfer of solar and terrestrial radiation (Source: https://earth.jaxa.jp/en/eo-knowledge/remote-sensing/index.html).

This radiation interacts with the atmosphere and can be detected by satellites to assess surface temperatures, land cover types, and atmospheric conditions. Figure 6.4 highlights the concept of radiative transfer in understanding Earth's energy balance, where thermal radiation travels through the atmosphere, interacting with gases and particles, before being detected by satellite sensors. This process depends on surface temperature and material properties. These measurements are crucial for assessing surface temperatures, climate monitoring, and environmental changes. Radiative transfer, as shown in figure 6.4, refers to the movement of energy in the form of radiation through the Earth's atmosphere and how it interacts with the surface. This process involves both incoming solar radiation (shortwave) and outgoing thermal radiation (longwave).

Absorption: Some of the incoming radiation is absorbed by the Earth's surface, heating it.

Emission: The surface re-emits this energy as thermal infrared radiation.

Scattering/Reflection: A portion of both solar and thermal radiation is scattered or reflected by clouds, gases, and aerosols.

The radiative transfer process is crucial for maintaining the Earth's energy balance, which is the equilibrium between the energy the Earth receives from the Sun and the energy it radiates back into space. This balance determines the Earth’s climate and surface temperatures. In remote sensing, understanding radiative transfer helps interpret data from satellite sensors. For instance, visible radiation allows for surface mapping (e.g., vegetation and water bodies), while thermal infrared radiation reveals temperature distributions and heat patterns. Satellites monitor this radiative energy to track weather patterns, climate change, and environmental shifts.

6.5. Thermal Sensors and Platforms

Various thermal sensors and platforms with their characteristics are shown in table 6.2.

Thermal Sensor	Platform Type	Spectral Range (µm)	Spatial Resolution	Temporal Resolution
Landsat 8/9 (TIRS)	Spaceborne (Satellite)	10.60 – 11.19, 11.50 – 12.51	100 m	16 days
MODIS (Terra/Aqua)	Spaceborne (Satellite)	3.66 – 4.08, 10.78 – 11.28, 11.77 – 12.27	1 km	1-2 days
ECOSTRESS	Spaceborne (Space Station)	8.3 – 12.5	70 m	Varies (targeted)
ASTER	Spaceborne (Satellite)	8.125 – 11.65	90 m	16 days
Sentinel-3 (SLSTR)	Spaceborne (Satellite)	3.74 – 12.0	500 m	1-2 days
HyTES	Airborne	7.5 – 12	2-50 m	Targeted campaigns
FLIR Systems (Airborne)	Airborne	7.5 – 13.5	Variable	Immediate (real-time)
INSAT-3D (Imager and Sounder)	Spaceborne (Satellite)	3.7 – 4.7, 10.3 – 12.5	1 km (TIR1), 4 km (TIR2)	30 min (over India)
Cartosat-3 (Thermal IR)	Spaceborne (Satellite)	8.0 – 12.0	30 m	5 days
Oceansat-3 (Sea Surface Temperature Monitor)	Spaceborne (Satellite)	10.5 – 12.5	1 km	Daily

TRISHNA (Upcoming mission)	Spaceborne (Satellite)	8.0 – 12.0	50 m	Daily

Table 6.2: Various thermal sensors and platforms

6.6. Processing of thermal data

Thermal images can be displayed in various forms. One common method is through grayscale images, where darker shades indicate cooler temperatures and lighter tones reflect warmer areas. Alternatively, thermal data can be presented in color, typically using a gradient from blue (cooler) to red (warmer). Figure 6.5 shows temperature image where red color denotes surfaces with high temperature and blue color surfaces represent cooler surfaces.

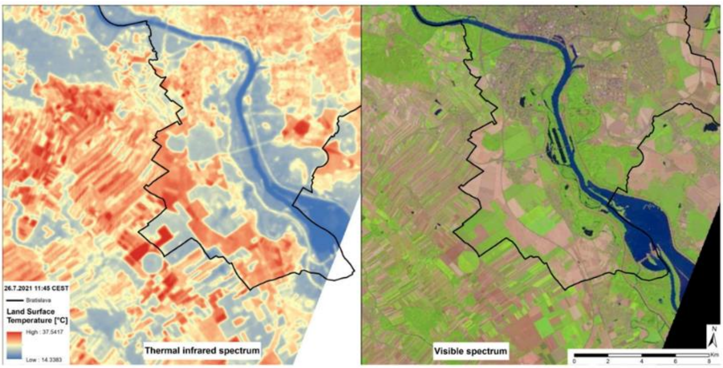


Figure 6.5: Temperature image derived from thermal image showing hotter regions in red and cooler areas in blue. Right image showing visible color composite image of the same (Source: https://doi.org/10.3390/land12020384).

6.6.1. Band ratios

In thermal imagery, band ratioing is a type of image enhancement applied to enhance specific features or surface characteristics that might be hard to distinguish using standard thermal images. By dividing the pixel values of one thermal band by those of another, subtle variations in surface temperature and emissivity can be highlighted. This is particularly useful for identifying thermal anomalies or distinguishing between different types of materials, such as separating areas with different thermal properties like urban surfaces from natural vegetation. In geology studies, ASTER data band ratios using bands 10-14 are used to highlight silica, carbonate rich rocks (Plescia et al., 2001).

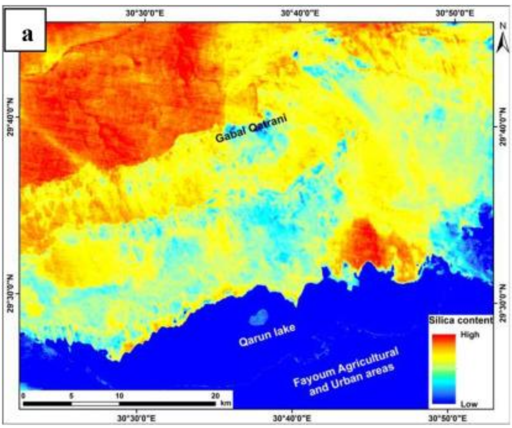


Figure 6.6: Band ratio B14/B12 showing colored ratio map (red color represents high silica content, and blue color represents low silica contents (Source: https://doi.org/10.1016/j.jafrearsci.2022.104683).

For example, in **volcanic monitoring**, band ratioing can help detect variations in lava temperature and distinguish active lava flows from cooler surrounding areas. Similarly, in **urban heat island studies**, band ratioing can help highlight areas with significantly higher temperatures, such as paved roads and buildings, compared to cooler, vegetated areas.

6.7. Applications of Thermal Remote Sensing

6.7.1. Environmental Monitoring (Urban Heat Islands, Climate Studies)

Thermal remote sensing plays a vital role in environmental monitoring, particularly in studying **urban heat islands** and climate change. Urban heat islands (UHIs) occur when cities experience significantly higher temperatures than surrounding rural areas due to human activities and heat-retaining surfaces like asphalt. Thermal sensors help map these temperature variations, providing data for city planners to mitigate the effects through urban greening or material changes (Kumar et al., 2015; Aulak et al., 2016). In **climate studies**, long-term thermal data enables scientists to track trends in surface temperatures, monitor global warming, and assess regional climate changes.

6.7.2. Agriculture (Soil Moisture, Plant Stress Detection)

In agriculture, thermal sensors are valuable for detecting **soil moisture levels** and identifying **plant stress**. Soil moisture impacts crop health, and remote sensing helps farmers monitor water distribution in fields. **Plant stress** due to drought or poor irrigation can be detected by observing elevated leaf temperatures, as stressed plants transpire less water and retain more heat. This data can optimize irrigation schedules, conserve water, and increase crop yields. Thermal imagery also aids in identifying heat-stressed areas of farmland, allowing for precision agriculture practices (Baluja et al., 2016). In India, studies have utilized thermal remote sensing for soil moisture estimation and crop stress detection, contributing to improved agricultural practices (Pereira et al., 2018; Singh et al., 2020).

6.7.3. Hydrology (Evapotranspiration, Water Body Monitoring)

In hydrology, thermal remote sensing is crucial for measuring **evapotranspiration**—the process by which water is transferred from land to the atmosphere through evaporation and plant transpiration. Monitoring evapotranspiration helps in understanding water usage in ecosystems and managing agricultural irrigation. **Water body monitoring** is another application, where thermal sensors track temperature changes in rivers, lakes, and oceans. This data is essential for assessing water quality, detecting thermal pollution, and monitoring changes in aquatic ecosystems due to climate shifts.

6.7.4. Geology and Volcanology (Thermal Anomalies, Volcanic Activity)

Thermal sensors are extensively used in **geology** and **volcanology** to identify **thermal anomalies** associated with geothermal activity or to monitor **volcanic activity**. Elevated surface temperatures in geothermal areas or around active volcanoes can indicate lava flows, magma movement, or eruptions. Remote sensing technology, including thermal infrared bands, helps geologists detect and analyze these thermal changes in real-time, providing crucial data for forecasting volcanic eruptions and monitoring the health of volcanic regions.

6.7.5. Disaster Management (Wildfires, Oil Spill Detection)

Thermal imagery is a critical tool in **disaster management**, particularly for detecting **wildfires** and **oil spills**. Thermal sensors can identify hotspots in fire-prone regions, helping detect wildfires early and allowing emergency services to respond quickly. During active fires, thermal images can map the extent and intensity of the blaze, guiding firefighting efforts. In the case of **oil spills**, thermal imagery can detect temperature differences between oil and water, helping in the identification and containment of spills. This makes thermal remote sensing an essential asset in both preventing and managing environmental disasters.

6.8. Challenges and limitations in thermal remote sensing

Thermal remote sensing faces several challenges that affect data accuracy and interpretation. Atmospheric absorption and scattering, particularly by water vapor and gases, can distort thermal radiation, requiring complex corrections. Sensor calibration is another issue, as thermal sensors can drift over time, leading to inaccuracies without regular re-calibration. The complexity of interpreting thermal data is affected by factors like surface emissivity, material properties, and environmental conditions, making it difficult to extract true temperature information. Additionally, thermal sensors often have lower spatial resolution compared to visible sensors, and limited temporal resolution, making it harder to monitor fast-changing events or capture fine details.

6.9. Conclusion

Thermal remote sensing offers a wide range of applications across diverse fields such as environmental monitoring, agriculture, hydrology, geology, and disaster management. By measuring the radiant temperature of the Earth's surface, thermal sensors provide critical data for tracking urban heat islands, monitoring climate changes, and optimizing water usage in agriculture. In hydrology, it aids in understanding evapotranspiration and water body dynamics, while in geology and volcanology, it allows for the detection of thermal anomalies and volcanic activity.

Despite the many advantages, challenges such as atmospheric effects, sensor calibration issues, and interpretation complexities must be addressed to ensure accurate data interpretation. Advancements in preprocessing techniques like atmospheric correction and geometric correction continue to improve the precision of thermal data.

Overall, thermal remote sensing is a powerful tool for understanding environmental and geological processes, responding to disasters, and managing resources.

Chapter 7
Basics of LiDAR Remote Sensing

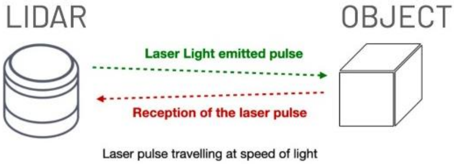
7.1. Introduction

In the realm of remote sensing technologies, Light Detection and Ranging (LiDAR) stands out as a transformative tool, offering unprecedented precision and detail.

Through the use of laser pulses to measure distances, LiDAR creates detailed, three-dimensional representations of landscapes, structures, and vegetation. This chapter delves into the principles of LiDAR, its applications, and its impact on various fields, providing a comprehensive overview of how this technology is reshaping our understanding of the world.

7.2. Basic principles of LiDAR systems

LiDAR sensors work on the principle of Time of Flight of light. The LiDAR instrument emits a laser beam which hits the target object, some of it is reflected back to the sensor. By calculating the time delay between emission and reception (Figure 7.1), and knowing the speed of light, the system can determine the distance to the object with high accuracy.



$$distance = \frac{c \times t}{2}$$

Figure 7.1: Depicts the working principle behind LiDAR system.

7.3. Different wavelengths for different applications

The laser source for a LiDAR system are available at different wavelength of light. 600-100nm lasers are very common for non-scientific purpose. 1550nm lasers are inherently eye safe as there is very little absorption by the eye at these wavelengths, hence high-power LiDAR systems are often produced at these wavelengths.

Yttrium Aluminium Garnet (YAG) based lasers are quite popular for topographic mapping LiDARs. 1064nm one is used usually for terrain mapping. Green vegetation tends to be very reflective at these wavelengths hence can be easily detected using these wavelength lasers from a very long distance.

Lasers at 532nm (also YAG based) are able to penetrate through water and hence are used for bathymetric applications (underwater depth research).

7.4. Types of LiDAR systems

LiDAR systems are deployed on various platforms to collect 3D data from different vantage points and for different applications. The choice of platform depends on the specific requirements of the study. Common types of LiDAR systems based on the platform are as follows:

1. **Airborne LiDAR (ALS):**
   Airborne LiDAR systems are mounted on aircraft, including helicopters and fixed-wing airplanes. They are used for large-scale topographic mapping, forestry assessments, land use planning, and environmental monitoring. Airborne LiDAR can cover vast areas quickly and is suitable for mapping applications.
2. **Terrestrial LiDAR (TLS):**
   Terrestrial LiDAR systems are ground-based and typically mounted on tripods, vehicles, or other fixed structures. They are used for capturing detailed 3D data of small to medium-sized areas, such as building facades, archaeological sites, infrastructure inspection, and indoor environments. TLS is known for its high accuracy and detail.
3. **Mobile LiDAR:**
   Mobile LiDAR systems are installed on vehicles, such as cars, trucks, or trains. They are commonly used for mapping roadways, railways, and urban environments. Mobile

LiDAR can efficiently collect data along transportation corridors.

4. **UAV/UAS LiDAR (Unmanned Aerial Vehicle/System):**
   LiDAR-equipped drones or UAVs are increasingly popular for capturing data in remote or hard-to-reach areas. They are used for applications like environmental monitoring, agriculture, search and rescue, and rapid response to natural disasters.
5. **Spaceborne LiDAR:**
   Spaceborne LiDAR systems are deployed on satellites orbiting Earth. They provide large-scale, global 3D mapping data for various applications, including climate research, disaster monitoring, and environmental studies.
6. **Bathymetric LiDAR:**
   Bathymetric LiDAR is specifically designed for underwater mapping. It is often mounted on boats or aircraft to measure the seafloor and underwater terrain. Applications include hydrographic surveys, coastal zone management, and marine habitat mapping.
7. **Handheld LiDAR:**
   Handheld LiDAR devices are portable and can be carried by an operator. They are used for tasks that require flexibility and access to hard-to-reach areas, such as archaeological site documentation, forestry, and indoor building modelling.

8. **Helmet-Mounted LiDAR:**

   Helmet-mounted LiDAR systems are used for real-time, point-of-view data collection. They are primarily used in applications like augmented reality and virtual reality, as well as for navigation and tracking in various industries.

Each platform has its own advantages and limitations, and the choice of platform depends on factors such as the desired spatial coverage, data accuracy, project budget, and logistical considerations. Different platforms offer the flexibility to collect LiDAR data for a wide range of applications and industries. In this chapter we will be discussing only the LiDAR based on Aerial platform (with little coverage of UAV based LiDAR), Terrestrial LiDAR and Space Bourne LiDAR as these platforms represents the most widely used LiDAR systems and have enough applications and software environment developed around them to be used by novice users.

7.5. Aerial LiDAR Systems

Airborne LiDAR scanning, often referred to as ALS (Airborne LiDAR System), is a remote sensing technique that employs laser pulses emitted from an aircraft to collect highly accurate 3D data of the Earth's surface and objects. This technology is instrumental in a variety of applications, including topographic mapping, forestry management, environmental monitoring, and infrastructure assessment.

Aerial LiDAR systems are usually of 3 types:

1. Fixed-wing aircrafts
2. Helicopters
3. Unmanned Aerial Vehicles (UAVs)

Aerial LiDAR Systems give output in the form of point cloud which represent the structure of the target surroundings.

A point cloud is a collection of data points in a 3D coordinate system. Each point represents a specific position in space and may include additional information such as color, intensity, or other attributes.

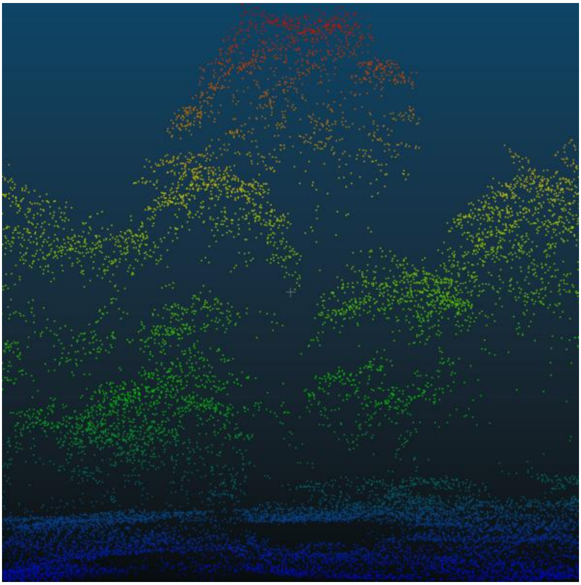


Figure 7.2 Point cloud representation of trees in a forest. Scanned using an Aerial LiDAR system.

Point clouds are typically generated using various 3D scanning technologies, such as LiDAR (Light Detection and Ranging), photogrammetry, structured light scanning, or laser scanning. Point clouds are used in a wide range of applications for capturing and representing the geometry and spatial characteristics of real-world objects and environments (figure 7.2).

7.6. Terrestrial LiDAR Systems

Terrestrial LiDAR scanning, also known as ground-based LiDAR, is a 3D laser scanning technique that is used to capture highly detailed and accurate 3D representations of objects, structures, or environments from a stationary terrestrial position.

Since, in case of terrestrial laser scanning the laser setup is mounted on stable platform the TLS system is able to very accurate point cloud of the surrounding (with positional accuracy of the order of few millimetre).

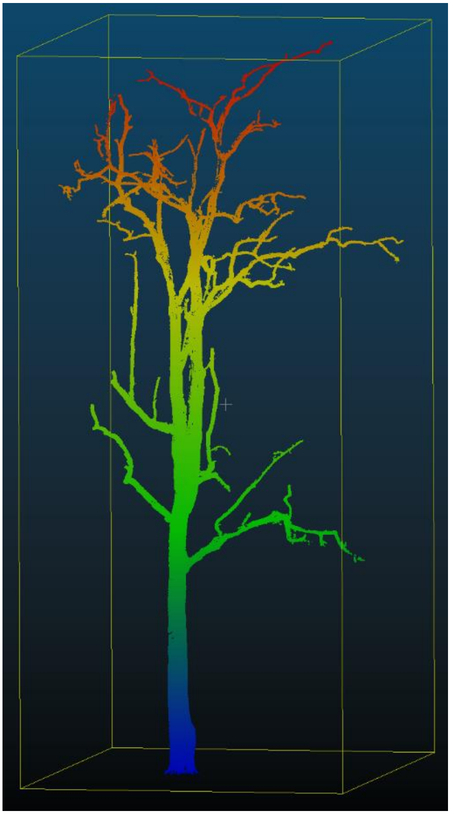


Figure 7.3 Shows the point cloud representation of a single tree, scanned using a Terrestrial LiDAR system.

In Terrestrial Laser scanning, the target object or surrounding is scanned from multiple directions (at least 3) and each resultant point cloud is merged with each other to create a complete point cloud. Figure 7.3 shows the point cloud of a tree perfectly scanned from five directions.

7.7. Spaceborne LiDAR Systems

With the success of LiDAR systems place being placed in airborne platforms, few space missions have been conducted to deploy LiDAR in spaceborne platform. The major advantages of placing LiDAR systems on spaceborne platform are follows:

- Global Coverage: Satellites can collect data from any location on Earth, even in remote or inaccessible areas.
- Persistent Monitoring: Satellites can provide continuous and regular data acquisition, making them suitable for long-term studies.
- Large-Scale Studies: Ideal for applications that require broad-area coverage, such as monitoring the effects of climate and global-scale environmental assessments.
- Consistent Data: Data from spaceborne LiDAR sensors is consistent and standardized, making it easier to compare and analyze.

There have been three major spaceborne LiDAR missions:

1. **ICESat-1: The Geoscience Laser Altimeter System (GLAS)**
   ICESat-1, short for the Ice, Cloud, and land Elevation Satellite-1, was a NASA satellite mission designed to monitor changes in the Earth's polar ice sheets, sea ice, and cloud cover. The mission aimed to provide valuable data to

help scientists better understand the dynamics of the Earth's cryosphere and its response to climate change.

2. **ICESat-2: The Advanced Topographic Laser Altimeter System (ATLAS)**

ICESat-2, short for the Ice, Cloud, and land Elevation Satellite-2, is a NASA satellite mission designed to continue and expand upon the work of its predecessor, ICESat-1.

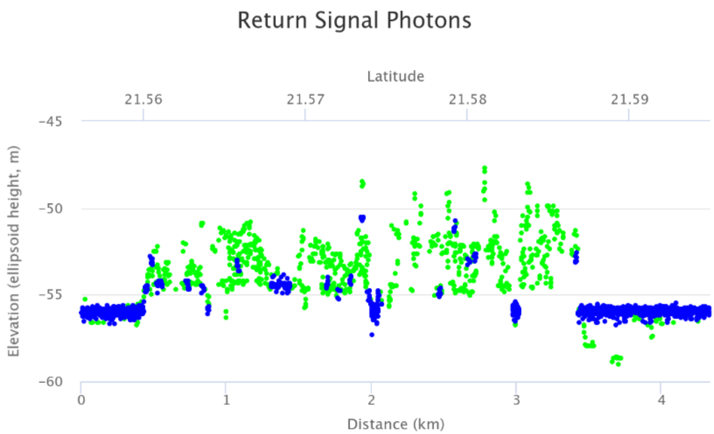


Figure 7.4 ICESat-2 data over Indian Sundarbans.

Launched on September 15, 2018, ICESat-2 is equipped with advanced technology to collect highly accurate elevation data of the Earth's polar ice sheets, sea ice, sea surface, vegetation canopy and other surfaces. Figure 7.4 shows the ICESat-2 data over the Indian Sundarbans.

3. **The Global Ecosystem Dynamics Investigation (GEDI)**

The Global Ecosystem Dynamics Investigation (GEDI) is a NASA mission aimed at enhancing our understanding of

Earth's forests and their role in the global carbon cycle. GEDI is a LiDAR instrument mounted on the International Space Station (ISS) that measures the three-dimensional structure of Earth's forests with unprecedented accuracy.

7.8. Conclusion

LiDAR is a state-of-the-art technology that enables us to capture very accurate 3-Dimensional structure of target object or surrounding. It works on the principle of time of flight of light beam. Different wavelength lasers are useful for different applications. Most common LiDAR systems are Aerial LiDAR systems (can cover few 100 Km^2), Terrestrial LiDAR System (can cover few hectares in detail) and Spaceborne LiDAR Systems (have global coverage).

Bibliography

1. Acker, J., Leptoukh, G., Shen, S., Zhu, T., Kempler, S., & Feldman, G. (2014). Remotely-sensed chlorophyll a observations of the Northern Red Sea: Seasonal and interannual variability. PLoS ONE, 9(11), e111437. https://doi.org/10.1371/journal.pone.0111437
2. Alavipanah, S. K., Saradjian, M. R., & Khakpoor, A. A. (2010). Criteria of selecting satellite data for studying land resources. DESERT, 15, 83–102.
3. Analytical Imaging and Geophysics LLC (AIG). (2001). ACORN User's Guide, Stand Alone Version. Analytical Imaging and Geophysics LLC.
4. Aulak, K. S., Choudhury, B. K., & Verma, P. (2016). Urban heat island effect in Mumbai city: Evidence from satellite remote sensing. Remote Sensing Applications: Society and Environment, 5, 16–23.
5. Baluja, J., Moya, J., & García, J. (2016). Evaluating the use of thermal imaging for precision agriculture. Precision Agriculture, 17(2), 109–126.
6. Ben-Dor, E., Irons, J. R., & Epema, G. F. (1999). Soil reflectance. In N. Rencz (Ed.), Remote Sensing for the Earth Sciences, Manual of Remote Sensing (Vol. 3, pp. 111–188). John Wiley and Sons.
7. Bioucas-Dias, J. M., Plaza, A., Camps-Valls, G., Scheunders, P., Nasrabadi, N. M., & Chanussot, J. (2012). Hyperspectral unmixing overview: Geometrical, statistical, and sparse regression-based approaches. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5(2), 354–379.
8. Boardman, J. W., & Kruse, F. A. (1994). Automated spectral analysis: A geological example using AVIRIS data, northern Grapevine Mountains, Nevada. Proceedings of the Tenth

Thematic Conference on Geologic Remote Sensing, 9, I-407–I-418.
9. Boardman, J. W., Kruse, F. A., & Green, R. O. (1995). Mapping target signatures via partial unmixing of AVIRIS data. In Summaries of the Fifth JPL Airborne Earth Science Workshop, JPL Publication 95-1 (Vol. 1, pp. 23–26).
10. Borel, C. C., & Gerstl, S. A. W. (1994). Nonlinear spectral mixing model for vegetative and soil surfaces. Remote Sensing of Environment, 47(3), 403–416.
11. Campbell, J. B. (1996). Introduction to Remote Sensing. Taylor & Francis.
12. Dwivedi, R. S. (2017). Spectral reflectance of soils. In Remote sensing of soils (pp. 163–180). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-53740-4_6
13. Encyclopaedia of Inland Waters. (2022). Encyclopaedia of Inland Waters (2nd ed.). Elsevier.
14. ENVI Manual. (2005). Flash Module User's Guide. Research Systems Inc.
15. ENVI User's Guide. (2001). Research Systems Inc. 948p.
16. Felde, G. W., Anderson, G. P., Cooley, T. W., Matthew, M. W., Berk, A., & Lee, J. (2003, July). Analysis of Hyperion data with the FLAASH atmospheric correction algorithm. In IGARSS 2003: IEEE International Geoscience and Remote Sensing Symposium (Vol. 1, pp. 90–92). IEEE.
17. Goetz, A. F. H., Ferri, M., Kindel, B., & Qu, Z. (2002). Atmospheric correction of Hyperion data and techniques for dynamic scene correction. IEEE, 1408–1410.
18. Goetz, A. F. H., Vane, G., Solomon, J. E., & Rock, B. N. (1985). Imaging spectrometry for Earth remote sensing. Science, 228, 1147–1153.
19. Gonzalez, R. C., & Woods, R. E. (2001). Digital Image Processing. Prentice-Hall.
20. Gonzalez, R. C., & Woods, R. E. (2008). Digital Image Processing (3rd ed.). Pearson Prentice Hall.

21. Green, A. A., Berman, M., Switzer, P., & Craig, M. D. (1988). A transformation for ordering multispectral data in terms of image quality with implications for noise removal. IEEE Transactions on Geoscience and Remote Sensing, 26(1), 65–74.
22. Jensen, J. R. (2000). Remote Sensing of the Environment: An Earth Resource Perspective. Prentice Hall.
23. Jensen, J. R. (2005). Introductory Digital Image Processing: A Remote Sensing Perspective (3rd ed.). Prentice-Hall.
24. Jensen, J. R. (2007). Remote Sensing of the Environment: An Earth Resource Perspective (2nd ed.). Pearson Prentice Hall.
25. Joseph, G. (1996). Imaging sensors. Remote Sensing Reviews, 13, 257–342.
26. Keshava, N., & Mustard, J. F. (2002). Spectral unmixing. IEEE Signal Processing Magazine, 19(1), 44–57.
27. Kruse, F. A. (1988). Use of airborne imaging spectrometer data to map minerals associated with hydrothermally altered rocks in the Northern Grapevine Mountains, Nevada and California. Remote Sensing of Environment, 24(1), 31–51.
28. Kruse, F. A., Lefkoff, B., & Dietz, J. B. (1993). Expert system-based mineral mapping in Northern Death Valley, California/Nevada, using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). Remote Sensing of Environment, 44(2), 309–336.
29. Kumar, P., Babu, M. T., & Kumar, S. (2015). Urban heat island effect in Delhi: A case study using remote sensing data. Journal of Environmental Management, 155, 22–31.
30. Lee, J. B., Woodyatt, A. S., & Berman, M. (1990). Enhancement of high spectral resolution remote sensing data by a noise-adjusted principal components transform. IEEE Transactions on Geoscience and Remote Sensing, 28(3), 295–304.

31. Lillesand, T., & Kiefer, R. W. (1987). Remote Sensing and Image Interpretation. Wiley.
32. Melgani, F., & Bruzzone, L. (2004). Classification of hyperspectral remote sensing images with support vector machines. IEEE Transactions on Geoscience and Remote Sensing, 42(8), 1778–1790.
33. Meyer, F. (2019). Spaceborne synthetic aperture radar – Principles, data access, and basic processing techniques. In A. Flores, K. Herndon, R. Thapa, & E. Cherrington (Eds.), SAR handbook: Comprehensive methodologies for forest monitoring and biomass estimation. NASA. https://doi.org/10.25966/ez4f-mg98
34. Mohamed, R. M., & Farag, A. A. (2005). Advanced algorithms for Bayesian classification in high dimensional spaces with applications in hyperspectral image segmentation. In IEEE International Conference on Image Processing (Vol. 2, pp. II-646). IEEE.
35. Pereira, L. S., Paredes, P., & Silva, A. P. (2018). Remote sensing for soil moisture and crop water stress in India. Agricultural Water Management, 208, 43–55.
36. Pignatti, S., Cavalli, M. R., Cuomo, V., Fusilli, L., Poscolieri, M., & San, M. (2009). Evaluating Hyperion capability for land cover mapping in a fragmented ecosystem: Pollino National Park, Italy. Remote Sensing of Environment, 3(12), 622–634.
37. Plescia, J. B., & Rowan, L. C. (2001). ASTER band ratioing for mapping of silica-rich and carbonate-rich rocks. Remote Sensing of Environment, 77(2), 220–231.
38. Richards, J. A., & Jia, X. (2006). Remote Sensing Digital Image Analysis: An Introduction. Springer-Verlag.
39. Roy, P. S. (1989). Spectral reflectance characteristics of vegetation and their use in estimating productive potential. Proceedings of the Indian Academy of Sciences - Plant Sciences, 99(1), 59–81.

40. Sabins, F. F. (1997). Remote Sensing: Principles and Interpretation (3rd ed.). W.H. Freeman and Company.
41. Singh, R. K., Sharma, A., & Kumar, S. (2020). Thermal remote sensing for crop stress
42. Srivastava A., Bharadwaj S., Dubey R.,.Sharma V. B,. Biswas S. (2022). Mapping Vegetation And Measuring The Performance Of Machine Learning Algorithm In Lulc Classification In The Large Area Using Sentinel-2 And Landsat-8 Datasets Of Dehradun As A Test Case, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLIII-B3-2022, 529–535.
43. Zhang X., and Li P. (2014) Lithological mapping from hyperspectral data by improved use of spectral angle mapper, International Journal of Applied Earth Observation and Geoinformation, Volume 31, 95-109.

Deputy General Manager

Regional Remote Sensing Centre-North
National Remote Sensing Centre
Indian Space Research Organisation
New Delhi