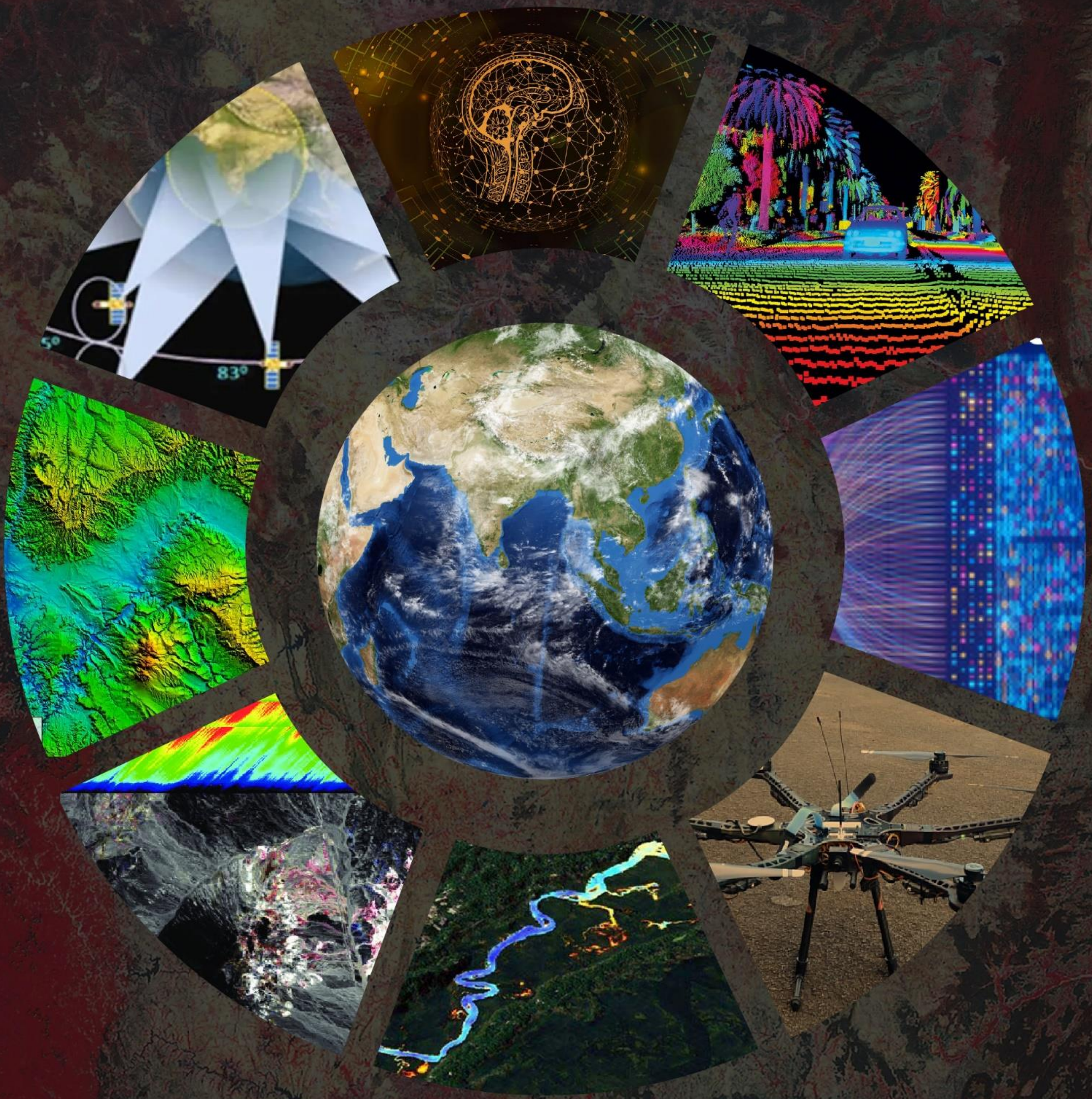
Geospatial Technologies



GEOSPATIAL TECHNOLOGIES

Published by:

Capacity Building and Programme Outreach Office
Indian Space Research Organisation Head Quarter
Department of Space, Antriksh Bhwan
Bangalore 560094, Karnataka, India

This publication is available in electronic form at:
jigyasa.iirs.gov.in

Acknowledgment

The book on Geospatial Technologies and its applications is compiled from the inputs of subject experts all across ISRO centres under the guidance and support from the Directors of IIRS, Dehradun, SAC, Ahmedabad NRSC, Hyderabad and NESAC, Shillong.

The team is thankful to the Secretary, Department of Space and the Chairman of ISRO Shri S Somnath for the encouragement, guidance and support in bringing out the book in Geospatial Technologies and Applications. Team is highly indebted for the guidance of overseeing committee in reviewing the course content and the chapters under the Chairmanship of Shri Shantanu Bhatawdekar, Scientific Secretary ISRO HQ, Shri N Sudheer Kumar, Director CBPO ISRO HQ, Shri NM Desai, Director SAC, Ahmedabad, Dr. Prakash Chauhan, Director NRSC Hyderabad, Dr RP Singh, Director IIRS Dehradun, Dr. SP Agarwal, Director NE-SAC Shillong, Shri SK Srivastava, CGM (RC), NRSC, Dr. Pramod Kumar[1], Dr. G Srinivas Rao[2], , Dr. Bimal Kumar Bhattacharya[3], Dr. S Manthira Moorthi[3], Dr Harish Karnataka[1], Dr Arijit Roy[1], Dr. Subra Nandy[1], Shri Ashish Joshi[1], Dr. Kamal Pandey[1], Dr. Ashutosh Bhardwaj[1] Dr Shovan Lal Chattoraj[1] and all the contributors across ISRO Centres.

The team is indebted to Ms. Shailja Mamgai[1] JRF and PhD Scholar for the support in final formatting of the chapters and Ms Nikhitha C and Shri Sujay Sreedhar for their contributions for books cover design and formatting the initial draft of chapters. Last but not the least the support and encouragement received from CBPO, ISRO HQ colleagues.

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FOREWORD

Geospatial science is an interdisciplinary field that combines many technologies and has an impact on numerous fields. Geospatial technology has a wide range of applications in practically every domain of natural resources, including agriculture, forestry, industries, rural, urban, water, and marine, and contributes significantly to the development of national infrastructure. These technologies are vital for land revenue, banking and finance, resource mapping and management, social planning, disaster management, e-governance, food security, and other purposes.

The National Geospatial Policy, 2022 aims to make India a world leader in global geospatial map with the best in class ecosystem for sustainable growth and economy for the nation through the integration of geospatial data/technology/concepts with industry 4.0 revolutionary technologies by growing web, cloud, and network infrastructure. The demand for qualified human resources for adopting technology for social and economic development across the country is growing by the day.

To fulfil the ever-increasing need, there is a need to build capacity through effective training and raise awareness among the many stakeholders, which include state and central ministries, industry, academics, entrepreneurs, and educated youth.

ISRO has launched many space missions for Earth observation applications. The Resourcesat, Cartosat, Oceansat, RISAT, INSAT2D/3DR class of satellite are providing temporal, multi-platform, multi-sensor satellite data of earth surface. The satellite data are critical inputs for geospatial technology for different thematic applications.

I am pleased to see that a course material encompassing all important topics in geospatial technology and applications has been created by various ISRO centres / institutions. A few practical sessions are also planned to provide hands-on experience.

I am confident that knowledge sharing will assist students, academics, industries, and researchers in improving their capabilities in the geospatial area and capitalising on growth possibilities.

S Somnath

PREFACE

In a frame work of National Geospatial Policy-2022, DOS accorded in principle approval for conducting an integrated course on Geospatial Technology and its applications for various user ministries and NGEs as a part of capacity building in space domain. Subsequently, CBPO in consultation with ISRO centres SAC, NRSC, IIRS and NE-SAC brought out the course curriculum.

The book on Geospatial Technology and its applications covers the chapters on Fundamental of Remote Sensing, Geographical Information System (GIS), Digital Image Processing, Advances in Remote Sensing, Microwave Remote Sensing, UAV Remote Sensing, Agriculture and Soils, Water Resources, Forestry and Ecology, Geoscience, Urban Development, Marine Applications, Atmospheric Science and Disaster. To have hands on different tools on Geo Spatial Applications the five demonstration topics are also covered in this programme e.g. on Remote Sensing, Geographical Information System, Digital Image processing, Geo portals and data dissemination and Open-source platforms for Geo-data processing.

The topics are contributed by Scientists across above ISRO centres and two books comprising twenty (20) topics on theory and five (5) practicals are brought out for Geospatial Technologies and its Applications. This book will be a basis for conducting the one-week training programme for BE/B Tech in Engineering or equivalent, BSc in any discipline, BA in Geology/Environment studies or 3 years Diploma in Engineering or equivalent fields. The students should have proficiency with Windows, MS Word and Excel.

The course will be conducted at eight identified Outreach & Training Centres (OTCs) at NRSC-RRCS North Delhi, RRSC South-Bengaluru, RRSC East-Kolkata, RRSC West-Jodhpur, RRSC Central-Nagpur, MCF-Bhopal, IIRS Dehradun, NESAC-Shillong.

Online course will also be made available in collaboration with iGOT Karmayogi (Department of Personnel & Training, GoI) platform.

N Sudheer Kumar
Director CBPO

Geospatial Technologies

Chapter 1

FUNDAMENTALS OF REMOTE SENSING

1.1 Introduction

Remote sensing is the acquisition of data for deriving information about objects or materials (targets) located at the Earth's surface or in its atmosphere by using sensors mounted on platforms located at a distance from the targets. Here, measurements are made in different spectral regions on interactions between the targets and electromagnetic radiation (EMR). The field of remote sensing encompasses techniques that obtain precise information about the earth's surface from a distance.

The advent of satellites is allowing the acquisition of information about the Earth and its environment. Sensors on the near-polar orbiting Earth resources and weather satellites provide information over 113 - 185 km and 2950 Km wide region respectively about patterns and dynamics of clouds, surface vegetation cover and its seasonal variations, surface morphology, sea surface temperature, wave heights and near sea surface wind. Geostationary satellites enable monitoring of the Earth's surface at 30 minutes interval.

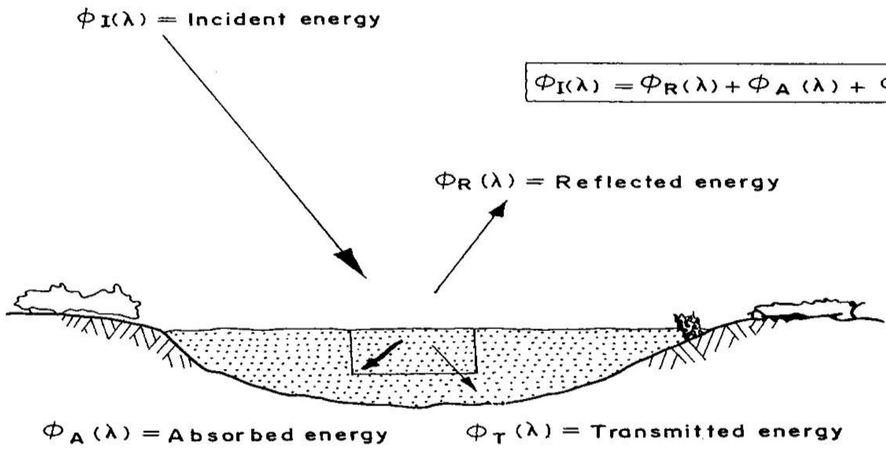

Fig. 1.1 Energy exchange processes in the natural environment (after Lillesand and Kiefer, 1987)

Remote sensing, a technique for making measurements on an object at a distance, to a great extent relies on the interaction of EMR with the matter. Different stages in remote sensing can be broadly enlisted as

- a source of electromagnetic energy (Sun/self-emission),
- transmission of energy from the source (Sun) to the surface of the earth wherein it also undergoes absorption and scattering during passage through the atmosphere,
- interaction of EMR with the earth's surface (reflection, scattering, absorption, and re-emission),

- transmission of reflected/scattered/emitted energy from the objects/features of the earth's surface to the remote sensors (with due modifications due to atmospheric effects), and sensor data output.

Fig. 1.1 shows the energy exchange processes in the natural environment. Macroscopically, the interactions are absorption, transmission, and reflection of radiation from the feature on the earth's surface. Microscopically, these are due to atomic and molecular absorption and scattering. Earth emits energy with peak emission in Thermal Infrared (8-12 µm) region and this is used for estimating the temperature of various features on the surface of the earth.

1.2 Electromagnetic Spectrum

Information from an object to the sensor is carried by electromagnetic energy and could be encoded in the form of frequency, intensity, or polarisation of the electromagnetic wave. The information is propagated by electromagnetic waves at the velocity of light from the object directly through free space as well as indirectly by reflection, scattering, and re-radiation by aerosols to the sensor. The interaction of electromagnetic waves with natural surfaces and atmosphere is strongly dependent on the frequency of the waves.

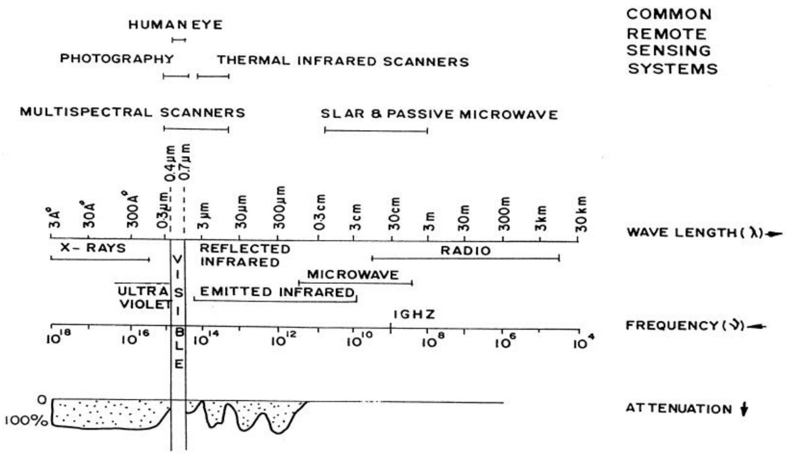

Fig. 1.2 Electromagnetic Spectrum (after Curran, 1988)

The electromagnetic spectrum is divided into a number of spectral regions as illustrated in Fig. 1.2. The radio band covers regions of wavelengths longer than 10 cm (frequency less than 3 GHz). The microwave band covers the neighbouring region, down to a wavelength of 1 mm (300 GHz frequency). The sensors operating in this region are RADAR, Microwave Radiometer, Altimeter, Scatterometer, etc. The spectral region from 0.7 µm to 1 mm is subdivided into near, middle, thermal, far infrared, and submillimeter subregions. The sensors operating in this region of EMR are imaging spectrometers, radiometers, polarimeters, and laser-based active sensing systems.

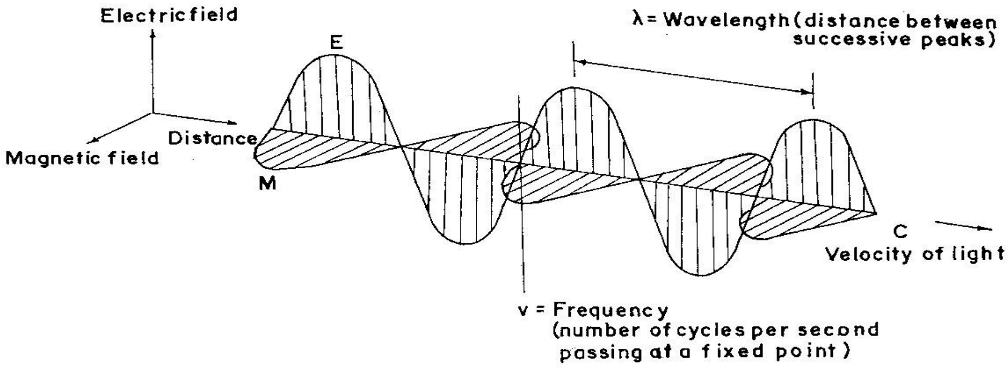

Fig. 1.3 An Electromagnetic wave and its components (after Lillesand Kiefer, 1987)

Visible light (0.4 - 0.7 µm) is only one of many forms of electromagnetic energy. Radio waves, thermal, ultraviolet, and X-rays are other familiar forms and all will propagate in accordance with basic wave theory. Wave theory describes electromagnetic energy as travelling in a harmonic sinusoidal fashion at the velocity of light 'c' which is 3×10^{10} cm/ sec. As depicted in Fig. 1.3, the distance from one wave peak to the next is the wavelength 'λ' and the number of peaks passing through a fixed point in space per unit time is the wave frequency 'v'. All the waves obey the general equation $c = \lambda v$. Although many characteristics of electromagnetic radiation are most easily described by wave theory, another theory i.e., particle theory offers useful insights into how electromagnetic energy interacts with matter during the transfer of momentum and energy. Particle theory suggests that EM energy is composed of many discrete units called Photons or Quanta. The energy of quantum is given as $E = hv$, where 'E' is the energy of quantum in Joules; h is Planck's constant (6.626×10^{-34} J-Sec); v is frequency. Wave and quantum models of electromagnetic radiation behaviour can be related by substituting for frequency $v = c/\lambda$ from wave theory in the above equation to obtain $E = hc/\lambda$. Thus, the energy of quanta is inversely proportional to its wavelength. The longer the wavelength involved, the lower is its energy content. This has important implications in remote sensing. The naturally emitted longer wavelength radiation, such as microwave emission from terrain features is more difficult to sense than radiation of shorter wavelengths such as thermal infrared radiation. The low energy content of longer wavelength radiation means that, in general, systems operating at longer wavelengths must collect energy from large areas of the earth at any given time in order to obtain detectable energy signals to maintain the satisfactory signal-to-noise ratio.

1.3 Atmospheric Effects in Remote Sensing

In the remote sensing technique, the electromagnetic radiation emitted or reflected from the objects of interest has to pass through the atmosphere before it is detected by the remote sensor. Remote sensing by satellites (at an altitude above 700 km) involves atmospheric degradation from the entire atmospheric column. Thus, the characteristics of the atmosphere significantly determine the effective use of the electromagnetic spectrum for remote sensing. The absorption and re-emission processes in the atmosphere are through changes in electronic, vibrational, and rotational quantization levels. The spectral line absorption in visible and near-IR regions is due to changing electronic quantization levels of atoms as is in the case of absorption of ultraviolet light by ozone. The transition of electrons in an atom or a molecule can occupy only certain energy levels, but not all possible energy levels. In certain wavelengths of incident radiation, the photon energy is just sufficient to cause a transition from one permissible energy level to another, thereby, getting selectively absorbed by molecules of certain gases. The vibrational energy of the molecule is related with the to and fro movement of atoms. The kinetic energy that causes the rotation of molecule as a whole is called rotational energy.

The energy E of an isolated molecule could be expressed as

$E = E_e + E_v + E_r + E_t + E_i$

where E_e, E_v, E_r, E_t and E_i refer to electronic, vibrational, rotational, translational and interaction energies. Here, the interaction component is assumed small enough to permit separate treatment of electronic, vibrational, and rotational spectra. Terrestrial radiation by virtue of energy considerations can have vibrational and rotational spectra. The low energy requirement for rotational lines as compared to that for vibrational lines leads to vibration-rotation bands.

The most important atmospheric constituents that influence incident radiation are water vapour (H_2O), Oxygen (O_2), Ozone (O_3), Carbon dioxide (CO_2), and aerosols. The following spectral regions in Table 1.1 are atmospheric windows with very little attenuation that could be used for remote sensing:

Table 1.1 Atmospheric windows in Remote Sensing

UV and Visible	0.30-0.75 μm
Near IR	0.77-0.90 μm 1.00-1.12 μm 1.19-1.34 μm
Mid - IR	1.55-1.75 μm 2.05-2.44 μm 3.5-4.16 μm
Thermal-IR	4.5-5.00 μm 8.0-9.20 μm 10.2- 12.40 μm
Microwave	17.0- 22.00 μm 2.06-2.22 mm 7.5-11.50 mm 20.0 mm & beyond.

The wavelengths shorter than 0.3 μm are completely absorbed (with the exception of 1216 ^{o}A wavelength) by the ozone layer in the upper atmosphere. The atmospheric attenuation at selective wavelengths in the reflected IR (near and mid-IR) region is mainly due to water vapour present in the atmosphere.

The CO_2 absorption bands around 4.3 and 15 μm have been in use to estimate the temperature of the atmosphere up to 50 km altitude while the 6.7 μm absorption band has been in use to estimate water vapour distribution up to 10 km altitude. Fig. 1.4 depicts the generalised absorption spectrum of the Earth's atmosphere. The attenuation of incoming solar and outgoing earth radiation is the consequence of atmospheric absorption and scattering. Scattering of electromagnetic radiation within the atmosphere reduces the image contrast and changes the spectral signature of ground objects as seen by the sensor. The scattering of electromagnetic radiation depends on the relative size of the gas molecule or particle with reference to the interacting wavelength. Gas molecules are of the order of 10^{-4} µm in size. The size of haze particles, which are water droplets formed by condensation around particles of soluble substances, varies from 10^{-2} to 10^{2} µm depending upon the state of relative humidity. The atmospheric scattering can be categorised as Rayleigh- or Mie- or Non-selective scattering.

For example, the scattering of visible light (0.4 mm to 0.75 µm) by pure gas molecules of the order of 10^{-4} µm in size is characterised under Rayleigh criteria and scattering is inversely proportional to the fourth power of wavelength. Hence, shorter wavelengths such as blue light are scattered severely as compared to green or red causing the sky to appear blue during day time. For this reason, no remote sensing measurements are undertaken in the 0.3-0.45 µm spectral window.

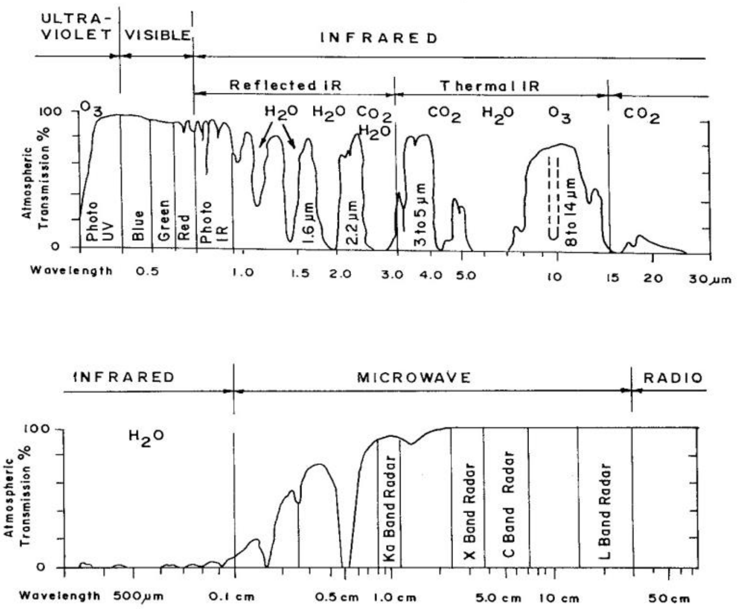

Fig. 1.4 Generalised absorption spectrum of Earth's atmosphere (after Sabins, 1987)

The Mie scattering occurs when the particle size is comparable to the interacting wavelength. Depending upon the particle size relative to wavelength, Mie scattering varies between λ^{-4} and λ^{0}. Non-selective scattering, which is independent of wavelength, occurs when the particle size is very much larger than the interacting wavelength. The particles such as in cloud, fog, and dust having dimensions ranging from 2 to 20 µm are responsible for non-selective scattering and these especially affect remote sensing in the infrared region. The process of scattering causes a reduction in the image contrast.

1.4 Interaction of Earth surface features with EMR

Interaction of Visible, Near Infrared, and Middle Infrared wavelengths with terrain features — conceptual aspects the spectral radiant flux (ϕ) incident on the earth's surface is reflected(ϕ_r), absorbed(ϕ_a), and transmitted(ϕ_t).

Thus, $\phi = \phi_r + \phi_a + \phi_t$

ϕ_r, ϕ_a and ϕ_t are dissimilar for different features on the earth's surface. This makes it convenient to identify various features on the Earth's surface based on their spectral properties. The remotely sensed ϕ_r signal measured as a function of wavelength is often referred to as the spectral signature of the target. The spectral reflectance factor of an object is the ratio of ϕ_r and ϕ in the given spectral band.

Two types of reflection are defined. When the surface is smooth, the reflection follows Snell's law (equal angles of incidence and reflection) and is called specular reflection. Specular reflection produces glint or glare: still water and some man-made (say, a mirror) structures reflect specularly. A rough surface reflects the incident EMR in all directions independent of the angle of incidence. This sort of reflection is called diffuse reflection. A perfectly diffuse surface is called Lambertian surface. The radiant flux from a perfectly diffuse or Lambertian surface is maximum along the normal to the surface and falls down as a cosine of angle with respect to normal. Most of the natural surfaces reflect in mixed mode.

Depending upon whether the surface is smooth or rough the reflection is specular or diffuse. The smoothness or otherwise of a surface depends on the wavelength of the incident radiation under consideration. According to the Rayleigh criterion, a surface is smooth if the surface height variations are less than $\lambda/8$, where λ is the wavelength of incident radiation. Otherwise, the surface is considered to be rough. Thus, for microwaves even rocky surfaces may be smooth whereas for visible radiation even sandy surface may be rough. Earth surface materials vary widely in their nature and composition; consequently, so in their reflective properties at various regions of the electromagnetic spectrum (neglecting the effect of the intervening atmosphere between the surface and the remote sensor). However, it must be recognised that in the final analysis, the combined earth atmosphere-sensor effects as recorded by the remote sensor must be taken into account. The variations in total reflectance of the Earth's surface are the combined effect of wavelength, angle of incidence, physical, chemical, and biological properties of the earth cover. Broadly, the reflected radiance, recorded by the remote sensor, is governed by a group of four components, viz., i) surface composition, ii) physical aspects of the surface (smooth, roughness, etc.), iii) angle of incidence and observation, iv) frequency or wavelength of incident radiation.

Spectral reflectance is the ratio of reflected energy to incident radiation as a function of wavelength. Many surface materials of the earth have different spectral reflectance characteristics when illuminated by different regions of the electromagnetic spectrum. For example, vegetation may reflect only 10 to 15% in the green portion of the spectrum, and as much as 40 to 60 percent in the near-infrared. Similarly, water and soil may have different reflection characteristics. However, spectral reflectance characteristics under certain conditions may be the same for some objects; for example, water and wet black soil. In such cases, the separation of objects based on a single band / wavelength would be difficult. Under these conditions, the other portion of EMR that provides separability would be an added advantage. Hence, the concept of studying the objects under multispectral mode is essential.

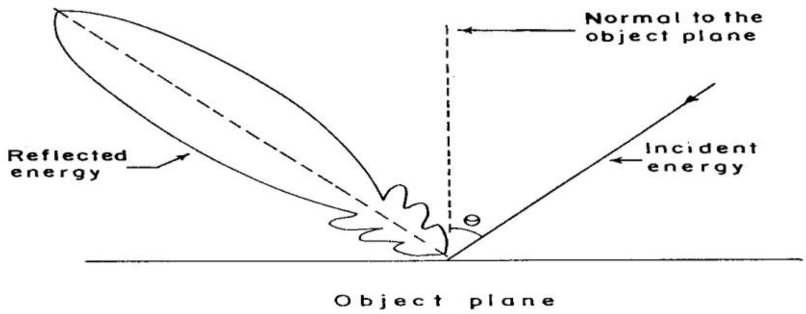

Fig. 1.5 Spectral Reflectance

The values of spectral reflectance of objects averaged over different well-defined wavelength intervals comprise the spectral signature of the objects. These are the features by which the objects can be uniquely distinguished. Measurement of spectral reflectance is made by spectro-photometers and spectro-radiometers. Spectrophotometers measure the absolute reflectance characteristics of samples in the laboratory. Spectro-radiometers are field instruments that measure the radiance. The Multi-Spectral Scanner (MSS), Thematic Mapper (TM) and Linear Imaging Self Scanning Sensor (LISS) are some of the examples of sensors used in satellites for sensing the radiances of the earth surface at distinct spectral bandwidths.

The major uses of spectral signatures in remote sensing are to

i) provide a comparison standard for identifying the spectra of unknown materials,
ii) recognise spectral regions in which various materials can be identified and
iii) provide input for atmospheric correction.

1.5 Spectral characteristics of vegetation, water, and soil

1.5.1 Vegetation

The spectral reflectance of vegetation canopy varies with wavelength. A leaf is built-up of layers of structural fibrous organic matter, within which are pigmented water filled cells and air spaces [Fig. 1.6 (a)]. The variation of spectral reflectance of a green leaf is given in Fig. 1.6 (b).

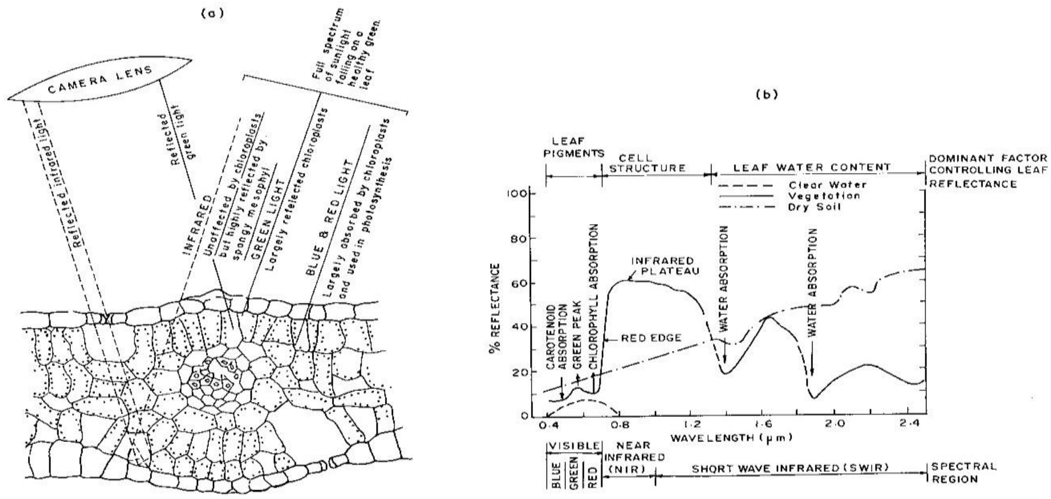

Fig. 1.6 (a) Structure of plant leaf and (b) a typical reflectance curve of green vegetation in the visible, near infrared and mid infrared region (after Goetz et al, 1983)

Each of the three features - pigmentation, physiological structure, and water content have an effect on the reflectance, absorptance, and transmittance properties of a green leaf. Plants contain four primary pigments, chlorophyll a, chlorophyll b, carotene, and xanthophyll, all of which absorb visible light for photosynthesis. Chlorophyll a absorbs at wavelengths of 0.45 µm and 0.66 µm and chlorophyll b absorbs at wavelengths of 0.45 µm and 0.65 µm. Carotene and xanthophyll pigments absorb blue to green light at a number of wavelengths. The discontinuities in the refractive indices within a leaf structure determine its near-infrared reflectance. These discontinuities occur between membranes and cytoplasm within the upper half of the leaf and more importantly between individual cells and air spaces of the spongy mesophyll within the lower half of the leaf leading to total internal reflection which is responsible for high reflectance factor (approx. 50%) in near-IR region.

In the visible wavelength, pigmentation dominates in spectral response of plants wherein chlorophyll is especially important. Absorption by chlorophyll gives very low reflectance in red and blue bands. The green colour of the leaf is responsible for peak reflectance at 0.54 µm. The middle infrared (MIR) has strong water vapour absorption bands as seen in dips just prior to 1.6 and 2.0 µm in Fig. 1.6 (b). The peak reflectance in MIR occurs at 1.6 and 2.2 µm. Thus, remote sensing measurements in 1.55 - 1.75 and 2.08 - 2.35 µm can give information about moisture content of the plant canopy.

The morphological characteristics of plants include size, shape, orientation of the leaves, plant height, and density. The spectral reflectance characteristics of a healthy green plant are governed primarily by its foliage. Several canopy models have shown that the physiognomic structure of the plant canopy and the light scattering between leaves causes the spectral response of a canopy to be notably different from that of a single leaf. Field reflectance is influenced by solar zenith angle, azimuth angle, sensor look angle, and soil background reflectance. In a broader sense plant's reflectance presents an integration of the reflectance contributions of its leaves, stems, flowering parts, and fruits modified by the spectral characteristics of the underlying soil and litter.

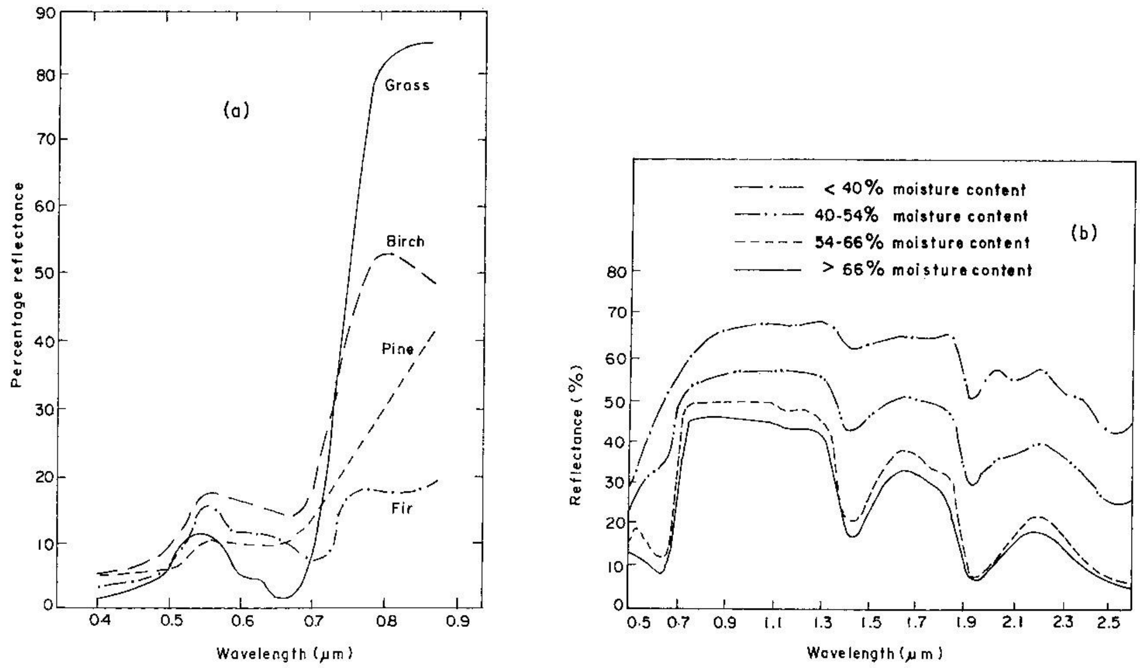

Fig.1.7 Spectral Response for (a) different canopies in visible and near IR (after Brooks, 1972) (b) for corn leaves under various moisture content (after Hoffer and Johannsen, 1969)

Fig. 1.7 (a) shows reflectance curves for three species of trees and grass. The differences in the reflectance values for these features are less in green and red and quite large in the case of NIR. Fig. 1.7 (b) shows the reflectance characteristics of the leaf for various moisture content levels wherein variations can be clearly observed around 1.4 and 1.9 µm.

Low pigment content results in higher reflectance in the red region. Stress in vegetation due to disease, insect infestation, and nutrient deficiency can also affect the reflectance characteristics. The seasonal state of maturity of a plant also influences its spectral reflectance by altering its proportions, or by controlling the presence or absence of some of its parts. Flowering for instance usually occurs over a short period during the growth cycle of vegetation. Deciduous plants shed leaves during peak winter and present a dramatically different appearance during the summer. Because of these factors, the spectral signature of a plant species may vary during a season and in its life cycle.

1.5.2 Soils

Soil is the result of decay, alteration, and disintegration of the upper layers of the earth's crust under the effect of life, atmosphere, and energy exchange. Soil reflectance depends on the chemical and physical properties of the components such as moisture, organic matter, iron oxide, texture, surface roughness, and sun angle. In the visible spectrum, soils usually have higher reflectance than plants. However, it is the opposite in the case of the near-infrared band, where plants have higher reflectance than soil.

Compare the reflectance of clay soils [Fig. 1.8 (a)] with that of sandy soils [Fig. 1.8 (b)] for different moisture content. At low moisture content levels for clay and sandy soils, the reflectance increases gradually in visible through near-infrared except in water absorption bands at 1.4 mm and 1.9 µm. The dry sandy sample does not show any ups and downs in the reflectance curve even in MIR. The clay contains water in its chemical formula, and even dry clay soil contains water and thus shows a dip in water vapour absorption bands, unlike the dry sand. Fig. 1.8 (c) gives the variation of spectral signature as a function of its inorganic content. The mineral composition of soils influences spectral reflectance. Soils formed on dissimilar rocks have different reflectance properties. Soil rich in calcium carbonate ($CaCO_3$) and poor in iron (Fe) gives higher reflectance in the visible and near-infrared regions than the soil having less $CaCO_3$ and high Fe [Fig. 1.8 (c)].

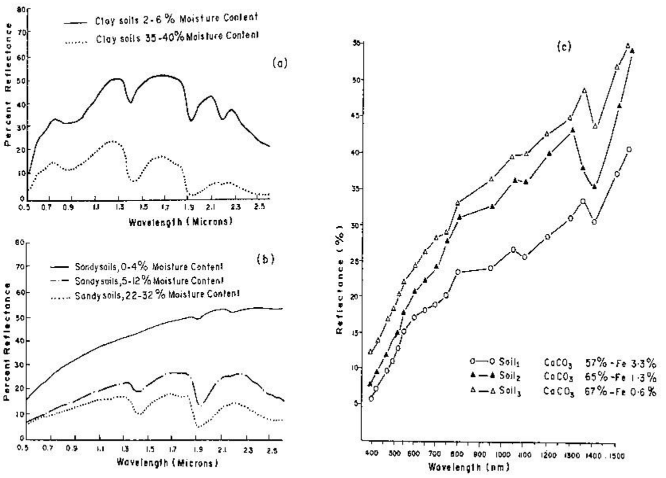

Fig. 1.8 Soil reflectance for (a) Clay soils for two moisture levels, (b) Sandy soils for three moisture levels (after Myers, 1975), and (c) Soil with different composition

Soils in arid areas may have high salt content which increases the reflectance. This influence is especially pronounced if salt crusts are formed on the soil surface. Three types of soluble salts are common in soil- -Sodium Carbonate (Na_2CO_3), Sodium Chloride (NaCl), and Potassium Hydrogen Sulphite ($KHSO_3$). They have uniform high reflectance (65 to 89 %) throughout the visible spectrum. Soils containing soluble salts do not change their spectral characteristics unless the salts form a superficial crust which makes them appear considerably brighter in the imagery.

1.5.3 Rocks

The reflectance properties of rocks vary considerably depending on rock types, chemical composition, weathering, rock out-crop, etc. Weathering influences spectral signatures in an unpredictable manner. Generally, weathered rocks give low reflectance. Fig. 1.9 (a) shows the change in the amplitude of the spectra.

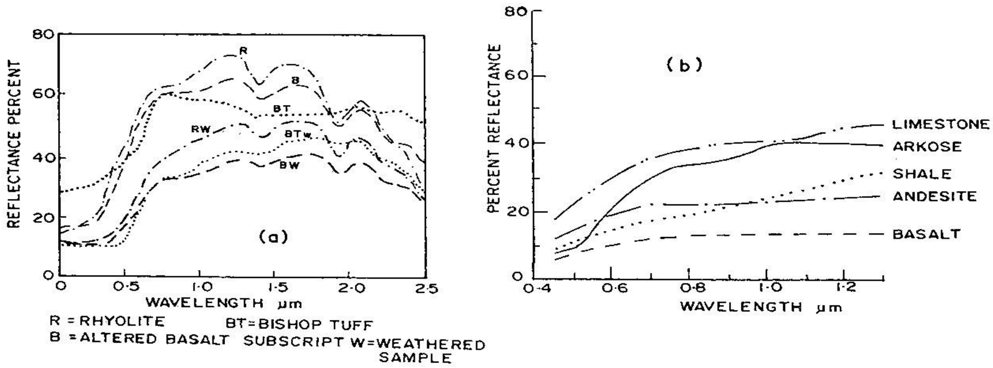

Fig. 1.9 Spectral reflectance characteristics of (a) fresh and weathered rocks (after Lyon, 1970) and (b) Volcanic and sedimentary rocks (after Goetz, 1976)

Homogeneous rock types give similar spectra at various points on the sample surface while inhomogeneous rocks show significant variations. A considerable difficulty may be expected while trying to apply laboratory-derived spectral recognition criteria to lithologic units in the field because field applications allow little or no opportunity for control of the critical "rock condition and orientation" parameters. Spectral signatures derived in the field are further complicated by noise introduced from soil, vegetation, moisture, and atmospheric effects. Fig. 1.9 (b) shows the variations in spectral reflectance as a function of typical volcanic and sedimentary rocks. From the curves we can observe that limestone, white sandstone, red sandstone, and basalt can be separated easily. The visible region (0.4 to 0.7 µm) offers a large difference in reflectance between different rocks. However, these relations will not remain constant because of the factors mentioned earlier. Although the reflectance of rocks provides a means of differentiation, other indicators (drainage, lineation, outcrop pattern, etc.) are necessary for their identification on remotely sensed imagery.

The 2.08 - 2.35 µm MIR band is found useful for studying thermally altered rocks. Most of the remote sensing instruments operate in 0.45 to 3.0 µm portion where reflected energy is more useful for remote sensing.

1.5.4 Water

The reflectance of EMR from water is affected by a number of variables such as suspended particles, floating materials, and water depth. Water gives low reflectance in visible and almost nil reflectance in near-infrared regions. Fig. 1.10 gives the typical reflectance response curve on the effect of increasing phytoplankton concentrations of a clear ocean.

The surface signal varies with the elevation of the Sun and the wave conditions. If the specular reflection is imaged by the camera or scanner, it is called sun glint.

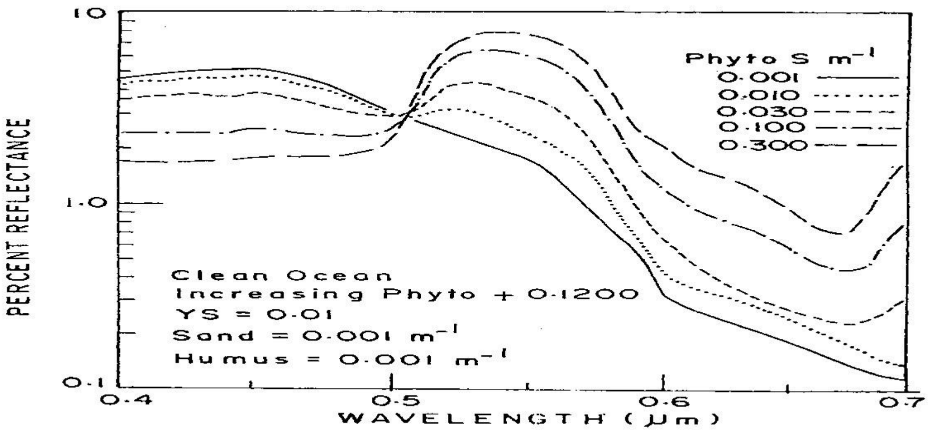

Fig.1.10 Effect of increasing Phytoplankton concentrations (After Suits, 1973)

The solar energy that is not specularly reflected is refracted downward into the water body. This refracted energy is either affected by absorption or gets scattered. Scattering in clear water is caused by water molecules and depends upon the wavelength of solar energy. Blue light is scattered more than red light. Most of the energy is scattered in a forward direction and eventually gets absorbed by the water. Only about 1 percent of energy is backscattered in very clear water. The backscattered energy that returns to the water surface carries information about the suspended sediments. Different wavelengths of light penetrate to different depths. In clear deep water, 50 % of the signal of blue light comes from a depth of 15 m but for red light (600 - 700 nm) most of the signal comes from a depth of less than 5 m. The remote signal from turbid water represents only near-surface conditions. Generally, turbid water is more reflective than clear water at all visible and near-IR wavelengths. The measured signal is dependent on (i) the wavelength used, and (ii) the size and shape of particles present deciding the relative contribution of reflectance, absorption, and scattering processes.

Mapping or monitoring water quality is considerably complex because the signal from the water body is composed of many components. The primary signal that is indicative of water quality is the volume reflectance or backscattered energy caused by the materials added to water. However, in addition to this desired signal, there may be a signal (but noise) caused by the reflection of the sunlight and skylight from the water surface and probably the signal reflected from the bottom of the water body in case of shallow depth clear water. As suspendable material is added to the volume of pure water, the only factor that will be significantly altered will be the volume reflectance which depends on the type and amount of material added. Each type of material such as red soil, blue algae, and paper-mill effluent reflects differently at different wavelengths. For a particular size and shape of particle, the back-scattered energy increases with the concentration that can be related to the remotely sensed signal strength.

1.6 Image Interpretation

Remote Sensing is broadly defined as collecting and interpreting information about a target without being in physical contact with the object. Aircraft and satellites are the common platforms for remote sensing data collection. In general, the data collected by a remote sensing system is commonly presented in the form of an image. Photo films are available that can capture pictures in 0.3 to 0.9 micrometers wavelength region. An image in black and white or colour can be generated with data captured in visible, Near Infrared, and Middle Infrared as well as in the Thermal region of electromagnetic radiation. For generating the colour composite image, data captured in three spectral bands are assigned to red, green, and blue colours respectively. Assignment of red, green, and blue colours to data acquired in Near-Infrared, red, and green bands respectively is called Standard False colour composite. Image interpretation is the act of systematic examination to identify the Physical nature of objects. It also involves deriving information on complex interaction of both surface & sub-surface features. The interpretation is not restricted to identifying objects on the image; it also usually includes the determination of their relative locations and extents. Visual interpretation of satellite images is being applied successfully in many fields, including geology, geography, agriculture, water resources, forestry, etc. A systematic study of satellite images usually involves a consideration of two basic visuals. Image interpretation involves analyzing satellite or aerial imagery to extract meaningful information about the Earth's surface. This process includes identifying and classifying land cover types, such as forests, agriculture, or urban areas. It also involves recognizing vegetation types, water bodies, infrastructure, topographic features, and assessing shadows and lighting conditions. Texture and pattern analysis, change detection, and detecting human activities are additional aspects of image interpretation. Factors like atmospheric conditions and their impact on image clarity are also considered. Image interpretation provides valuable insights for various applications, such as environmental monitoring, land management, urban planning, and disaster response.

(1) Image elements and (2) Terrain elements.

1.6.1 Image Elements

Following are the eight characteristic image elements that aid image interpretation.

- (i) Tone / Colour,
- (ii) Texture,
- (iii) Pattern,
- (iv) Shape,
- (v) Size,
- (vi) Shadows,
- (vii) Site and
- (viii) Association.

Tone / Colour: Refers to relative shades of Grey on B/W images or colours on FCC (False Colour Composite) images. Tone is directly related to the reflectance of light from terrain features. For example, water, which absorbs nearly all incident light produces a dark tone, whereas, dry sand reflects a high percentage of light and consequently produces a very light tone on the image. Tone/colour is a fundamental property of an image and conveys more information to an alert interpreter than any other interpretation element. Without tonal differences, shapes, patterns, and textures of the objects described below, could not be discerned. Some of the terms often used to describe relative tonal values are light, moderate, medium, dark etc. Absolute tonal values in terms of photo density have no physical significance for interpretation purposes and are practically never used. The variation in Grey tones can be transformed into corresponding colours of various shades / lines on FCC. Colour imagery normally provides better thematic information than single-band B/W imagery, by virtue of the more spectral information it contains.

Texture: Refers to the frequency of tonal changes in an image. Texture is produced by an aggregate of unit features which may be too small to be clearly discerned individually on the image. It is a product of their individual shape, size, pattern, shadow and tone. By definition, texture is dependent on the scale. As the scale of the photograph is reduced the texture of a given object becomes progressively finer and eventually disappears. Some of the terms often used to describe relative texture values qualitatively are coarse, fine, medium, smooth, rough, etc. It is rather easier to distinguish various texture classes visually than digital oriented techniques.

Pattern: Relatives to the spatial arrangement of the objects. The repetition of certain general forms or relationships is characteristic of many objects, both natural and manmade, and gives objects a pattern which aids the image interpreter in recognizing them. For example, interbedded sedimentary rocks typically give an alternating tonal pattern which aids in its identification.

Shape: Relates to the general form, configuration or outline of an individual object. Shape is one of the most important single factors for recognizing objects from images. For example, a railway line is usually readily distinguished from a highway or a dirt road because its shape consists of long straight tangents and gentle curves as opposed to the shape of a highway. The shape of an object viewed from above may quite different from its profile view. However, the plan view of the object is more important and sometimes a conclusive indication of their structure, composition and function is possible.

Size: The size of an object can be an important tool for its identification. Objects can be misinterpreted if their sizes are not evaluated properly with reference to the scale of the product. Although, the third dimension, i.e., the height of the object, is not readily measurable on satellite images, but valuable information can be derived from the shadows of the objects. Images with stereoscopic coverages, such as IRS-IC/ID and SPOT, it is possible to measure the third dimension (height). For planar objects, it is easier to calculate the areal dimensions on imagery, for example-alluvial fan; flood plain, etc.

Shadow: is of importance to photo interpreters in two opposing respects (1). The outline or shape of a shadow affords a profile view of objects, which aids interpretation, and (2) objects within shadow reflect little light and are difficult to discern on photographs, which hinders interpretation.

Site: Location of objects in relation to other features may be very helpful in identification. Aspect, topography, geology, soils, vegetation, etc. are distinctive factors that the interpreter should use when examining the site.

Association: It is one of the most helpful clues in the identification of landforms. For example, a floodplain is associated with several fluvial features such as terraces, meanders, ox-bow lakes, abandoned channels, etc. Similarly, a sandy plain in a desert is associated with various types of sand dunes.

1.6.2 Terrain Elements

In addition to the image elements described above, the terrain elements listed below are also highly useful for image interpretation. They are

(i) Drainage patterns,
(ii) Drainage density
(iii) Topography/Landform and

(iv) Erosion status.

Drainage patterns: The drainage patterns and texture seen in images are good indicators of landform and bedrock type and also suggest soil characteristics and site drainage conditions. For example, the dendritic drainage pattern is the most common drainage pattern found in nature. It develops under many terrain conditions, including homogenous unconsolidated materials, rocks with uniform resistance to erosion such as horizontally bedded sedimentary rocks and granitic gneissic terrains.

Drainage Density: Drainage density or texture refers to the drainage lines within a given unit area. There are three broad classes referred to as coarse, medium and fine drainage texture. In a given climatic area, coarse textured pattern would tend to develop where the soils and rocks have good internal drainage with little surface runoff, whereas a fine textured pattern would tend to develop where the soils and rocks have poor internal drainage and high surface runoff. Soft, easily eroded rocks such as shale would tend to develop fine textured drainage patterns, whereas sandstone develops coarse textured drainage patterns.

Topography/Landform: The size and shape of a landform are probably its most important identifying characteristics. There is often a distinct topographic change at the boundary between two landforms as can be seen in several images. Identification of landforms can help to decipher the underlying geology.

Erosion: In general, the deformation status and overall erosion within a given area can be accessed from the image which aids interpretation, particularly for geological mapping purposes. For example, a highly deformed and eroded rock unit can be considered older than the surrounding less eroded rock units. It also implies the natural characteristics of underlying materials.

Understanding the principles of remote sensing is very much essential towards satellite data utilization for qualitative and quantitative analysis. The spectral behaviour of various objectives in different spectral regions of the electromagnetic spectrum would help in interpreting multispectral data and imagery. Knowledge on atmospheric windows for remote sensing would help designing future sensors for space-based observations.

1.7 Introduction to Remote Sensing Sensor Systems

Monitoring of environment and agriculture at regional as well as global scale and acquiring high-resolution images for urban and cadastral level planning had been the driving force for the development of space-based remote sensing. Remote Sensing technology has penetrated in all the segments of natural resources as it provides precise information in image mode. Since the 1960s a variety of Remote Sensors have been used for studying about reflectance/emission/scattering properties of the earth's surface features as well as the atmosphere. Sensors at the early stages of technology recorded data in black & white and a little later colour images were produced. In particular, colour images provide better flexibility for the derivation of information in several application fields. In order to view images in colour, multispectral sensors and cameras have been used in Remote Sensing. In reality, colour is a continuous univariate function of wavelength which can be quantized into an arbitrary number of dimensions. Recording reflected energy from the target in spectrally higher dimensions will improve image analysis capabilities. The collection and processing of images of the same area under many spectral regions, called bands, is often referred to as *multispectral imaging*. Higher (i.e., *finer*) spatial resolutions are provided by aircraft-based platforms, while frequent and global coverage at somewhat coarser resolution is feasible through satellites. Present day satellite sensor systems provide images with spatial resolutions comparable to that of aerial photographs.

Remote sensors can be grouped into two major categories - (1) passive sensors and (2) active sensors. Sensors which sense natural radiation either emitted by or reflected from the earth's surface are called passive sensors. Thus, in passive sensing systems, there is no control over the source of electromagnetic radiation. The examples of passive remote sensors are photographic cameras, multispectral scanners, etc. The sensors which transmit their own source of EMR for illuminating the objects are called active sensors. Examples of active sensors are SAR (Synthetic Aperture Radar), LIDAR (LIght Detection and Ranging), etc.

Optical/Infrared Imaging sensors, which are passive, are of two kinds: (a) whisk broom systems and (b) push-broom systems. The former is characterized by a multispectral radiometer by which an image of an area can be recorded using a combination of the motion of the platform and a rotating or oscillating mirror scanning perpendicular to the flight direction. LANDSAT - 5 Thematic Mapper and NOAA AVHRR are examples of sensing systems which use the whisk broom method. Because of time spent in mechanical movement, dwell (or integration) time is shorter. Dwell time is a measure of how long the scanner is focused on a particular ground resolution cell (pixel) and is analogous to the shutter speed of the camera used for entertainment photography. For sensors which provide very fine spatial resolution data, dwell time is relatively smaller. The limiting factor on resolution is that the dwell time must be long enough to obtain a good quality data (i.e., a large signal-to-noise ratio must exist). Pushbroom sensors use an array of Charge Coupled Devices (CCD), which avoid the mechanical motion of oscillating mirrors used in whisk broom sensors so that more integration time is available. Most of modern passive remote sensors use push-broom technology.

Based on the spatial and spectral resolution, the macro, meso and synoptic levels of synthesized information is available in remote sensing images and visual interpretation is the primary technique in extracting intelligence from remotely sensed images.

1.7.1 Airborne Platforms

Airborne platforms involve the use of sensors and instruments mounted on aircraft, helicopters, drones, or other flying platforms. Airborne remote sensing allows for more flexible and targeted data acquisition compared to spaceborne platforms. It is often used for high-resolution data collection over smaller areas, specific regions of interest, or in situations where on-demand and rapid data acquisition is required. Airborne platforms are commonly used for applications such as aerial photography, LiDAR scanning, thermal imaging, and hyperspectral imaging.

1.7.2 Space Based Platforms

Platforms in space are very less affected by the atmosphere and hence the orbits can be well-defined. The entire earth or any designated portion can be covered at specified intervals. Synoptic coverage of the earth on a periodic basis with the least maintenance cost is immensely useful for the management of natural resources. The space-borne platforms are divided into low-altitude polar orbiting satellites and high-altitude geostationary satellites. Development and launching of artificial satellites began sometime in the fifties for defence purposes. Thereafter, with the launch of Landsat-1 in 1972, space technology was utilised for the study of meteorology and the earth's natural resources. Most earth observation satellites, such as IRS, Landsat, etc., revolve in near-polar orbits with lower altitudes. These satellite orbits are “Sun-synchronous” such that they cover each area of the world at a constant local time of day.

1.7.3 Characteristics of Remote Sensors

The factors that govern the capability of remote sensors to detect variations in reflectance between objects are the radiometric resolution of the sensor, the surface roughness of the objects and spatial variability of reflectance within the scene. The technology of sensor systems operating in the microwave region of the EMR spectrum is quite different from that used for the visible/IR part of the spectrum. In remote sensing, a given area of the earth's surface is observed by the sensor with each measurement corresponding to an elemental area on the surface and over a number of spectral bands.

The utility and characterization of satellites are made based on

a) Spatial resolution

b) Spectral resolution

c) Radiometric resolution and

d) Temporal resolution of the remote sensing system.

Imaging sensors are often described by spatial, spectral, temporal and radiometric resolutions. “Spatial resolution” refers to the projection of a single detector element onto the ground which is also known as Instantaneous Field of View (IFOV). In other words, it is a measure of the smallest object that can be resolved by the sensor as an independent object. This implies that the smaller the size of the pixel, the better (or finer) the spatial resolution. “Spectral resolution” is described in terms of the number of bands used for data acquisition and it is of usual interest to note the changes in the reflectance characteristics of various ground cover features in each spectral band. Any measurement is the weighted average over some range of wavelengths (i.e., the bandwidth). The narrower the bandwidth, the better is the spectral resolution. “Temporal resolution” refers to the repeativity of a satellite data acquisition of the same area and “Radiometric resolution” is best described by quantization levels or the number of grey shades available in a single band data.

Broadly the remote sensing systems are operational in the Optical Remote sensing region and Microwave region. Further new concept of Hyperspectral remote sensing is also emerged out.

1.8 Optical Remote Sensing Instruments

Satellites are capable of recording information in reflective region of remote sensing. The instruments are operational in visible, Near-infrared and short-wave infrared regions. Presently various countries including India are launching a number of satellites operational in the optical region of the electromagnetic spectrum.

India began to develop indigenous Indian Remote Sensing (IRS) satellite program to support the national development in the areas of agriculture, water resources, forestry & ecology, geology, watershed, marine fisheries and coastal management. Currently, data from various IRS satellites is received and utilised by several countries worldwide. With the availability of high-resolution satellite data, new applications like mapping of urban sprawl, infrastructure planning, etc., have been initiated. Table 1.2 gives the details of various IRS satellites now operational by providing data.

Table 1.2 Currently Operational Indian Remote Sensing Satellites and their Characteristics

Satellite (launch date)	Sensor(s)	Resolutions				Swath (km)
		Spatial	Spectral* (µm)	Radio metric (bits)	Temporal (days)	
Cartosat 3 (Nov 27, 2019)	PAN MULTISPECTRAL	0.28 m 1.12 m	0.45 - 0.9 B1:0.45 - 0.52 B2:0.52 - 0.59 B3:0.62 - 0.68 B4:0.77 - 0.86	11 11	5	~17 ~17
Resourcesat – 2 (Apr 20, 2011)	AWiFS LISS III LISS IV(Steerable)	56m nadir 23.5 m 5.8 m	B 2345 B 2345 B 234	12 10 10	5 24 5	737 141 70
Cartosat - 2B (July 12, 2010)	Steerable Pan ±26° along & across track	< 1	0.5 - 0.75	10	4	9.6
Oceansat - 2 (Sept 23, 2009)	OCM (±20° Al) ROSA SCAT (Ku)	236x360 - 50 km	8 Bands L1 & L2# 13.515 GHz	12 - -	2 - -	1420 - -
Cartosat - 2A (Apr 28, 2008)	Steerable Pan ± 45° along & across track	< 1 m	0.5 – 0.85	10	4	9.6
IMS - 1 (TWS) (Apr 28, 2008)	Mx HySI	37 m 505.6 m	B 123 64 B(8nm)	10 11	24 ,,	151 130
Cartosat - 2 (Jan 10, 2007)	Steerable Pan ± 45° along & ± 26° across track	0.8 m	0.5 - 0.85	10	4 / 5	9.6
Cartosat - 1 (May 5, 2005)	Pan Fore +26° Pan Apt -5°	2.54 m	0.5 - 0.85	10	5	29.42 26.24
Resourcesat - 1 (Oct 17, 2003)	AWiFS LISS III LISS IV(Steerable)	56m nadir 23.5 m 5.8 m	B 2345 B 2345 B 234	10 7 7 of 10	5 24 5	737 141 23.5MX/70 mono

* B2: 0.52 - 0.59 µm, B3: 0.62 - 0.68 µm, B4: 0.77 - 0.86 µm, B5: 1.55 - 1.70 µm # L1 – 1560-1590 MHz, L2 – 1212-1242 MHz

Multiple sensors like Linear Imaging Self Scanning (LISS-III), LISS-IV and Wide Field Sensor WiFS) are placed on a single satellite to cater to the requirements of various users with varying spatial resolutions. Cartosat series satellites have only a Panchromatic (PAN) camera for acquiring high-resolution black & white data with a much flexibility of meeting user requirements.

The Resourcesat-2 is a continuation of IRS 1C/1D and Resourcesat-1 satellites with enhanced capabilities. All the sensors onboard are of pushbroom type. One important feature is that the LISS-IV sensor offers 5.8 m spatial resolution at the nadir. LISS-IV can operate in multispectral as well as in mono mode (B3) with a swath of 70 km. LISS III, also onboard this satellite along with LISS-IV, is similar to that in IRS – 1C/1D except that the resolution of the shortwave infrared band (i.e., 'B5') is also 23.5 m. Advanced Wide Field Sensor (AWiFS) sensor with 56 m spatial resolution is also provided. The AWiFS camera has two modules AWiFS-A and AWiFS-B and provides a combined swath of 740 km.

Oceansat-2 is ISRO's second in the series of Indian Remote Sensing satellites dedicated to ocean research and will provide continuity to the applications of Oceansat-1 (launched in 1999). The main objectives of OceanSat-2 are to study oceans and the atmosphere to facilitate climatic studies. Oceansat-2 will carry three payloads including an Ocean Colour Monitor (OCM) with eight spectral bands, similar to the one carried on board Oceansat-1.

The OCM bands are 402-422, 433-453, 480-500, 500-520, 545-565, 610-630, 725-755, 845-885 nanometers with a spatial resolution of 360 x 236 m with a swath width of 1420 km and having along track steering capability up to ± 20° in steps of 5°. The other two payloads are Ku-band Pencil beam Scatterometer (SCAT), an active microwave device used to derive wind vectors of the ocean surface and a piggy-back payload called a Radio Occultation Sounder for Atmospheric Studies (ROSA). ROSA is a new GPS occultation receiver provided by ASI (Italian Space Agency). The objective is to characterize the lower atmosphere and the ionosphere, opening the possibilities for the development of several scientific activities exploiting these new radio occultation data sets.

IRS-P5 (CARTOSAT-1) has a panchromatic sensor with 2.5 m resolution with the fore-aft stereo capability to cater for applications in cartography, terrain modeling, cadastral mapping, etc. Cartosat-2, 2A & 2B have also a panchromatic (PAN) sensor with better than 1 m spatial resolution to cater to applications in cartography, cadastral mapping etc. Very high-resolution remote sensing data is currently available.

The Multispectral and PAN data available from Quickbird and IKONOS have created new openings in the utilization of satellite data for utility mapping and large-scale mapping. The IKONOS was launched by Space Imaging (now GeoEye), USA on 24th September, 1999. IKONOS is the first civilian satellite to offer a spatial resolution of 1 m in panchromatic mode. The IKONOS Panchromatic images are used for large-scale mapping and defence applications.

The Quickbird was launched by Digital Globe, USA on 18 October 2001. It is also the first civilian satellite to offer a sub-metre resolution. Later it launched WorldView-1 & 2 and WorldView-2 with a spatial resolution of 46 cm (PAN) is currently the highest spatial resolution offering satellite and hence is being used for applications which demand high spatial resolution.

1.9 Microwave Sensors

The RADAR stands for Radio Detection and Ranging. It operates in the Microwave Range of Electromagnetic Spectrum. Radar is basically used as an active remote sensing system as it transmits its own source of energy to illuminate the terrain to capture the image of an area. Like visible and infrared remote sensing, radar remote sensing can also provide satellite-based images. In earlier stage, Side Looking Airborne Radar (SLAR) was widely used. However, to provide a uniform azimuth resolution, Synthetic Aperture Radar (SAR) concept was evolved. Currently, all the airborne and spaceborne microwave remote sensing satellites operate with Synthetic Aperture Radars (SARs).

The RADAR return (echo) depends on the modification of the radar signal affected by the target. The parameters affecting the radar return can be grouped into two classes (1) system parameters and (2) terrain parameters.

The system parameters that influence the radar return are

(1) Frequency/wavelength of operation

(2) Polarization

(3) Incidence angle

(4) Look direction.

The terrain parameters are

(1) Surface geometry

(2) Surface roughness and

(3) Dielectric properties of material.

Applications of microwave remote sensing include: Classification, topography, flood mapping, mapping surface water (lakes, rivers, etc.), soil moisture, mineral and petroleum prospecting, monitoring oil spills, wind-speed/direction over the sea, snow mapping, etc.

Presently, ERS, Radarsat and ENVISAT are widely used by the Remote Sensing community for various applications, especially for flood mapping and monitoring. The detailed specifications of Radarsat are as follows:

RADARSAT - 1, launched in 1995, uses a Synthetic Aperture Radar (SAR) sensor to image the earth at a single microwave frequency of 5.3 GHz in the C band (wavelength of 5.6 cm). The Radarsat - 1 can image the earth, day or night, in any atmospheric conditions, such as cloud cover, rain, snow, dust or haze. Radarsat can be operated in one of the seven beam modes. The modes include fine mode (which covers an area of 50 km by 50 km with a resolution of 10 m), standard mode (area of 100 km x 100 km and a resolution of 30 m) and ScanSAR wide (area of 500 km x 500 km area with a resolution of 100 m). Radarsat – 2 launched in December, 2007 and have multiple polarizations with the highest resolution of 3 m with 100 m. positional accuracy.

ENVISAT is a 'heavy' satellite and has ten different kinds of sensors. Among these is a C band Advanced Synthetic Aperture Radar, which is polarimetric and can function in image mode as well as in wave mode.

Radar Imaging Satellite-1 (RISAT-1)

Radar Imaging Satellite-1 (RISAT-1) is a state-of-the-art Microwave Remote Sensing Satellite launched by India on April 26, 2012, which carries a Synthetic Aperture Radar (SAR) Payload operating in C-band (5.35 GHz), enabling imaging of the surface features during both day and night under all weather conditions. This will be operational in multi-polarisation and multi modes of image acquisition. The SAR is an all-weather imaging sensor capable of taking images in cloudy and snow-covered regions and also both during day and night. Table 1.3 gives the details of the modes of operation of the RISAT-1 satellite.

Table 1.3 RISAT-1 Modes of Operation

Mode	Look	Resolution	Swath	Polarisation
Coarse Resolution ScanSAR Mode (CRS)	2-4	50	220	Single, Dual, Circular
Medium Resolution ScanSAR Mode (MRS)	1-2	25	115	Single, Dual, Circular
Fine Resolution Stripmap Mode (FRS-2)	9-12	9	25	Quad, Circular
Fine Resolution Stripmap Mode (FRS-1)	Single	3-6	25	Single, Dual, Circular
High Resolution SPOT Light Mode (HRS)	Single	1	10x10	Single, Dual, Circular

Future Satellites

RESEOURCESAT-3: A follow on to Resourcesat-2, it will carry a more advanced LISS-III-WS (Wide Swath) Sensor having a similar swath and revisit capability as Advanced Wide Field Sensor (AWiFS), thus overcoming any spatial resolution limitation of AWiFS. The satellite would also carry Atmospheric Correction Sensor (ACS) for quantitative interpretation and geophysical parameter retrieval.

1.10 Conclusions

Remote sensing data provide useful information for monitoring and management of natural resources. Remote sensing of the earth and its environment is one of the major applications of space technology in India. India has made significant progress towards this goal by conducting through reception and processing of data from various Indian Remote Sensing satellites. Several national-level projects like forest mapping, wasteland mapping, drought monitoring, land use/land cover mapping, high-resolution data for cadastral level planning and utility mapping.

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Chapter 2

GEOGRAPHIC INFORMATION SYSTEMS (GIS)

2.1 Introduction

Geographic information System (GIS) is an emerging technology, which integrates geographical or locational data and information with Information and communication technologies for understanding and solving geographical problems. GIS provides integrated software tools that captures, stores, analyzes, manages, and presents data related to location(s). When we study the concept and theory of geographical data and information then it is referred as Geographical Information Science and when we study it with respect to the societal context then it is referred as Geographical Information Studies. Sometimes it is also termed as Spatial Information Systems as it deals with location data for objects positioned in any space, not just geographical. The data related to geographical information about the earth and its feature is also known as "Spatial Data". The spatial data uses different data models to represent geographical features in a computer system. Typically, spatial data are of two types according to the storing technique i.e., raster and vector data. The non-spatial or attribute data models are used to store and manage the characteristics of geographical features in GIS. The discipline that deals with all aspects of spatial data handling is called Geoinformatics or Geomatics. It can be defined as a "*Science and technology which integrates GIS, information technology and mathematics to study the geography*".

During the initial phases of development, GIS has been extensively used for data creation/conversion/digitization of paper maps, storing and generating printable maps. With the advent of time, the scenario has changed drastically wherein the spatial analysis became the core strength of GIS for scientific analysis and planning. GIS also facilitates modeling to arrive at local specific solutions by integrating the spatial and non-spatial data such as thematic layers and socio-economic data. The modern GIS is capable to handle large amount structured and unstructured data for informed planning and decision making. This has enabled the development of advanced spatial algorithms, spatial modeling techniques and better display and visualization systems.

GIS systems are used in many areas such as cartography, remote sensing, land surveying, public utility management, natural resource management, precision, agriculture, photogrammetry, geography, urban planning, emergency management, navigation, aerial video, and localized search engines and in many location-based services. The major applications of GIS include: earth surface based scientific investigations, resource management, reference, and projections of a geospatial landscape—both manmade and natural, asset management and location planning, archaeology, environmental impact study, infrastructure assessment and development, urban planning; cartography, for a thematic and/or time based purpose, criminology, marketing, logistics, population and demographic studies, location attributes applied statistical analysis, defense and strategic applications; and many more. Some of the specific use cases of GIS are: (i) GIS may allow emergency planners to easily calculate emergency response times and the movement of response resources in the case of a natural disasters. (ii) GIS might be used to find wetlands that need protection strategies regarding pollution; or GIS can be used by the industry for site suitability analysis to setup new business locations.

In this chapter, we will be discussing the basic concepts of GIS, data models, projection systems, spatial relationships and analysis, spatial data quality and uncertainty issues in GIS.

2.2 Types of GIS: Evaluation of GIS

The advancements in geospatial technology are allied with high computing capabilities and advanced visualization systems using contemporary ICT solutions. GIS has quickly incorporated distributed systems and databases for interoperable solutions for effective decision making whereas microcomputer has allowed GIS to be applied to new fields and has improved GIS education and awareness. Due to advancements in ICT, the data creation and storage mechanism has drastically changed in recent past using online participatory approach known as crowdsourcing or collaborating mapping. Today, the current GIS technology enables the concept of "map anywhere and serve anywhere". With recent developments, there is a leap in the development of spatial analysis tools and logical processing methods in online GIS applications and platforms. This enabled the development of numerous spatial algorithms, spatial modeling techniques and better display and visualization of geospatial data for effective planning and decision-making.

2.2.1 Desktop or Single user GIS

The desktop GIS or single user GIS is an entry-level, low-cost solution that provides basic GIS data access, querying as well as map production and spatial analysis capability to its users. Desktop GIS applications provide excellent platform for geospatial data analysis to GIS professionals by providing the tools and technologies to analyze the patterns and problems for effective land management solutions. Technically, the desktop GIS is a collection of software and data products that runs on standard desktop computers. In a typical desktop GIS configuration, the digital geo-spatial data storage mechanisms vary from simple file system to database systems. Some of the popular desktop GIS softwares are listed in table 2.1.

Table 2.1 Popular desktop GIS software

Name of the software	Software type	Description
GRASS GIS	Free and Open source	Major tools available in the software includes geospatial data management and analysis, image processing, graphics and maps production, spatial modeling, and visualization (http://grass.osgeo.org)
QGIS	Free and Open source	QGIS is one of the most popular users friendly and open-source GIS software which provides extensive tools for vector data handling. It can be easily integrated with GRASS and R (http://www.qgis.org/en/)
gvSIG	Free and Open source	Gvsig Desktop (gvSIG from this point forward) is a free GIS software and aims to represent, edit, analyse and

Name of the software	Software type	Description
		manage information from the point of view of spatial relations (http://www.gvsig.com/en)
R Geostats	Free and Open source	RGeostats is the Geostatistical Package developed by the Geostatistical Team of the Geosciences Research Center of MINES ParisTech **(**http://rgeostats.free.fr/)
ILWIS	Free and Open source	ILWIS is popular GIS and image processing platform which provides various tools for raster and vector data analysis with special emphasis on water resource applications (http://www.ilwis.org/)
ArcGIS	Commercial	ArcGIS is popular commercial desktop GIS software which provides vector and raster-based GIS data creation, processing and analysis tools with various extensions especially in windows operating system platform. Vector data handling is major strength of ArcGIS (https://www.arcgis.com/)
ERDAS Imagine	Commercial	ERDAS is a popular commercial image processing software which provides various spatial data analysis tools for raster data formats **(**http://www.hexagongeospatial.com)
ENVI	Commercial	ENVI is popular image processing software which provides tools for LiDAR, SAR, multispectral or hyperspectral data sets (http://www.exelisvis.co.uk/).

2.2.2 Web-GIS and Geospatial Web

The recent advancements in Internet and related technologies have extended the use of geospatial data and information for variety of applications at different levels. The integration of GIS and Internet technology has emerged as one of the exciting technological advancements in geospatial domain known as Internet or Web based GIS. Some of the popular web based spatial data and information services are Google Maps, Bhuvan geoportal, Bing Map, OpenStreetMap, etc. Today, Internet is emerging as a popular means of GIS data accessing, analyses and transmission and information services for various online applications.

The web-based GIS applications are dynamic in nature, which is very important for its wider utilization e.g., if any client(s)/ user(s) or database administrator updates the data or information at server end, it will be available to all the users concurrently. It can also link real time data and information such as satellite images, weather information, traffic movements and accident information, etc. by integrating online sensors and observatories. A typical GIS application usually includes three essential elements: a) presentation also known as 'Graphical User Interface' (GUI), b) logic or processing, and c) data. The relationship between these three elements is that one element sends the request to other element and the other elements responses to the request through the same interface. This making and fulfilling of request is called client/ server-computing model. The element that makes request is called ‘client’ and the element that fulfils the request is called ‘server’.

In geospatial domain, the web services are very important to achieve interoperability in data and information available with different data providers. Today, the geospatial services available in Internet through various geoportal s are increasing rapidly. There is a need of a methodology to locate desired services that provide access, data discovery and analysis capabilities for geospatial data. The interoperability of services across organizations and providers is important for seamless integration and sharing of spatial data from a variety of sources. Different organizations and commercial vendors develop their own data standards and storage structures for geospatial data. If GIS services are not interoperable, these data sets cannot interact or get overlaid to each other even though they are in the same organization or they belong to same commercial vendor. To solve the interoperability problems in GIS, the Open Geospatial Consortium (OGC) has introduced data and service standards by publishing specifications for the GIS services. OGC is a not-for-profit, international, voluntary, consensus standards organization founded in 1994. The major objectives of OGC are to lead in the development, promotion and harmonization of open geospatial standards. OGC have around 500+ members from industry, government, research and university across the world. The OGC GIS services can be grouped into six major categories as shown in table 2.2.

Table 2.2 OGC Service specifications

S. No	Type	Use	Example
1	Catalogue Services	Allows users and applications to classify, register, describe, search, maintain, and access information about Web Services	CS Core,CS-W ebRIM, CS-W 19115/19119 CS-W ebRIM for EO, etc.
2	Processing Services	Provide operations for processing or transforming the data as per user defined parameters	Sensor Planning Service (SPS), Web Processing Service (WPS), Coordinate Transformation Service (CTS and Web Coverage Processing Service (WCPS), etc.
3	Encoding	Defines symbology encoding, an XML language for styling information that can be applied to digital feature (vector) and coverage data (raster)	Geography Markup Language (GML), CityGML Styled Layer Descriptor (SLD), SWE Common, etc.
4	Data Services	Tightly coupled with specific data sets and offer access to full or a portion of geospatial data. Original data access without physical download	Sensor Observation Service (SOS), Web Feature Service (WFS), etc.

S. No	Type	Use	Example
5	Portrayal Service	Used for simple data visualization like map rendering and cartographic representation of the maps	Web Map Service (WMS) and Web Map Tiling Service
6	Others Services	Project/operation specific and other Web 3.0 services	GeoXACML, GeoRSS, Geospatial Objects, OWS Common, etc.

2.2.3 Mobile and Participatory GIS

The mobile GIS is a new technological advancement in geospatial domain and it has the strength not only to deliver the geospatial data to the mobile users everywhere and anytime, but also it can be used as an effective mode of geographic data creation and collection using participatory approach. Mobile GIS is an extension of Internet or web-based GIS which provides GIS functionalities in portable devices such as mobile, PDA, tablet etc. Mobile GIS is an integration of various technologies viz. Mobile technology, GIS, GNSS, wireless communications, etc. Mobile GIS is a cost-effective solution for data collection and creation directly from fields. Some of the exciting applications of mobile GIS include Location Based Services (LBS), crowdsourcing/ voluntary geographic information (VGI) and participatory GIS. Today, the mobile devices are embedded with GNSS which adds a location tag with the information transmitted by the device. The communication channels [like General Packet Radio Service (GPRS), Code division multiple access (CDMA), Worldwide Interoperability for Microwave Access (WiMAX), etc.] are required to transmit the information from mobile device to the receiver.

The mobile GIS architecture is a combination of client at mobile and host at server level. The data and information is published at server end for mobile user similar to web based GIS application. The only major configuration required at server end is to tune the data size for low storage and limited computation devices like mobile and PDA. The mobile GIS applications are best suited for smartphone devices where the multimedia components with GPS facility are available for the users. GIS operations in smart mobile phones are through the ICT evolution which has many exciting new applications of GIS. The mobile users are moving in a geographic space and they know their positions and they have access to the widely available geographic data and information from variety of servers. The mobility is "key" for mobile GIS applications. The theme specific GIS applications like mobile GIS for mapping, field data collection, spatial analysis and Location Based Services (LBS) etc. have become very popular among user communities.

The mobile GIS requires GIS applications and software to be installed on the smart mobile devices where the communication part can be online or offline depending upon requirements and availability. The GPS is one of important component of Mobile GIS where the location of the geography feature will be presented using coordinates recorded using GPS. The accuracy of the location varies from kilometer to a meter level.

2.2.4 Cloud Computing GIS

Cloud computing is one of most recent advancement in technology which has directly influenced the involvement of IT and related technologies in various business sectors. Cloud computing platform offers various services in virtual environment such as Software as Service (SaS), Infrastructure as Service (IaS) and Platform as Services (PaS). Here, Infrastructure refers to IT infrastructure and Platform refers to computer platform which are required to run any software application (s). The cloud computing technology has revolutionized the functioning and operations of IT services in Internet platform. Typically, the cloud computing is an integration of hardware, software, peoples (users), data and applications. GIS has adopted the cloud computing technology to enhance its uses and outreach by shifting various geospatial tools and functionalities to the cloud. Cloud-based tools are accessed for web-based GIS as geo-web services.

The cloud GIS can be considered as next generation GIS which offer 'GIS on Demand' based on user(s') or organization(s') requirements. The GIS software, data (spatial and non-spatial), computation infrastructure and platforms requirements are available for hire with a full scalability option. Various public and private clouds are getting popular such as ArcGIS Online, Cloud GIS (www.giscloud.com), Amazon web service, ThunderMaps, etc. In India, two major initiatives from Government namely, MEGHDOOT from Center for Development of Advanced Computing (CDAC) and National Informatics Centre (NIC) Cloud (http://cen.gisserver.nic.in) are getting popular among the users.

2.3 Geographical Data Representation

The data is a row of facts and figures on a subject or theme with respect to qualitative or quantitative variables. The power of GIS is its 'data', which allows various analytical capabilities to present the information in meaningful ways. Without data, GIS will become a simple drawing tool, which will be same as Computer Aided Design (CAD). GIS data represents geographical objects such as land use, land cover, elevation, trees, river, roads and other infrastructures in a digital form. In general, the geography is represented as either a Field or an Object. A field is a phenomenon that has a value everywhere in the geographic space. It can be discrete or continuous. An object is usually well distinguishable, discrete bounded entities. The space between them is potentially empty. The real objects can be divided into two major categories:

2.3.1 Discrete Data

Discrete data, which is also known as thematic, categorical, or discontinuous data in GIS often represents objects in both the feature (vector) and raster data storage systems (please refer following section for raster and vector data models). A discrete object(s) will have known and definable boundaries in the geography. In discrete object it is easy to define precisely where the object begins and where it ends. Typically, a house is a discrete object within the surrounding landscape. Its boundaries and corners can be easily marked. Other examples of discrete objects could be lake, roads, and ward boundaries in the city.

2.3.2 Continuous Data

A continuous surface represents a geographic phenomenon in which each location on the earth surface is have a value or its relationship from a fixed point in space or from an emitting source. Continuous data is also referred to as field, non-discrete, or surface data. One type of continuous surface is derived from those characteristics that define a surface, in which each location is measured from a fixed registration point. These include elevation (the fixed-point being sea level) and aspect (the fixed-point being direction: north, east, south, and west). Another type of continuous surface includes phenomena that progressively vary as they move across a surface. The most suitable examples of progressively varying continuous data are temperature, fluid and air movement. These surfaces are characterized by the type or manner in which the phenomenon moves. The continuous and categorical data in a map representation are shown in Fig.2.1.

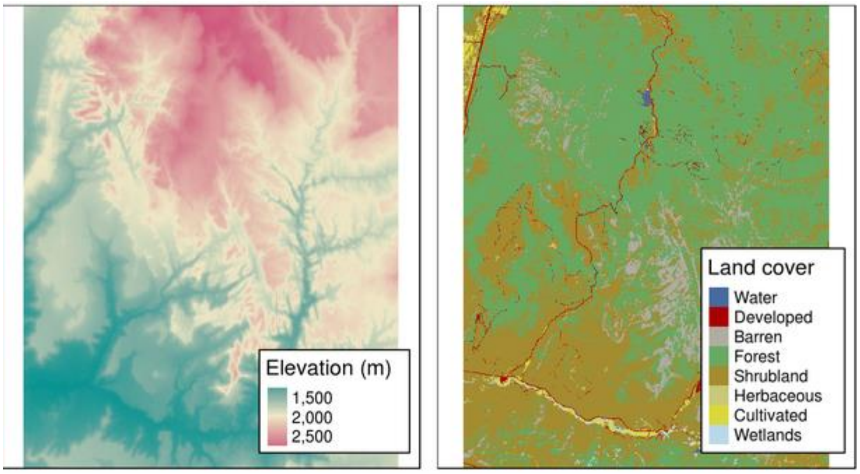


Fig. 2.1 Continuous and Categorical Data

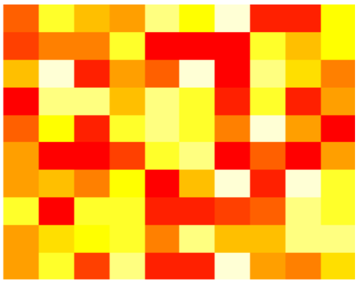
2.4 GIS Data Models

The real-world observations (objects or events that can be recorded in 2D or 3D space) need to store in the computer system for effective understanding and analysis. Conversion of real-world geographical variation into discrete objects or continuous field is done through data models. Typically, a Model is an abstract representation of the reality. It represents the linkage between the real-world domain of geographic data and computer representation of these features. Data models discussed here are for representing the spatial information. Primarily in GIS, data models are of two types: (a) raster and (b) vector.

2.4.1 Raster Data Model

The raster data model consists of uniform series of square pixel and is referred to as a grid-based system. Typically, a single data value will be assigned to each grid location. Each cell in a raster carries a single value, which represents the characteristic of the spatial phenomenon at a location denoted by its row and column and is known as digital number or pixel value. The raster data model averages all values within a given pixel to produce a single value for the region. Therefore, the more area covered per pixel, the less accurate the associated data values. The area covered by each pixel determines the spatial resolution of the raster model from which it is derived. Specifically, resolution is determined by measuring one side of the square pixel. A raster model with pixels representing 10 m x 10 m (or 100 square meters) in the real world would be said to have a spatial resolution of 10 m; a raster model with pixels measuring 1 km x 1 km (1 square kilometer) in the real world would be said to have a spatial resolution of 1 km; and so forth.

Aerial photos and satellite imageries are commonly used form of raster data model, with one primary purpose in mind: to display a detailed image on a map area, or for the purposes of rendering its identifiable objects by digitization. Additional raster data sets used by a GIS contains information regarding elevation, a digital elevation model, or reflectance of a particular wavelength of light. Raster models are simple with which spatial analysis is easier and faster. Raster data is stored in various formats; from a standard file-based structure of TIF/TIFF, JPEG, IMG, GRID etc. Sample raster representation is shown in Fig. 2.2.



A simple raster image of 10 x10 array of cells or pixels

Sample satellite image (Cartosat-2) – Raster representation

Fig. 2.2 Sample Raster representation in Image

2.4.2 Vector Data Model

In vector data model the geographical features are stored in three basic geometries i.e., point, line and polygon. Vector data models use points and their associated X, Y coordinate pairs to represent the vertices of geographical feature (s). The characteristics of a geographic phenomenon are stored in a separate attribute table as a file or as a table in a database management system. The spatial information and the attribute information are linked via a simple identification key attribute or field that is given to each feature in a map. The vector model is extremely useful for describing discrete features, but less useful for describing continuously varying features such as temperature, soil type, elevation etc. Three basic geometries of vector data model are discussed here:

Points: Points are zero-dimensional objects that contain only a single coordinate pair i.e. (x, y). Zero-dimensional points are used for geographical features that can best be expressed by a single point reference i.e., by simple location. Examples include street light, well location, building location or location of any point of interest. Points can also be used to represent areas when displayed at a small scale. For example, cities on a map of the world might be represented by points rather than polygons. No measurements are possible with point features. The representation in X, Y coordinates are shown in Fig. 2.3.

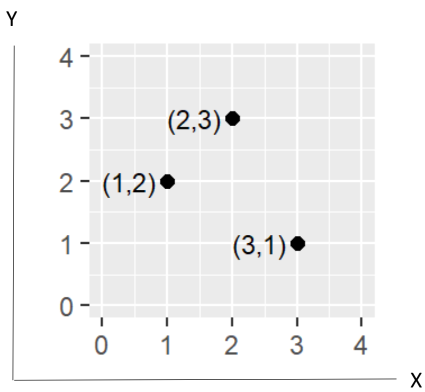


Fig. 2.3 Vector points defined by X and Y coordinate values

Lines or Polylines: One-dimensional lines or polylines are used for linear features such as rivers, roads, railroads, trails, and topographic lines. Typically, lines are composed of multiple, explicitly connected points and have the property of length but not area. A polyline is created with a sequence of two or more coordinate pairs called vertices. A vertex is defined by coordinate pairs just like a point, but what differentiates a vertex from a point is its explicitly defined relationship with neighbouring vertices. A sample coordinate representation of line feature is shown in Fig. 2.4.

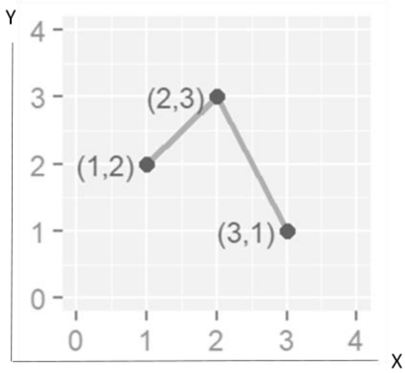


Fig. 2.4 A simple polyline object defined by three connected vertices

Polygons: Polygons are two-dimensional geometry used for geographical features that cover a particular area of the earth's surface. Such *features may include lakes, park boundaries, buildings, city boundaries, or land uses. A polygon is composed of one or more lines whose starting and ending coordinate pairs are the same*. Polygons have the topological relations such as inside, within, and outside; in fact, the area that a polygon encloses is explicitly defined and calculated in GIS. Polygon features can measure perimeter and area but not length. A sample polygon representation in X, Y coordinates is shown in Fig. 2.5.

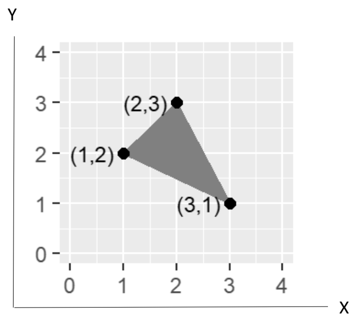


Fig. 2.5 A simple polygon object defined by an area enclosed by connected vertices

Vector features can be made to respect spatial integrity through the application of topology rules such as 'polygons must not overlap'. Vector data can also be used to represent continuously varying phenomena. Contour lines and triangulated irregular networks (TIN) are used to represent elevation or other continuously changing values. TINs record values at point locations, which are connected by lines to form an irregular mesh of triangles.

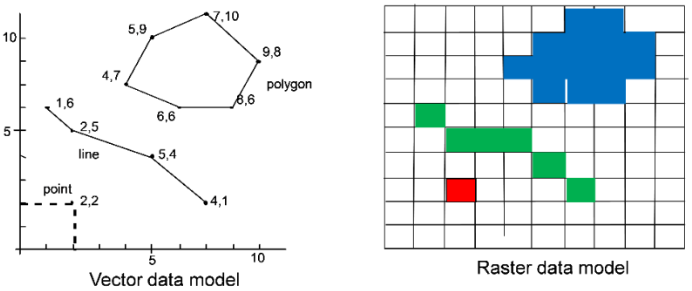


Fig. 2.6 Vector and Raster representation of geographic feature

2.4.3 Attribute Data Model

The attribute data model in GIS refers to the way in which non-spatial information is stored, organized, and linked to spatial features. It involves associating a set of attributes or characteristics with each geographic object or location in a GIS dataset. These attributes can represent various types of information, such as demographic data, land use categories, population densities, temperature values, or any other relevant data that describes the features in the dataset.

Attributes are typically stored in tabular form, with each row representing a unique spatial feature, and each column representing a specific attribute. For example, in a dataset of cities, the attributes might include the name of the city, its population, area, elevation, and so on. The attribute data model allows GIS users to attach meaningful information to spatial objects, facilitating data analysis and decision-making processes.

2.4.3.1 Types of Attributes

In GIS, attributes can be classified into different types based on their nature and characteristics. The most common attribute types include:

1. **Categorical Attributes**: Categorical attributes represent discrete classes or categories, such as land use types (residential, commercial, industrial) or soil types (sandy, loamy, clayey). They are often represented as text or alphanumeric values.
2. **Numeric Attributes**: Numeric attributes represent quantitative or continuous data, such as temperature, population density, or elevation. They can be further categorized as either continuous (e.g., temperature values) or discrete (e.g., population counts).
3. **Date/Time Attributes**: Date and time attributes capture temporal information associated with spatial features. They can be used to analyze patterns, track changes over time, or perform temporal queries.
4. **Text Attributes**: Text attributes store descriptive information in the form of text strings. They are commonly used to store names, addresses, descriptions, or other textual data related to spatial features.

2.4.3.2 Importance of the Attribute Data Model

The attribute data model plays a crucial role in GIS analysis and decision-making processes. Here are some key reasons why it is significant:

- **Data Analysis and Visualization**: By linking attributes to spatial features, the attribute data model enables powerful data analysis and visualization capabilities. It allows users to explore patterns, relationships, and trends within the data. For example, by analyzing demographic attributes in relation to spatial distribution, planners can make informed decisions about resource allocation, infrastructure development, or social services.

- **Querying and Filtering**: The attribute data model provides the foundation for querying and filtering spatial data based on specific attribute criteria. This allows users to extract subsets of data that meet certain conditions. For instance, one can query a GIS dataset to find all cities with a population over a certain threshold, facilitating targeted analysis or decision-making.
- **Spatial Analysis**: Attributes are critical for performing spatial analysis operations in GIS. By combining spatial and attribute data, users can conduct advanced analysis techniques such as spatial statistics, network analysis, or suitability modeling. These analyses help identify spatial patterns, assess relationships, and generate meaningful insights.
- **Decision-Making and Planning**: The attribute data model supports informed decision-making and planning processes by providing valuable information about spatial features. By analyzing attributes such as land use, population density, or environmental factors, decision-makers can assess the potential impacts of development projects, identify suitable locations for infrastructure, or evaluate the effectiveness of policies and regulations.
- **Data Integration**: The attribute data model facilitates data integration by enabling the combination of different datasets based on common attributes. This integration enhances the richness and comprehensiveness of spatial analysis by incorporating diverse data sources. For example, integrating demographic data with land use data can help understand the social and economic characteristics of different areas.

While the attribute data model offers numerous benefits, there are some challenges and considerations to keep in mind:

5. **Data Quality**: Ensuring the accuracy, completeness, and consistency of attribute data is essential for reliable analysis. Data quality issues, such as missing values, inconsistent formats, or errors, can affect the reliability and validity of analytical results.
6. **Data Standardization**: Harmonizing attribute data from different sources or datasets may require data standardization to ensure compatibility and consistency. Establishing common attribute standards and guidelines is crucial for effective data integration and interoperability.
7. **Database Design**: Designing an efficient attribute database structure is critical for optimal data storage, retrieval, and analysis. Choosing appropriate data types, establishing relationships between tables, and considering indexing strategies are important factors to consider during database design.
8. **Privacy and Security**: Attribute data often contains sensitive information, such as personal or confidential data. Protecting privacy and ensuring data security are paramount considerations in GIS projects, requiring proper data handling practices and compliance with relevant regulations.

The attribute data model forms the backbone of GIS analysis, enabling the integration of non-spatial information with spatial features. It empowers users to explore, analyze, and visualize data, supporting informed decision-making and planning processes. By understanding the types of attributes, their significance, and the challenges involved, GIS professionals can harness the power of attribute data to gain valuable insights and address complex spatial problems. As GIS technology continues to evolve, the attribute data model will remain a vital component in unlocking the full potential of geospatial analysis.

2.4.4 Object Orientation Data Models

The object-oriented data models allow to store and manage geospatial data inside Relational Database Management System (RDBMS). The data types are defined as an object to store vector and raster data inside RDBMS. In an object-oriented data model, we not only define data structure in database management system but also define the operations that can be performed on it. Some of the popular examples of object-oriented data model in GIS are ESRI Geodatabase, POSTGIS, Oracle spatial etc. These data models provide power of RDBMS for geospatial data for effective management of the data especially in multi user environment and are also known as Spatial Database Management System (SDBMS). In addition to typical SQL queries such as SELECT, CREATE statements, spatial databases can perform a wide variety of spatial operations like:

- *Spatial Measurements*: Finds the distance between points, polygon area, etc.
- *Spatial Functions*: Modify existing features to create new ones, for example by providing a buffer around them, intersecting features, etc.
- *Spatial Predicates*: Allows true/false queries such as 'is there a residence located within a mile of the area we are planning *to* build the landfill? ‘
- *Constructor Functions*: Creates new features with an SQL query specifying the vertices (points of nodes) which can make up lines. If the first and last vertices of a line are identical the feature can also be of the type polygon (a closed line).
- *Observer Functions*: Queries which return specific information about a feature such as the location of the center of a circle

2.5 Projections, Coordinate Systems and Registration

Projection systems are a fundamental component of GIS, allowing us to accurately represent and analyze spatial data. By transforming the Earth's curved surface onto a flat map, projection systems play a crucial role in maintaining spatial accuracy, preserving shape, distance, and area measurements. A projection system in GIS refers to a mathematical model used to represent the three-dimensional surface of the Earth on a two-dimensional plane. Since the Earth is a spherical object, it is impossible to perfectly represent its curved surface on a flat map. Therefore, projection systems are employed to minimize distortions in size, shape, distance, and other properties when converting Earth's features to a map. Projection systems involve the transformation of geographic coordinates (latitude and longitude) into projected coordinates (x and y) on a map. This transformation is achieved through mathematical formulas based on specific projection methods.

The earth can be represented by various models, each of which may provide a different set of coordinates (e.g., latitude, longitude, elevation) for any given point on the Earth's surface. The simplest model is to assume the earth is a perfect sphere. As more measurements of the earth have accumulated, the models of the earth have become more sophisticated and more accurate. In fact, there are models that apply to different areas of the earth to provide increased accuracy (e.g., North American Datum, 1927 - NAD27 - works well in North America, but not in Europe).

A major thing to be noticed in map projection is the way by which the properties of a map i.e., shape area, distance and direction, getting affected. Different projections take care of different properties and unfortunately it is impossible or rather not yet possible to have all these properties without being affected in one map projection.

2.5.1 Conformal projections: Shape preserving

Conformal projections preserve local shape. Graticule lines on the globe are perpendicular. To preserve individual angles describing spatial relationships, a conformal projection must also present graticule lines intersecting at 900 angles on the map. This is accomplished by maintaining all angles, including those between intersections of arcs. The drawback is that the area enclosed by a series of arcs may be greatly distorted in the process. No map projection can preserve shapes of larger regions.

2.5.2 Equal Area Projections: Area Preserving

An equal-area map projection, which is also known as an equivalent map projection, correctly represents areas of the sphere on the map. In this projection, the meridians and parallels may not intersect at right angles. In some instances, especially maps of smaller regions, it will not be obvious that shape has been distorted, distinguishing an equal-area projection from a conformal projection may prove difficult unless documented or measured.

2.5.3 Equidistant Projections: Distance Preserving

An equidistant map projection correctly represents distances between certain points. An equidistant map projection is possible only in a limited sense. That is, distances can be shown at the nominal map scale only from one or two points (TWO-POINT-EQUIDISTANT) to any other point on the map or in certain directions. If the scale on a map is correct along all meridians the map is equidistant along the meridians. If the scale on a map is correct along all parallels the map is equidistant along the parallels. No map is equidistant to and from all points on a map.

2.5.4 True-direction Projections: Direction Preserving

The shortest route between two points on a curved surface such as the Earth is along the spherical equivalent of a straight line on a flat surface; that is, the great circle on which two points lie. True-direction or azimuthal projects are used to rectify some of the great-circle arcs, giving the directions or azimuths of all points on the map correctly with respect to the center.

2.5.5 Cylindrical Projection

Cylindrical projections wrap a cylinder around the Earth, resulting in a flat map. This projection preserves the shape and direction of features but introduces distortions in area and distance as you move away from the equator. Cylindrical projections are often used for mapping large areas, such as world maps.

2.5.6 Conical Projection

Conical projections wrap a cone around the Earth, resulting in a flat map. This projection is suitable for representing mid-latitude regions, as it preserves both shape and area within a limited range. However, distance distortions increase as you move away from the central latitude. Conical projections are commonly used for mapping countries or regions that span a significant range of latitudes.

2.5.7 Planar Projection

Planar projections project the Earth's surface onto a flat plane, typically tangent to a specific point on the Earth. This projection preserves distances from the tangent point but introduces significant distortions in shape and area away from that point. Planar projections are often used for mapping small-scale areas, such as city maps or regional plans.

2.5.8 Considerations in Projection Selection

Selecting the appropriate projection for spatial analysis requires careful consideration. Here are some key factors to keep in mind:

Purpose of the Analysis: Consider the specific purpose of your analysis and the geographic extent of the area you are mapping. Different projection systems are suitable for different purposes, such as measuring distances accurately, preserving shape, or minimizing area distortions.

Spatial Extent: Take into account the geographic extent of your study area. Some projection systems are better suited for global or continental maps, while others are more appropriate for smaller regions or local areas.

Coordinate System: Coordinate systems, such as geographic (latitude and longitude) or projected (x and y), are closely tied to projection systems. Ensure that the coordinate system aligns with the projection system you choose for accurate spatial analysis.

Data Compatibility: Consider the compatibility of your data with the chosen projection system. Some datasets may already be projected, requiring you to match the projection system to avoid further distortions or conflicts.

Projection systems are integral to GIS, enabling us to accurately represent and analyze spatial data. By transforming the Earth's curved surface onto a flat map, projection systems minimize distortions in size, shape, distance, and other properties. Understanding the different types of projection systems and their considerations is essential for selecting the appropriate projection for spatial analysis. By carefully choosing the projection system that best suits your needs, you can ensure the accuracy and reliability of your GIS analyses and effectively communicate spatial information.

2.6 Spatial Relationship

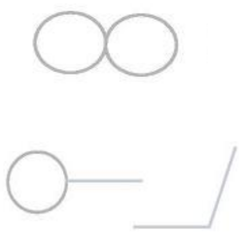
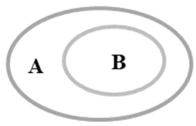
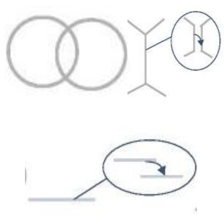
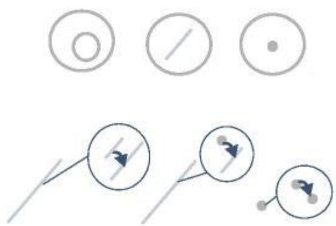
Spatial relationships are relation between objects in space in relation to some reference object when geometric properties are considered. Three types of spatial relationships are considered in geographic domain i.e., topological, metric and directional. The topological relationships are those that do not change under topological transformations and are defined as mathematical relationship between earth objects. The metric relationships are defined by measures of a metric space, and distances and angles are of those relations. The directional relationships are represented by relative orders between objects with respect to their directions.

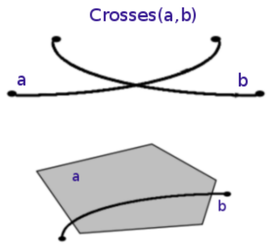
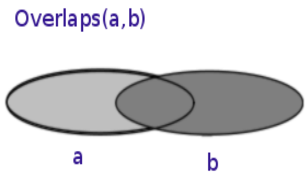
2.6.1 Topological Relationship

The topology in GIS is generally defined as the spatial relationships between adjacent or neighbouring features in geographic plane. Mathematically, the topology assumes that geographic features occur on a two-dimensional plane. Through planar enforcement, spatial features can be represented through nodes (0-dimensional cells); edges, sometimes called line (one-dimensional cells); or polygons/area (two-dimensional cells). Because features can exist only on a plane, lines that cross are broken into separate lines that terminate at nodes representing intersections rather than simple vertices. Some of examples of topological relationship are continuity, connectivity, contiguity, and adjacency in geographical domain.

The geographic objects are represented in three geometries i.e., point, line and polygons. The spatial relationships use the terms interior, boundary, and exterior with respect to these geometries. For example, a point is a 0-dimensional geometry that has an interior and an exterior, but no boundary. A line is a 1-dimensional geometry that has an exterior, an interior, and a boundary. As the boundary is at the end points of a line, if the line is a closed ring, there is no boundary. The polygon is a 2-dimensional geometry that has an exterior, an interior, and a boundary.

Table 2.3 Description of the spatial relationships

Spatial Relationship	Description	Example
Touches	A part of the geographical object from map layer 1 comes into contact with the boundary of a geographical object from map layer 2. The interiors of the features do not intersect	
Contains	A geographical object from map layer 1 completely encloses a geographical object from map layer 2. contact with any part of a geographical object from map layer 2	
Intersects	Any part of a geographical object from map layer 1 comes into contact with any part of a geographical object from map layer 2.	
Within	A geographical object from map layer 2 completely encloses a geographical object from map layer 1.	

Spatial Relationship	Description	Example
Crosses	The interior of a geographical object from map layer 1 comes into contact with the interior or boundary (if a polygon) of a geographical object from map layer 2 at a point.	
Overlaps	The interior of a geographical object from map layer 1 partly covers a geographical object from map layer 2. Only geographical object of the same geometry can be compared.	

2.6.2 Metric Relationship

Metric or distance relationship specify how far is the geographical object away from the reference geographical object. The Metric relationships include distance, direction (angle), and area. For example, the terminology such as at, nearby, in the vicinity, & far away can be used to define the metric relationship. We can also understand it by saying that Dehradun city is at 300 kilometers from New Delhi.

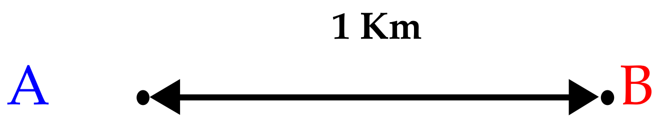


Fig. 2.7 Metric relation between two points representing the distance

2.6.3 Directional Relationship

Directional relations are qualitative spatial relations that describe how a geographic object or a region is placed relative to other geographic objects or regions with respect their directions. The directional information is expressed as qualitative term using symbolic representation. For instance, north, south, east, west, southeast, southwest, northeast are directional relations. Such relations are used to describe and constrain the relative positions of a geographical objects or regions and can be used to pose queries such as “Find all objects/regions ‘a’, ‘b’, and ‘c’ such that ‘a’ is north of ‘b’ and ‘b’ is southeast of ‘c’.

2.7 Spatial Analysis – Analysis based on Geolocation of Entities

The core design of GIS itself is based on modelling of real-world phenomenon to assist in better decision making. Analysis of the data in GIS domain is carried out through two types of data models viz. raster model and vector model (Fig. 8). The vector model is the discrete model of the real-world phenomena where the entities are represented using point, line and polygon features along with associated attributes whereas the raster data model represents the real-world entities as continuous grid i.e., pixel. Accordingly, the methods of spatial analysis vary for both the data models.

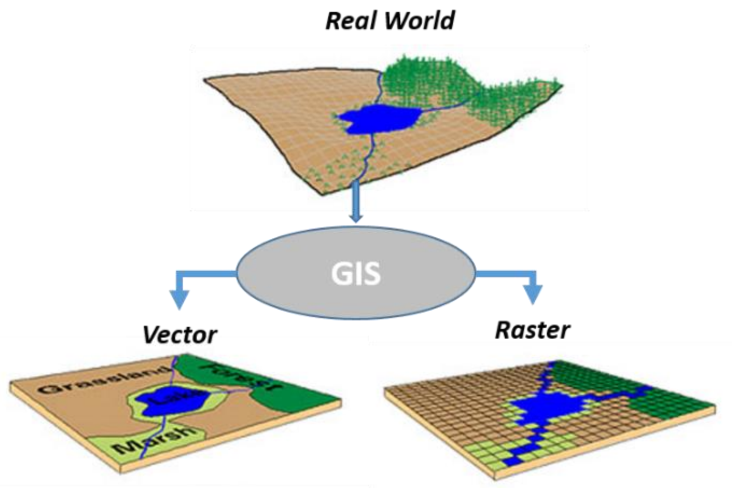


Fig. 2.8 Basic concept of GIS design

The spatial analysis transforms the data captured by the GIS data capture system and maintained by data management system to useful information to be visualized by the Geo-visualization system. For example, a utility company providing power supply to households throughout a province may periodically need to analyze the total power consumption, the statistical distribution of peaks in consumption, the typical breakdown rate of power supplies during storms, the capacities of long-range connections, the overall flow capacity of a network, and others.

The ultimate goal of any information system is to transform raw data into useful information for better decision making. All types of analysis are performed as procedures of this system. The operation available in spatial analysis makes it the most sought for section of GIS. Day by day the requirement for spatial analysis is increasing. There is a demand for newer analysis operations to be performed by GIS. For example, finding the shortest route and tourist guide information system by means GIS is popular in web applications.

The main objective of this chapter is to make the reader understand the analysis of spatial data. By the end of this chapter, the reader should be able to understand the following points:

(i) The basic spatial analysis.
(ii) Type of spatial analysis i.e., vector and raster data analysis.
(iii) Method of vector and raster data analysis.
(iv) Difference between vector and raster data analysis

2.7.1 Vector Based Analysis

As mentioned above vector data model utilizes the geo-coordinates for spatial feature representation, this spatial representation includes one or multiple attributes as well. The attributes and geometry both contribute in the analysis process. Typical subtypes of vector GIS analysis functions include Geometrical Analysis, Topological Analysis, Interpolation and Approximation, Planning and Simulation

Geometrical Analysis is related to the proximity analysis (Buffering), overlays, distance measurement, pattern analysis and map manipulation (Fig. 2.9).

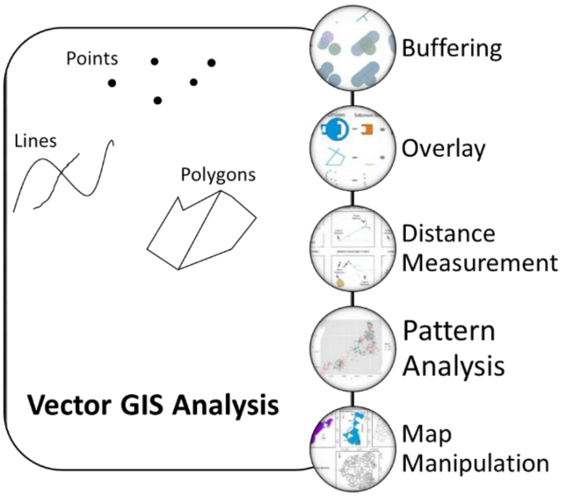


Fig. 2.9 Basic methods of Vector GIS data analysis

Geometry of features stored in GIS is of great importance, the location of a feature, also compared with the location of other features, is a basic ingredient of geospatial information. Two or more sets of features may have to be overlaid and their geometries intersected to obtain ranges, neighbourhoods, and buffers. Apart from these, the operations like topological analysis, network analysis adjacency and containment operations are also complemented by geometry of the features. These operation or functions are at the core of many spatial analysis processes, since geometry is a basic aspect of geospatial data. Polygon overlay, intersection, range queries, buffering, and nearest-neighbour search are examples of geometrical operations. Spatial filters in special arrangements help boost the performance of geometric operations.

Buffer analysis creates a boundary for the selected entity which can be any of the three features a point, line or polygon. The boundary defined can be used for the analysis with the boundary or outside the boundary. It should be clearly noted that the unit of buffer distance for the boundary is the unit of the layer. So, if you want to generate a 100m buffer around a road for restricting the construction of shops within this buffer, then you have to take care that the road layer is in planner projection system viz. UTM, LCC etc. The buffer analysis has the following primary variants:

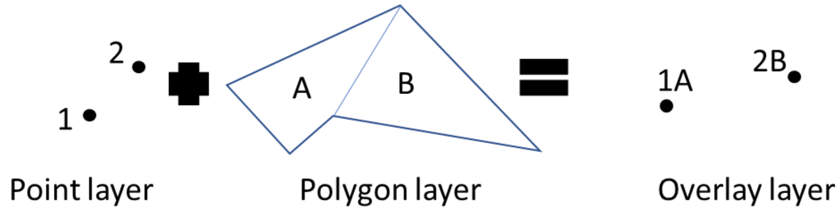
- The buffer distance can be constant throughout the feature or it can depend a specific attribute value of the feature e.g., the buffer around the schools within a city can depend on the type of the school i.e., primary school with 100m buffer, secondary school with 50m buffer and higher secondary school with 25m buffer, these buffer distances need to be defined as a field in the attribute table of the school layer.
- The buffer can be on multiple zones e.g., buffer along river can be at 50m, 100m and 200m with different restriction within these buffer areas.
- The buffer can be towards specific side of the feature e.g.; it can be towards either left or right side of a road depending upon the context of application

Applications of buffer analysis include government defining a distance of 200m from the river where no anthropogenic activities should be carried out. Nuclear power plant can also define a buffer distance around the nuclear reactor where any kind of movement is restricted.

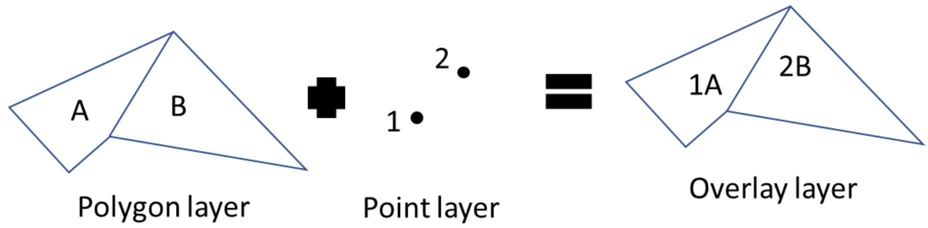
Overlay analysis is another vector-based analysis which takes two or more vector layers as input to create a user defined output layer for example if we have a land use map, population layer and a road layer then the local governing body can create a suitability map for setting up an industrial site which can benefit maximum population (population layer) and is well connected from road (road layer) as well as do not disturb any existing land use pattern (land use layer).

The basic geometrical operations performed in vector overlay analysis are:

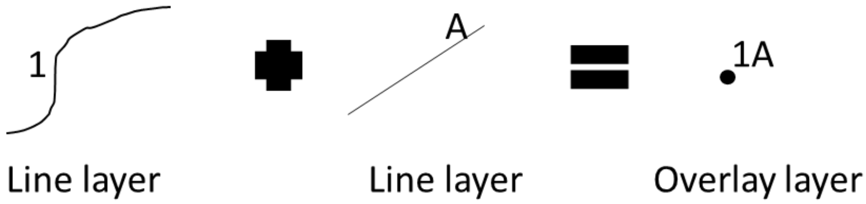
(i) Point-in-Polygon Overlay: This operation creates a point layer as output with all the point within the overlay extent and with all the attributes of point and the polygon.



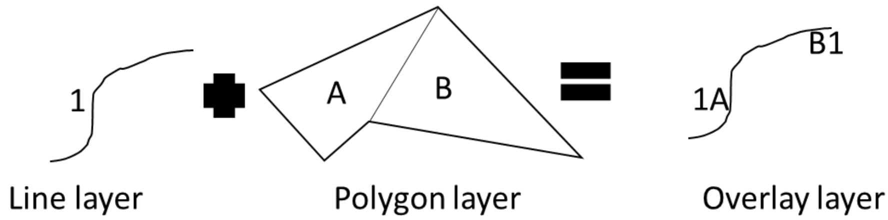
(ii) Polygon-in-Point Overlay: This operation is similar to the point-in-polygon but the output is the polygon layer with all the attributes of polygon and point layer with the overlay extent (Shown below).



(iii) Line-in-Line Overlay: This overlay operation requires two line layers and produces a point layer as output containing the points at the intersection of the two-line layers. The output point layer contains attributes from both the input layers.

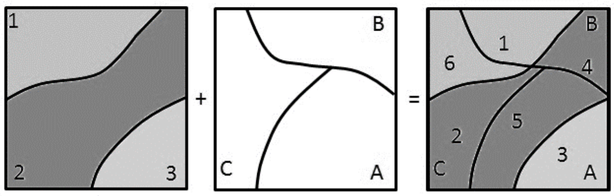


(iv) Line-in-Polygon Overlay: The output of this operation is a line layer divided into different part as per the boundaries of the polygon layer and contains the attributes from both the layers.



(v) Polygon-in-Line Overlay: This operation generates the polygon output layer and the polygon falling within the line boundaries contains the attributes of line as well along with the attributes of the polygon.

(vi) Polygon-in-Polygon Overlay: The input layers for the operation are the two polygon layers and it produces a polygon layer as the output which contains a different set of polygons features which are created by the intersection of input polygon boundaries. The polygons in the output layer contain the attributes from all the intersection input polygons.



Polygon Topology

ID	Polygon (A)	Polygon (B)
1	1	B
2	2	C
3	3	A
4	2	B
5	2	A
6	1	C

Based upon the above operations, many overlay functions and methods can be defined. Some of the most popular methods of vector overlay analysis are as follows:

(i) Union Operation: The union operation takes two polygon layers as input, creates an output layer with features, and attributes from both the layers. For example, if we have land use map polygon and the soil map polygon layer then the union operation will create an output layer with many polygons and each polygon having either land use or soil or both the information. The union operation is similar to the polygon-in-polygon operation.

(ii) Intersect Operation: Intersect operation takes any feature (point or line or polygon) layers as one of the input and other the input layer as a polygon feature. The first layer is called the input layer and the other polygon layer is called the intersect layer. This operation preserves the features common to both the input layers; the output features have attributes from both the input layers. For example, the intersection of land use layer and soil layer will create an output layer in which the features will have information from both the layers.

(iii) Symmetric Difference: Symmetric difference is the opposite of the intersect operation where the output layer consists of features which are not common to the input layers. This operation takes both the input layer as polygon layer and contains the features (polygon) and attributes from either one of the input layers. It does not contain the common features of the input layers.

(iv) Identity: Identity is similar to minus operation, it takes two feature layers (one of them is referred as input layer (point or line or polygon) and the other one is referred as identity layer (only polygon), this operation produce the output layer with geometry or spatial extent from the input layer but attributes from both the layers.

Distance measurement is one of another analysis in vector GIS wherein distance between geo-coordinates is measured in accordance with ground measurement i.e., the distance measured in layer is same as measured in ground. The measurements are like distance of a point from another point or line or a polygon, it can be between two lines or even between two polygons.

Pattern Analysis is very useful for determining and analyzing the distribution of spatial features. It provides the quantitative analysis of the distribution in terms of clustering, dispersion and randomness. The popular methods of pattern analysis are nearest neighbour analysis, spatial autocorrelation and clustering.

Map manipulation refers to the different kind of operation for making the layer specific to context and more readable. Some of the function involved in map manipulation are clip (extracting the features within a given boundary), dissolve (aggregating the feature based on attributes), append (combing the feature from different layer to create new layer), eliminate (removing the feature not meeting a specific condition, used for maintaining minimum mapping unit), update (edit the features), erase (remove the feature), split (dividing the feature into two or more feature) and many more.

Topological Analysis refers to network analysis as in routing and guidance. Topology is the branch of mathematics which deals with the spatial properties and relationship among features. These relationships among features are independent of any continuous deformation e.g., stretching etc. Topological operations presuppose a topologically correct data structure that is not inherent but has to be set up. They most often comprise also metrical aspects such as distances. Routing, traveling salesman problems, accessibility, and fleet management are prominent examples of topological operations.

Interpolation and Approximation is also an essential segment of GIS analysis. It is constituted by the statistical functions, for example, ranking, regression, trend surfaces, prediction, and filtering. Interpolations and approximations are used for lines and surfaces. Digital Terrain Models (DTM) is at the core of many other GIS analysis functions. They give reasonable estimates for heights based on interpolation and approximation assumptions. DTM can be used to generate contour lines, slope, and aspect models, viewshed models, and others.

Simulation and planning are introducing a wide arena of models and analysis requirements ranging from urban planning and its effects on flood disaster management to agriculture and geotargeting simulation models. GIS lends itself perfectly to simulation and planning. The what-if kind of scenario can be addressed by simulation operations and further planning can be done on that basis for future. These operations provide efficient means to model different variants of a planned project. Visualizing them brings more groups closer to the decision-making process. By also analyzing secondary effects, we become aware of future impacts of today's activities.

2.7.2 Raster Based Analysis

As discussed above the raster-based GIS analysis takes the input data in the form of regular grid represent the space with an attribute value in each grid cell. The cell or the grid value is used for the geospatial analysis. Broadly, the raster-based analysis is centered around the local, zonal, neighbourhood and physical distance-based operations (Fig. 2.15).

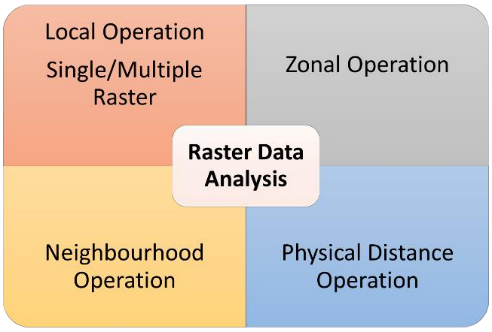


Fig. 2.15 Basic Raster Data Analysis in GIS

Local Operations refers to the cell-by-cell operation in a geospatial raster data grid. The operation can be carried out on a single raster or on a set of different raster data sets. The operation can be any function based on the cell value(s) of the raster dataset(s). For example, a simple operation can be multiplying the entire raster data by a constant value, all the cell values are multiplied by the given constant value one-by-one. Similarly, the different raster data sets can be added or subtracted cell by cell e.g., calculating the Normalized Difference Vegetation Index (NDVI) is one such operation where multiple raster datasets are used.

For a single raster data operation, a number of functions are available like arithmetic, logarithmic, trigonometric and exponential operations. One of the popular applications of local operation is conversion of the slope layer from a radian to degree or vice versa, it involves trigonometric calculation on each cell value of the slope raster grid (Fig. 2.16).

$$57.296 \times \arctan\left(\begin{bmatrix} 10.6 & 3.1 & 15.1 \\ 18.5 & 12.5 & 19.4 \\ 14.1 & 20.2 & 17.8 \end{bmatrix} \div 100 \right) = \begin{bmatrix} 6.05 & 1.77 & 8.58 \\ 10.48 & 7.12 & 10.97 \\ 8.02 & 11.41 & 10.09 \end{bmatrix}$$

Fig. 2.16 Single raster layer local operation

Multiple raster operation involves the cell-by-cell calculations between two or more raster data sets. For example, calculation of the NDVI involves two raster data sets in which addition, subtraction and division operations are performed on cell-by-cell basis i.e. (addition of cell values/subtraction of cell values) as illustrated in Fig. 2.17

$$\left(\begin{bmatrix} 12 & 31 & 21 \\ 15 & 40 & 32 \\ 14 & 29 & 19 \end{bmatrix} - \begin{bmatrix} 4 & 12 & 9 \\ 7 & 3 & 11 \\ 3 & 10 & 7 \end{bmatrix} \right) \div \left(\begin{bmatrix} 12 & 31 & 21 \\ 15 & 40 & 32 \\ 14 & 29 & 19 \end{bmatrix} + \begin{bmatrix} 4 & 12 & 9 \\ 7 & 3 & 11 \\ 3 & 10 & 7 \end{bmatrix} \right) = \begin{bmatrix} 0.5 & 0.44 & 0.4 \\ 0.36 & 0.86 & 0.48 \\ 0.64 & 0.48 & 0.461 \end{bmatrix}$$

Fig. 17 Multi raster layer local operation

Similarly, a larger number of other measures can be applied on multiple rasters, measures like summary statistics (maximum, minimum, sum, mean, median etc.) are focused on numerical data values whereas the measures like majority, minority, uniqueness etc. are suitable for raster data with categorical values. Some of the application of local operations include change detection, site suitability analysis, satellite data classification for information extraction etc.

Neighbourhood Operations refers to the operations where the value of a central cell is recalculated based on its neighbouring cell values (Fig.2.18). There are many mechanisms to choose the neighbour of a cell viz. rectangle (a 3X3 area centered at the focal cell), circle (the cells located at the distance of selected radius), annuluses (a doughnut shaped neighbour), and wedges (Cone shape neighbour) etc. The selection of these neighbours is application dependent. The most popular application is the image filtering wherein a neighbourhood window is selected and is moved across the image from one focal cell to another while calculating the new values for the focal cell based on the neighbours, the output produced by such operation enhances certain features in the image viz. edges or homogenous patches.

37	13	23	39
23	**32**	25	35
12	42	29	17
16	44	41	49
37	41	30	10
32	46	31	16
43	27	14	10
14	32	16	47
43	23	38	37

Fig. 2.18 A rectangular neighbourhood operation

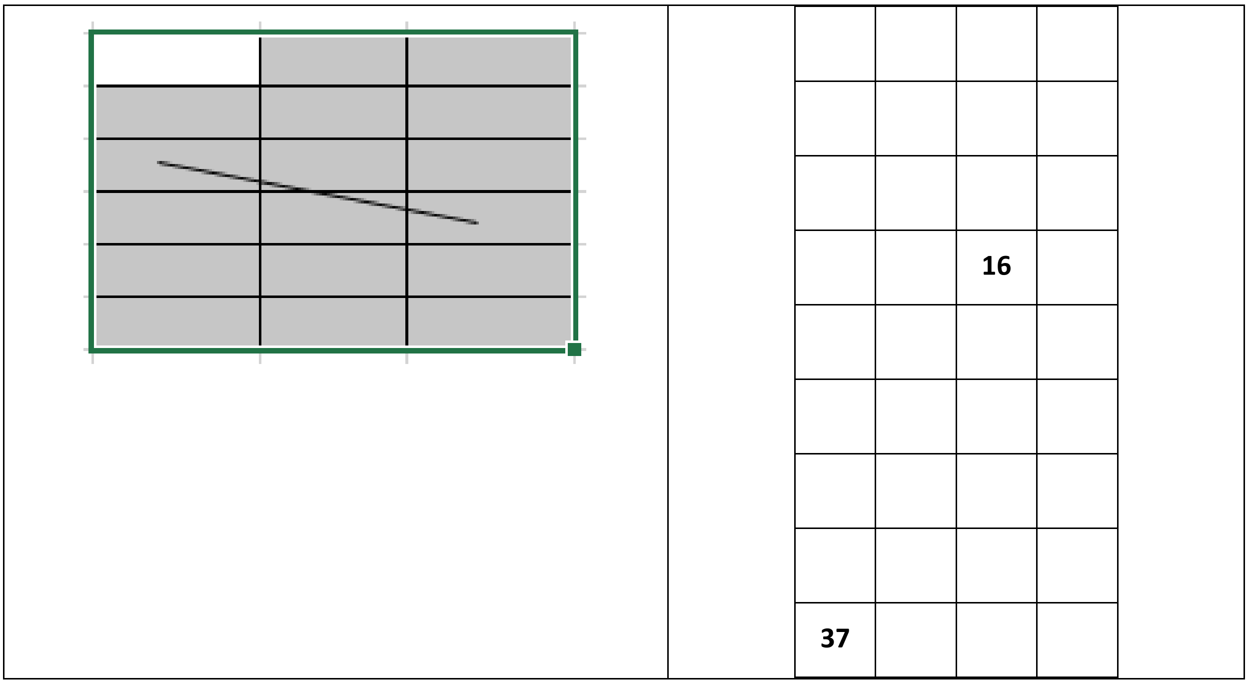
Zonal Operations select a specific zone consisting of a group of cells and generates statistics for the zone. It can be applied on a single raster (Fig. 2.19) or more than two raster data. For the single raster, the zonal operation summarizes the cell values zone wise, whereas in case of two raster, it considers one of the rasters as zonal raster and summarizes the cell values of the other input raster for each zone in the zonal raster.

44	49	10	28
17	**23**	43	16
35	40	35	16
43	21	21	13
12	11	30	37
25	29	17	38
12	17	23	36
19	27	16	25
47	16	38	22

Fig. 2.19 Single layer zonal operation (three zones)

Physical Distance Operations

Physical distance and cost distance are the two important distances, which are used in a number of spatial operations. The physical distance (Fig. 2.20**)** is measured using Euclidean distance formula ($cell\ size\ \times \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$) whereas the cost distance refers to the cost of traversing the physical distance. One very popular application where distances are taken into consideration for spatial analysis is the travelling salesman problem.



(a) (b)

Fig. 2.20 (a) Coordinates of the center of the cell are taken for distance calculation

(b) Physical distance operation empty cell gets the value in terms of distance from the nearest

(c) source cell i.e., either 37 or 16.

2.8 Spatial Data Quality and Uncertainty

A wealth of information is derived from spatial data through numerous techniques but not all data is ready to use and for information extraction, even a small error in the data can negatively impact the decision-making process leading to heavy losses in terms of revenue, opportunities and other resources. The discrepancies in the spatial data quality (SDQ) occur mainly due to (1) data capture flaws (2) data transfer (3) cartographic effects (4) metadata (5) data source (6) data format (Fig. 2.21).

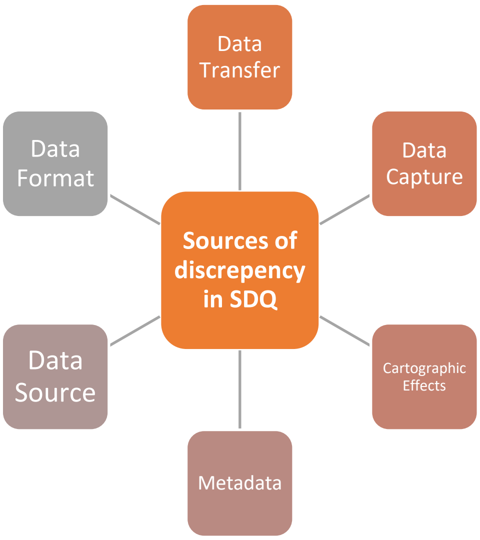


Fig. 2.21 Sources of Data Discrepancies in SDQ

The source used for data collection many have inherent flaw, which propagates to the data also. The source can be a machine, old records or even the clients providing data to organisation.

Today there are numerous data format for spatial data storage and transfer and each format have their own merits and demerits. These formats are optimised for specific requirements e.g., one of the most common vector data format in GIS is shape file, which is simple and easily portable, but it does not contain topology, similarly example exists with raster data format also.

How the spatial data has been captured can also add discrepancy in the data i.e., a building or a well can be captured as a point or as a polygon, similarly two close by building can be misinterpreted as a single building. Scale of data capture plays important role to maintain desired quality of the data.

The cartographic effects refer to representation of the feature using various symbols, colours, size, texture, orientation etc. Although certain features are represented using a standard symbology but some representations are specific to application domain and intermixing of domain specific features representation degrades the data quality.

Data transfer strategy also induces discrepancy in the quality of the data. Often it is observed that in order to transfer the data suitable for desktop-based application to web based application, the user tries to optimise the data for making it web suitable. In such cases, the data quality is compromised in order to suit a particular platform or application.

Metadata is the data about the data; it conveys important ancillary information about the data. Quality of data is ensured if the metadata is regularly updated with the latest information, if there is any change in the original data and it is not updated in the metadata it leads to gaps in the information and propagates further as well in subsequent steps.

Researchers and Decision Makers across the globe have highlighted the concern on the impact of poor quality in research out comes and decision-making activities. International geospatial organisation like International Society of Photogrammetry and Remote Sensing (ISPRS), Association of Geographic Information Laboratories in Europe (AGILE) have also emphasised on data quality standards. Several seminars and workshop are conducted annually by these organisations on spatial data quality standards. All these efforts are directed towards providing quality data for spatial decision-making.

The quality of the spatial data plays an important role in any geospatial workflow implementation; it is often considered as one of the critical pillars of geospatial technology and is defined as "fitness for use". A geospatial workflow encompasses spatial temporal and thematic dimension of an application and according the quality of the data in these dimensions should be taken into consideration. The five important component of spatial data quality are (1) precision (2) accuracy (3) consistency (4) completeness and (5) lineage.

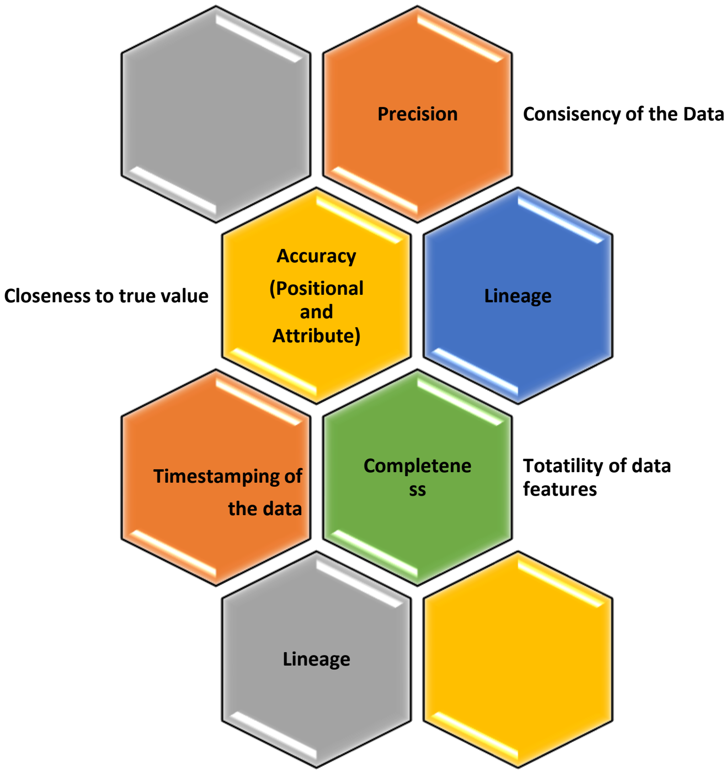


Fig. 2.22 Components of Spatial Data Quality

The five important pillars of spatial data quality (Fig. 2.22) ensure reliability in the spatial data for obtaining meaningful results. The first and foremost component is the completeness of the data, which measures the degree of totality of features in the dataset. Accuracy is the measure of closeness to the true value i.e., and it is quantified by the difference between the observed value and the true value or the accepted values. Accuracy is further quantified via two components i.e., positional and attribute where positional accuracy is the measured by shift in geometric location from the actual ground location. The lineage component related to the true time stamping of the spatial data i.e., correct data creation/update date ensures that the decisions made from the data with correct timestamping. Data precision refer to the measure of data consistency; a consistent data ensures faithfulness of the data. Precision is often linked with the granularity or the resolution of spatial datasets.

2.9 Conclusion

In conclusion, this chapter on Geographic Information Systems (GIS) has provided a comprehensive overview of the fundamental concepts, techniques, and applications within the field. We have explored the principles of spatial data, data models, and the various components of a GIS system, including data acquisition, storage, analysis, and visualization. The chapter has delved into spatial analysis methods, such as overlay analysis, network analysis, and interpolation techniques, highlighting their significance in solving real-world problems. Furthermore, we have examined the diverse range of applications where GIS is applied, including urban planning, environmental management, transportation, and public health.

The key characteristics and functionalities of various types of GIS, including desktop GIS, web GIS, mobile GIS, and enterprise GIS. Each type offers unique advantages and capabilities, tailored to specific user needs and requirements. Desktop GIS provides powerful analysis tools and a comprehensive workspace for data management, visualization, and advanced spatial analysis. Web GIS allows for easy sharing and collaboration of geospatial data and maps over the internet, enabling widespread access and interactivity. Mobile GIS brings GIS capabilities to the field, facilitating data collection, navigation, and real-time updates. Enterprise GIS caters to large-scale organizations and integrates GIS technology into their existing infrastructure and business systems. By understanding the different types of GIS, professionals and researchers can harness the appropriate tools and technologies to effectively address geospatial challenges and leverage the power of spatial data in their respective domains.

By understanding the core principles and applications of GIS, readers can appreciate the power of spatial data and how it can inform decision-making, enhance resource management, and address complex spatial challenges. This chapter serves as a solid foundation for readers to delve further into the exciting and ever-evolving field of GIS and its role in shaping our understanding of the world around us.

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Chapter 3

GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS) & LAND SURVEYING

3.1 Introduction

Traditional methods of surveying and navigation resort to tedious field work and astronomical observations for deriving positional and directional information. Diverse field conditions, seasonal variations and many unavoidable circumstances always bias the traditional field approaches. Astronomical observation of celestial bodies was one of the standard methods of obtaining coordinates of a position, i.e., a location. This method is prone to visibility and weather condition and demands expertise handling. However, due to rapid advancement in electronic systems, every aspect of human life is affected to a great deal providing increased efficiency and ease of work. The field of surveying and navigation has tremendously benefited through electronic devices. Global Navigation Satellite Systems (GNSS) based services in short time solve many of the critical situations in surveying/navigation precisely. Currently, the GNSS is extensively contributing to the concept of integrated Digital Earth. Successful attempts were made by USA and Russia since early half of 19th century to use space based artificial satellites for positioning-based experiments. The TRANSIT (Navy Navigation Satellite System) and TSYKLON satellite-based navigation systems were developed by USA and USSR respectively to establish network of control points over large regions of Earth. Establishment of modern geocentric datum and its relation to local datums was successfully achieved through the regional satellite-based navigations systems, i.e., TRANSIT and TSYKLON. Rapid improvements in higher frequency transmissions and precise clock signals along with advanced stable satellite technology have been instrumental for the development of global positioning system (GPS). Today, the positioning sensors like GPS or GNSS, Assisted/Supported GNSS and attitude sensors such as gyroscopes or inertial measurement unit (IMU) mounted on equipment's over satellites, aerial, and ground-based platforms play a vital role in remote sensing activities at global level. These sensors / equipment's provide information on position, navigation and time (PNT) along with the parameters of orbit or path travelled by sensors. Spencer et al. (2003) discuss the features and operational requirements of GPS in a detailed manner [1]. Whereas, the positioning systems in wireless sensor networks, and cellular networks, wireless LANs are discussed by Dardari et al. [2].

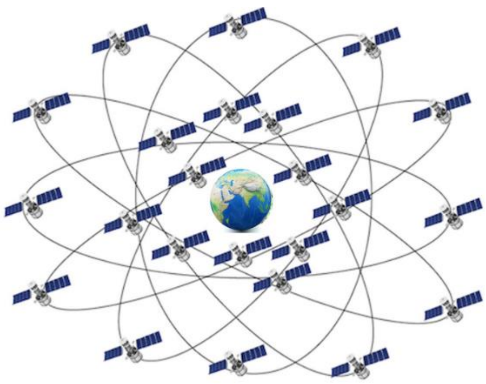


Fig. 3.1 The Global Positioning System (GPS) constellation

The NAVSTAR GPS (Navigation System Time and Ranging Global Positioning System) is a satellite-based radio navigation system. It is providing precise three-dimensional position, navigation (path) and time information to a suitably equipped user. GPS has been under development in the USA since 1973 and achieved its final operational capability (FOC) in 1995. The US Department of Defense developed it as a worldwide navigation and positioning resource for military as well as civilian use for 24 hours and for all weather conditions primarily. The NAVSTAR GPS in its final configuration consists of minimum 21 satellites (plus 3 active spares) at an altitude of 20200 km above the earth's surface (Fig.3.1). Russian GLONASS has been aimed at similar capabilities and achieved its final operational capability (FOC) in 1995. Global Navigation Satellite System (GNSS) is also ususally defined as a worldwide position and time determination system that includes one or more satellite constellations, aircraft receivers and system integrity monitoring, augmented as necessary to support the required navigation performance for the intended operation. Nowadays, about 30 or more satellites are maintained in NAVSTAR GPS and 24 or more satellites are maintained in GLONASS. The Beidou constellation developed by China was completed in early 2020 and is capable of providing PNT services globally. Galileo the fourth upcoming GNSS constellation has 23 operational satellites as of 13, June 2023 and need few more satellite launches for the completion of the Galileo constellation (https://www.gsc-europa.eu/system-service-status/constellation-information). Further sections explain the satellite-based positioning systems with NAVSTAR GPS as the major example, followed by details of other systems in brief.

3.2 Basic principle of positioning with GPS

The GPS satellites act as reference points from which receivers on the ground resects, their position. The range or the distance between the receiver and the satellite is determined from the travel time (arrival time – transmission time) of the C/A code. However, since the receiver clocks are not accurate as compared to the atomic clocks used on satellite, this range estimate is referred as the pseudorange. The ranging errors in turn have a component in the satellites (clocks and orbital specification), propagation (plasmasphere, ionosphere, atmosphere, and multipath) and in the receiver (tracking and intermodulation) [3]. The fundamental navigation principle is based on the measurement of pseudoranges between the user and four satellites (Fig. 3.2). Ground stations precisely monitor the orbit of every satellite and by measuring, the travel time of the signals transmitted from the satellite four distances between receiver and satellites will yield accurate position, direction and speed. Though three-range measurements are sufficient but fourth observation is essential for solving clock synchronization error between receiver and satellite.

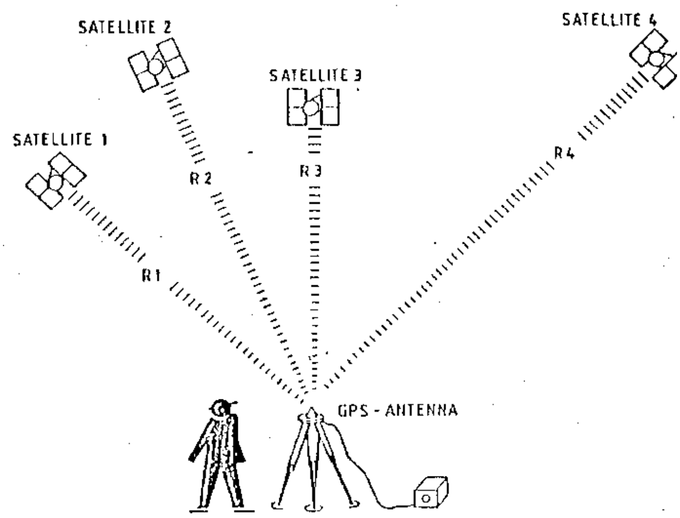


Fig. 3.2 Basic principle of positioning with GPS

Thus, the term "pseudoranges" is derived due to the presence of errors, which need to corrections in the later part through data processing techniques. The secret of GPS measurement is due to the ability of measuring carrier phases to about 1/100 of a cycle equalling to 1.9 to about 3 mm in linear distance, depending on the carrier wave. Moreover, the high frequencies L1, L2 and L5 carrier signals can easily penetrate the ionosphere to reduce its effect. Dual or Multi frequency observations are important for large station separation and for eliminating most of the error parameters. There has been significant progress in the design and miniaturization of stable clock. GPS satellite orbits are stable because of the high altitudes and no atmosphere drag. However, the impact of the sun and moon on GPS orbit though significant can be computed completely and effect of solar radiation pressure on the orbit and tropospheric delay of the signal have been now modelled to a great extent from past experience to obtain precise information for various applications.

Comparisons of main characteristics of TRANSIT and NAVSTAR GPS reveal technological advancement in the field of space-based positioning system (Table 3.1).

Table 3.1 Details of TRANSIT AND GPS

Details	TRANSIT	NAVSTAR GPS
Orbit Altitude	1000 Km	20,200 Km
Orbital Period	105 Min	12 Hours
Frequencies	150 MHz 400 MHz	1575 MHz 1228 MHz
Navigation data	2D :	4D : X,Y,Z, t velocity
Availability	15-20 minute per pass	Continuously
Accuracy	30-40 meters (Depending on velocity error)	15m (P code/No. SA 0.1 Knots)

Repeatability	-------	1.3 meters relative
Satellite Constellation	4-6	21-24
Geometry	Variable	Repeating
Satellite Clock	Quartz	Rubidium, Cesium

NAVSTAR GPS provides standard positioning services (SPS) and precise positioning services (PPS) through encryption using W-Key, for authorized users. These systems are extensively useful in RS&GIS for mapping and resource management applications [4]–[7]. The GPS provides code division multiple access (CDMA) signals. The numbering of GPS satellites is done in two ways namely, Satellite Vehicle (SV) numbers or Psuedo Random Numbers (PRN). PRN refers to the satellite that transmits specific week portion of the PRN-code, whereas the SV number represents the launch sequence number. Fig. 3 shows the basic design of NAVSTAR GPS describing the carrier waves (L1, L2, L5), codes (C/A, P(Y), L1C, L2C, M, I5, Q5) and satellite messages having information of Almanac as well as ephemeris used for commonly available PNT services. These codes and carrier waves are used for the computation of pseudoranges and fixing the location of the receiver. Until recently the positioning accuracies of standalone, GPS were of the order of 10-20m using the trilateration method of surveying for civil use. However, as per the 5th Edition report on GPS Standard Positioning Service (SPS) Performance Standard released in April 2020 the latest GNSS equipment's will provide the horizontal accuracy of 3m or better and vertical accuracy can be achieved with an accuracy of 5m or better for 95% of the time [8].

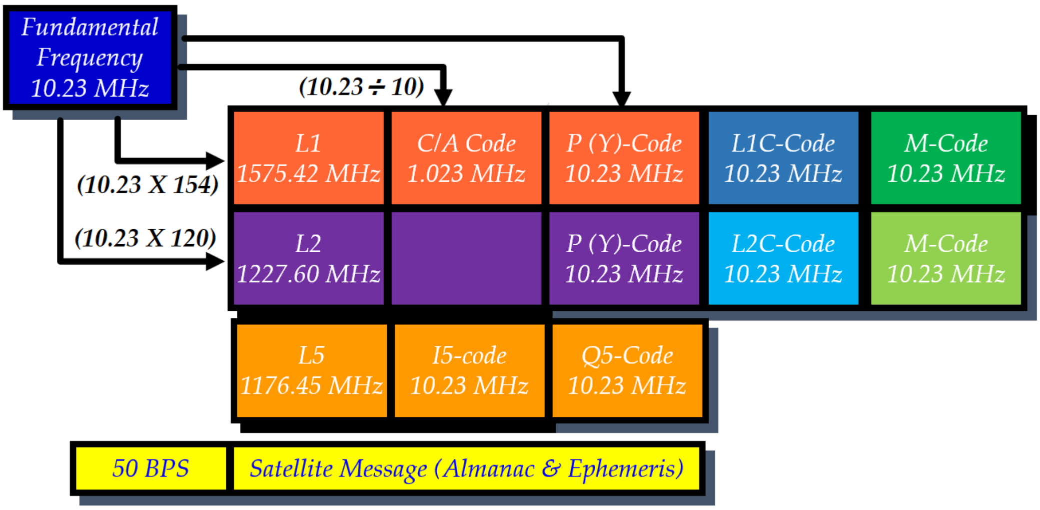


Fig. 3.3 The basic design of NAVSTAR GPS describing the carrier waves and codes used for PNT [9].

Initially, GPS has been designed for providing standalone navigational accuracy of ±10m to ±15 m for SPS users after the removal of Selective Availability (SA) on 1 May 2000. However, sub meter as well as centimeter level accuracies, in the relative or the differential mode has been achieved and it has been proved that broad varieties of problems in geodesy or geodynamics can be tackled through GPS. Commonly, when more than one GPS constellation is used for an application, it is termed as GNSS solution. Versatile use of GNSS for a civilian need in following fields have been successfully practiced viz. navigation on land, sea, air, space, high precision kinematics survey on the ground, cadastral surveying, geodetic control network densification, high precision aircraft positioning, photogrammetry, monitoring deformations, hydrographic surveys, active control survey and many other similar jobs related to navigation and positioning.

3.3 Segments of GPS

To have a better understanding of GPS or GNSS, space-based navigation systems are usually considered as a combination of three major segments namely, space segment, Control segment and User segment. Space segment deals with GPS satellites systems, Control segment describes ground-based time and orbit control prediction, whereas User segment includes various types of existing GPS receivers and its application (Table 3.2). A 6-orbit based design is used for NAVSTAR GPS with minimum four satellites in each orbit as shown in Fig. 3.4. The official U.S. Government information about the Global Positioning System (GPS) and related topics are given on http://gps.gov/ with regular updates on newer satellites joining the constellation and / or completing their life cycle. GLONASS (Global Navigation & Surveying System) a similar system to NAVSTAR GPS is developed by Russia and is now a valuable complementary system to GPS and a part of GNSS.

Table 3.2 Brief account of the function and of various segments along with I/O information.

Segment	Input	Function	Output
Space	Navigation message	Generate and Transmit code and carrier phases and navigation message	P-Code C/A Code L1, L2, L5 carrier Navigation message
Control	P-Code Observations, Time	Produce GPS time predict ephemeris manage space vehicles	Navigation message
User	Code observation, Carrier phase observation, Navigation Message	Navigation solution Surveying solution	Position velocity time

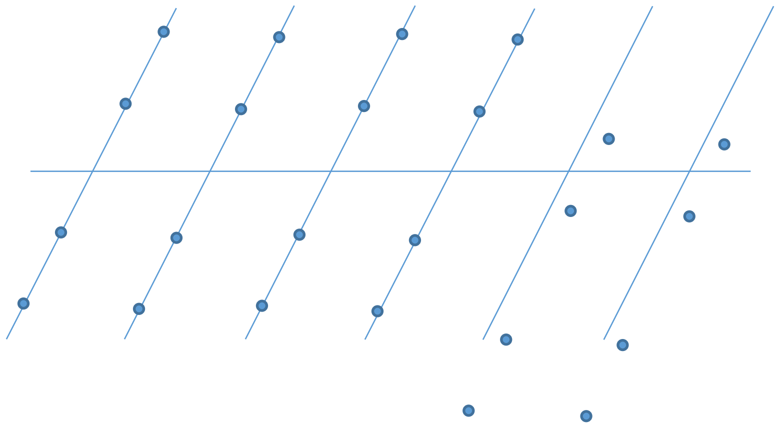


Fig. 3.4 The 6-orbit based design of NAVSTAR GPS with minimum four satellites in each orbit

3.4 Components of GPS receiver

The main components of a GPS receivers are: antenna with pre-amplifier, RF section with signal identification and signal processing, Micro-processor for receiver control, data sampling and data processing, precision oscillator, power supply, user interface, command and display panel, memory, data storage. Some of the antennas are: mono pole or dipole, Quadrifilar helix, Spiral helix, Microstrip, Choke ring.

3.5 Classification of GPS receivers

GPS receivers can be divided into various groups according to different criteria. Most prominent classification of GPS receivers is based on acquisition of data types, for example: C/A code receiver; C/A Code + L1 Carrier phase; C/A Code + L1 Carrier phase + L2 Carrier phase; C/A code + p_code + L1, L2 Carrier phase; L1 Carrier phase; L1, L2 Carrier phase; L1, L2, L5 Carrier phase. Some of the important features for selecting geodetic receivers are: tracking of all satellites, both frequencies, full wavelength on L2, low phase noise-low code noise, high sampling rate for L1, L2 and L5, high memory capacity, low power consumption, full operational capability under anti spoofing condition. Further, it is recommended to use dual or multi - frequency receiver to minimize influences due to ionosphere and take advantages in ambiguity solution. Since, the data formats are many including various proprietary formats of various original equipment manufacturers (OEMs); a common format is being designed for global users considering ease of work as well as compatibility issues for optimal solutions and is known as Receiver Independent Exchange (RINEX) format.

RINEX Data format: Receiver Independent Exchange Format is globally accepted standard data interchange format for raw satellite navigation system data. This was first developed by the astronomical Institute of the University of Berne for easy exchange of GPS receiver data collected from different receivers manufactured by different firms. There is a need to have a common format to make use of data collected by various receivers as each vendor have their own proprietary format of storing the received GNSS data.

3.6 Types of GPS Positioning

Major types of possible positioning methods are: Single Point Positioning (Static mode or Kinematic mode), Relative or Differential Point Positioning (Static mode or Kinematic mode), Real-time data collection (point, line, and area), Post mission processing. The processing takes care of the various sources of errors namely, satellite clock errors, receiver clock errors, satellite orbit errors, atmospheric errors (Ionosphere and Troposphere), multipath error and human errors. Geometric Dilution of Precision (GDOP) is the factor or measure available in the GNSS equipment's as an indicator of the quality of signal.

3.7 Dilution of Precision (GDOP)

The term Dilution of Precision (DOP) is used in the context of Global Navigation Satellite Systems (GNSS) to describe the degree to which location measurements are accurate and reliable. It depicts the impact of different variables that may cause ambiguity or inaccuracy when a precise position is determined using satellite-based positioning systems like GPS. A dimensionless number or ratio, often ranging from 1 to infinity, is used to express DOP. The position estimation's accuracy and precision increase with decreasing DOP values. Higher values signify greater uncertainty, while a DOP value of 1 implies optimal circumstances. There are various DOP types that concentrate on various facets of position estimation:

Position Dilution of Precision (PDOP): PDOP measures how accurately satellite positions are geometrically positioned in reference to a receiver's position. It considers satellite geometry, in particular the geographical distribution of satellites and their angular positions in the sky. Better placement accuracy is indicated by lower PDOP values.

Horizontal Dilution of Precision (HDOP): HDOP is a subset of PDOP and exclusively takes into account the horizontal aspect of location estimate. It evaluates the precision and dependability of the latitude and longitude horizontal coordinates obtained from satellite measurements. Higher HDOP values suggest more accurate horizontal placement.

Vertical Dilution of Precision (VDOP): Position estimation's vertical component is the subject of the VDOP algorithm. It evaluates the precision and dependability of an elevation or altitude measurement obtained from satellite data. Lower VDOP values suggest more precise vertical placement.

Time Dilution of Precision (TDOP): TDOP is a method for assessing the precision and dependability of time measurement used in position estimation. It measures the synchronisation quality of the satellite clocks and the effect it has on time-based measurements.

For a better understanding of the accuracy of position estimates generated from GNSS systems, DOP values are crucial. Higher DOP values signify increasing uncertainty due to poor satellite geometry or other error-inducing causes, while lower DOP values often indicate better positioning accuracy. DOP values are frequently included in the output from GNSS receivers to help users evaluate the accuracy of location measurements.

3.8 Other satellite-based positioning systems

Earlier NAVSTAR GPS (popularly known as GPS) and GLONASS were the only global satellite positioning systems, however now many nations or space agencies are making an effort to have their own satellite positioning system providing position and other applications available at either regional or global scale. Hence, the satellite positioning system has given rise to new term called Global Navigation Satellite System (GNSS). Some of the satellite positioning systems are listed below in table 3. A resultant total of signals, from a greater number of redundant signals from satellites enable user in obtaining high accuracy by reducing the errors using the least square adjustment method in the computation of coordinates for a location. GNSS provides Standard Positioning Service (SPS) and

High/Precise/Restricted Positioning Service (HPS / PPS / RS) for its authorized users. Galileo has planned to provide more services on becoming fully operational, such as open services (OS), search and rescue (SAR), public regulated services (PRS), commercial services (CS), and Safety of Life (SoL) services [10]. These systems are extensively useful in RS&GIS for mapping and resource management applications [4]–[7]. The Galileo High Accuracy Service (HAS), as an Initial Service has begun on 24 January 2023. The users within the service area of HAS, are getting an accurate positioning solution as a free of charge service, through the Galileo signal (E6-Band) and by terrestrial means (Internet), using a Precise Point Positioning algorithm in real-time. The Chinese Beidou system is the latest addition to GNSS and is under extensive use worldwide, after completion of its constellation of satellite in 2020. Beidou is providing the Precise point positioning and Satellite based augmentation service (SBAS) (http://www.csno-tarc.cn/en/system/constellation). The fourth system GALILEO is being developed by the EU and is expected for completion soon [11]. DORIS is developed by the French Space Agency CNES (Centre National d'Études Spatiales), in cooperation with the Institut Géographique National (IGN) for precise orbit determination for low-altitude Earth satellites (https://ggos.org/item/doris/).

Table 3.3 Satellite positioning system having global coverage (13.06.2023)

System	Country	Orbital height & period	Number of satellites	Frequency
GPS	USA	20,200 km, 12.0h	≥ 24 (at present 31)	1.575 GHz (L1 signal) 1.227 GHz (L2 signal) 1.176 GHz (L5 Signal)
GLONASS	Russia	19,100 km, 11.3h	24	Around 1.602 GHz (SP)* Around 1.246 GHz (SP)*
Galileo	European Union	23,222 km, 14.1h	23 as on 13 June, 2023 (initial operations started from 15 Dec. 2016)	1.164-1.215 GHz (E5a and E5b) 1.215-1.300 GHz (E6) 1.559-1.592 GHz (E2-L1-E11)
Beidou	China	21,150 km, 12.6h	Over 40 satellites (operational / Experimental)	B1: 1,561098 GHz B1-2: 1.589742 GHz B2: 1.207.14 GHz B3: 1.26852 GHz

*The frequency varies with each satellite.

[#] Source: http://www.csno-tarc.cn/en/system/constellation

Delft University initially proposed the Eurofix concept in 1989 for a PNT solution by combining Satellite based navigation systems (GNSS) and terrestrial navigations systems (LORAN/Chayka) [12]. Eurofix has a large potential in improving the PNT solution over continental areas and can become an alternative ground-based solution to the satellite-based augmentation systems (SBAS) such as Wide Area Augmentation System (WAAS) in the USA or the European Global Navigation Overlay System

(EGNOS) in the EU [13]. Reelektronika has developed a powerful alternative PNT solution for Integrated GNSS eLoran/Chayka called the Loradd++, providing with very small size chip (60 x 30 x 8 mm) having Dual-channel receiver and Low power < 500 mW (3.3V) requirements.

3.9 Regional satellite navigation systems

These systems have limited coverage over a specific area. Some of such systems are IRNSS or NAVIC, the initial BEIDOU-1/2, and QZSS developed by India, China, and Japan respectively to have coverage over their respective nations and regions of interest.

3.9.1 Indian Regional Navigational Satellite System (IRNSS)

The Indian Regional Navigational Satellite System (IRNSS) is an autonomous regional satellite navigation system developed by the Indian Space Research Organization (ISRO), which is under independent control of Indian government. It is also known as the Navigation Indian Constellation (NAVIC) providing the navigation services. The Indian NaVIC satellites are placed at either geostationary or geosynchronous orbits (36,000 km), to have a larger signal footprint and requirement of lower number of satellites to map the region. The satellites launched under the NavIC are namely: - IRNSS-1A, IRNSS-1B, IRNSS-1C, IRNSS-1D, IRNSS-1E, IRNSS-1F, IRNSS-1G, IRNSS-1I and NVS-01. IRNSS-1H has failed during the launch. Three of the satellites in the constellation are placed in geostationary orbit. These GEOs are located at 34 East, 83 East and 132 East longitude positions. Two of the GSOs cross the equator at 55 East and two at 111 East with an inclination of about 29 degrees. Such an arrangement ensures that all seven satellites have continuous radio visibility with Indian control stations. The satellite payloads consist of atomic clocks and electronic equipment to generate the navigation signals. Fig. 3.5, depicts the space segment of IRNSS.

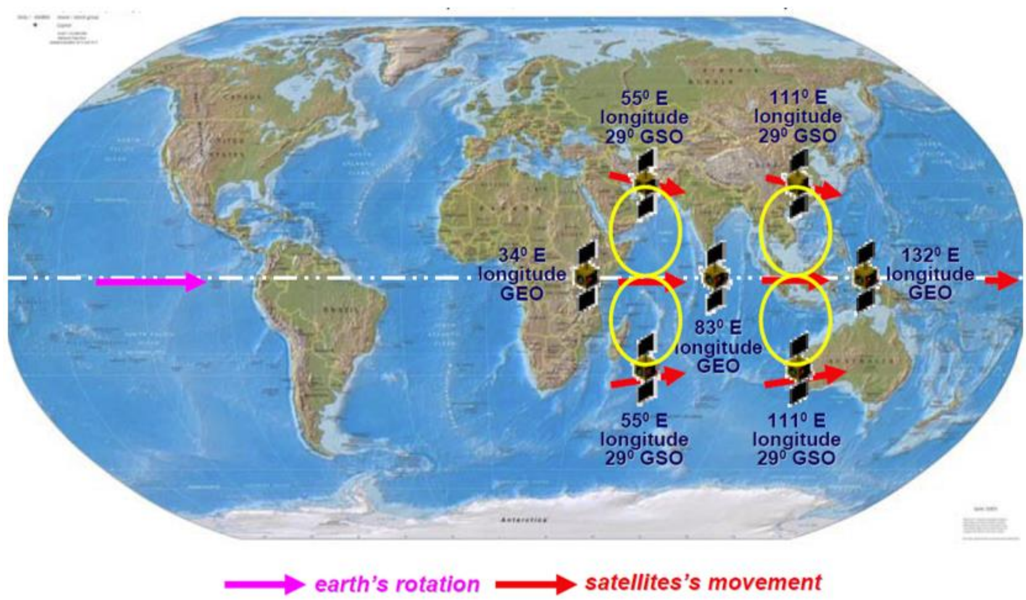


Fig. 3.5 IRNSS Space Segment

IRNSS/NavIC provides precise and accurate PNT services over the Indian region and up to 1500 kilometers beyond the Indian boundaries. Regional systems also provide standard positioning services (SPS) and precise positioning services (PPS) through Restricted services (RS) for authorized users which are encrypted [14]. Regional satellite-based navigation systems are extremely useful in RS&GIS applications [15], [16] particularly for georeferencing, triangulation and validations studies. In a study by Dey et al. (2020) on IRNSS signals, the diurnal variation of the position error indicated a maximum at afternoon hours, coinciding with the time of maximum total electron content (TEC) over the equatorial ionization anomaly (EIA) crest region [17]. Studies have shown that IRNSS can provide a positional accuracy of the order of 10m throughout Indian landmass and 20m in Indian Ocean region [18]. The IRNWT (IRNSS Network Time) is determined from a clock ensemble composed of the cesium and hydrogen maser atomic clocks at the INC (Indian Navigation Centre) ground stations. the satellite clock errors are expected to be well within 5-10ns which fulfills the timing requirements [19].

The IRNSS-1A, was the first of the IRNSS satellites developed by India, constituting the IRNSS space segment, and was designed with a mission life of 10 years (Table 4) and was launched successfully at 23:41 hrs. on 1st July 2013. It has a lift-off mass of 1,425 kg, and the satellite was launched into a sub–Geosynchronous Transfer Orbit with a 284 km perigee (nearest point to Earth) and 20,650 km apogee (farthest point from the Earth) with an inclination of 17.86 degree with respect to the equatorial plane. It is designed to provide accurate position information service to users in the country as well as the region extending up to 1,500 km from its boundary, which is its primary service area. Fig. 3.6 depicts the IRNSS Configuration / Architecture. The data from the satellite would help the country in a range of fields including disaster management, vehicle tracking, fleet management, precision farming, marine navigation, mapping, and geodetic data capture, precise timing, visual and voice navigation for drivers, integration with mobile phones and terrestrial, aerial and marine navigation, terrestrial navigation aid for hikers and travelers.

Table 3.4 IRNSS-1A specifications

Lift-off Mass	1425 kg
Physical Dimensions	1.58 metre x 1.50 metre x 1.50 metre
Orbit	Geosynchronous, at 55 deg East longitude with 29 deg inclination
Power	Two solar panels generating 1660 W, one lithium-ion battery of 90 Ampere-Hour capacity
Propulsion	440 Newton Liquid Apogee Motor, twelve 22 Newton Thrusters
Control System	Zero momentum system, orientation input from Sun & star Sensors and Gyroscopes; Reaction Wheels, Magnetic Torquers and 22 Newton thrusters as actuators
Mission Life	10 years
Launch date	Jul 01, 2013
Launch site	SDSC SHAR Centre, Sriharikota, India
Launch vehicle	PSLV - C22

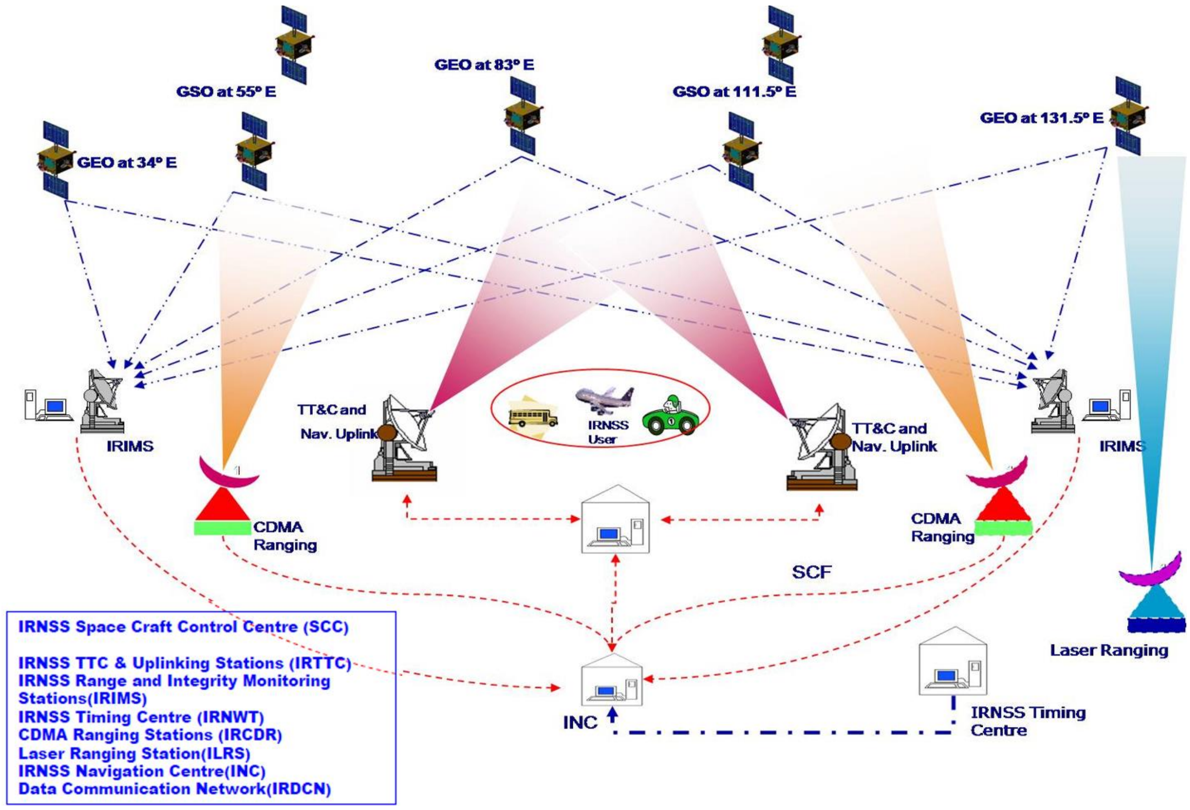


Fig. 3.6: Depicts the IRNSS Configuration / Architecture

IRNSS satellite carries navigation payload, which transmit navigation service signals to users, by operating in L5 (1176.45 MHz) and S band (2492.028 MHz) with a highly accurate Rubidium atomic clock and the ranging payload of a C-band transponder, which facilitates accurate determination of the range of the satellite. IRNSS is providing a position accuracy of better than 20 meters (upto 5m) in the primary service area. The navigational system provides two types of services -- Standard Positioning Service, which is provided to all the users and Restricted Service, which is an encrypted service provided only to the authorized users. An additional L1 band (Table 5) will now be available from IRNSS 1J onwards (https://www.isro.gov.in/update/25-jun-2021/navic-l1-adopts-indigenous-digital-codes-designed-isro-and-iisc). NVS-01 is the first of the second-generation satellites envisaged for the NavIC / IRNSS services was successfully launched on May 29, 2023. The new NVS series of satellites will sustain and augment the NavIC with enhanced features. This series incorporates L1 band signals additionally to widen the services including the interoperability with the other GNSS systems. An indigenous atomic clock is also flown in NVS-01.

Table 3.5 Specification of New NavIC Signals (IRNSS 1J onwards with additional L1 band)

	Centre Frequency	**Bandwidth**	**SPS Modulation**
L-Band (L1)	1575.41 MHz	24 MHz	S-BOC
L-Band (L5)	1176.45 MHz	24 MHz	BPSK
S-Band	2492.028 MHz	16.5 MHz	BPSK

India is also contributing to the International GNSS Station (IGS) services with the data availability through the IGS website. The Fig. 3.7, displays the locations of Indian IGS stations as part of the efforts helpful in global studies including the tectonic studies.

Fig. 3.7 Depicts the International GNSS Station (IGS) locations (https://network.igs.org/)

3.9.2 GPS Aided GEO Augmented Navigation (GAGAN)

GAGAN is a Satellite Based Augmentation System (SBAS) implemented jointly with Airport Authority of India (AAI). The main objectives of GAGAN are to provide Satellite-based Navigation services with accuracy and integrity required for civil aviation applications and to provide better Air Traffic Management over Indian Airspace. The system is interoperable with other international SBAS systems and provide seamless navigation across regional boundaries. The first GAGAN navigation payload was flown on GSAT-8, which was launched on May 21, 2011, and the second on GSAT-10 launched on Sep 29, 2012. GSAT-15 has also been added in GAGAN and it carries a Ku-band beacon as well to help in accurately pointing ground antennas towards the satellite.

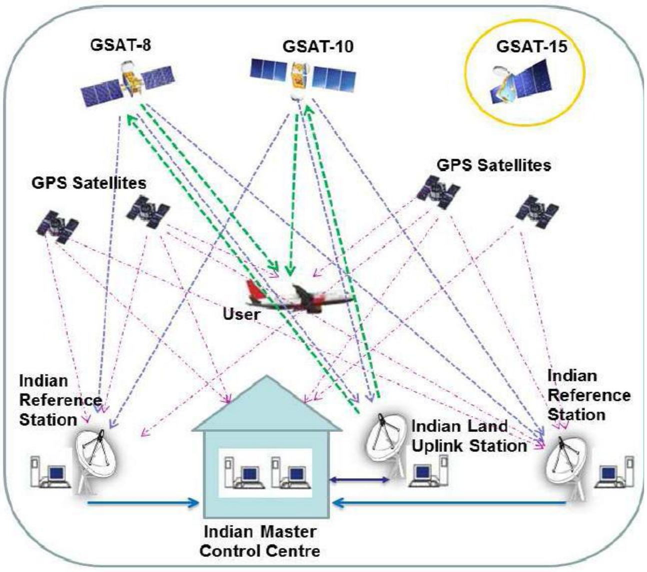


Fig. 3.8 GAGAN SBAS Infrastructure

Fig. 3.8 and 3.9, depicts the infrastructure and assistance mechanism of GAGAN respectively. Fig. 9 depicts various advantages also, which are obtained by an aircraft during its entire journey including take off, en-route operation and landing. It saves time, fuel and provide high capacity as well as safety. GAGAN will also be useful for neighbouring countries too [20].

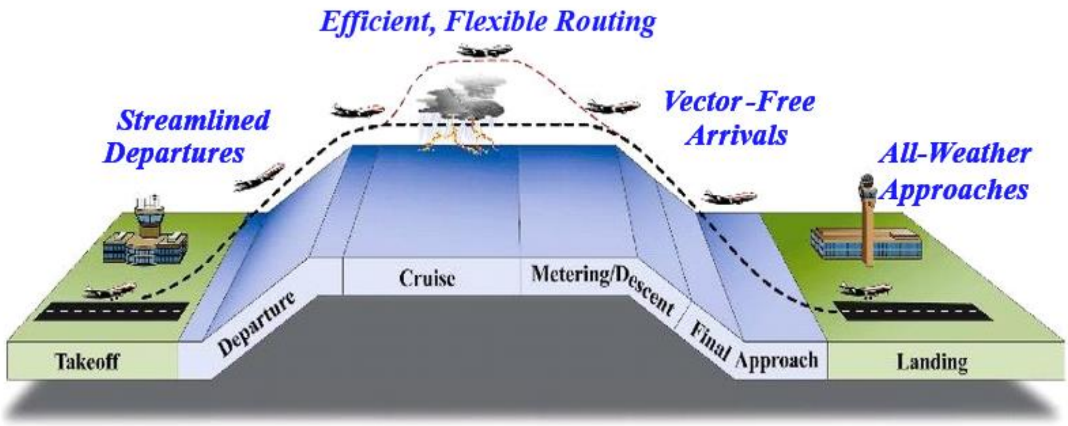


Fig. 3.9 GAGAN assistance in various stages of flight

3.10 Mobile Mapping

Mobile Mapping is the combination of geographic information system (GIS) software, global positioning systems (GPS), and mobile computing devices. Mobile Mapping fundamentally changes the way information is collected, used in the field, and shared with the rest of an organization. Mobile Mapping allows you to visualize information in a digital map, collect information where you observe it, and interact directly with the world around you, while improving productivity and data accuracy. Until recently, gathering and using information in the field was a paper-based process with multiple points of data entry without access to real-time information or the ability to accurately communicate field observations back to the office. In a server-based database system, various components collaborate to enable efficient data storage, retrieval, and management. The server hosts the database software and handles client requests, while the database management system (DBMS) provides an interface for interacting with the database. Data is stored in physical data files on storage devices, and indexes are created to speed up data retrieval. Caching stores frequently accessed data in fast memory, enhancing performance. The query optimizer analyzes queries to determine the best execution plan, and security measures ensure data protection. Backup and recovery mechanisms safeguard against data loss, while logging and transaction management maintain data consistency. These components collectively create a robust and secure environment for effective database operations. The recent developments in mobile mapping technologies have benefited many field-based information gathering, user tasks by increasing the efficiency and accuracy with which field workers collect information. Mobile mapping greatly improves the field processes which include Asset inventory, Asset maintenance, Inspections and Incident reporting using Personal digital assistant (PDA). PDA is a handheld computer, also known as a palmtop computer. PDA has a touch screen for entering data, a memory card slot for data storage and at least one of the following for connectivity: IrDA (Infrared Data Association), Bluetooth and/or Wi-Fi.

3.10.1 Architecture of Mobile GIS

The architecture of mobile GIS is very similar to that of Internet-based GIS, using client-server architecture. It has three major components: the client, the server, and the network services. Client-server applications usually implement what is referred as Three-Tiered Architecture. This architecture divides the application into a presentation tier, a business logic tier and a data management tier. Each tier can be replaced or updated without affecting the others. The presentation tier consists of client-side components, which are used to send requests to the server and to view the results (maps and data). The business tier is the core of any solution and consists of the server-side components including the Web server and application server. The data management tier is responsible for the management of both spatial and attributes data in the application. In some cases, one server is used for both the business and data management tier. In other cases, each tier can be on a separate server.

3.11 Land Surveying & Geodesy

Survey is an age-old science developed with the evolution of human beings to meet their requirements of finding a location, as per the development-taking place in their habitation as well as exploration. The location can be defined with respect to any reference coordinate system or datum. Surveying [21], land deformation mapping [22] and cadastral mapping [23], [24] are some of the successful applications which use latest tools such as android devices having GNSS, mapping software and many more. Traditional techniques of land surveying have been using devises like chain, tape, Plane Table, Levelling equipment, Compass, Theodolites, Tacheometers, EDMs (Electronic Distance Measurements) and Total Station. The traditional techniques required a clear line of sight between the two consecutive points surveyed, however the GNSS do not have this requirement as they are getting signals directly from the satellites, which can be processed, independently for two locations across baselines in either real time (RT) or post-processed mode. Extensive countrywide applications have been carried out in India covering various states comprising urban as well as rural parts for land management. These applications take advantage of all the available technologies such as RS&GIS, LiDAR, GNSS and allied technologies as per specific requirements. Survey of India, Town and Country Planning Organisation, and National Remote Sensing Centre are some of the most active contributors to this activity under the Government of India (GoI).

Geodesy is the science of accurately measuring and understanding three major fundamental properties of the Earth namely, its geometric shape, its orientation in space, and its gravity field along with the temporal changes in them. By using GPS, geodesists can monitor the movement of any site using the traditional or GNSS based survey methods. The World Geodetic System 1984 (WGS84) is the most commonly used datum currently which features coordinates that change with time considering the tectonic movements and other Earth dynamics. It also represents the best fit curve for the Earth defining its major axis and minor axis. WGS84 is defined by the National Geospatial Intelligence Agency (NGA) while keeping it consistent with the International Terrestrial Reference Frame (ITRF). ITRF is maintained by the International Earth Rotation and Reference Systems Service (IERS).

Survey of India is establishing and enabling the Continuously Operating Reference Stations (CORS) network for its users. The data is made available to its various users such as government agencies, researchers, and academic institutions through its website: https://cors.surveyofindia.gov.in/. The CORS network developed by SOI is going to aid in various mapping and monitoring activities in India. CORS stations are established and maintained by ISRO also through its institutions like IIRS and NRSC. The Fig. 3.10 shows the CORS established at Dehradun.

Fig. 3.10 CORS Stations established at IIRS Campus showing NetR9 receiver at the top of tower with an antenna Radome. Housing for other instrumentation and accessories is visible at the bottom

NRSC has Aerial Services and Digital Mapping (ASDM) facility, which has two operational aircrafts and generates large-scale topographic maps and very high-resolution Digital Terrain Models (DTM) for highly flood prone river reaches in India and for 2D/3D mapping in urban areas for various applications including infrastructure planning. The details of various operational projects can be seen at: https://www.nrsc.gov.in/EOP_Aerial_OperationalProjects/. These include various maps generated for TCPO and state departments, including maps for important engineering works such as Katra-Qazigund Railway track for Ircon International Limited (IRCON), Ministry of Railways. Kinematic GPS (KGPS) Survey along with DGPS survey was used to triangulate and mapping along Katra-Qazigund Railway track, corridor data. NRSC has carried out extensive pilot studies on mapping using various scales and methods for Nizamabad District. Digital Orthoimages were generated for Cadastral mapping project covering entire Nizamabad district covering 6300 sq. km. (rural) & 300 sq. km. (urban) [25]. The GNSS instruments are used in large number of projects and studies at Indian Institute of Remote Sensing (IIRS). For example, it was used for survey of large area extending from Dehradun region to Chandigarh region. The GNSS control points were used for triangulation of Cartosat-1 data, followed by Digital elevation model (DEM), and orthoimages generation. These datasets were further used for geological and watershed related studies. The datasets were used for assessment of openly accessible DEMs and development of DEM fusion techniques obtaining a copyright with many publications [7], [26]–[28]. THE GNSS datasets are also used for tectonic studies and estimation of Total Electron Content (TEC) [29]–[31]. Additionally, the Department of Land Resources (DoLR) has a Digital India Land Records Modernization Programme (DILRMP) to optimally plan sustainable improvement in productivity and livelihood / income potential of land, which requires mapping for its Land resources (https://dolr.gov.in/).

Currently, in this era of high resolution and very high-resolution datasets, an accurate Earth geoid model representing the equipotential gravitational surface is a prerequisite for applications in cartography, photogrammetry, geophysics, and oceanography. The most popular earth gravity models used in the field of remote sensing are the Earth Gravitational Model 1996 (EGM96), and Earth Gravitational Model 2008 (EGM 2008), due to their high utilization in open-source digital elevation models and other photogrammetric products. Satellite gravity missions aided significantly in the past two decades for development of several high-degree geopotential models using satellite tracking data. These missions included the Gravity Recovery and Climate Experiment (GRACE) and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE). The EGM96 was jointly developed by the Goddard Space Flight Center (GSFC), NASA; National Imagery and Mapping Agency (NIMA), and Ohio State University (OSU). EGM96 computations included information from all available surface gravity, ocean altimeter and satellite-based observation datasets. Geoid Heights (N) can be calculated using services such as, GeographicLib online service with GeiodEval software utility and conversion of elevations can be done using equation 1 between the GPS/GNSS heights and the EGM or Mean Sea Level (MSL) heights.

$$H_{EGM} = h_{GPS} - N \qquad \textbf{(1)}$$

where, N is the Geoid Height, h_{GPS} is the GPS elevation at the GCP location and H_{EGM} height is the elevation in the respective geoid models (EGM84, EGM96 and EGM2008) [32]. The selection for the version of EGM can be done in the utilities available online or in the software.

3.11.1 Methodology for GNSS Survey and Photogrammetric Mapping for Land Surveying

The methodology for GPS / GNSS survey from planning to quality assessment is described in the flowchart shown in Fig. 3.11. It is an essential part to control the final accuracy achieved in the process of satellite triangulation (Fig. 3.12), which further controls the photogrammetric product generation cycle.

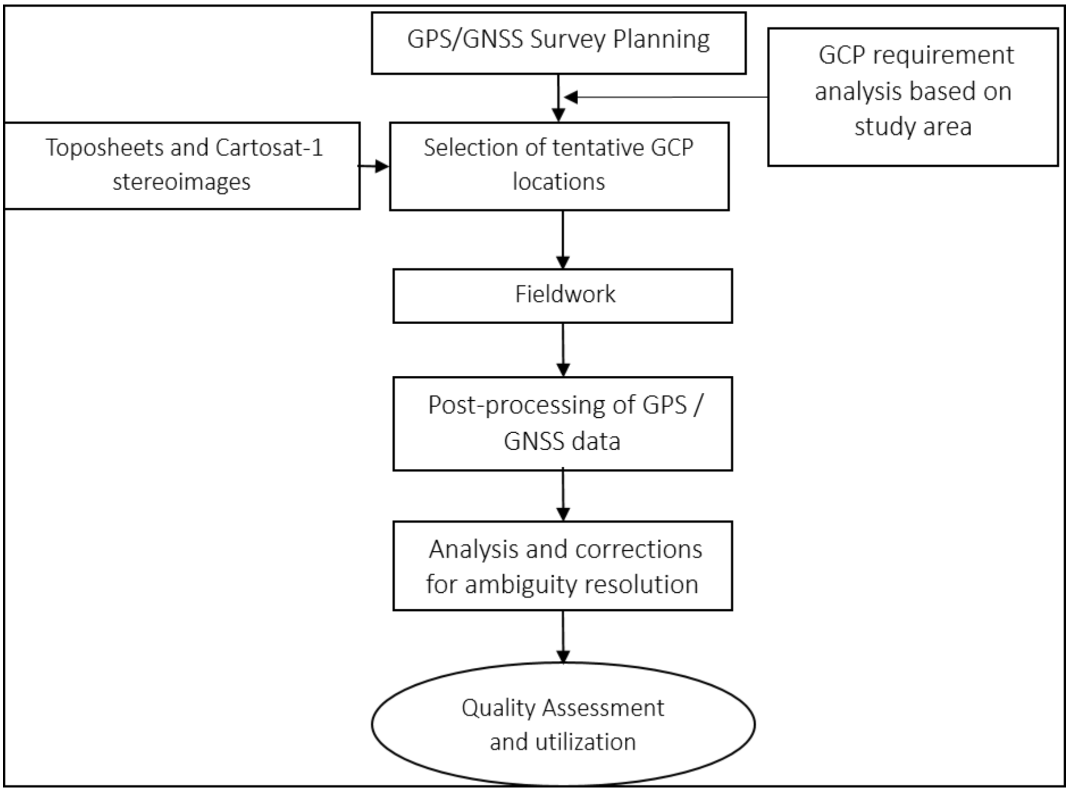


Fig. 3.11 Methodology for Differential GPS / GNSS survey

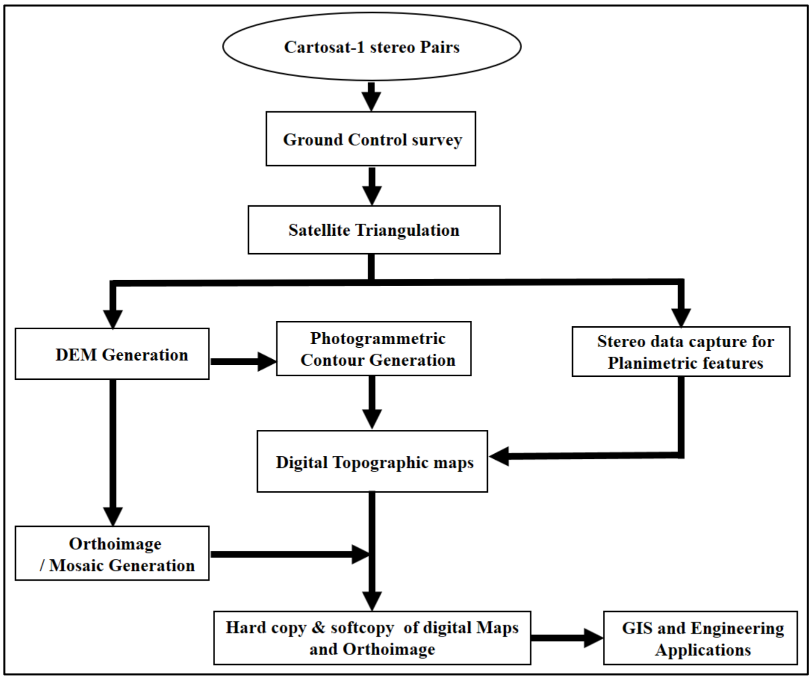
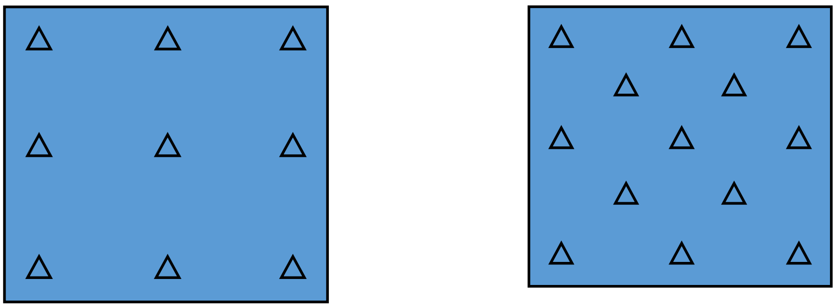


Fig. 3.12 Methodology for Photogrammetric procedure

3.11.2 GPS/GNSS Survey Planning and processing methods

The GNSS Survey Planning first considers the peripheral control and control in the center for generating a stable stereo model. The ground control surveys were conducted in static mode for the collection of GCPs. The location of GCPs is selected first at the von grubber locations and then more number of points are selected in the image to provide a nearly uniform distribution of GCPs (Fig. 13) in the Cartosat-1 stereo pairs subjected to local constraints and accessibility at various experimental sites namely, Jaipur, Delhi, Dehradun, Chandigarh and Kendrapara region (Fig. 3.14). This distribution provides the maximum model space for mapping. The GCPs should be sharply visible in both the images constituting the stereopairs. The duration of observation depends primarily on the baseline lengths to fulfil the criteria of signals received by the basestation and rover from the minimum common four number of satellites. This condition is nowadays met very easily in short duration surveys because of the large number of GPS/GNSS satellites. Secondly, the receivers at rover locations should operate for a time sufficient for receiving the complete almanac data [28].



a) *(b)*

Fig. 3.13 Depicts ideally planned scheme for distribution of GCPs for conducting GNSS survey (a) plan indicates von-Grubber location and (b) plan represents further densification)

The base station or known location is mostly not available from any previously conducted surveys, and thus these are computed by the processing of the base station GPS / GNSS data, with respect to the IGS stations or by independent single point positioning (SPP) at the experimental sites. Once, the coordinates of the base station are computed, the rover station datasets are processed with respect to the base station in DGPS / DGNSS processing mode using Leica Ski-pro or Trimble business center (TBC) software. The frequent cycle slip durations and high DOP value duration of GPS / GNSS data, are to be excluded during the post-processing. Both Leica and Trimble GNSS data processing software provide a very user-friendly graphical user interface (GUI) for identification, selection, and exclusion of such datasets for specific durations. This exclusion is especially executed for the GCPs with unresolved ambiguities and has been done in a step-by-step iterative process by the selection of datasets identified by satellite vehicle (SV) number observing the impact on the processing. The root mean square error (RMSE) attained for the satellite triangulation is better than a pixel resulting in the photogrammetric generation of significantly more accurate digital elevation models (DEM) as compared to the DEMs based on rational polynomial coefficients (RPC) alone and further improved orthoimages for the study sites using Cartosat-1 stereo pairs (Fig. 3.14). Another method for more accurate computations of coordinates is by using the scientific software for GNSS data processing, such as BERNESE from University of Berne, Switzerland; GAMIT from MIT, USA; GIPSY from Jet Propulsion Laboratory, USA; DIPOP from University of Brunswick, Canada; and GEONAP from University of Hannover, Germany. Scientific software allow the processing by consideration of various parameters related to Earth, tidal and atmospheric, which may be having a standard default values in the commercial software as per various standard models.

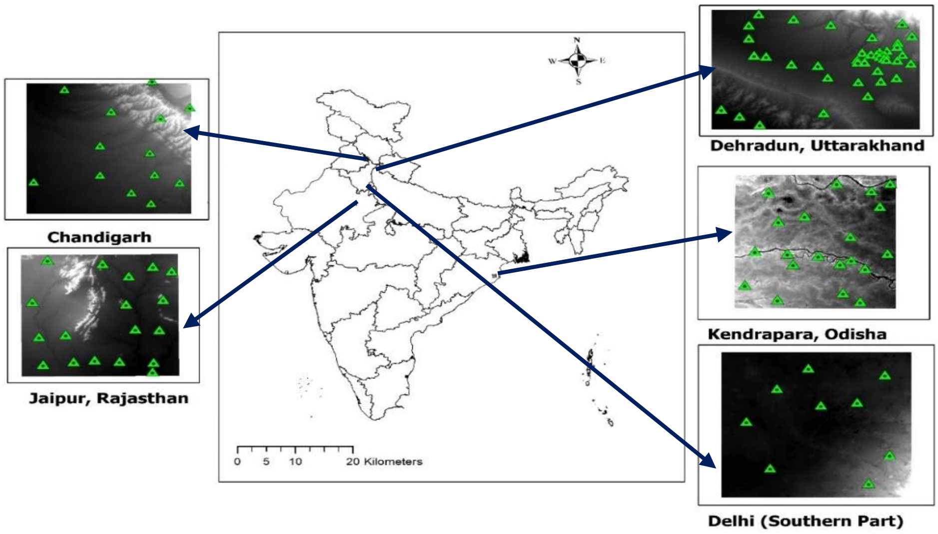


Fig. 3.14 Location map depicting DEMs of experimental sites with overlaid GCPs collected using Differential GPS survey [28]

The DGPS / DGNSS survey usually takes a couple of days to a few weeks depending on the area of experimental sites, accessibility of GCP locations, baseline lengths, and the number of GCPs to be collected through survey. When the surveys are done using two geodetic receivers the coverage of GCP locations for observations can be planned more flexibly due to radial baselines only. However, when three or more geodetic receivers are used, the practice of occupying the last point (GCP) of the previous day, as the first GCP point for the starting new survey day is followed to maintain a triangular pattern of generating baselines. The observations with three or more GNSS receivers are always recommended for better mathematical solution and high geodetic accuracy. The observations were always taken for sufficient duration to get a good dataset with four minimum satellites between operating geodetic receivers, further assisting in error adjustments during the post-processing.

3.11.3 Basics of Cartography

Map-making is an inherent cognitive capability of human beings to fulfill their basic needs and desire to explore the Earth and beyond. This art usually referred to as Cartography, has moved a long way from markings on the trees and cave stones as well as directions through celestial bodies using heuristics to today's latest applications based on geodesy and web cartography running in real-time. The photogrammetric processing required for cartography purposes, topographic mapping, and photogrammetric product generation need high accuracy in both horizontal (planimetric) and vertical directions (Fig. 3.13).

Traditionally Robinson defined Cartography as, "The making and study of maps in all their aspects, cartography consists of a group of techniques fundamentally concerned with reducing the spatial characteristics of a large area--a portion or all of the earth, or another celestial body--and putting it in map form to make it observable" [33]. Dent [1985] describes maps as "graphic representations of the cultural and physical environment". The four ways of communication are prime to the cartographic concept namely, Literacy, Articulacy, Mathematics (Numeracy) and Graphicacy. Fig. 3.15 represent a simplistic process for preparation and delivery to a recipient.

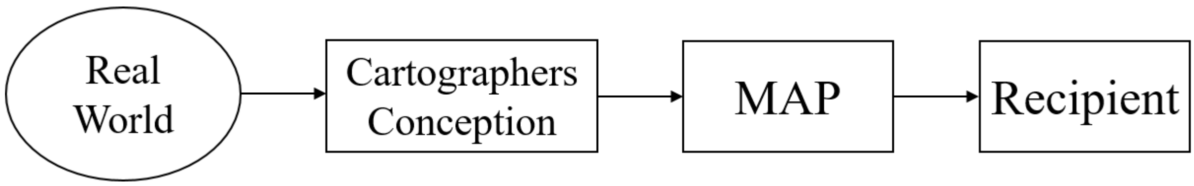


Fig. 3.15 Map making process

Cartographers must pay special attention to coordinate systems, map projections, and issues of scale and direction that are in most cases of relatively little concern to other graphic designers or artists. The Cartographers seek to make use of visual resources such as colour, shape and pattern to communicate information about spatial relationships. Proper usage will define memorability and interpretability of the map. Fig. 3.16 displays a map from the Bhuvan Portal hosted by NRSC, ISRO (https://bhuvan-app1.nrsc.gov.in/bhuvan2d/bhuvan/bhuvan2d.php). Cartographers employ symbols to represent location, direction, distance, movement, function, process, and correlation. These features of the real world are abstracted and symbolized on maps as points, lines, and areas. A tremendous amount of practice and skill is involved in choosing effective strategies for symbolization. The visual variables include: Position (x, y-coordinate), Form or shape, Colour or hue, Orientation, Texture (fineness or coarseness of elements in a pattern), Values (grey tone), and Size (Fig. 3.17). Currently, the software provides better design of maps and better map symbols in a shorter time. Wide ranges of easy-to-use cartographic tools are available to automatically or semi-automatically correct and symbolise the geo-spatial data.

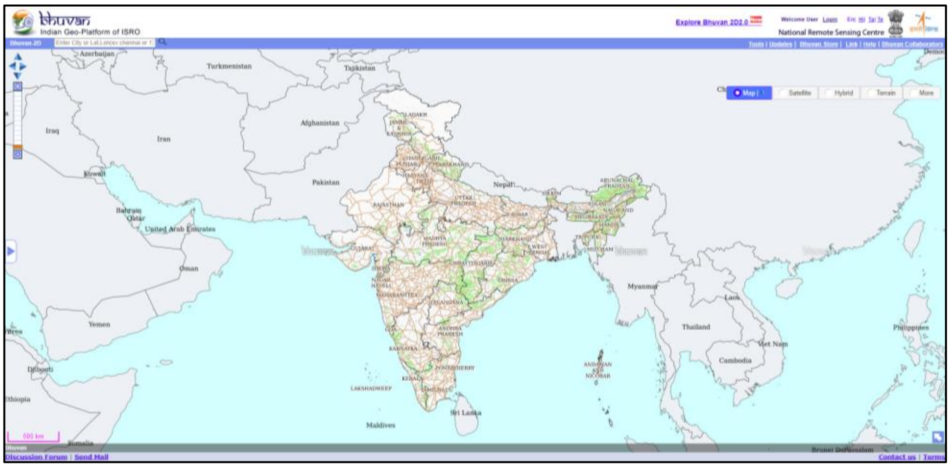


Fig. 3.16 Displays India and Surroundings on the Bhuvan Portal

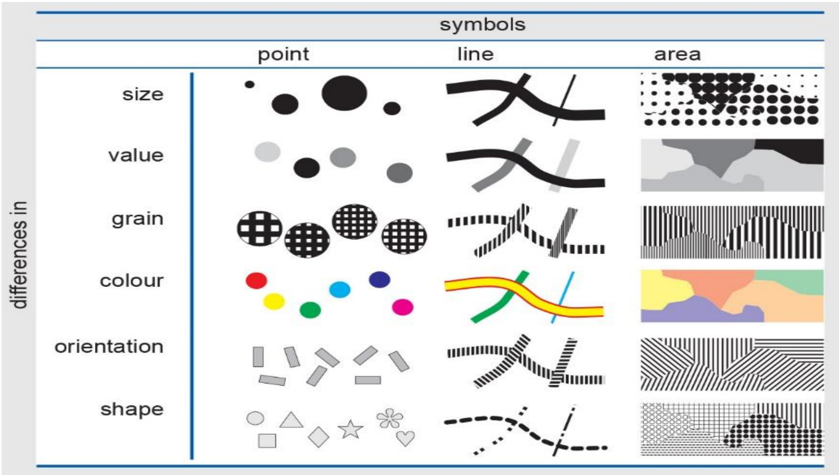


Fig. 3.18 Depicts the visual variables

French Cartographer Bertin has provided the guidelines for the use of various perception properties as shown in Fig. 3.18. The four properties of Association, Selection, Order and Quantitative perception are defined as follows:

- Association: A visual variable has associative perceptual properties, if spontaneously all symbols differentiated by that variable are seen as of equal importance.
- Selection: A visual variable has selective perceptual properties, if spontaneously all symbols differentiated by that variable can be arranged visually in distinct groups.
- Order: A visual variable has ordered perceptual properties, if spontaneously all symbols differentiated by that variable can be placed in an unambiguous order.
- Quantitative Perception: A visual variable has quantitative perceptual properties, if spontaneously a distinct quantity may be associated to each symbol differentiated by that variable.

	Position	Form	Orientation	Colour	Texture	Value	Size
Associative	+ (good)	+	+	+	0	-	-
Selective	- (bad)	-	0 (moderate)	++ (very good)	+	+	+
Ordered	-	-	-	-	0	++	+
Quantitative	-	-	-	-	-	-	++

Fig. 3.18 Perception properties of visual variable

3.12 Major challenges in the existing methods

The terrestrial and satellite-based navigation techniques have their own set of merits and challenges. The terrestrial based navigation techniques largely depend on factors such as the distribution of the towers in the ground network, their maintenance issues and line of sight. Whereas in the case of GNSS the major constraint is in the covered areas such as dense forest canopy regions, and tunnels, or underground regions. LAN or RFID can provide the indoor or covered locations in such cases [34]. A rugged and robust system can be developed using the combination of these techniques. ESA is developing a future satellite constellation that will orbit the moon and provide navigation and telecommunication services to lunar explorers providing the navigation services beyond the fifth lagrangian point between the Earth and the Moon [35]. The availability of smartphones have brought the GNSS and its services in the hand of common man, however many practical solutions to the different requirements of various applications is still a challenge. Newer applications need to be built around the smartphones especially the Android based devices, which support the GNSS packages including the IRNSS signals. BhuvanLite can also be integrated on android devices to work in an integrated way with NavIC.

3.13 Conclusions

The terrestrial and Satellite-based navigation techniques have matured individually or jointly for the use of civilian as well as authorized users with innumerable applications. The applications are available for various usages over land, ocean, air, and space up to the fifith (5^{th}) lagrangian point between the Earth and the Moon. Soon, the services will be available beyond the 5^{th} lagrangian point till the moon considering the plans for the establishment of the beacon at Moon. The internet and the internet-based mobile platforms have also revolutionized the application by making it possible for a common man to use the GNSS services and applications based on the GNSS services. Further, the results of the land-based experiments for providing ground control for satellite datasets confirmed that the DGPS / DGNSS method could achieve sub-pixel-level accuracy for the satellite triangulation of Cartosat-1 stereopairs as observed for all the five experimental study sites implying high utility in mapping. The new signals and the increased strength of signals further made it possible to use GNSS in an indoor environment also. The developments indicate further easing of life and processes by usage of GNSS and applications based on it in future. NavIC in context to India will also lead the developments for various guaranteed user applications under all conditions, since it is developed by ISRO, Government of India.

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Important Web URLs

https://www.isro.gov.in/IRNSS_Programme.html

https://www.gps.gov/

https://glonass-iac.ru/en/about_glonass/

http://en.beidou.gov.cn/SYSTEMS/System/

http://www.gps.gov/systems/augmentations/

https://www.gps.gov/technical/ps/2020-SPS-performance-standard.pdf

https://www.gsc-europa.eu/

https://www.gsc-europa.eu/galileo/services/galileo-high-accuracy-service-has

https://ggos.org/item/doris/

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http://www.csno-tarc.cn/

https://dolr.gov.in/

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https://www.aai.aero/en/content/what-gagan

https://www.isro.gov.in/SatelliteNavigationServices.html

Chapter 4

DIGITAL IMAGE PROCESSING

4.1 Introduction

In this chapter we will discuss about image processing fundamental concepts in remote sensing with an emphasis on sampling, filtering, enhancement, transformations, and classification methods. Let us start with some basic terminologies.

Image Processing is the process of performing operations on an image to extract useful information from it. Image Analysis is the process of transforming an image into measurement quantities. Image understanding is the task of transforming an image into some high-level description. The various steps in Image Processing involve;

(1) Acquiring an image: Images are typically generated by illuminating a scene and absorbing the energy reflected by the objects in that scene. The incoming energy lands on a sensor material responsive to that type of energy and this generates a voltage. Collections of sensors are arranged to capture images.

(2) Pre-processing: This process involves radiometric and geometric corrections to the data for fidelity.

(3) Enhance and restore images: This step involves colour, contrast, and edge enhancement of the image.

(4) Prepare for display or printing: This involved adjusting the image size, Colour mapping, gamma-correction, etc for visualization and display purposes.

(5) Extract information from images: This step involves segmentation/classification of the image. This is generally accomplished using machine learning techniques. Geophysical parameter retrieval is also a major step which helps to extract information from images.

(6) Facilitate image storage and transmission: This involves efficient storage of an image in a disk using techniques such as compression.

The above steps can be compared with the diagram described in Fig. 4.1 from a standard digital image processing textbook.

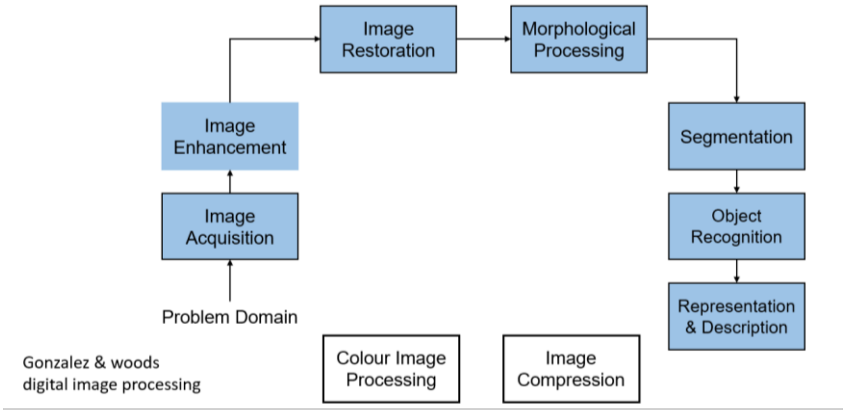

Fig. 4.1 Stages in Image Processing

4.2 Image Representation

Images are represented as numeric objects. It is a matrix with a value range dictated by analog to digital conversion. The value of each cell is represented by a function of position. The value of each cell is called Digital Number (DN). An image has a chosen origin of the coordinate system in 2D or more dimensions. Fig. 4.2 shows the image representation as a matrix.

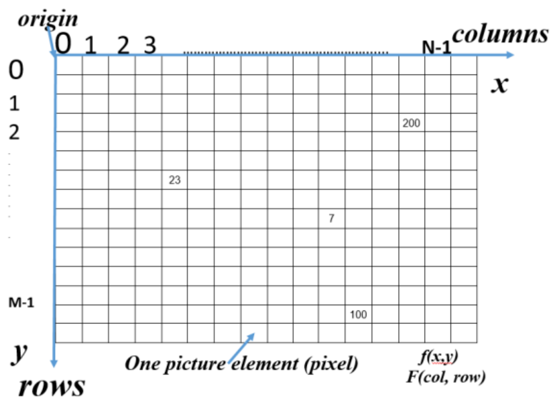

Fig. 4.2 Image Representation as Matrix

4.3 What is an Image in Remote Sensing?

A panchromatic (single wide optical band) image is a 2D light intensity function, f(x, y), where x and y are spatial coordinates and the value of f at (x, y) is proportional to the recorded brightness of the scene at that point. If we have a multispectral image, f(x, y, z) is a vector, each component of which indicates the recorded brightness of the scene at point (x, y) at the corresponding spectral band z.

Panchromatic images are called Gray level images, and more than one band (at least require 3 bands) is called as colour image and can be assessed for the true colour representation of world objects or its radiance properties. Fig. 4.3 shows an example of a typical colour image.

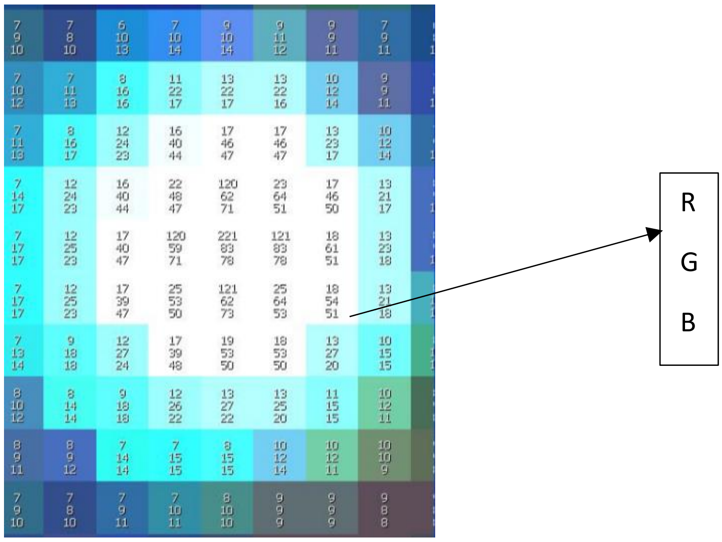

Fig. 4.3 A typical colour Image RGB; Bigger numbers represent brighter regions of the image

4.4 Image Sampling and Quantisation

A digital sensor can only measure a limited number of samples at a discrete set of energy levels. Quantization is the process of converting a continuous analog signal into a digital representation of this signal. This is generally accomplished by the process of quantization wherein the real-world analog signal is transformed into a set of Gray levels to provide a digital representation of data. Fig. 4.4 (a) shows the image sampling and quantisation process.

The quality of an image is largely subjective and very much application dependent. Basically, an image is of good quality if it is not noisy and it is not blurred, it has good contrast in the chosen resolution. The ability of our eye to detect fine spatial detail depends on the contrast of the target and background related to the resolution of the image.

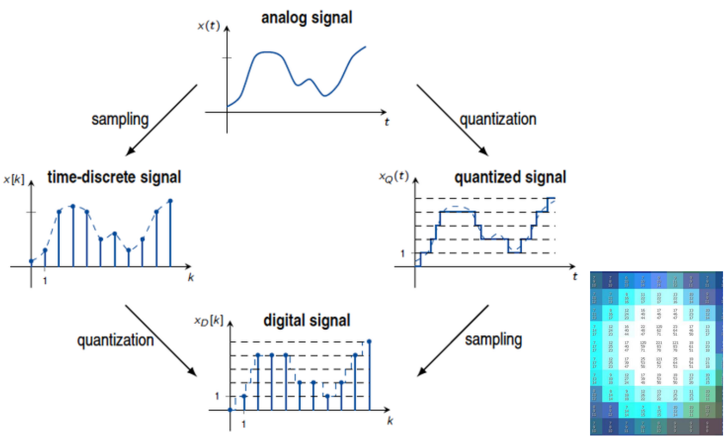

Fig. 4.4 (a) Image sampling and Quantisation

4.5 Image Histograms

Histogram of images provides a description of the image appearance globally. Histogram gives huge information about image attributes and hence histogram modeling through spatial domain techniques is of great importance in Digital Image Processing. In general, a histogram is the estimation of the probability distribution of a particular type of data. An image histogram offers a graphical representation of the tonal distribution of the Gray values in a digital image. By viewing the image's histogram, we can analyse the frequency of appearance of the different Gray levels contained in the image. A histogram divides the variable into bins, counts the data points in each bin, and shows the bins on the x-axis and the counts on the y-axis. Fig. 4.4(b) presents histograms of the B, G, and R bands of a multispectral image. Study the peak values, and shape of the envelope of the histogram using the Gaussian curve using the mean and standard deviation of the individual bands.

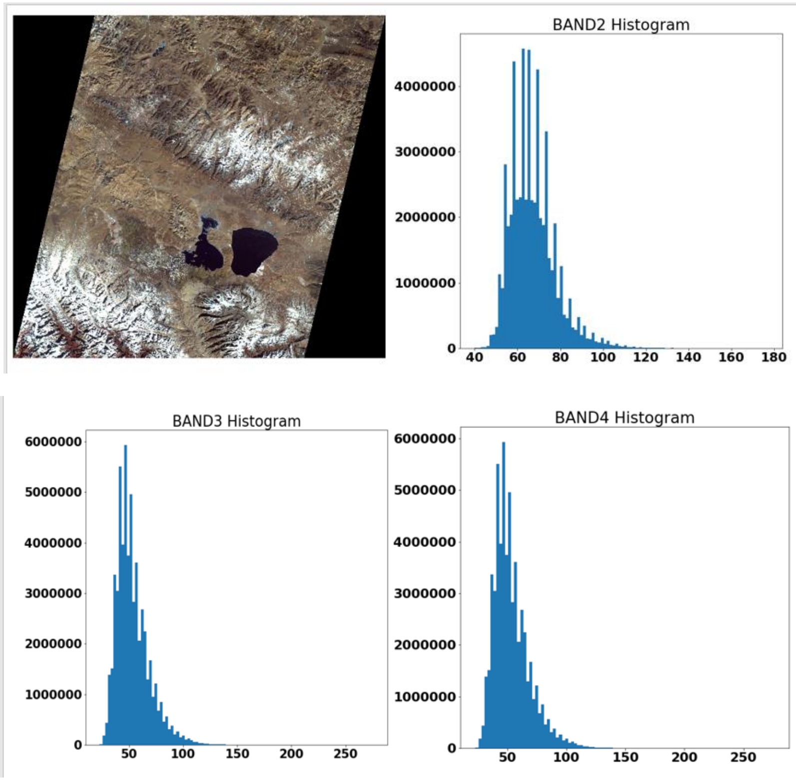

Fig. 4.4(b) Image Histograms

4.6 Image Enhancements

Below are the basic operations involved in image enhancements.

4.6.1 Thresholding

Thresholding transformations are particularly useful in situations where we want to isolate an object of interest from a background. The operation is generally accomplished by setting to 1 all pixels in an image whose Gray level values are greater than some threshold counts and setting to 0 all the pixels whose Gray level values are lesser than that threshold. Fig 4.5 shows an example of thresholding operation in an image.

4.6.2 Histogram manipulation

Original images would generally occupy a narrow dynamic range which can be enhanced for better viewing/interpretability. Histogram equalization is a method in image processing of contrast adjustment using the image's histogram. This method usually increases the global contrast of many images, especially when the image is represented by a narrow range of intensity values. Through this adjustment, the intensities can be better distributed on the histogram utilizing the full range of intensities evenly. This allows for areas of lower local contrast to gain a higher contrast. Histogram equalization accomplishes this by effectively spreading out the highly populated intensity values which are used to degrade the image contrast. Histogram equalization often produces unrealistic effects in photographs; however, it is very useful for scientific images like thermal, satellite, or x-ray images.

Adaptive histogram equalization (AHE) is a computer image processing technique used to improve contrast in images. It differs from ordinary histogram equalization in the respect that the adaptive method computes several histograms, each corresponding to a distinct section of the image, and uses them to redistribute the lightness values of the image. It is therefore suitable for improving the local contrast and enhancing the definitions of edges in each region of an image. However, AHE has a tendency to over-amplify noise in relatively homogeneous regions of an image. Fig 4.6 shows an example of Image histogram-based enhancement tasks. Original images could occupy a narrow dynamic range; we have to enhance them for better viewing. Histogram, its range, cumulative histogram, desired range, and a mapping function are used in enhancing the images.

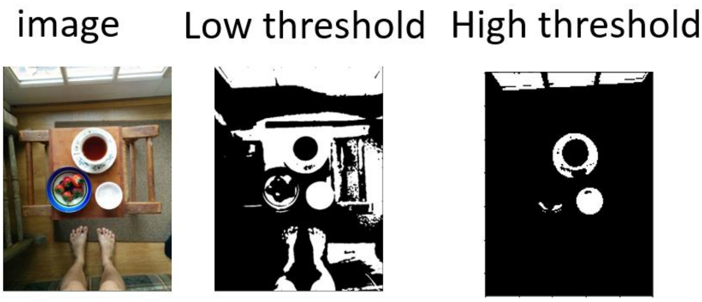

Fig. 4 5 Thresholding images for segmentation

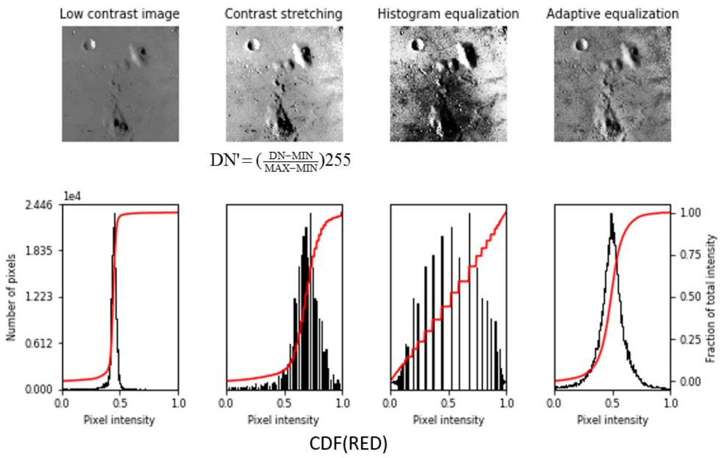

Fig. 4.6 Image histogram-based enhancement

4.7 Image Correlation and Convolution

Let us introduce two more operations which are most important in any practical image processing enhancement task.

Correlation The correlation of two continuous functions f(x) and g(x), denoted by f(x) o g(x), is defined (in 1-dimension) by the relation:

$$f(x) \circ g(x) = \int_{-\infty}^{+\infty} f(\alpha) g(x+\alpha) d\alpha$$

where alpha is a dummy variable of integration.

Convolution The convolution of two continuous functions f(x) and g(x), denoted by f(x) * g(x), is defined (in 1-dimension) by the relation:

$$f(x) * g(x) = \int_{-\infty}^{+\infty} f(\alpha)g(x-\alpha)d\alpha$$

where alpha is a dummy variable of integration.

4.7.1 Image Manipulation

Images are manipulated to enhance their visual quality and also to upskill their further usage in machine vision tasks. Image restoration, denoising, and edge enhancement all change the radiometric counts of the image for increasing their usage. Image manipulation tasks are generally accomplished with spatial domain methods which directly operate on pixels' radiometric values or using frequency domain methods which operate on the frequency content of the image which is derived from the Fourier transform. Fourier transforms are useful in removing selective bands of noise in the images and can be applied to the whole image in a single operation.

Spatial domain image manipulation is generally accomplished using template (windowing) operations in which a square or a rectangular matrix containing some weight is scanned across the image, point-wise multiplication of image radiometric counts lying within the template window with weights are performed and results are noted and placed in the centre the position of the template window. Some examples of Template Operations include image correlation, convolution for spatial smoothing, spatial differentiation, and edge enhancements of the image. Fig. 4.7 shows the steps involved in a typical spatial domain image manipulation operation.

A very common example of an image manipulation task is image denoising. A median filter or more generally called a rank order filter is one such filtering technique. It replaces the image value with the local median. The filter is applied by sorting the values in the neighbourhood defined by the template, selecting the median value, and assigning this value to the pixel. Gaussian filter is another example of spatial domain filtering which used Gaussian weights in the template window. Fig. 4.8 shows the image denoising outputs on a noisy image obtained with Gaussian and median filters.

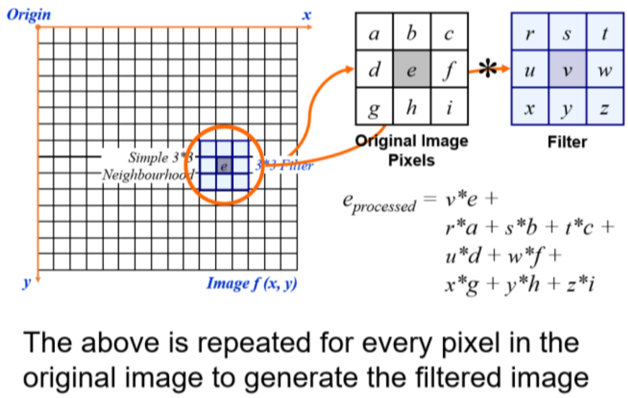

Fig. 4.7 Spatial Domain Image Manipulation Operation

Fig. 4.8 Image Denoising using Filters

Having introduced basic concepts of image processing, let us go to remote sensing image processing.

4.8 Quality of Images of Remote Sensing

The quality of the imagery reaching the end user from an Earth observation camera depends primarily on the imaging optics, the focal plane detector array and associated electronics, and the processing (applying corrections, map projection, etc.) of the raw data. The function of imaging optics is to transfer the radiance from the object space to the image plane. In doing so, the optical system should ensure geometric and radiometric fidelity of the image, that is, the ability to maintain the shape, orientation, relative dimension, and relative radiance values as in the object space. Signal to Noise Ratio (SNR) and Modular Transfer Function (MTF) or edge response are the quantities specified to indicate the quality of the remote sensing images.

4.8.1 Spatial Resolution

The spatial resolution of the sensor is the smallest unit of a digital image that can be assigned colour and intensity. It has dimensions that are not necessarily related to the sensor system parameters since the data can be sampled at different spacing than the detector footprint).

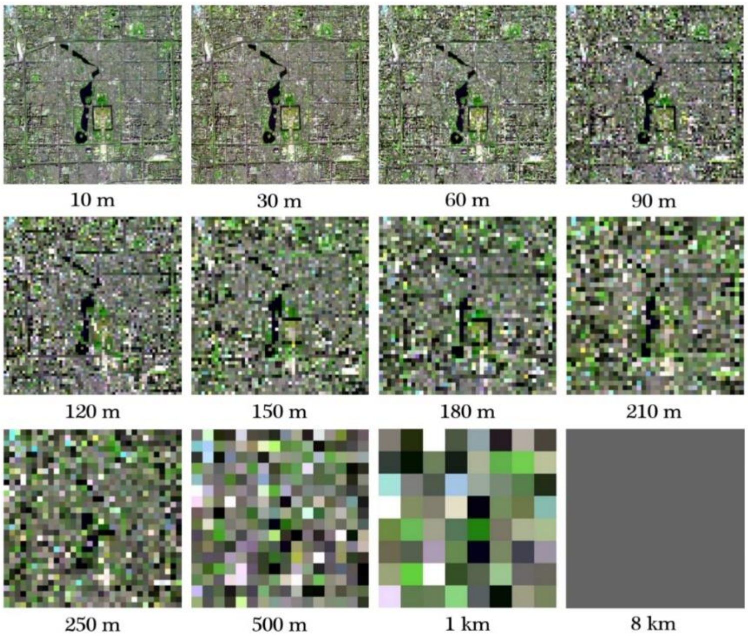

Fig. 4.9 Effects of Increasing Spatial Image Resolution

Thus, when one says 5.8 m is the spatial resolution of the IRS 1C/D PAN camera, it only means the projection of one CCD element on the ground through the imaging optics from the satellite orbit is 5.8 m, which is the "footprint" of the detector element on the ground depending on the instantaneous field of view (IFOV) of the camera. That is, 5.8 × 5.8 m is the smallest area from which the radiance is recorded as a separate unit. This footprint is referred to as the instantaneous geometric field of view (IGFOV) that is, the geometric size of the image projected by the detector on the ground through the optical system. It does not guarantee that all footprints of 5.8 m dimension are distinguishable in IRS1C/D PAN. However, it is also true that one may be able to detect a high-contrast object that is smaller than the IGFOV if its signal amplitude is large enough to significantly affect the Gray scale value of that pixel (for example, roads with widths much smaller than 80 m can be seen in Landsat MSS). This is because the instantaneous FOV alone does not adequately define the spatial response of an imaging system. Fig. 4.9 shows the effect of increasing spatial image resolution, the features which are not seen at 8 km spatial resolution become more and more clear as the resolution is increase to 10 m.

4.8.2 Spectral Resolution

In multispectral remote sensing, the variation in reflected/emitted spectral radiation is used to distinguish various features. In multispectral imaging cameras, we sample the reflected/emitted spectrum by making measurements at a few selected wavelengths.

There are three aspects to be considered in the spectral domain:

- location of the central wavelength,
- the bandwidth, and
- the total number of bands

The spectral resolution of the sensor defines the minimum difference between the wavelength that the sensor can distinguish. A sensor with a higher spectral resolution will be able to identify targets with very small spectral differences as compared to the sensor with a coarser spectral resolution. Fig. 4.10 shows the difference between a high and low spectral resolution response function.

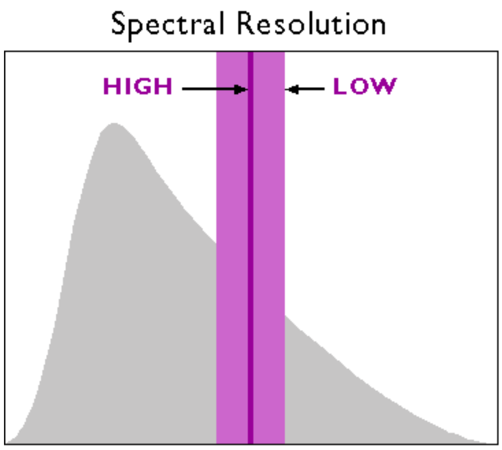

Fig. 4.10 EM Spectrum Spectral Resolution

4.8.3 Radiometric Resolution

Radiometric resolution is a measure of the capability of the sensor to differentiate the smallest change in the spectral reflectance/emittance between various targets.

The sensors respond only to those radiance values lying between the lower and upper radiance settings. The lower level is usually set to zero radiance. The upper level is usually referred to as the saturation radiance (SR) since for any radiance input beyond SR, the output of the sensor remains constant. Thus, the maximum radiance we can measure is SR. The SR setting depends on the mission objective. For example, for cloud/snow radiance measurement, the value is kept at or a little above 100% reflectance of solar irradiance, whereas for the ocean colour measurement ~10% reflectance is adequate, as ocean-leaving radiance itself is only a few percent of solar irradiance. In electro-optical sensors, the output is usually digitized, to produce discrete levels. The digitization is referred to as quantization and is expressed as "*n*" binary bits. Thus 7-bit digitization implies 27 or 128 discrete levels (0–127). Fig. 4.11 shows the Gray levels and radiometric resolution.

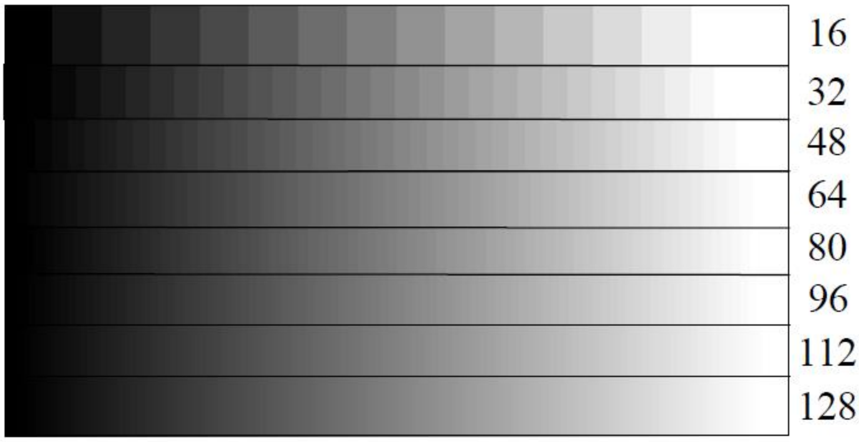

Fig. 4.11 Gray levels and Radiometric Resolution

4.8.4 Temporal Resolution

Temporal resolution refers to the temporal frequency with which a given scene can be imaged, usually expressed in days. The IRS-1C LISS-III camera has a temporal resolution of 24 days. That is any part of the globe (except around the pole) can be imaged every 24 days. This is also called repeativity. Repeativity depends on the orbit characteristics and the swath. The larger the swath, the higher will be the temporal resolution. Thus, SeaWiFS with a swath of about 3000 km has a temporal resolution of 1 day. Of course, the highest temporal resolution is possible by geosynchronous observation systems such as Meteosat, INSAT, and VHRR, with a temporal resolution ranging from a few minutes to 30 minutes, depending on the mode of operation. Higher temporal resolution enables monitoring of rapid changes, such as forest fires, floods, etc., and also improves the probability of obtaining cloud-free imagery over areas that experience frequent cloud cover.

Here, the repeativity of 24 days of IRS-1C means that the sub-satellite track repeats (except for slight orbit perturbations) every 24 days. Therefore, the images taken every 24 days have the same instrument view angle for any location, which is important. Fig. 4.12 shows how multiple satellites can be used to increase the temporal resolution of data.

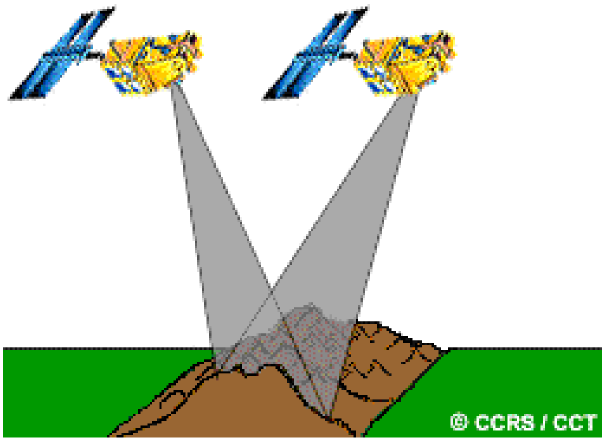

Fig. 4.12 Temporal Resolution

4.9 Instrument Parameters

We present below a set of instrument parameters that should be specified for every Earth observation camera. See Fig. 4.13.

4.9.1 Spatial domain

a. IFOV/IGFOV (Instantaneous Field of View/Instantaneous Geometric Field Of View)

b. FOV/Swath (Field of View/Swath)

c. MTF at IFOV

d. MTF at twice IFOV

4.9.2 Spectral domain

a. Central wavelength

b. Bandwidth (using the moment method)

c. Out-of-band contribution

4.9.3 Radiance domain

a. Saturation radiance (SR)

b. S/N (i) at 90% SR (ii) at 10% SR

c. Number of digitization bits

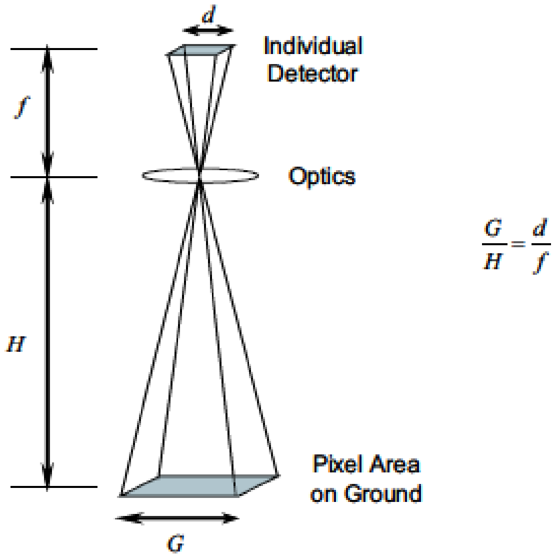

Fig. 4.13 Projection of pixel on Ground

4.10 Atmospheric interactions

The interactions of electromagnetic waves with planetary atmospheres are governed by the characteristics of the propagating wave (mainly its wavelength), the physical characteristics of the atmosphere (pressure, temperature, and suspended particulates), and its constituents. These interaction mechanisms are relatively complex to model because of the three-dimensional nature of the propagation medium and the multiplicity of the interaction mechanisms: scattering, absorption, emission, and refraction. It is required to model and remove atmospheric contributions in the brightness, radiance (or) reflectance depending upon the chosen application. Fig. 4.14 shows the diagram representing the interactions of sunlight and target signatures with the atmosphere.

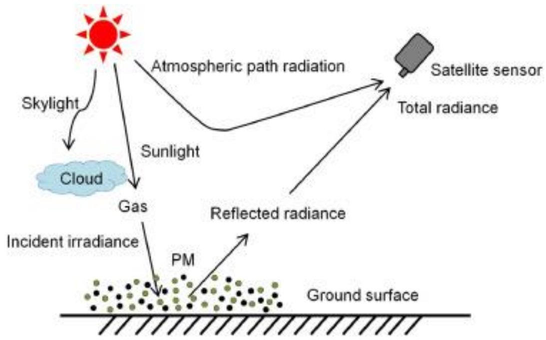

Fig. 4.14 Interaction with the atmosphere

4.11 Spectral Signature

The spectral signature is the most diagnostic tool in remotely identifying the composition of a surface unit. A trade-off generally exists between spectral resolution, spectral coverage, radiometric accuracy, and identification accuracy. In the case of hyperspectral imagers, the spectral signature corresponds to high-resolution (spectrally) radiometric measurements over a fairly broad region of the spectrum. In this case, surface units can be separated, classified, and identified based upon some unique characteristic in their reflectivity spectrum, such as a diagnostic absorption band or combination of absorption bands, a diagnostic reflectivity change at a certain wavelength, or a ratio of reflectivity in two separate spectral regions. Fig. 4.15 shows the spectral signatures of various targets observed on Earth.

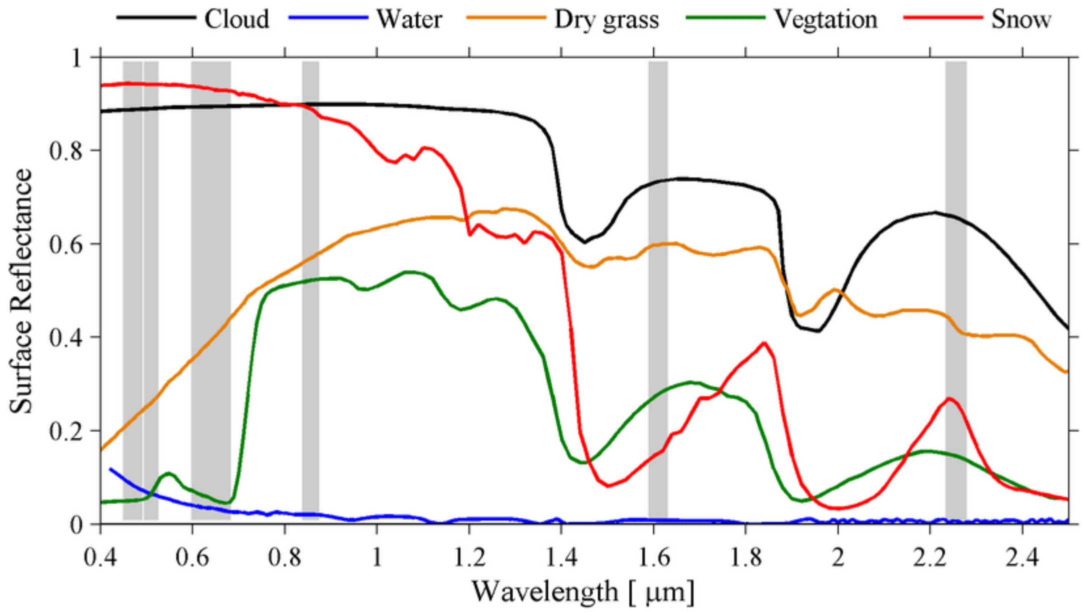

Fig. 4.15 Spectral Signatures of Various Targets

4.12 Different Levels of Corrections and data products

Level-0	reconstructed and unprocessed instrument data (raw) at full resolution with telemetry artifacts removed
Level-1	Input Level-0 data is time tagged or referenced, radiometric coefficients applied, geometric coefficients, and georeferencing parameters computed. Sub-level in this category, the data may be transformed with the geometric coefficients computed.
Level-2	Input is Level-1 data, from which the geophysical parameters retrieved
Level-3	Binned products from Level-2 outputs

4.13 Radiometric Corrections

Radiometric errors may be introduced during imaging (atmosphere, optics, detector …), digitization, or transmission. Radiometric correction restores an image to a condition of flawless imaging pipeline.

The raw data is corrected for both geometric and radiometric distortions. Radiometric distortions arising due to the following factors are corrected.

(i) Non-uniform response of the detectors.

(ii) Specific detector element failure.

(iii) Data losses during communication or archival/retrieval.

(iv) Blur in the image arises due to the combined effect of optics, detector, atmosphere turbulence & scattering, and attitude variation.

(v) Noise in the image occurs from various sources.

(vi) Narrow dynamic range in the image.

(vii) Image-to-image variations, wherever applicable.

A radiometric correction look-up table (LUT) is prepared for normalizing the responses of all detector elements using the ground calibration data. The same data can be used for the conversion of radiometrically corrected digital number (DN) values back to absolute units by the users of the data products. Correction for major frame synchronization losses (scan line losses) will be done using appropriate averaging of the neighbouring pixel values. If data losses occur in more than two consecutive scan lines, they will be replaced by a line consisting of all dark (minimum DN value) pixels. The failed detector pixel values (if any), will be replaced with the average of the adjacent pixels on the same scan line. Fig.4.16 shows the effect of radiometric correction of satellite images. The stripes seen in the data are corrected by the inversion process.

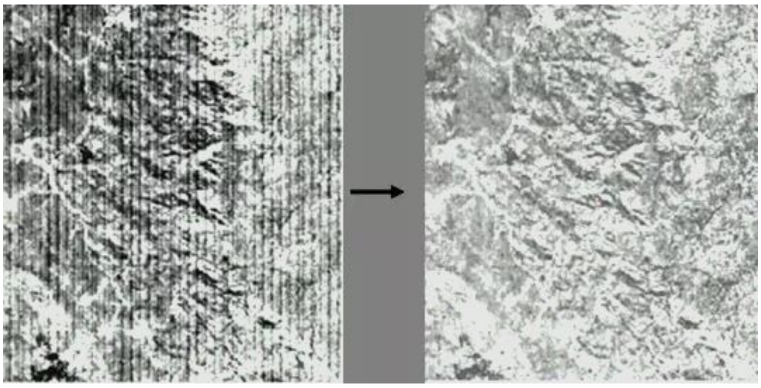

Fig. 4.16 Effect of Radiometric Correction on Satellite Images

4.14 Restoration

Blur in the image is corrected by estimating the point spread function (PSF) from laboratory calibration data or using in-orbit stellar data. It is also possible to estimate PSF directly from the image if a suitable target for extracting PSF is available in the imagery. After proper estimation of the PSF, image deconvolution is performed to get a sharp image. The image deconvolution process which is performed for getting a sharper image also increases noise in the image. Therefore, after deconvolution, generally, a noise filtering operation is performed to get a noise-free image without degrading image sharpness. Fig. 4.17 shows the effect on image quality after image restoration.

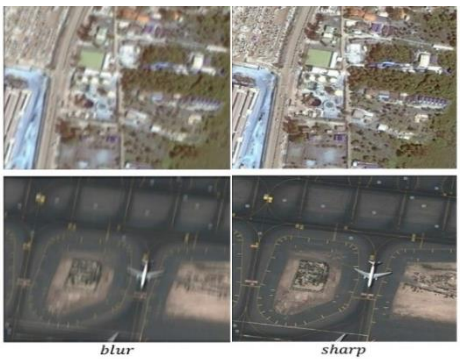

Fig. 4.17 Effect of Image Restoration

4.15 Geometric correction of remotely sensed satellite images

The raw data acquired from the satellite suffers degradation geometrically due to various factors related to orbital, platform, sensor, and scene. They can be listed as follows

- the rotation of the earth during image acquisition
- the curvature of the earth and terrain undulations
- panoramic effects related to the image geometry
- variations in the platform altitude, attitude, and velocity
- Datum and map projections

Let us understand the geometric correction of satellite images by the following points

- The objectives of geometric correction are to compensate for distortions introduced by a variety of factors so that the corrected imagery will have the geometric integrity of a planimetric map.
- Geometric correction of satellite based remote sensing data involves removing degradations introduced related to the platform (orbit and attitude states), sensor (dynamic focal plane geometry), and scene (curvature, topography, etc) due to the perspective imaging geometry.
- Geometric correction is needed to determine the correct ground position of a point visible in an image of the Earth.
- The geometrically corrected data exhibits the desired quality for image interpretation.
- Geometric correction comprises two essential steps that are spatial mapping and resampling. The spatial mapping can be achieved with different methods ranging from the true mathematical description of imaging geometry to simple polynomial mapping. This spatial mapping is conveniently called the geometric correction procedure.

4.15.1 Geometric Correction Approach

Let us call that corrected image space as output space. Then our interest is to establish a mapping between the input space (an image that is acquired) and the output space. The spatial mapping can be achieved with different methods ranging from the true mathematical description of imaging geometry to simple polynomial mapping. There are two categories of distortions to be modelled such as systematic and non-systematic or random distortions to establish the mapping between the input space and the output space. The systematic distortions are predictable and can be modelled with the true mathematical description of imaging. The non-systematic or random distortions are corrected statistically by comparing ground control points (GCP). GCPs are known to have precise coordinates in the output space, which is nothing but geographical coordinates.

The output space is translated, rotated, and scaled version of the input image for want of geometrical fidelity w.r.t the topographic map. The translation, rotation, and scaling are not the same for the whole image but varies pixel to pixel. Systematic corrections are so important to bring the required geometric fidelity within the image. To evolve a rigorous geometric correction procedure to remove systematic distortions, we need to understand the whole process of satellite imaging in detail involves the following processes.

- Satellite Imaging process

- Errors in the satellite data
- Corrections to minimize distortions
- Rectification procedure.

Geometric correction is achieved by solving a look point equation relating the imaging detector location in the focal plane and the imaged topographic point on the earth by establishing coordinate transformations starting from the detector coordinate system through camera, satellite, orbital, Earth Centred Inertial (ECI) and Earth Centred Earth Fixed (ECEF) all in 3D (see Fig. 4.18). Further, the coordinates are converted to geographic and map projected coordinate systems to comply with geospatial standards.

4.15.2 Geometric Correction Models

While modeling the imaging geometry, a simple pin hole geometry is sufficient to establish image to object coordinate transformations which involves solving the earlier mentioned look point equation which is essentially a problem of intersecting a line with an ellipsoid (here the geometry may be overlooked neglecting exact light ray modeling). Geometric correction involves modeling all systematic errors in the raw imagery. Pre-flight and in-flight calibration data are put to use for constructing the look point equation. A complete mapping between the corrected image coordinates and the radiometrically conditioned input image is established using a **rigorous geometric model or physical sensor model** that includes camera geometric parameters such as focal length, detector size, etc using a pinhole geometry.

A more elaborate imaging geometry model could be the collinearity equations (projective geometry) which relate, detector coordinates to object coordinates but use a projective transformation which can handle perspective geometry better than the pin hole geometry model due to the reference data used at every transformation step. Fig. 4.18, 4.19(a) & 4.19(b) shows the various geometric coordinate transform steps.

In either of the models, the geometric degradations related to platform, sensor, and scene related can be represented as a series of coordinate transformations in layman terms.

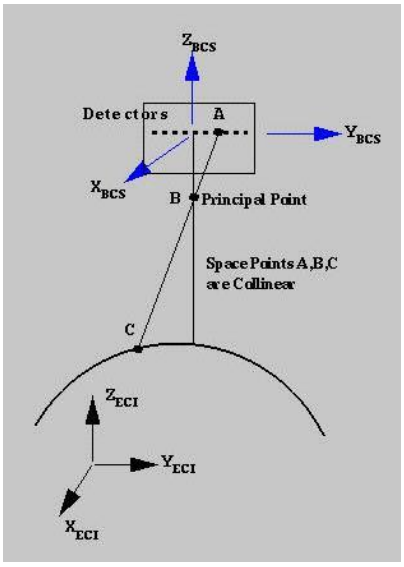

Fig. 4.18 Geometric coordinate transform

The physical and generalized sensor models are two widely used imaging geometry models in the photogrammetry and remote sensing. Utilizing the rational function model (RFM) to replace physical sensor models in photogrammetric mapping is becoming a standard way for economical and fast mapping from high resolution images. However, in terrain independent RFM estimation physical sensor model is employed to create a dense 3-D object point grid.

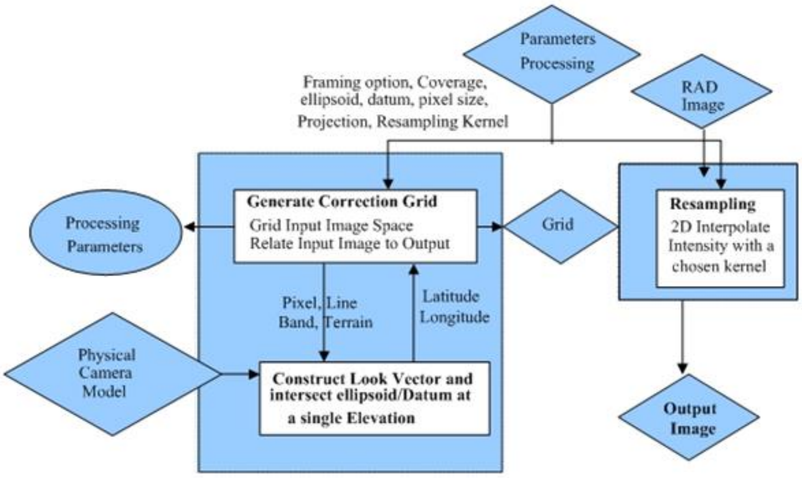

Fig. 4.19(a) Geometric Correction Process

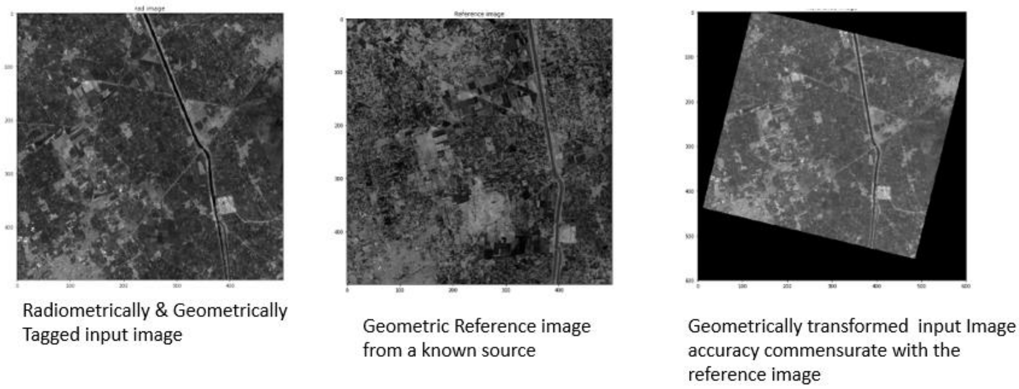

Fig. 4.19(b) Georeferencing using a reference image

4.16 Image to Image Registration

Remote sensing application scientists use the global and repetitive measurements provided by a wide variety of remote sensing systems. To derive useful information from the data it is usually required to use different data sets together: - from different spectral bands, taken at different times, taken from different types of sensors, and so forth. Image registration is also required for the mosaicking of images to cover a larger area in a single scene. These data sets in general are not necessarily geometrically aligned on a pixel-to-pixel basis. The set of data has to be *registered* before it can be subjected to digital data analysis. Thus, image registration is the first step before applying the digital analysis technique in all remote sensing applications that utilize multiple image inputs, including multi-sensor image fusion. Image registration is also used in many application domains other than remote sensing, such as medical image analysis, computer vision, astrophysics, military applications, etc. Feature collection and matching, spatial mapping between input and reference coordinates, and warping are the major steps in image registration.

Image registration is the process of overlaying two or more images that represent the same geographical area such that the corresponding pixels in all the sets of images that are registered belong to the same parcel on the ground. In this section we shall describe various steps involved in image registration i.e., aligning two images- the *reference image* and the one which is to be matched to the reference image called the *sensed image*.

We need to make choices, such that,

a) The **feature space** extracts the **information** in the images that will be used for **matching**,

b) The **search space** is the **class of transformations** that is capable of aligning the images,

c) The **search strategy** decides how to choose the next transformation from this space, to be tested in the search for the **optimal transformation**,

d) The **similarity metric** determines the **relative merit** for each test. Search continues according to the search strategy until a transformation is found whose similarity measure is satisfactory. Fig. 20 shows the satellite image before and after band registration.

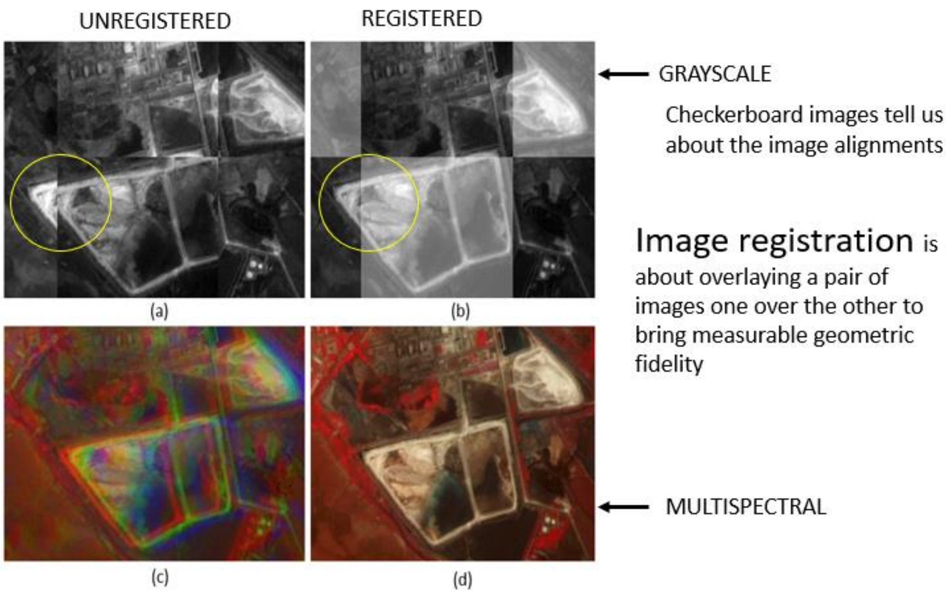

Fig. 4.20 Image Registration, (a) Image without registration, (b) Image with registration with a reference image (c)No Band to Band registration (d) Band to Band registered

4.17 Spatial Transformations

Once the feature matching has been carried out the next step is to establish a transformation function (also referred as mapping function) to align the sensed image with the reference image. The mapping functions are computed using the coordinates of control points in the two images to establish the geometric relation between the two images which is essentially a mathematical model which describes the allowable transformations. This is used to transform geometry of one image to that of the other to spatially align them. The transformation should not change the overall geometric relationships between points after the transformation i.e., triangle in the image should be mapped as similar triangle after transformation in a linear transform framework. A general linear (or) affine transformation is presented as

$$X = a_0 + a_1.x + a_2.\,y$$

$$Y = b_0 + b_1.x + b_2.\ y$$

Whereas a non-linear transformation (polynomial) which may not preserve rigidity

$$X = a_0 + a_1.x + a_2.\ Y + a_3.x.y + a_4.x^2 + a_5.y^2 + \ldots$$

$$Y = b_0 + b_1.x + b_2.\ Y + b_3.x.y + b_4.x^2 + b_5.y^2 + \ldots$$

The parameters (a_0, a_1, a_2, … b_0, b_1, b_2…) of the mapping functions (translation, scale, and rotation) are computed by means of the established feature correspondence of the *control points* acquired from the matching process. In general, the function should be flexible and general enough to handle all possible degradations which might appear in the sensed image. When cause of some of the misregistration is known (such as scale change due to height variation, scan non-linearity, etc.) pre-correction for such deviations can be done before generating the mapping function. When the distortions producing the miss match are fairly uniform global models are possible that use all CPs for calculating one set of the mapping function parameters valid for the entire image. However, when the distortions vary across the image then local mapping functions need to be generated treating the image as a composition of patches and the function parameters depend on the location in the image; the procedure is also known as rubber-sheeting or spline transformation.

4.18 Resampling

Image resampling is the process of geometrically transforming digital images in georeferencing and band to band registration or any spatial transform application. After the transformation, the corrected (transformed) image coordinates may not have a one-to-one relationship with the rows and columns of the original image. As the transformed image locations are not integral ones, the intensity value for this location has to be interpolated from neighbours of the input image location in the query. The number of neighbours decides the interpolator kernel size and functional polynomial form. A surface is fitted with the discrete values of neighbours at the queried location. Now that you have a continuous model of the image/signal, the intensity of the desired location can be estimated and posted to the corrected image location. Signal proceeding theory tells us that, only a Sinc kernel can reproduce the signal. More the span of the kernel better the modeling of the local signal. Three interpolation routines generally are used for resampling the image.

(i) Nearest neighbour:

- In this procedure a pixel is selected that is nearest to the estimated col/row of the reverse least squares:
- The advantage of this approach is that it retains the original image histogram (distribution).
- The disadvantage of this approach is that visually the resulting images can be "blocky".

(ii) Bilinear:

- This approach uses the four surrounding neighbours with equal weighting.
- Assumes that the pixel value lies on a planar surface.
- The disadvantages of this approach are that it modifies the original histogram and can give a blurred image.

(iii) Cubic:

- This approach uses the 16 nearest pixels to estimated col/row (unequal weighting).

- This approach is computationally the most intensive.
- Although there is considerable modification of the original histogram, this approach produces the best visual results.

Fig. 4.21 shows the various kernels and spatial transformation tasks**.**

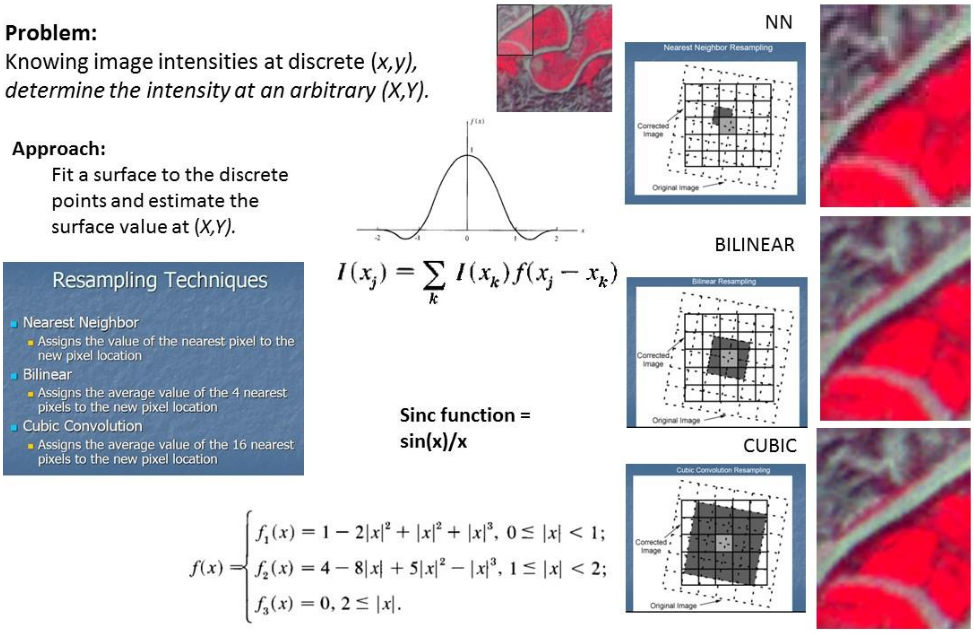

Fig. 4.21 Resampling Kernels

Band Ratioing

The process of dividing the pixel values in one image by the corresponding pixel values in a second image is known as ratioing. It is one of the most commonly used transformations applied to remotely-sensed images. There are two reasons why this is so. One is that certain aspects of the shape of spectral reflectance curves of different Earth surface cover types can be brought out by ratioing. The second is that undesirable effects on the recorded radiances, such as that resulting from variable illumination (and consequently changes in apparent upwelling radiance) caused by variations in topography can be reduced.

4.19 Principal Component Analysis (PCA) Image transform

Principal Component Analysis (PCA) is a popular dimensionality reduction technique used in Machine Learning applications. PCA condenses information from a large set of variables into fewer variables by applying some sort of transformation onto them. The transformation is applied in such a way that linearly correlated variables get transformed into uncorrelated variables. Correlation tells us that there is a redundancy of information and if this redundancy can be reduced, then information can be compressed. For example, if there are two variables in the variable set which are highly correlated, then, we are not gaining any extra information by retaining both the variables because one can be nearly expressed as the linear combination of the other. In such cases, PCA transfers the variance of the second variable onto the first variable by translation and rotation of original axes and projecting data onto new axes. The direction of projection is determined using eigenvalues and eigenvectors. So, the first few transformed features (termed as Principal Components) are rich in information, whereas the last features contain mostly noise with negligible information in them. This transferability allows us to retain the first few principal components, thus reducing the number of variables significantly with minimal loss of information. Fig. 4.22 shows an example of 7 band multispectral image. Fig. 4.23 shows the components derived after applying the principal component analysis technique. It can be clearly seen that although there are 7 bands in the original image, but most of the information is redundant and major information is present in the first 3-4 components only.

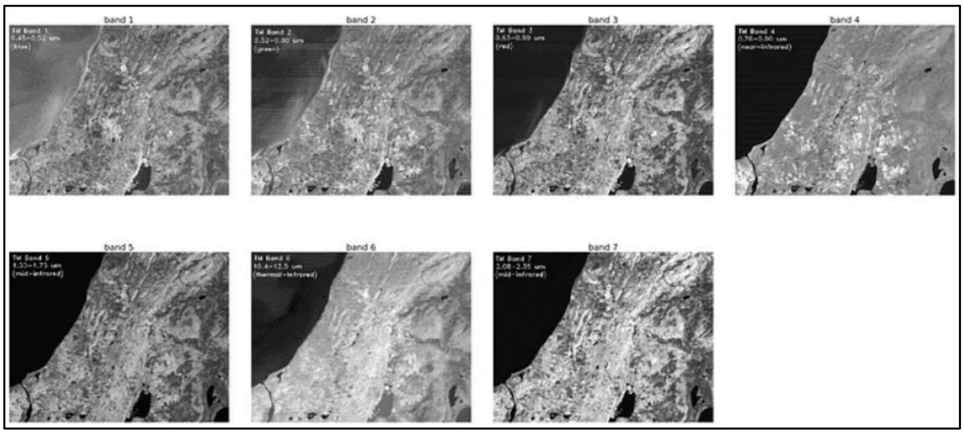

Fig. 4.22 Seven Bands of Multispectral Image

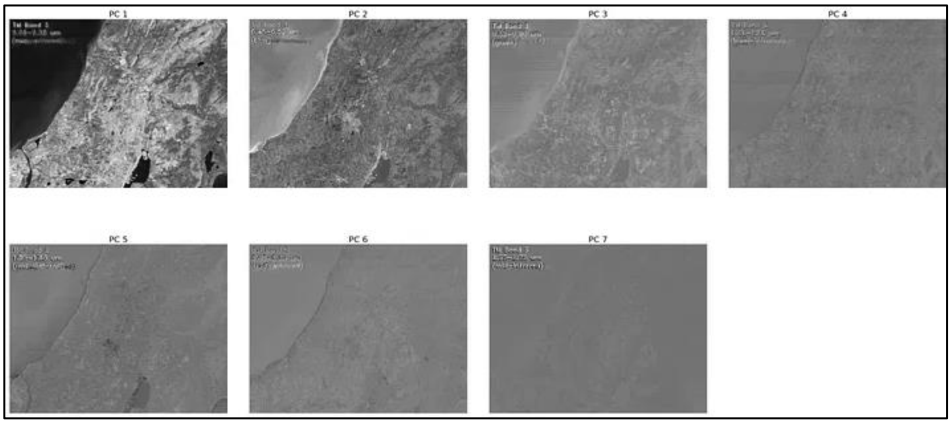

Fig. 4.23 Principal Components of Multispectral Image after PCA

4.20 Classification

The next step is to classify units based on a set of criteria. Classifications extend not only to individual images, but also to a number of images taken at different times of the same area or of different areas.

Classification of images involves using a set of rules to decide whether different pixels in an image have similar characteristics. These rules in effect divide the total data space into subsets separated by so-called decision boundaries. All pixels that fall within a volume surrounded by such decision boundaries are then labelled as belonging to a single class. The classification criteria range from the simplest, such as all areas with identical reflectivity in a certain spectral band being put into the same class with distinct statistics, to more sophisticated criteria, such as comparing the measured spectra over a large wavelength range. Some intermediate criteria include albedo (simple and composite), specific spectral absorption bands, spectral response slope in specific spectral regions, or the presence of specific spectral features.

Two major approaches are used in classifying images: supervised and unsupervised classifications. In the case of supervised classification, a user will specify so-called feature vectors or classes from training samples to be used in the comparison process. These vectors can be thought of as defining the centroids of the decision volumes that are separated by the decision boundaries.

These feature vectors can be extracted from the image to be classified or could come from a library of spectral signatures either measured in the laboratory or in the field. In the case of unsupervised classification, the computer is allowed to find the feature vectors without help from an image analyst. In the simplest form, known as the K-means algorithm, K feature vectors are typically selected at random from the data space. Machine learning-based classifiers are algorithms that automatically categorize or label data based on patterns and features. They are trained on labeled datasets and can predict the class or category of new, unseen data. Examples of such classifiers include Support Vector Machines (SVM), Naive Bayes, Decision Trees, Random Forests, Gradient Boosting, and Neural Networks. Each classifier has its strengths and suitability for different tasks. SVM aims to find an optimal hyperplane, Naive Bayes uses probabilistic principles, Decision Trees create hierarchical structures, Random Forests combine multiple trees, Gradient Boosting builds ensembles iteratively, and Neural Networks learn complex patterns. Selecting the right classifier depends on the specific problem and the characteristics of the dataset.

Once the feature vectors (classes) are identified, classification rules are used to assign pixels in the image to one of the feature vectors. Many different classification rules are used, ranging from the simple nearest-neighbour distance classifier, to neural network schemes, to sophisticated schemes that take into account the expected statistical distributions of the data. To apply these rules during the classification process, a so-called distance measure is typically defined. The nearest-neighbour scheme, for example, simply calculates the Euclidian distance between a pixel and each of the feature vectors as if each spectral measurement represented an orthogonal axis in the data space. In other cases, the distance definition includes some measure of the probability that a pixel may be similar to a particular feature vector. During the classification process, the distance between a pixel and each of the feature vectors is computed. The pixel is then labelled the same as the feature vector for which this distance is the smallest. If this smallest distance is larger than some threshold specified by the analyst, the pixel will not be classified. Fig. 4.24 shows an example of a Multispectral Image and its Classified Map.

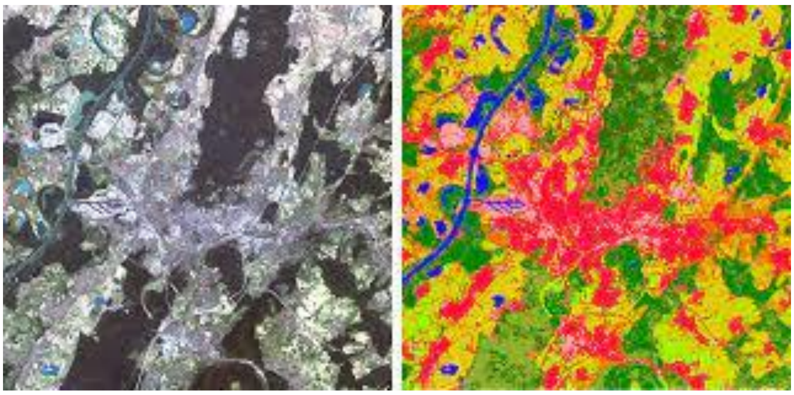

Fig. 4.24 Multispectral Image and its Classified Map

4.21 Classification Accuracy Assessment

The classification accuracy was obtained by analysing the confusion matrix. The surveyed vector was first converted to a raster of appropriate cell size with class code as attribute. An error matrix of the classified image against the wall-to-wall surveyed image was generated. From the error matrix, various measures of accuracy [such as producer's, user's, overall and mapping accuracies, and kappa coefficient (K^)] were generated for the sake of completeness and easy reference, their definitions with mathematical expression are given below:

	REFERENCE			Row Total	User's accuracy
Classified	X_{11}	X_{12}	X_{13}	$X_{1+} = x_{11}+x_{12}+x_{13}$	X_{11}/x_{1+}
	X_{21}	X_{22}	X_{23}	X_{2+}	X_{22}/ X_{2+}
	X_{31}	X_{32}	X_{33}	X_{3+}	X_{33}/X_{3+}
Column Total	$X_{+1} = x_{11}+x_{21}+x_{31}$	X_{+2}	X_{+3}	$N = X_{1+}+ X_{2+} + x_{3+} = X_{+1} + X_{+2} + X_{+3}$	
Producer's accuracy	X_{11}/X_{+1}	X_{22}/X_{+2}	X_{33}/X_{+3}		

Let Xij = number of pixels classified in class i but was actually in class j;

N = total number of pixels in the matrix;

xi+ = marginal total of row i,

x+i = marginal total of column i.

Producer's Accuracy: This is a measure of individual class accuracy which is obtained by dividing the number of correctly classified pixels by the total number of pixels in a class in reference (multiplied by 100 for conversion to percent, a usual practice). It conveys how much percent of the total class area was correctly classified. It can be expressed as

Producer's Accuracy of class i = Xii/X+i

= (1 – error of omission)

User's Accuracy: This is a measure of individual class accuracy which is obtained by dividing the number of correctly classified pixels by the total number of pixels classified in this class. It conveys how much percent of the class pixels was correctly classified. It can be expressed as

User's Accuracy of class i = X_{ii}/Xi_{+}

=(1 – error of commission)

Mapping Accuracy: This is a measure of individual class accuracy. It treats commission as well as omission as an error. It conveys how much percent of the class pixels was correctly mapped. It can be expressed as

Mapping Accuracy of class i $= x_{ii} / (X_{i+} + x_{+i} - X_{ii})$

$=(1 -$ error of commission $-$ error of omission$)$

Overall Accuracy: It is a measure of joint accuracy of all the classes taken together. It is obtained by dividing the total number of pixels correctly classified divided by the total number of pixels. It can be expressed as

Overall Accuracy $= \Sigma\ x_{ii}/N$

$=$ [1- abs (error of omission - error of commission)]

Kappa coefficient: It is a measure of joint accuracy of all the classes taken together. It is similar to overall accuracy after deducting the effects of chance agreement (Cohen, 1960). It can be expressed as

$$k\hat{} = \frac{\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} x_{i+} * x_{+i}}{N^2 - \sum_{i=1}^{r} x_{i+} * x_{+i}}$$

Where, k^ is the kappa coefficient in percent.

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Chapter 5

HYPERSPECTRAL REMOTE SENSING

5.1 Introduction

Hyperspectral remote sensing is a powerful and advanced technique used to acquire detailed and precise information about the Earth's surface and its characteristics. This form of remote sensing involves capturing data across numerous narrow and contiguous spectral bands, resulting in a hyperspectral image. The spectral bands are typically narrower than those in traditional remote sensing, allowing for enhanced discrimination and analysis of specific features and materials. Hyperspectral remote sensing enables the identification and characterization of objects and materials based on their unique spectral signatures, providing valuable insights into vegetation health, mineral exploration, water quality, urban mapping, and more. In this instruction, we will explore the principles, techniques, and applications of hyperspectral remote sensing, delving into the spectral range, data acquisition, preprocessing, analysis methods, and the interpretation of hyperspectral imagery. By understanding and applying hyperspectral remote sensing, researchers and professionals can unlock a wealth of detailed information about the Earth's surface, contributing to a wide range of scientific, environmental, and resource management endeavours.

“Hyperspectral imaging refers to a technique used to capture and analyze information from a wide range of electromagnetic wavelengths within the electromagnetic spectrum. It involves acquiring data from multiple contiguous spectral bands, typically covering a much larger number of bands compared to traditional imaging systems. Each band corresponds to a narrow spectral range, resulting in a highly detailed spectral profile for each pixel in the image. This technique enables the identification and characterization of objects and materials based on their unique spectral signatures, providing valuable insights into vegetation health, mineral exploration, water quality, urban mapping, and more. By understanding and applying hyperspectral remote sensing, researchers and professionals can unlock a wealth of detailed information about the Earth's surface, contributing to a wide range of scientific, environmental, and resource management endeavours.

In this instruction, we will explore the principles, techniques, and applications of hyperspectral remote sensing, delving into the spectral range, data acquisition, preprocessing, analysis methods, and the interpretation of hyperspectral imagery.

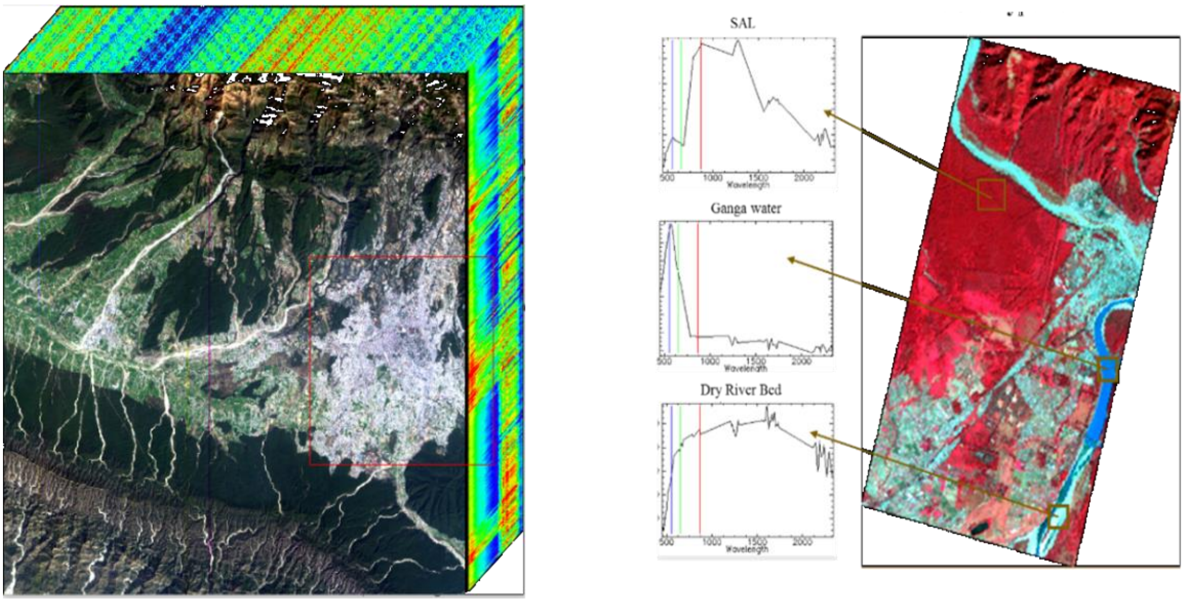


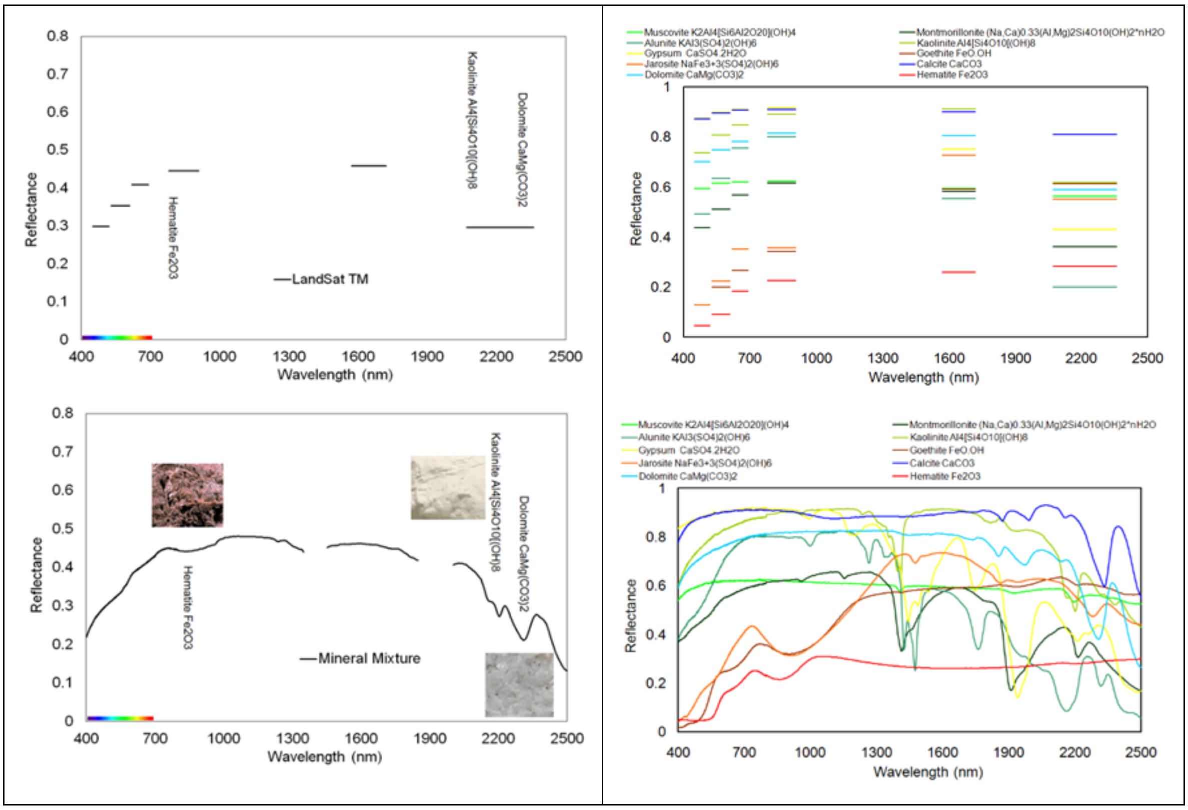
Fig. 5.1 Hyperspectral Image: Contiguous Spectral Bands and Spectral Signature

5.2 Multispectral vs. Hyperspectral Imagery

Multispectral and hyperspectral imaging are two techniques used in remote sensing and image analysis to capture and analyze data from the electromagnetic spectrum. While they share similarities, there are key differences between them.

Table 5.1- Multispectral vs. Hyperspectral

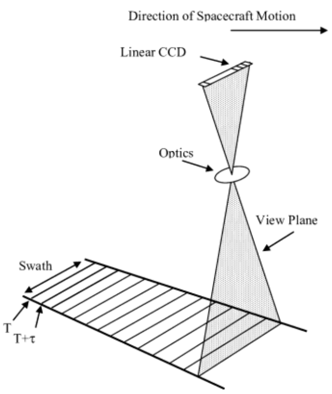
Multispectral Imagery	Hyperspectral Imagery
Multispectral imaging involves capturing data from a few discrete and broad wavelength bands, typically ranging from three to ten bands.	Hyperspectral imaging involves capturing data from numerous narrow and contiguous wavelength bands, typically ranging from dozens to hundreds of bands.
The broad bands provide a relatively coarse representation of the energy reflected by the target in different portions of the electromagnetic spectrum	The narrow contiguous bands provide a detailed representation of the energy reflected by the target in different portions of the electromagnetic spectrum
This technique provides valuable information about specific characteristics of the objects or areas being observed.	This technique enables the acquisition of highly detailed spectral information, making it particularly useful in applications where precise identification and classification of materials or objects are required
The data captured by multispectral sensors can help identify specific features or phenomena based on the spectral response in the limited bands of the sensor.	This technique enables the acquisition of highly detailed spectral information, making it particularly useful in applications where precise identification and classification of materials or objects are required
Spectral Characteristics of Multispectral and Hyperspectral Imageries	

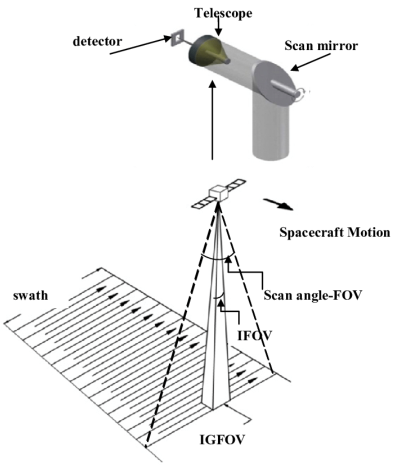
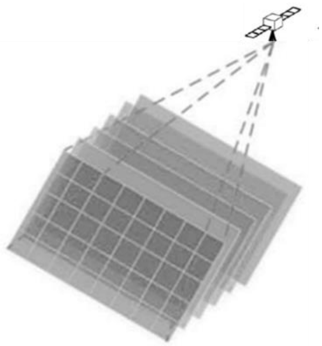
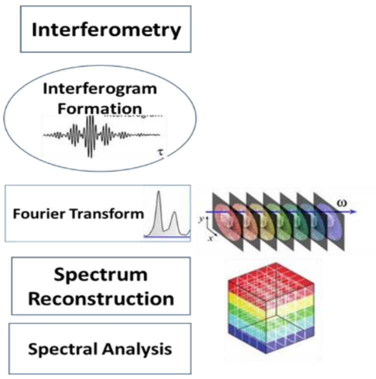


5.3 Different types of hyperspectral imaging techniques

There are primarily five popular hyperspectral imaging techniques, which are as follows:

Table 5.2 Types of hyperspectral image techniques

Pushbroom/Swath Imaging  Figure Source: Dr. by George Joseph	This technique involves capturing a continuous line or swath of data as the sensor and the scene move relative to each other. A linear or two-dimensional array of detectors is used to record the spectral information across the scene. Pushbroom imaging is commonly used in airborne and spaceborne hyperspectral sensors.
Whiskbroom/Scanning Imaging	Whiskbroom imaging involves scanning a narrow line or "whisk" across the scene to collect the spectral data. A single detector or a small array of detectors is used to capture the reflected or emitted light.

 Figure Source: Dr. by George Joseph	The scanning motion can be achieved mechanically or by using a rotating mirror. Whiskbroom imaging is often used in laboratory setups or some handheld hyperspectral devices
Snapshot Imaging 	Snapshot hyperspectral imaging aims to capture the entire hyperspectral cube in a single snapshot. Various techniques such as diffractive optics, spectral filters, or tunable filters are employed to disperse the light and capture the spectral information simultaneously. Snapshot imaging offers the advantage of acquiring the entire scene instantly but may have limitations in terms of spectral resolution or sensitivity.
Fourier Transform Imaging 	Fourier transform spectroscopy (FTS) is a technique used in hyperspectral imaging to acquire spectral data. Interferometers, such as Michelson or Sagnac interferometers, are employed to modulate the incoming light and obtain spectral information through Fourier transformation. FTS-based hyperspectral imaging offers high spectral resolution and accuracy but typically requires longer acquisition times.

Raman Spectroscopy	Raman spectroscopy is a hyperspectral imaging technique that utilizes the Raman scattering phenomenon. The sample is illuminated with a laser, and the scattered light is collected and analyzed. Raman hyperspectral imaging can provide detailed molecular information about the sample, enabling chemical identification and analysis. It is primarily used in ground-based spectroscopy

ISRO has developed hyperspectral imaging sensors for its remote sensing missions. One such sensor is the Hyperspectral Imaging Satellite (HySIS), which was launched in 2018. HySIS employs a **Pushbroom imaging** technique combined with hyperspectral data acquisition.

5.4 Platforms for Hyperspectral Imaging

There are several platforms available for hyperspectral image sensing, depending on the specific application and requirements. Here are a few commonly used platforms:

- Satellite Platforms: Satellites equipped with hyperspectral sensors provide a global-scale view and can capture hyperspectral images of large regions of the Earth's surface. Satellite platforms offer the advantage of continuous monitoring and can be used for various applications, including land cover mapping, mineral exploration, and disaster assessment.
- Airborne Platforms: Airborne platforms include airplanes and unmanned aerial vehicles (UAVs), also known as drones. These platforms are equipped with hyperspectral sensors and can capture images from a higher altitude, covering larger areas. Airborne platforms are commonly used in remote sensing applications such as environmental monitoring, agriculture, and geological surveys.
- Ground-Based Platforms: Ground-based platforms consist of stationary hyperspectral sensors placed on tripods or other fixed structures. These platforms are useful for capturing high-resolution hyperspectral images of smaller areas, such as vegetation analysis, object identification, and surveillance.
- Handheld and Portable Platforms: Handheld hyperspectral sensors are compact and lightweight devices that can be carried by an operator. These platforms are suitable for field-based applications, such as forestry, environmental monitoring, and precision agriculture. Portable platforms are larger and more capable versions of handheld devices, often used in research and field campaigns.
- Underwater Platforms: Hyperspectral imaging is also applicable underwater for tasks such as coral reef monitoring, marine ecosystem analysis, and underwater archaeology. Underwater platforms may include autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), or specialized imaging systems mounted on submarines.

The choice of platform depends on factors such as the desired spatial resolution, spectral range, coverage area, mobility requirements, and budget constraints. Each platform has its advantages and limitations, so it's important to select the most suitable one for a particular application.

5.5 Applications of hyperspectral imageries

Hyperspectral remote sensing is the emerging field for the range of the Earth observation applications as well as planetary and space science. Hyperspectral imagery has a wide range of applications across various fields due to its ability to capture detailed spectral information. Here are some of the key applications of hyperspectral imagery:

Fig. 5.2 Broad range of hyperspectral remote sensing applications

- Atmospheric Studies: Hyperspectral imagery allows to study gaseous composition estimation and monitoring, Aerosol optical depth (AOD) estimation mapping and characterization and Cloud Physics
- Environmental Monitoring: Hyperspectral imagery is used for monitoring and assessing various environmental parameters. It aids in the detection and mapping of land cover and land use changes, monitoring vegetation health, assessing water quality, detecting and tracking algae blooms, and monitoring coastal and marine ecosystems.
- Agriculture and Crop Monitoring: Hyperspectral imagery enables precise monitoring of crops and vegetation. It helps in identifying crop stress, nutrient deficiencies, disease outbreaks, and invasive species. Hyperspectral data can be used to optimize irrigation, fertilizer application, and pest control, leading to improved crop yields and resource management.
- Geology and Mineral Exploration: Hyperspectral imagery is valuable for geological mapping and mineral exploration. It allows for the identification and mapping of various minerals and rock types based on their unique spectral signatures. Hyperspectral data aids in locating mineral deposits, mapping geological structures, and assessing the potential for resource extraction.
- Forestry and Biodiversity Mapping: Hyperspectral imagery assists in forest monitoring, including species classification, tree species mapping, estimation of forest biomass, and detection of forest disturbances such as wildfires, pest outbreaks, and deforestation. It also contributes to biodiversity mapping, habitat assessment, and monitoring of endangered species.
- Urban Planning and Infrastructure Monitoring: Hyperspectral imagery helps in urban planning, land use mapping, and monitoring urban growth. It supports the assessment of urban heat islands, identification of impervious surfaces, and monitoring infrastructure development and changes.

- Disaster Management: Hyperspectral imagery aids in disaster management and response. It assists in rapid damage assessment after natural disasters such as earthquakes, floods, and wildfires. Hyperspectral data can help identify affected areas, assess the extent of damage, and support post-disaster recovery and planning.
- Archaeology and Cultural Heritage: Hyperspectral imagery is useful for archaeological surveys, identifying buried structures, mapping ancient landscapes, and monitoring the deterioration of cultural heritage sites. It assists in the analysis and preservation of historical artifacts and structures.
- Oceanography: Measurement of photosynthetic potential by detection of phytoplankton, detection of yellow substance and detection of suspended matter. It also helps in measuring the depth of water, investigations of water quality and monitoring coastal erosion.
- Oil Spill Studies: Different types of oils have varying spectral signatures. Hyperspectral imagery can help identify the type of oil present in a spill. This information is important for understanding the potential environmental impacts, selecting appropriate cleanup techniques, and determining the source of the spill. Oil Type Identification: Different types of oils have varying spectral signatures. Hyperspectral imagery can help identify the type of oil present in a spill. This information is important for understanding the potential environmental impacts, selecting appropriate cleanup techniques, and determining the source of the spill.

These are just a few examples of the numerous applications of hyperspectral imagery. The unique spectral information captured by hyperspectral sensors allows for detailed analysis and identification of materials and phenomena, making it a valuable tool in many scientific, environmental, and resource management disciplines.

5.6 Hyperspectral Imaging Sensors

There are several hyperspectral imaging sensors that have been developed by various organizations and are currently in use. Here are some examples of existing hyperspectral imaging sensors:

5.6.1 Existing Airborne Sensors

Table 5.3 Airborn hyperspectral sensor

S. No.	Sensor	Spectral coverage (nm)	No. of Bands	Band width (nm)	Spatial Resolution	Altitude and Swath
1	GERIS-Geophysical Environment ResearchImaging SpectrometerII Built by GER corp USA in 1987	400 - 1000 1400 - 1800 2000 - 2500	24 7 32	25.4 120.0 16.5		variable

S. No.	Sensor	Spectral coverage (nm)	No. of Bands	Band width (nm)	Spatial Resolution	Altitude and Swath
2	DAIS 7915- Digital Airborne Imaging Spectrometer - built by GER corp USA in 1995	498-1010 1500-1800 1970-2450 3000-5000 8700-12300	32 8 32 1 6	16 100 15 2000 600		variable
3	CASI- Comapct Airborne Imaging Spectrometer- Built byITRES research ltd Canada began flying in1988	400-800	288	1.8	10 m	variable
4	AVIRIS- Airborne Visible / Infrared imaging spectrometerfirst in 1987 , 1989	400 - 2450	224	9.6	20 m	20 Km 11 Km
5	ASAS- Advanced SolidState Array Spectroradiometer	465 - 871	29	15		
6	GEOSCAN- Advanced Multispectral Scanner (AMSS)	500 - 11500	24	42 - 530		
7	HYDICE- Hyperspectral Data	400 - 2500	210	10.2	3m	6 Km

5.6.2 Space Borne Hyperspectral Imaging Sensors

Table 5.4- Spaceborn hyperspectral sensor

S. No	Sensor	Spectral coverage (nm)	Bands	Band width (nm)	Spatial Resolution	Swath
1	HYSI (Hyperspectral Imager) on IMS (Indian Mini Satellite)	400-950	64	8	505.6	130
2	Hyperion- EO-1	400-2500	220	10	30m	7.5 Km
3	HSI- Hyper Spectral Imager	400 - 2500	384	5	30m	7.7 Km
4	CHRIS(Compact HighResolution Imaging Spectrometer) on PROBA	450-1050	62	10	18 m	14 Km
5	MERIS - Medium Resolution Imaging Spectrometer. (ENVISAT)	390-1040	15	Programmable widthand position	300m	1150Km
6	HJ-1A China	450-950	110 - 128	5	100m	50 Km
7	PRISMA	400-1010 920-2505 400-700	66 171 1	12 12 12	30m 30m 5m	30 Km

5.6.3 Planetary Mission using Hyperspectral Imaging Sensors

Table 5.5- Hyperspectral planetary missions

S. No.	Sensor	Spectral coverage (nm)	No. of Bands	Band width (nm)	Spatial Resolution	Swath (Km)
1	HYSI – Chandrayan	400-950	64	15	80	20
2	Moon Mineralogy Mapper : M3- on boardChandrayan	430-3000	86 260	20-40 10	Global: 140 m Target: 70 m	40
3	Mars: Mars ExpressOMEGA	350 – 5100	352	7-20	300m- 4.8Km	
	CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)	362-3920	544	6.55		9.4 to 11.9

5.7 Software for Hyperspectral data analysis

There are several software tools available for hyperspectral data analysis, ranging from open-source solutions to commercial software packages. These tools offer various functionalities for processing, visualization, and analysis of hyperspectral data. Here are some commonly used software for hyperspectral data analysis:

- Spectral Python (SPy): Spectral Python is an open-source library specifically designed for hyperspectral image analysis. It is written in Python and provides a wide range of functions and algorithms for hyperspectral data processing, visualization, and analysis. SPy integrates well with other Python libraries and is widely used in the scientific community.
- HYPERSPECTRAL IMAGE ANALYSIS TOOLBOX (HIAT): HIAT is an open-source toolbox developed by the Norwegian University of Science and Technology (NTNU). It provides a range of functions and algorithms for preprocessing, visualization, and analysis of hyperspectral data. HIAT offers capabilities such as atmospheric correction, classification, and spectral unmixing.
- RSGISLib: RSGISLib is an open-source software library developed by the Remote Sensing Group at Aberystwyth University. It provides a collection of functions and tools for processing and analyzing remote sensing and hyperspectral data. RSGISLib is primarily used in the command-line interface and offers capabilities such as image segmentation, classification, and spatial analysis.
- ENVI: ENVI (Environment for Visualizing Images) is a widely used commercial software package developed by Harris Geospatial Solutions. It provides a comprehensive set of tools for

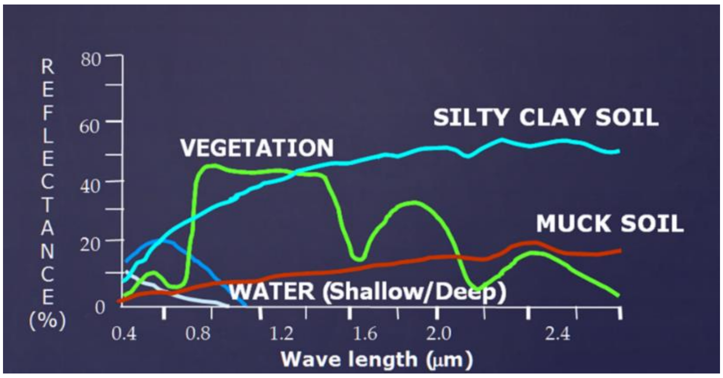
hyperspectral data analysis, including preprocessing, image classification, spectral unmixing, and change detection. ENVI also offers advanced features for visualization, data fusion, and integration with GIS (Geographic Information System) platforms. FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) is a software module included in the ENVI software package. It is specifically designed for atmospheric correction of hyperspectral data, removing the atmospheric effects and improving the accuracy of spectral analysis.

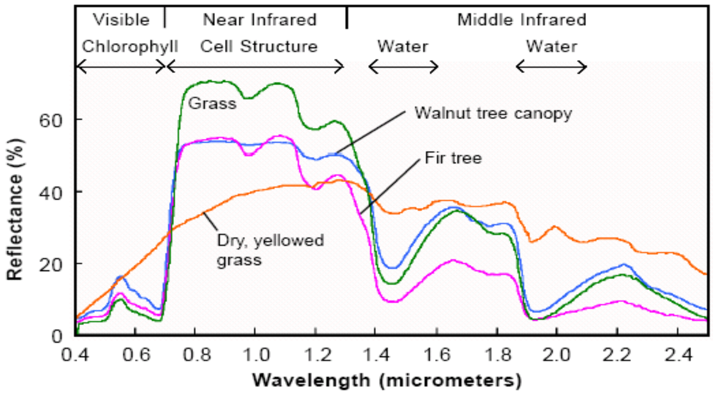
- MATLAB: MATLAB is a programming language and environment commonly used for scientific computing and data analysis. It offers numerous toolboxes and libraries for hyperspectral data processing and analysis. The Hyperspectral Imaging Toolbox for MATLAB provides functions for spectral analysis, endmember extraction, classification, and feature selection.

5.8 Spectral signatures of various natural features

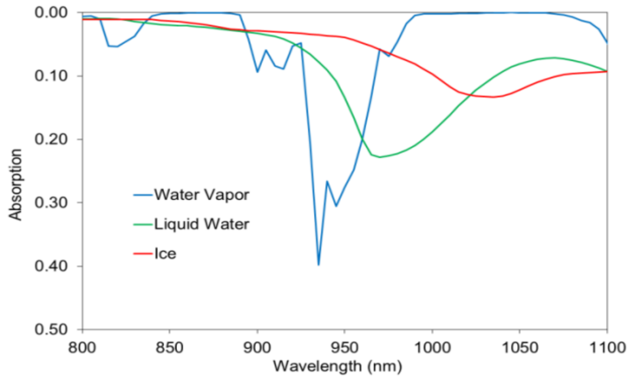
Here are some examples of spectral signatures for various natural features that can be observed in hyperspectral imagery.

Table 5.6 Examples of Spectral signatures

<table>
<tr>
<td>Spectral signature of various natural features. It tells how an object reflect the light of different colour</td>
<td>


</td>
</tr>
<tr>
<td>Typical spectral signatures for typical selected land targets</td>
<td>


</td>
</tr>
</table>

Typical spectral signatures for different phases of water (H_2O) e.g., vapour / liquid / ice. This characteristic is used for classification and mapping of water vapour / liquid / ice through hyperspectral remote sensing.	

5.9 Hyperspectral Imagers Developed by ISRO

ISRO (Indian Space Research Organisation) has developed and deployed several hyperspectral payloads as part of its remote sensing missions. Here is a summary of some of the notable hyperspectral payloads developed by ISRO:

- Hyper Spectral Imager (HySI): The Hyper Spectral Imager (HySI) is a hyperspectral imaging instrument developed by ISRO. The uniqueness of the HySI was in its capability of mapping the lunar surface in 64 contiguous bands in the VNIR region with a spectral resolution of better than 15nm and spatial resolution of 80m. The data from this instrument helped in improving the available information on mineral composition of the surface. Also, the study of data in deep crater regions, which represents lower crust or upper mantle material, helped in understanding the mineralogical composition of Moon's interior.

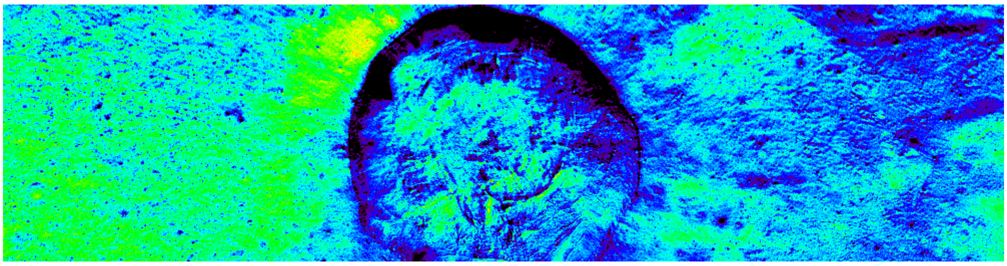


Fig. 5.3 LUNAR FeO

- Hyperspectral Imaging Satellite (HySIS): HySIS is a hyperspectral imaging satellite developed by ISRO. It was launched in 2018 as a primary payload on the PSLV-C43 mission. HySIS is designed to capture hyperspectral data in the visible to near-infrared regions, enabling detailed analysis of Earth's surface and resources.

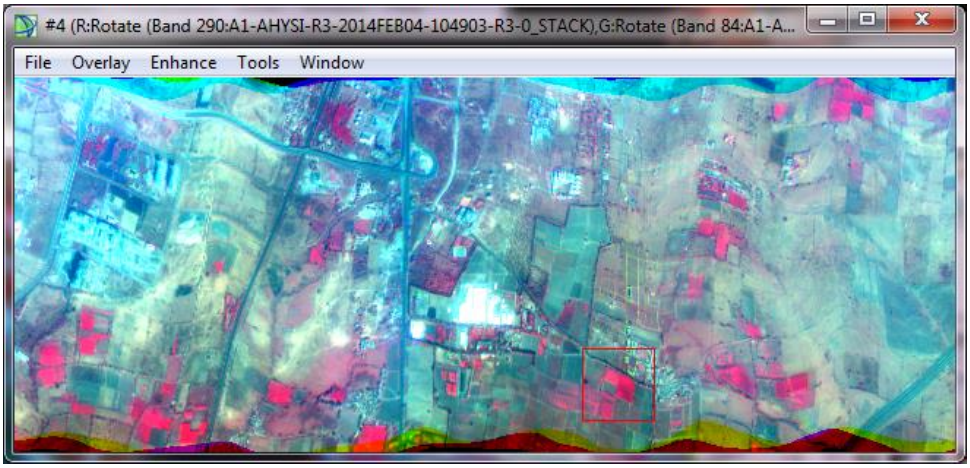


Fig.5.4 Image taken by Airborne HySI

- Imaging Spectrometer Payload (ISP): The Imaging Spectrometer Payload (ISP) is a hyperspectral imaging instrument developed by ISRO for the Indian Remote Sensing satellites (IRS series). ISP operates in the visible to near-infrared spectral range and is used for various applications, including agriculture, land cover mapping, and environmental monitoring.
- Infrared Imaging Spectrometer (IIRS): The Infrared Imaging Spectrometer (IIRS) is a hyperspectral payload onboard the Chandrayaan-2 lunar mission launched by ISRO in July 2019. It operates in the infrared region and is designed to study the mineralogy and composition of the lunar surface. By analyzing the reflected sunlight from the lunar surface in different infrared bands, the IIRS provided valuable insights into the composition and distribution of various minerals on the Moon. It allowed for the identification and mapping of different mineralogical features and the study of lunar geology. Salient Features of IIRS are as follows:

Table 5.3 Features of IIRS

Parameter	**Specifications**
GSD (m)*	80 x 80
Swath (km)	20
Spectral Range (µm)	0.8 to 5
Spectral sampling (nm)	20
SNR	500
No. of spectral bands	250

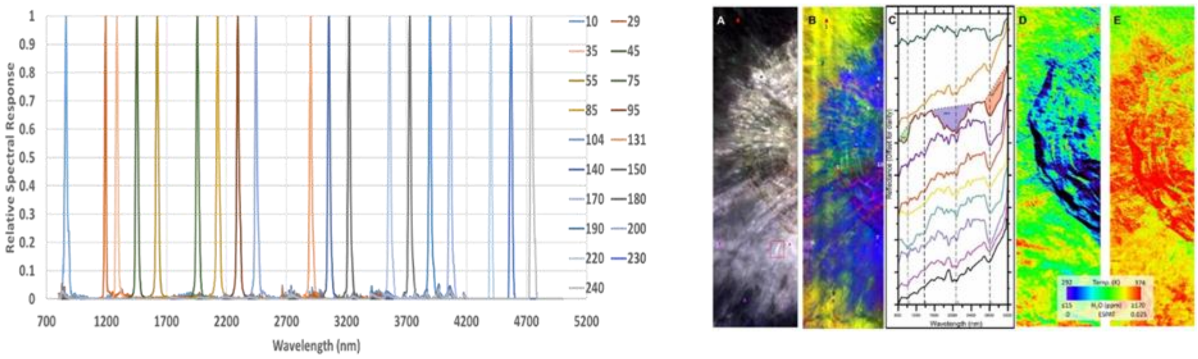


Fig. 5.5 (a) Spectral bands of IIRS and (b) On-board images by IIRS

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Fundamental of remote sensing by Jeroge Joseph

Grating Handbook

JPL/NASA website

ESA websites

PDR document of HySI (CH-1, CH-2), HySIS, Mars orbiter mission

Various papers and articles

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Chapter 6

MICROWAVE REMOTE SENSING

6.1 Introduction

Wavelength range (1mm – 1m) of microwave region of electro-magnetic (EM) spectra used in the remote sensing process for acquiring remotely sensed images provide a unique set of information about the targets on the surface and environment of earth or any other planet. The basic reason of using microwaves for remote sensing is that they have different unique characteristics compared to other EM radiation used in remote sensing. Microwaves have the capability to interact with other media and mainly governed by different physical parameters to those that effect other forms of EM radiation. Microwave sensors have their own source of energy and thus microwave remote sensing comes under active remote sensing. In microwave remote sensing, the sensor itself transmits microwave energy towards the earth's surface and subsequently receives the backscatter energy from the targets on the earth's surface. Microwave images have various advantages in comparison with optical remote sensing images such as – i) high penetration capability through clouds, rain droplets, haze, dust, fog etc. in the atmosphere, vegetation cover and top layer of soils or sand etc. on the earth's surface; ii) day and night all weather imaging capability; and iii) No requirement of background source of illumination such as the Sun. of course, there are some technical disadvantages too associated with microwaves such as- i) use of longer wavelength means requirement of large antenna size; and ii) most power consumption as it is active sensing.

The microwave region / band of EM spectra is further divided into different sub-bands as shown in Table 6.1. The longer wavelengths penetrate more than the shorter wavelengths. Therefore, shorter wavelengths extract more information about the upper layer of the target being sensed. On the other hand, longer wavelengths get information about lower layers. Microwave scattering from the surface relates not only to its roughness (i.e., geometry) but also to its electrical (dielectric) properties.

Table 6.1 Microwave bands and their frequency and wavelength ranges

Microwave Bands (Radar Nomenclature)	Frequency Range	Wavelength Range
Ka	27.0 – 40.0 GHz	1.11 - 0.75 cm
K	18.0 – 27.0 GHz	1.67 - 1.11 cm
Ku	12.0 – 18.0 GHz	2.5 - 1.67 cm
X	8.0 – 12.0 GHz	3.75 - 2.5 cm
C	4.0 – 8.0 GHz	7.5 - 3.75 cm

S	2.0 – 4.0 GHz	15 - 7.5 cm
L	1.0 – 2.0 GHz	30 - 15 cm
P	0.3 – 1.0 GHz	100 - 30 cm

6.2 Microwave Remote Sensing Systems

There are mainly two types of microwave remote sensing systems (instruments): Passive and active as shown in Fig. 6.1. The passive sensors record the microwave energy in two ways – i) emitted from the earth's surface and atmosphere, ii) scattered or reflected from the earth's surface. Since microwaves have longer wavelengths or lower frequencies compared with the optical wavelengths or frequencies, therefore the low energy is available with smaller area of interest (resolution cell) which is difficult to record by the passive sensor, and the field of view of such sensors are kept larger to detect enough signal energy from a resolution cell. Passive sensors such as Radiometers measure the microwave radiation that is emitted or scattered from the earth's surface or atmosphere. The microwave emission depends upon the physical temperature and electrical (dielectric constant) properties of the earth's surface with modulation by the intervening atmosphere. Since radiometers contain no transmitters, and thus typically consume much less power. The radiometers can be divided into two main categories based on aperture type like real aperture radiometers and sounders, and synthetic aperture radiometers. Radiometers frequently operate over a broader frequency range (bandwidth) than radar sensors and primarily rely on real-aperture antennas, although synthetic-aperture radiometers (interferometers) are also used for both Earth remote sensing and astronomical observation. Sounders are specialized radiometers designed for extracting vertical profiles of atmospheric parameters.

The active microwave sensors are generally divided into two distinct categories i.e., imaging radars and non-imaging radars and generate their own illumination by transmitting microwave EM signals (transmitting antenna) to the targets and then receives the backscattered echo (receiving antenna) from the targets of interest. Radar systems can be used to determine time delays to measure the distance between the radar and the target. It can also be used to determine the direction of the target by pointing of the antenna and the target velocity by measuring Doppler shift of the echo. Active microwave sensors (radars) can therefore provide two very different types of information – i) time delay in backscatter echo which provides distance information, and ii) the properties of the backscatter echo such as intensity and polarization. One of the important application of radars is to measure scattering cross section by comparing the energy of received and transmitted signals. The most common form of imaging active microwave sensors is radar which may be a real aperture radar (RAR) and synthetic aperture radar (SAR) and are operated in side looking mode rather than nadir looking. Non-imaging microwave active sensors include altimeters and scatterometers. In most cases these are profiling devices which take measurements in one linear dimension, as opposed to the 2D representation of imaging sensors. Altimeters provide very precise measurements of their distance from the target surface, and are essential in soft-landing missions. Satellite altimeters have been widely used for ocean studies and have become essential tools for the study of ocean circulation. Altimeters have also been used for measuring the topography of other planets such as perpetually cloud-covered Venus. Radar altimeters transmit short microwave pulses and measure the round-trip time delay to targets to determine their distance from the sensor. Generally, altimeters are nadir looking and measure time delay from nadir directed echoes to estimate altitude or height or elevation of the targets such as aircrafts, topography, sea surface height etc. Scatterometers focus on precise recording of the echo characteristics such as radar cross sections, and normally used to estimate wind speeds, characterization of different materials and surface types. A scatterometer is a device used for measuring the radar scattering coefficient quantitatively. Weather radars are specially designed scatterometers with ranging capability that measure rainfall and other meteorological phenomena.

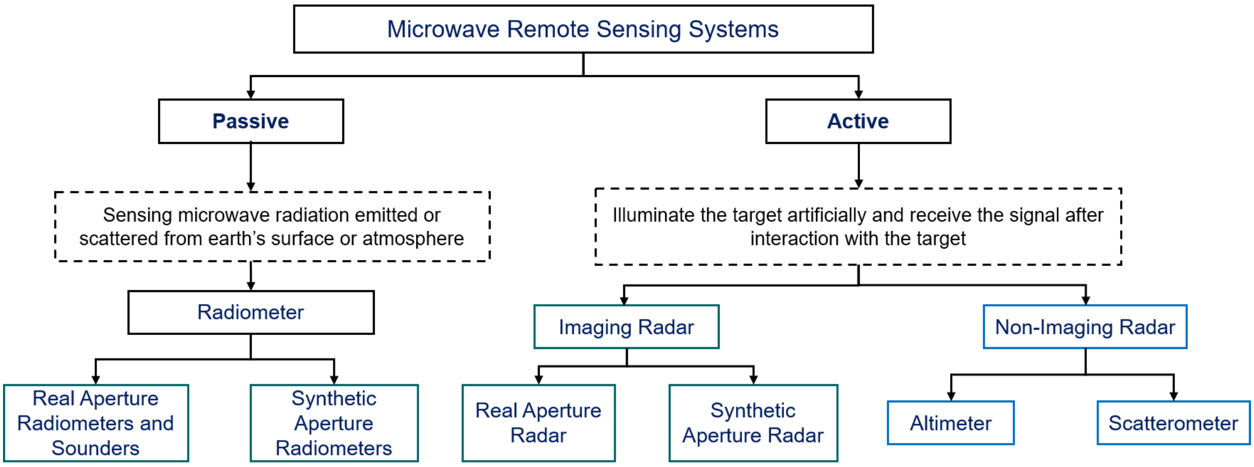

Fig. 6.1 Types of microwave remote sensing systems

Current advancements of SAR include interferometric SAR (InSAR) and polarimetric SAR (PolSAR). InSAR is a special SAR configuration used to measure topography, motion of targets on land surfaces, and terrain deformations such as landslide, land subsidence, earthquake deformation, volcanic eruption, plate tectonic movement, infrastructural deformation etc. PolSAR is equipped to image the targets/objects in different polarizations which can obtain much more information about the target.

6.3 Principle of Radar

The term RADAR or Radar stands for RAdio Detection And Ranging. The term radar is reserved for echo-location using radio waves or microwaves. Radar works on the principle of echo-location. The basic working principle of radar devices is simple - extremely short pulses of radio waves or microwaves are transmitted, reflected off a target and then returned as a backscatter echo (Fig. 6.2). Microwave radar transmit a microwave signal (or pulse of duration τ) that travel with almost speed of light (c), and measure the backscatter echoes which return after interaction with target/object. The pulse duration is the time between the pulse transmission and echo response. It measures the time delay between transmitted signal (or pulse) and backscattered echo, and thus the distance between radar and target, called slant range (S), can be measured as the speed of signal is known. The two-way slant range distance (2S) between radar transmitting antenna – target – radar receiving antenna travelled by the signal (or pulse) is given as-

$$S = \frac{c\tau}{2} \qquad \dots (1)$$

Equation (1) represents the fundamental measurement strategy of all radar systems.

The microwaves transmitted by pulse-modulated radars consists of a series of equally spaced pulses, separated by very short but relatively long periods during which no energy is transmitted. If the distance to a target is to be determined by measuring the time required for one pulse to travel to the target and return as a backscattered echo, it is necessary that this cycle be completed before the pulse immediately following is transmitted. This is the reason why the transmitted pulses must be separated by relatively long non-transmitting time periods. Otherwise, transmission would occur during reception of the reflected echo of the preceding pulse. If this transmission and reception is done by a single antenna, the relatively weak reflected echo would be blocked by the relatively strong transmitted pulse.

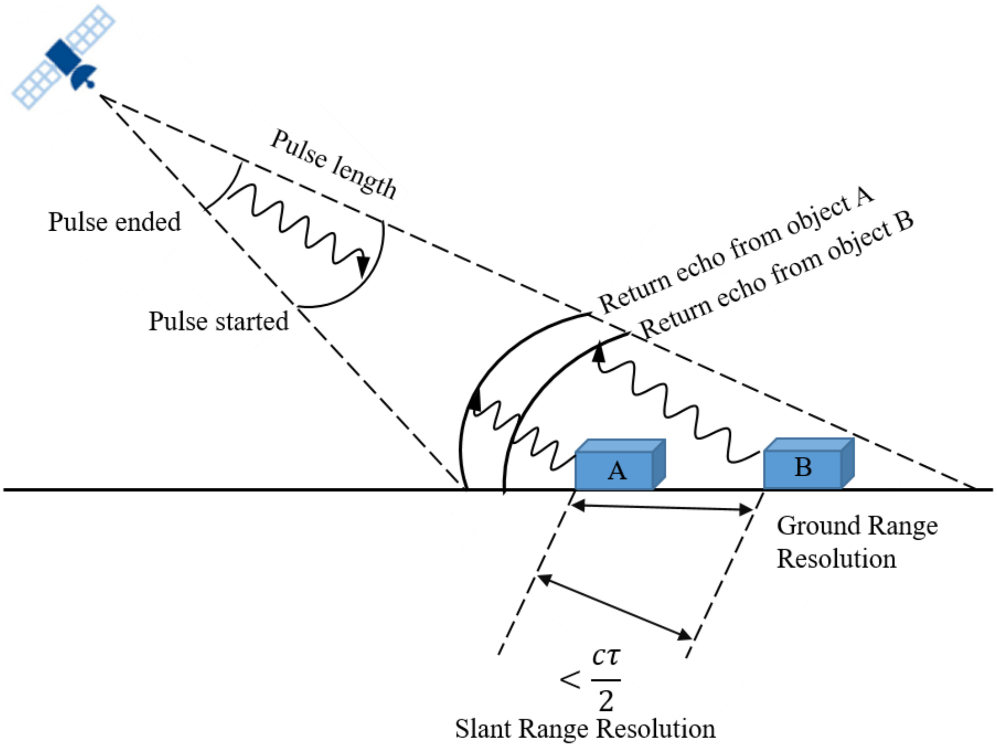

Fig. 6.2 Working Principle of Radar

6.4 Imaging and Non-imaging Radars

Imaging radar is similar to a photograph taken by a camera, but the image is of radar waves, not visible light. The most common form of imaging active microwave sensors is radar. The sensor transmits a microwave (radio) signal towards the target and detects the backscattered portion of the signal. The strength of the backscattered signal is measured to discriminate between different targets and the time delay between the transmitted and reflected signals determines the distance (or range) to the target. The transmitter generates successive short bursts (or pulses of microwave at regular intervals which are focused by the antenna into a beam. The radar beam illuminates the surface obliquely at a right angle to the motion of the platform. The antenna receives a portion of the transmitted energy reflected (or backscattered) from various objects within the illuminated beam. By measuring the time delay between the transmission of a pulse and the reception of the backscattered "echo" from different targets, their distance from the radar and thus their location can be determined. As the sensor platform moves forward, recording and processing of the backscattered signals builds up a two-dimensional image of the surface. For the radar to distinguish between two objects, the spatial resolution should be equal or greater the half the pulse length. Even though the SR does not change with the distance of the transmitter, the ground-range (GR) resolution decreases with the increase in slant range.

Non-imaging radar are profiling devices which take measurements in one linear dimension, as opposed to the two-dimensional representation of imaging sensors. The example instruments for non-imaging radar are Scatterometer and altimeters. Scatterometer - It makes precise quantitative measurements of the amount of energy backscattered from targets. The amount of energy backscattered is dependent on the surface properties (roughness) and the angle at which the microwave energy strikes the target. Ground-based scatterometers are used extensively to accurately measure the backscatter from various targets in order to characterize different materials and surface types. Altimetry sensor sends a pulse of radar energy toward the earth and measures the time it takes to return to the sensor. The pulse's round-trip time determines how far the satellite is from the reflecting surface. Altimeters look straight down at nadir below the platform and thus measure height or elevation. With a known reference, this information is used to measure the altitude of various features at the earth's surface. With enough precision, a radar altimeter can determine the height of the sea ice surface above sea level, which is utilized to calculate the total thickness of the sea ice. Thus, non-imaging radar finds application in ocean topography, glacial ice topography, sea ice characteristics and classification of ice edge.

6.5 Synthetic Aperture Vs Real Aperture Radar

In 1951, Carl Wiley of Goodyear Aerospace Corporation in the United States was the first to find out that side-looking radar can improve the azimuth resolution by utilizing the Doppler shift present in echoes. Wiley called his airborne radar a 'Doppler beam-sharpening' system. This landmark discovery marks the birth of presently called 'Synthetic Aperture Radar (SAR)' technology. When compared with real aperture side-looking airborne radar (SLAR), SAR technology permitted the generation of side-looking radar images having along-track target resolution independent of its distance from the radar and with feasibly short antenna. This led to a concept of fine-resolution imaging radar, which are space borne.

Radar in which antenna beam width is controlled by its physical length are called real aperture radar (RAR). They have relatively simple design and data processing strategy. RAR working is restricted to short range, low altitude, and short wavelengths. Therefore, they have limited area of coverage, and more affected by the atmosphere.

Synthetic aperture radar (SAR) is the most common form of active microwave radar sensors. SAR systems have an antenna of shorter physical length but able to synthesize the effect of a long antenna due to sequential transmission and reception of pulses and echoes respectively, to attain high spatial resolution images. The along track motion of sensor is used to create an array of antennas that can be linked together mathematically and thus the effective antenna length increases with range, and thus a virtually constant azimuth resolution irrespective to range is obtained.

6.6 Imaging Geometry of SAR

In principles, SAR is a coherent imaging technique and captures two-dimensional reflectivity image of a given area under study. The SAR system (air-borne or space-borne) transmits the polarized (plane or circular) EM wave/signal (microwave) in a side looking direction (slant range) and towards the ground. This microwave signal interacts with the objects on the ground and then SAR receiver receives scattered signal from the ground objects. Depending upon the transmitter and receiving units (antenna), the SAR acquisition systems are of two type namely mono-static and bi-static. If a single antenna is used for transmission and reception of SAR signals, it is called mono-static, and in bi-static SAR systems, the transmitting and receiving antennas are spatially separated.

In the ordinary imaging geometry of a SAR system (Figure 3a), the sensor platform moves along the flight direction, also called azimuth direction. The SAR system (sensor) transmits the microwave pulses in the slant range direction, also called line of sight (LoS) which is perpendicular to the azimuth direction. This transmitting pulse is governed by look angle, which is related to depression angle as well as incidence angle (Fig. 3b). For flat terrains, the incidence angle and radar look angle, both are same and depression angle is complementary angle of look angle. The area illuminated by radar pulse on the ground surface is called radar footprint and since the platforms moves in azimuth direction then the footprint generates the swath. The near and far sides of swath are called near and far ranges. In practice, neither the earth surface is flat nor the terrain is uniform and thus earth's curvature and terrain slops affect the imaging geometry of SAR systems (Fig. 6.3). The incidence angle is the angle between the radar beam (slant range direction) and earth's surface normal (Fig. 6.4). For hilly surfaces, normal is drawn on terrain surface which depends on slope angle and thus the local incidence angle (θ_l) is calculated. If slope angle is (θ_s) and look angle is (θ_r), then the local incidence angle is defined as-

$$\theta_l = \theta_r - \theta_s \qquad \ldots..(2)$$

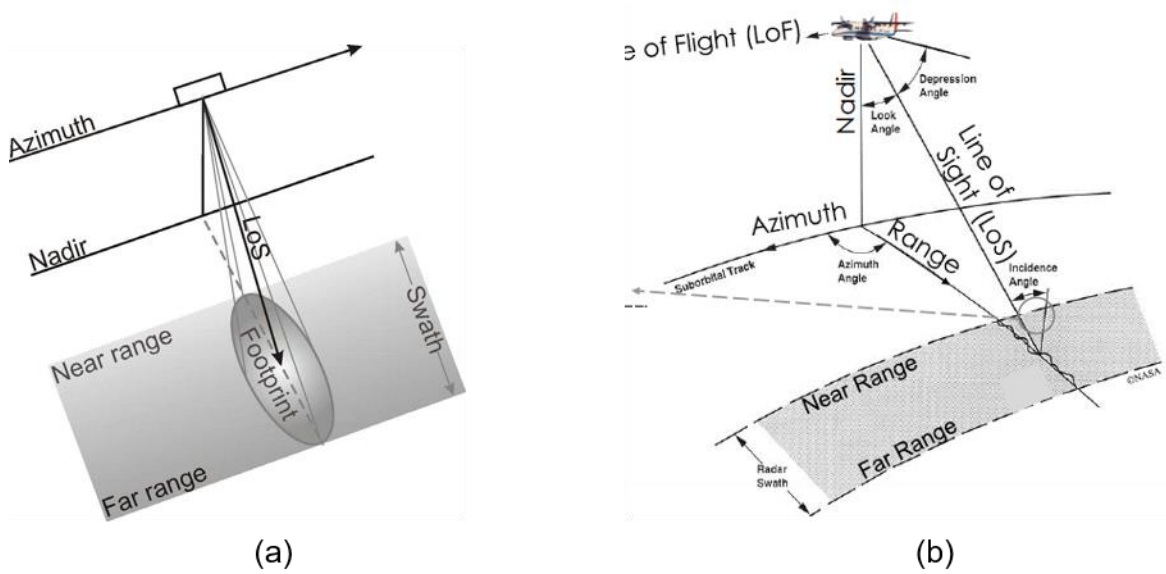

Fig. 6.3 Imaging Geometry of SAR system

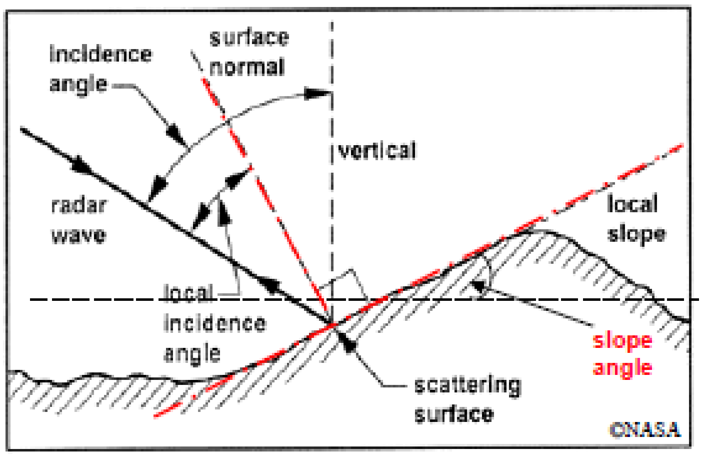

Fig. 6.4 Local Incidence Angle

Coherent radar imaging is done with speed of light and backscattered echo (at the rate of pulse repetition frequency) is complex in nature and contains amplitude (brightness) and phase information. Imaging by radar systems is being done in two directions i.e., in range direction and in azimuth direction and hence governed by two spatial resolutions i.e., range resolution and azimuth resolution.

In imaging along range direction, the chirp signal (not a pulse to avoid peak energy of high voltage) is transmitted with speed of light from the sensor and a chirp echo is received by the sensor (Fig. 6.5) and then the received chirp signal is correlates with the replica of transmitted chirp (coherent demodulation).

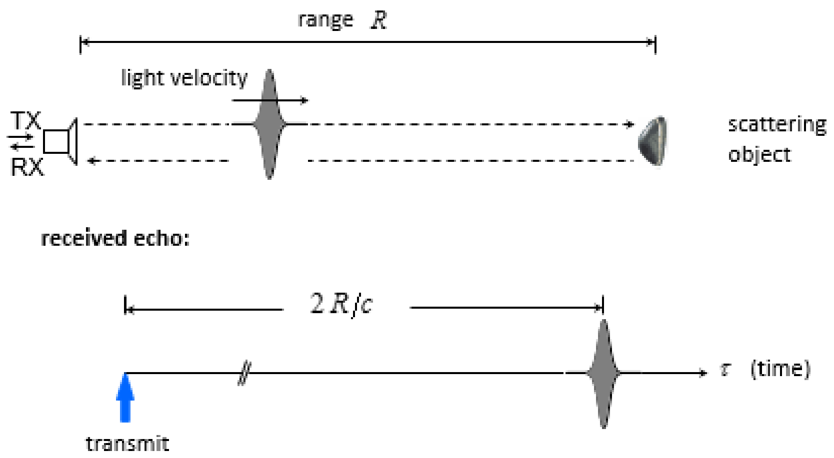

Fig. 6.5 Chirp signal transmission and reception

After coherent demodulation, the signal can be represented as-

$$y = Ae^{i\phi} \quad ..(3)$$

Where y is the signal displacement in range direction, A and ϕ are the amplitude and phase of the chirp signal. The square of the amplitude is known as the intensity or power of received echo.

In imaging along azimuth direction, the azimuth chirp echo is formed by the range chirp echo depending upon the phase relation between different range chirp signals as shown in Figure 6.6.

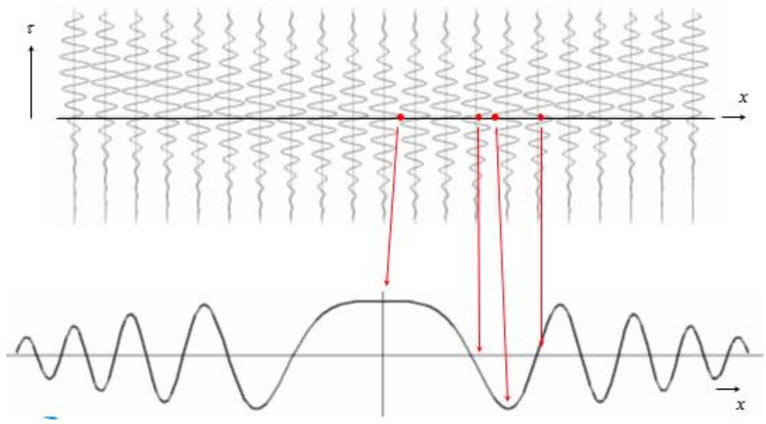

Fig. 6.6 Formation of Azimuth Chirp Signal

6.7 Imaging resolutions

There are two types of the spatial resolutions in a SAR system namely slant range resolution or resolution in slant range direction and azimuth resolution or resolution in azimuth direction.

Slant Range Resolution: Resolution in slant range direction (R_{sr}) is a function of the SAR pulse duration (popularly known as length of pulse or pulse length). SAR pulses are transmitted with some time delay and then these pulses incident on different scatterers and resolved with their time delay. Mathematically it can be expressed as

$$R_{sr} = \frac{c.\tau_p}{2} \quad \quad .... (4)$$

Where c *and* τ_p are the speed of light and pulse length respectively.

From this equation (4), it is obvious that slant range resolution can be increased by transmitting shorter pulses but it is very difficult because of establishment of frequency modulation. Normally, a frequency modulated pulse (chirp signal) $s(t) = \exp(i\pi f_{rcr} t^2)$ is applied, with a bandwidth $B_w = |f_{rcr}|.\tau_p$. So, it leads to the following expression of slant range resolution.

$$R_{sr} = \frac{c}{2B_w} \quad \quad .... (5)$$

Where f_{rcr} is called the range chirp rate.

The ground range resolution is horizontal expression of slant range resolution and mathematically defined as-

$$R_{gr} = \frac{c\tau_p}{2\ cos\gamma} \quad \quad .... (6)$$

Where $\gamma = \frac{\pi}{2} - \theta_r$ is the depression angle of SAR system.

It is very important to note that the ground range resolution decreases with increasing value of depression angle and does not define when $\gamma = \frac{\pi}{2}$. This is the reason by which vertically down looking radars are not operated and these are operated only in side looking geometry.

Azimuth Resolution: The azimuth resolution is defined at a given *slant range distance* from the platform. Therefore, at a slant range distance (S), the azimuth resolution of SAR system with real antenna (real aperture radar) is given expressed as-

$$R_{az} \cong \frac{\lambda.S}{D_{az}} \cong \beta_{az}.S \quad \quad .... (7)$$

Where $\beta_{az} = \frac{\lambda}{D_{az}}$ is the opening angle of antenna along the azimuth, D_{az} is the antenna length along the *azimuth* direction, and λ is the wavelength of chirp signal.

This equation describes that the azimuth resolution decreases with increasing value of wavelength and increases as the length of the antenna increases. For getting constantly high resolution across the full swath, which means with variable slant range distances because across the swath, slant range varies from its near value to far value. For this concept of synthetic aperture in azimuth direction was proposed to increase the length of radar antenna synthetically. The radar antenna length can be synthesized (increased) by operating real antenna in a pulsed mode shown in Fig. 6.7. In this configuration, during overflight, the same scatterer can be imaged many times, a longer antenna can be easily synthesized by sending a narrow beam and coherent combination of the received pulses.

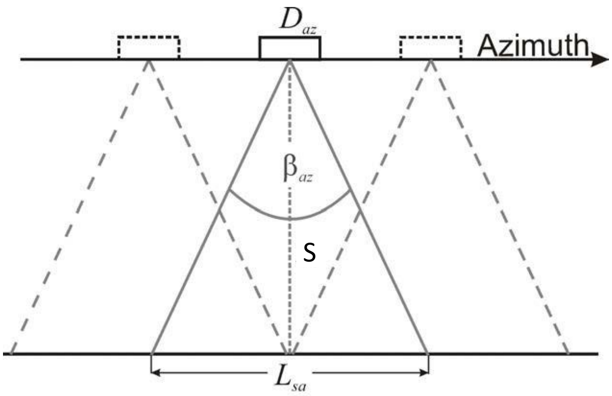

Fig. 6.7 Formation of synthetic aperture geometry of SAR

The opening angle of antenna for the synthetic aperture is obtained from $\beta_{az} = D_{az}/2S$ where 2S is the two-way path length. In this way, the azimuth resolution of a synthetic aperture radar (R_{az}) becomes independent of both the parameters i.e., slant range distance and wavelength. Thus, the azimuth resolution only depends only on the physical length (generated synthetically) of the SAR antenna in azimuth direction (antenna length D_{az}).

Note: SAR image resolutions are not same as the image sampling. SAR image sampling means sampling in range as well as azimuth direction, also called range sampling (δ_{rg}) and azimuth sampling (δ_{az}), and are expressed as-

$$\delta_{rg} = \frac{c}{2f_{rs}} \quad \text{and} \quad \delta_{az} = \frac{v}{PRF} \qquad \ldots.(8)$$

Where f_{rs} represents sampling frequency in range direction, PRF is pulse repetition frequency in azimuth direction and v is the speed of the SAR platform.

6.8 Backscattering coefficient

The linkage between the SAR imaging system and scatterer is described in terms of a relationship, which is known as radar equation. For a point scatterer (single target) placed in a lossless medium, the radar equation, is given by

$$P_r = \frac{P_t G_t A_r}{(4\pi)^2 R^4} \sigma_{RCS} \qquad \ldots..(9)$$

Where the received power P_r per pulse is the function of the transmitted power (P_t), transmitting antenna gain (G_t), effective area of receiving antenna (A_r) which is further related with the receiver antenna gain (G_r) as $A_r = (\lambda^2 G_r)/(4\pi)$, R is the slant range distance from platform to the ground point scatterer and σ_{RCS} is the cross sectional area of radar, popularly known as radar cross section.

The radar cross section (σ_{RCS}) represents the cross-sectional area of a perfect isotropic scatterer that generates corresponding backscattered power density towards the receiving antenna and appears like an observed scatterer. The value of the σ_{RCS} depends on the chemical (dielectric content, density etc.) and geometry (orientation, shape, size) properties of the scatterer, nature of SAR imaging system and different acquisition parameters like wavelength, polarization, incidence angle.

The value of radar cross section (σ_{RCS}) for natural targets (like bare rough surfaces, vegetated surface etc.) with distributed scatterers (Gaussian scatterers), is calculated by averaging σ_{RCS} value of individual isotropic scatterers present in the resolution cell, and then it is normalized by unit ground area (A_g) and hence it is called normalized Radar backscattering coefficient (σ^0)

$$\sigma^0 = \frac{\sigma_{RCS}}{A_g} \quad with \quad A_g = \frac{\delta_{rg}.\delta_{az}}{sin\theta} \qquad \ldots..(10)$$

Where θ represents is the local incidence angle, δ_{az} is the sampling in azimuth direction and δ_{rg} is the sampling in the range direction.

For single scatterer, the radar cross section (σ_{RCS}) is given as-

i) For metal sphere of radius R: $\sigma_{RCS} = \pi R^2$

ii) For Corner Reflector of side length L: $\sigma_{RCS} = \frac{4\pi L^2}{3\lambda^2}$

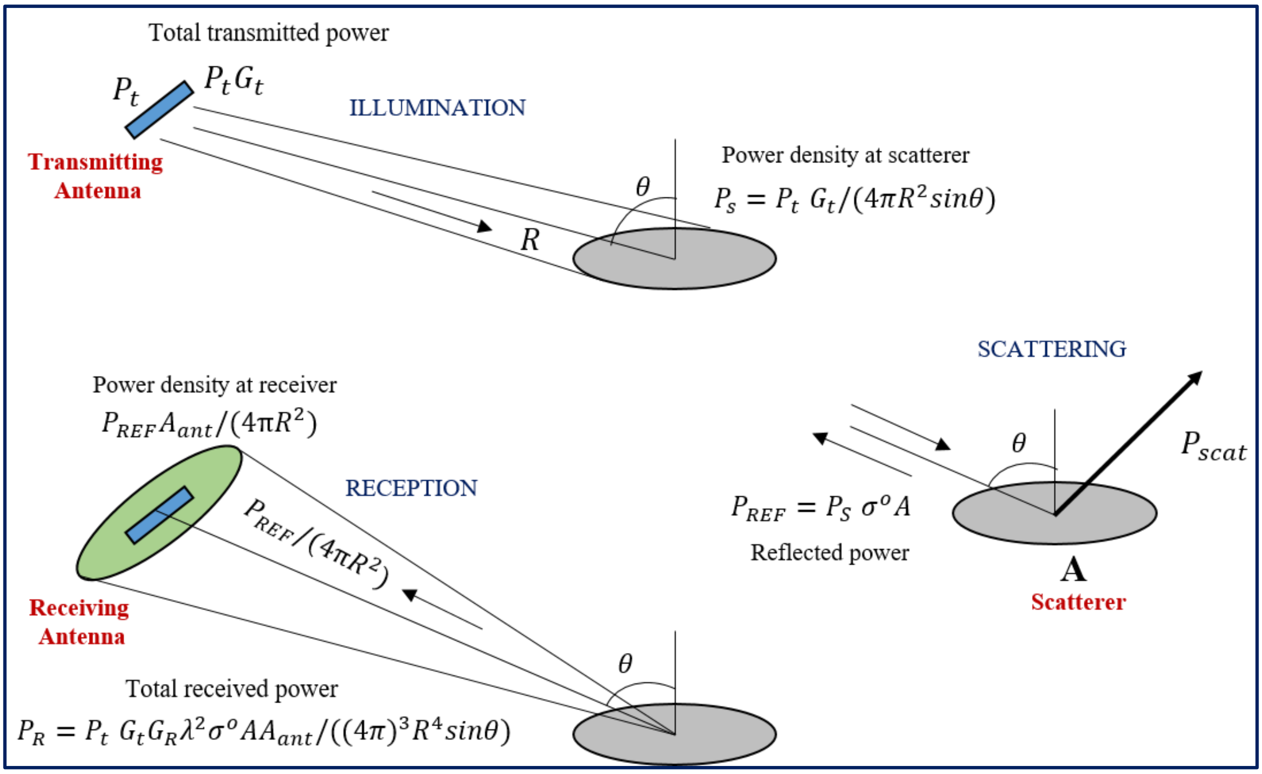

Fig. 6.8 Graphical Representation of Radar Equation

The detailed graphical representation of radar signal transmission, interaction with scatterers and then backscattered signal reception by the radar and hence the calculation of radar backscattering coefficient is shown in Figure 6.8.

6.9 Speckle Reduction

Speckle or speckle noise is caused by random positive (constructive) and negative (destructive) interference of wave contributions (SAR signals) from the many individuals but differently located scatterers within one resolution cell. The properties of Speckle phenomenon are studied statistically due to unknown detailed structure present in the resolution cell.

The *Speckle* noise is generally modeled with the help of a multiplicative noise model and it can be minimized under the application of multi-looking or polarimetric filtering techniques for improving the radiometric resolution on the cost of spatial resolution. Multi-looking over SAR images is applied by an averaging operator over image pixels. This pixel averaging can be applied in the spatial domain or frequency domain. In spatial domain it can be performed by including certain number of neighbouring pixels and in the frequency domain it is applied by adding several sub-apertures incoherently which were obtained by splitting of synthetic aperture. The effective number of looks L_{ne} for quantization purpose can be obtained by the possible number of looks L_n of SAR system. Mathematically it can be expressed as

$$L_{ne} = \frac{\delta_{rg}\delta_{az}}{R_{sr}R_{az}} . L_n \qquad \ldots\ldots(11)$$

6.10 SAR sensor systems

Since 1978 onwards, successful operationalization of different SAR systems started at airborne and space-borne platforms and meet the requirements of diverse range of applications. Few SAR sensors launched by various space agencies are shown in Table 6.2.

Table 6.2 Past and present Space borne SARs

Satellite	Owner	Band	Resolution	Look Angle	Swath	Life-time	Polarization
ERS-1	ESA	C	25 m	23^0	100 km	1991-2000	S
ERS-2	ESA	C	25 m	23^0	100 km	1995-2012	S, D
Radarsat-1	Canada	C	10-100 m	$20^0 - 59^0$	50-500 km	1995-2013	S, D
ENVISAT	ESA	C	25 m - 1 km	$15^0 - 40^0$	100-400 km	2002-2012	S, D
ALOS	Japan	L	10 – 100 m	$35^0 - 41^0$	70-360 km	2006-2011	S, D
Cosmo	Italy	X	1 – 16 m	--	--	2007-	S, D
TerraSAR-X	Germany	X	1 – 16 m	$15^0 - 60^0$	10 – 100 km	2007-2017	S, D, Q
TanDEM-X	Germany	X	1 – 16 m	$15^0 - 60^0$	10 – 100 km	2010-2015	S, D, Q

Radarsat-2	Canada	C	3 – 100 m	$15^0 - 59^0$	10 – 500 km	2007-2015	S, D, Q
ALOS-2	Japan	L	3 – 100 m	$8^0 - 70^0$	25 – 350 km	2014-2021	S, D, Q
Sentinel-1	ESA	C	5 – 50 m	$20^0 - 46^0$	20 – 400 km	2016-2023	S, D
RISAT-1	India	C	1 – 50 m	$15^0 - 60^0$	10 – 225 km	2012-2017	S, D, Q & H
NovaSAR-S	UK	S	6 – 30 km	$14^0 - 58^0$	13 – 400 km	2018-2025	S, D, Q

*S = Single, D = Double, Q = Quad and H = Hybrid Polarization

6.11 Basics of SAR Interferometry

Synthetic aperture radar Interferometry is an imaging technique for measuring the topography of a surface, its changes over time, slow movement of targets on the earth surface, and other changes in the detailed characteristics of the surface. A conventional SAR only measures the location of a target in a two-dimensional coordinate system, with one axis along-track and other along cross-track. The development of interferometric SAR techniques enables the measurement of the third dimension, i.e., height. The interferometric radar technique utilizes the differences in phase information from at least two SAR acquisitions to generate maps of surface variations (digital elevation). The SAR acquisitions are displaced from each other in space or time. Typically, there are following types of interferometry:

i) Single pass SAR interferometry, and
ii) Repeat pass SAR interferometry.

In single pass interferometry, two SAR acquisitions are captured in a single pass. When the acquisitions are separated in space, it is called 'Single Pass Cross-track Interferometry'. On the other hand, if they are separated in time, it is called 'Single Pass Along-track Interferometry'. The single Pass along-track Interferometry can be realized either using two independent SARs (bi-static) or using single SAR platform (mono-static). In repeat pass interferometry, single SAR acquisitions are acquired in repeat orbits. Historically, the early exploitation of satellite-based interferometric SAR included use of Seasat data in 1980s, however, the notable expansion of the technique happened in 1990s, with the launch of various other SAR sensors (Table 6.1).

An essential prerequisite for high-precision cross-track and along-track interferometry is the provision of suitable baselines. Baseline is the physical/spatial or temporal separation of acquisitions. For this, we consider DEM generation by cross-track interferometry, where the range of suitable baselines is limited by several factors.

Differential SAR Interferometry (DInSAR): In DInSAR technique is normally used for – i) DEM generation and the measurement of target movements. Considering a single pixel point target P and satellite acquire image from satellite position C and then assuming the point target moves from P to Q and then satellite acquire image from satellite position D. Assuming, the estimated phases from both the positions are ϕ_C and ϕ_D respectively. In this situation, the interferometric phase is given as

$$\Delta\phi_{int} = \phi_D - \phi_C = \frac{4\pi}{\lambda}(DQ - CP) + \phi_{scatt-D} - \phi_{scatt-C} \quad ..(12)$$

Equation (12) can also be written as

$$\Delta\phi_{int} = \phi_D - \phi_C = \frac{4\pi}{\lambda}(DP - CP) + \frac{4\pi}{\lambda}(DQ - DP) + \phi_{scatt-D} - \phi_{scatt-C} \quad ..(13)$$

In equation (3) the first term is topographic phase component ϕ_{topo} and the second term is called deformation phase ϕ_{defo} in the satellite LOS direction. Assuming the scattering of both the SAR signals is same, then the last two term of equation (13) can be assumed to be cancelled. Thus, the phase difference (interferometric phase) is the sum of topographic phase and deformation phase.

In general, the phase difference (interferometric phase) is the contribution of many other factors too such as orbital phase due to orbital inaccuracies, atmospheric phase due to atmospheric propagation delay and atmospheric inhomogeneities, phase due to earth's curvature (flat earth phase), decorrelation noise and phase unwrapping term. Therefore, the comprehensive form of equation (13) is

$$\Delta\phi_{int} = \phi_{flat} + \phi_{defo} + \phi_{topo} + \Delta\phi_{orb} + \Delta\phi_{atm} + \phi_{noise} + 2\pi n \quad ..(14)$$

Where ϕ_{flat} is the flat earth phase component, ϕ_{defo} is the deformation phase component, ϕ_{topo} is the residual topographic error component, ϕ_{orb} is the orbit phase component due to orbital errors, ϕ_{atm} is the atmospheric phase delay, and ϕ_{noise} is the decorrelation noise term. The last term, $2\pi n$, where 'n' is an integer value called phase ambiguity is a result of the wrapped nature of interferometric phase. Moreover, the interferometric phase is bound in the range $[-\pi, \pi]$ i.e., 2π.

From this interferometric phase, it is clear that – i) if you are interested in DEM generation, you have to remove the unwanted phase components i.e., phase components due to flat earth, deformation, orbital inaccuracies, and atmospheric delays, from interferometric phase then it will be equal to topographic phase only. The topographic phase can be converted into height or elevation values and hence DEM will be generated. Here it is important to note that the removal of decorrelation noise term is not possible and phase unwrapping is essential just to calculate the value of 'n'; ii) if you are interested in deformation analysis, you have to remove the unwanted phase components i.e., phase components due to flat earth, topography of earth, orbital inaccuracies, and atmospheric delays, from interferometric phase then it will be equal to deformation phase only. The deformation phase can be converted into displacement using $\phi_{defo} = (4\pi/\lambda). D_{LOS}$ where D_{LOS} is the displacement of target along the radar line of sight (LOS) direction; and iii) if you are interested in atmospheric modelling for signal delays, you have to remove the unwanted phase components i.e. phase components due to flat earth, deformation, topography of earth, and orbital inaccuracies, from interferometric phase then it will be equal to atmospheric phase only. The atmospheric phase can be converted into propagation delays of SAR signals in the atmosphere.

6.12 SAR Polarimetry

6.12.1 Polarization of EM Wave

The EM wave propagates with speed of light and oscillation patterns of its electric field component are known as polarizations. The classification of polarizations is based on geometry of oscillation pattern.

Popular pattern geometries are linear, circular and elliptical and hence polarizations are called as linear or plane polarization (horizontal and vertical), circular polarizations (left and right) and elliptical polarizations (left and right). Normally, the polarimetry of SAR systems is based on plane or circular polarizations of transmitted and received signals. During the interaction of transmitted signal with scatterer, the polarization of transmitted signal is adjusted (either horizontal or vertical in case of plane polarization and left or right in case of circular polarization) depending upon the physical (dielectric content, density etc.) and geometrical (size, shape, orientation) properties of the scatterer. Therefore, SARpolarimetry is capable to provide a unique set of information which is useful for the retrieval of physical parameters of scatterer and also interpretation of scattering processes during interaction.

The behavior of EM waves in space and time is described by a set of EM wave equations, called Maxwell's equations. Maxwell's equations in electromagnetism are defined as-

$$\nabla.\vec{D}(\vec{r},t) = \rho(\vec{r},t) \qquad .... (15)$$

$$\nabla.\vec{B}(\vec{r},t) = 0 \qquad .... (16)$$

$$\nabla \times \vec{E}(\vec{r},t) = -\frac{\partial \vec{B}(\vec{r},t)}{\partial t} \qquad .... (17)$$

$$\nabla \times \vec{H}(\vec{r},t) = \vec{J}(\vec{r},t) + \frac{\partial \vec{D}(\vec{r},t)}{\partial t} \qquad .... (18)$$

Where $\vec{D}(\vec{r},t)$, $\rho(\vec{r},t)$, $\vec{B}(r,t)$, $\vec{E}(\vec{r},t)$, $\vec{H}(\vec{r},t)$ $and\, \vec{J}(\vec{r},t)$ represent the space-time variable electric induction, volume density of free charges, magnetic induction, electric field, magnetic field and total current density respectively. For homogeneous and isotropic medium, the EM wave equation can be expressed as

$$\Delta\vec{E}(\vec{r},t) - \mu_c\varepsilon_c\frac{\partial^2\vec{E}(\vec{r},t)}{\partial t^2} - \mu_c\kappa\frac{\partial\vec{E}(\vec{r},t)}{\partial t} = -\frac{1}{\varepsilon_c}\frac{\partial\nabla\rho(\vec{r},t)}{\partial t} \qquad ..... (19)$$

Where the permittivity ε_c, the permeability μ_c and the conductivity κ of homogeneous and isotropic medium are scalars and independent of the fields. The permittivity and permeability have absolute values and are complex quantities.

In monochromatic plane wave solution, the attenuation factor is same for all the components of the electric field vector and hence not related to the wave polarization. If the electrical field is defined in an orthogonal basis $(\hat{x},\hat{y},\hat{z})$ $with\, \hat{k} = \hat{z}$, then in a lossless medium the time dependent electric field can be expressed as

$$\vec{E}(z,t) = \begin{bmatrix} E_{ox}\cos(\omega t - k_c z + \psi_x) \\ E_{oy}\cos(\omega t - k_c z + \psi_y) \\ 0 \end{bmatrix} \qquad ..... (20)$$

Where (E_{ox}, E_{oy}) and (ψ_x, ψ_y) are the amplitudes and phases of electric field vector along the x- ad y-directions respectively, and ω and κ are the angular frequency and propagation constant of the wave.

6.12.2 Polarization Ellipse

We know that the propagation of a plane monochromatic polarized wave traces a helicoidal trajectory along the $\hat{z}$ axis. Practically, representation and analyses of 3D helicoidal curves are difficult and therefore in general the characterization of the EM wave is preferred in time domain at a fixed position $z = z_0\ (say)$.

Thus, the time dependent behaviour of the EM wave is exercised at a fixed location along the $\hat{z}$ axis, in a plane of equal phases (equi-phase) and perpendicular to the direction of propagation. As the time varies, the EM wave crosses equiphase planes and traces a locus of a characteristic elliptical. This temporal wave trajectory can be determined from the following parametric equation among the different components of $\vec{E}(z_0, t)$.

$$\left(\frac{E_x(z_0,t)}{E_{0x}}\right)^2 - 2\frac{E_x(z_0,t)E_y(z_0,t)}{E_{ox}E_{oy}}\cos(\psi_y - \psi_x) + \left(\frac{E_y(z_0,t)}{E_{0y}}\right)^2 = \sin(\psi_y - \psi_x) \quad \ldots.(21)$$

This equation represents an elliptical geometry, and popularly known as polarization ellipse which explains the polarization of EM wave. The shape, size and orientation of polarization ellipse can be studied using three main parameters of ellipse itself as shown in Figure 9.

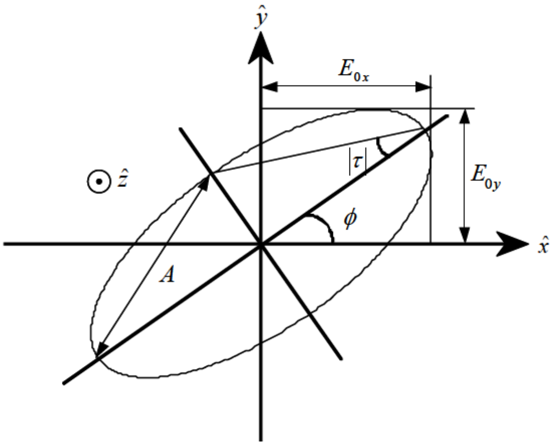

Fig. 6.9 2D Polarization Ellipse

These three parameters so called polarization ellipse parameters, are-

i) *Ellipse Amplitude (A): It is determined from the axis of the polarization ellipse*

$$A = \sqrt{{E_{0x}}^2 + {E_{0y}}^2} \quad \ldots.(22)$$

ii) Orientation angle of ellipse, $(\phi)\epsilon[-\pi/2, \pi/2]$: It is an angle formed by the major axis of ellipse with the x-axis.

$$tan2\phi = 2\frac{E_{0x}E_{0y}}{{E_{0x}}^2 - {E_{0y}}^2}cos\psi \quad with\ \psi = \psi_y - \psi_x \quad \ldots..(23)$$

iii) Ellipse aperture or ellipticity angle, $|\tau|\epsilon[-\frac{\pi}{4}, \frac{\pi}{4}]$ *: It is defined as*

$$|sin2\tau| = 2\frac{E_{0x}E_{0y}}{{E_{0x}}^2 + {E_{0y}}^2}|sin\psi| \quad \ldots..(24)$$

Where ψ is the phase angle.

The ellipticity angle(τ) determines rotation of field vector, while looking towards propagation direction $(\hat{z})$. If rotation is clockwise direction (right hand rotation) is written with negative sign and that of anticlockwise direction (left hand rotation) is expressed with positive sign.

The plane monochromatic waves can also be represented in terms of complex Jones vector. The Jones vector describes the polarization of wave with least amount of information. Jones vector $\vec{E}$, is expressed in terms of space-time dependent electric vector $\vec{E}(z,t)$ as-

$$\overrightarrow{E_J} = \vec{E}(z,t)\big|_{z=0} = \begin{bmatrix} E_{ox} \exp\,(\mathrm{j}\psi_x) \\ E_{oy} \exp(j\psi_y) \\ 0 \end{bmatrix} \qquad \ldots\ldots(25)$$

The *Jones vector* and parameters of the *polarization ellipse* are associated with each other in the following manner-

$$\overrightarrow{E_J} = A\exp(j\psi)\begin{bmatrix} \cos\,(\phi) & -\sin\,(\phi) \\ \sin\,(\phi) & \cos\,(\phi) \end{bmatrix}\begin{bmatrix} \cos\,(\tau) \\ j\sin(\tau) \end{bmatrix} \qquad \ldots\ldots(26)$$

Where ψ is the absolute phase term, ϕ is the angle of orientation and τ is the angle of ellipticity.

6.12.3 Polarization Ratio and State

The best way to characterize the polarization state of a Jones vector is to form its polarization ratio which are given as-

$$\rho = \frac{\mathrm{E_y}}{\mathrm{E_x}} = \frac{\mathrm{E_{0y}}}{\mathrm{E_{0x}}}.\mathrm{e}^{\mathrm{j}(\psi_\mathrm{y}-\psi_\mathrm{x})} \qquad \ldots.(27)$$

In term of polarization ellipse parameters

$$\rho = \frac{\sin\phi\cos\tau + \mathrm{j}.\cos\phi\sin\tau}{\cos\phi\cos\tau - \mathrm{j}.\sin\phi\sin\tau} \qquad \ldots.(28)$$

Knowledge of ρ easily discriminate the canonical polarization states-

i) For linear or plane polarization, the angle of orientation is given by $\phi = tan^{-1}(\rho)$

$$\arg(\rho) = 0 + n\pi \qquad \ldots\ldots.(29)$$

ii) The polarization is circular, sign(agr(ρ))

$$\rho = e^{j\pi/4} \qquad \ldots..(30)$$

The polarization is called left circular if $agr(\rho)$ is positive and right circular if $agr(\rho)$ is negative.

iii) Elliptical polarization

Elliptical polarization is defined for other possible conditions under circular polarization category.

Further for left elliptical polarization the value of $agr(\rho)$ is positive and negative for right elliptic polarization.

6.12.4 Stokes Vector

The Jones vector can be obtained by two complex quantities (equation 27), which means in order to measure the Jones vector of the received signal of radar system, the radar imaging system should record the amplitude as well as phase information of received backscatter wave.

Currently available SAR systems are coherent and are capable to measure the amplitude and phase of the received signal. Earlier, only non-coherent systems were available which were only capable to measure the power of received backscattered wave. Therefore, characterization of wave polarization was necessary to be done by using power measurements only. This characterization of wave polarization generally carried out with the help of Stoke's vector.

Let for a given wave the Jones vector is $\underline{E}$, therefore the Hermitian product can be written as-

$$\underline{E}.\underline{E}^{\dagger} = \begin{bmatrix} E_x E_x{}^* & E_x E_y{}^* \\ E_y E_x{}^* & E_y E_y{}^* \end{bmatrix} \qquad \ldots\ldots..(31)$$

This Hermitian product (2x2) can be decomposed by the Pauli group of matrices. The Pauli group of matrices are-

$$\sigma_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \sigma_1 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \sigma_2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \sigma_{3=} \begin{bmatrix} 0 & -j \\ j & 0 \end{bmatrix} \qquad \ldots..(32)$$

So the decomposition of (31) is follows-

$$\underline{E}.\underline{E}^{\dagger} = \frac{1}{2}(g_0\sigma_0 + g_1\sigma_1 + g_2\sigma_2 + g_3\sigma_3) = \frac{1}{2}\begin{bmatrix} g_0 + g_1 & g_2 - ig_3 \\ g_2 + jg_3 & g_0 - g_1 \end{bmatrix} \qquad \ldots\ldots..(33)$$

Where (g_0, g_1, g_2, g_3) are the Stokes parameters. This set of parameters is denoted as-

$$\underline{\mathrm{g_E}} = \begin{bmatrix} \mathrm{g}_0 \\ \mathrm{g}_1 \\ \mathrm{g}_2 \\ \mathrm{g}_3 \end{bmatrix} = \begin{bmatrix} |\mathrm{E_x}|^2 + |\mathrm{E_y}|^2 \\ |\mathrm{E_x}|^2 - |\mathrm{E_y}|^2 \\ 2\mathrm{Re}(\mathrm{E_x}\mathrm{E_y}{}^*) \\ -2\mathrm{Im}(\mathrm{E_x}\mathrm{E_y}{}^*) \end{bmatrix} = \begin{bmatrix} E_{0x}{}^2 + E_{0y}{}^2 \\ E_{0x}{}^2 - E_{0y}{}^2 \\ 2E_{0x}E_{0y}cos\psi \\ 2E_{0x}E_{0y}sin\psi \end{bmatrix} \qquad \ldots..(34)$$

And these parameters have the following relationship-

$$g_0{}^2 = g_1{}^2 + g_2{}^2 + g_3{}^2 \qquad \ldots\ldots.(35)$$

From this equation, it is clear that only three stokes parameters are independent and one is dependent. Where the parameter (g_0) is equal to the total wave power, g_1 is the total power of plane polarized components, g_2 is the total power of plane polarized components obtained at tilt angles ψ=45 or 135 degrees, while g_3 represents the total power of circular polarized components in the plane wave case. It is important to note that if any of the parameters is having non-zero value, it means a polarized component is present in the plane wave.

The Stokes parameters are sufficient to characterize the relative phase and magnitude, and thus, the wave polarization state. Since in equation (34), the Stokes parameters are observed from only measurement of powers and therefore, the Stokes vector can characterize the polarization state of a wave with the help of these four real parameters.

The stokes parameters can also be expressed in terms of polarization ellipse parameters (equations 20, 21, 22) as-

$$\underline{\mathrm{g_E}} = \begin{bmatrix} A \\ Acos(2\phi)\cos(2\tau) \\ Asin(2\phi)\cos(2\tau) \\ A\sin(2\tau) \end{bmatrix} \qquad \ldots\ldots.(36)$$

For a given polarization state, the stokes vector can be expressed as -

$$\underline{g_E} = A^2 \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(2\phi) & -sin(2\phi) & 0 \\ 0 & sin(2\phi) & cos(2\phi) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(2\tau) & 0 & -sin(2\tau) \\ 0 & 0 & 1 & 0 \\ 0 & sin(2\tau) & 0 & cos(2\tau) \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & cos(2\psi) & -sin(2\psi) \\ 0 & 0 & sin(2\psi) & cos(2\psi) \end{bmatrix} \underline{g_{\hat{x}}} \qquad \ldots \ldots (37)$$

Where $\underline{g_{\hat{x}}}$ denotes the stokes vector which is associated with the horizontal plane polarization.

6.12.5 Scattering Matrix

For one pixel, the Jones vectors of incident and scattered plane wave ($\underline{E}^i, \underline{E}^s$) under field conditions are related with the scattering matrix [S] as

$$\underline{E}^s = \frac{e^{jkR}}{R}[S]\underline{E}^i \qquad \ldots \ldots (38)$$

The scattering matrix $[S_{BI}]$ for bistatic acquisition in (H, V)-basis is

$$[S_{BI}] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

$$= e^{j\phi_{HH}} \begin{bmatrix} |S_{HH}| & |S_{HV}|e^{j(\phi_{HV}-\phi_{HH})} \\ |S_{VH}|e^{j(\phi_{VH}-\phi_{HH})} & |S_{VV}|e^{j(\phi_{VV}-\phi_{HH})} \end{bmatrix} \qquad \ldots \ldots \ldots (39)$$

In this equation, first letter of subscript denotes the transmitted and second letter of subscript denotes the received polarization. From this equation, it is obvious that scattering matrix is complex in nature and have four amplitudes parameters and three differential phases parameters. The absolute phase term ϕ_{HH} shows secondary importance in polarimetric SAR analyses.

In monostatic acquisition, $S_{HV} = S_{VH} = S_{XX}$ $(Reciprocity\ theorem)$, therefore the scattering matrix $[S_M]$ is written as

$$[S_M] = \begin{bmatrix} S_{HH} & S_{XX} \\ S_{XX} & S_{VV} \end{bmatrix}$$

$$= e^{j\phi_{HH}} \begin{bmatrix} |S_{HH}| & |S_{XX}|e^{j(\phi_{XX}-\phi_{HH})} \\ |S_{XX}|e^{j(\phi_{XX}-\phi_{HH})} & |S_{VV}|e^{j(\phi_{VV}-\phi_{HH})} \end{bmatrix} \qquad \ldots \ldots \ldots (39)$$

In this acquisition, the parameters are reduced to five (three amplitudes and two differential phases). These parameters can be used to characterize the scatterers.

The total backscattered energy from the scatterer, and received and recorder by the imaging system can be expressed-

$$SPAN([S]) = Tr\left([S][S]^{\dagger}\right) \qquad \ldots \ldots (40)$$

Where † represents the transpose-conjugate or Tranjugate or conjugate-transpose operator of a matrix.

Let us consider a single scatterer per resolution cell and hence this can be fully described by the scattering matrix [S]. It means this scatterer (deterministic) can be imaged coherently like a single 'point scatterer'. On the other hand, distributed scatterers are equivalent to multiple point scatterers per resolution cell, which means distributed scatterers induce depolarization effect and can be described with the help of second order formulation. Therefore, the scattering matrix [S] can be vectorised with the help of a vector operator to generate a system vector (scattering vector)

$$\underline{k} = Vec([S]) = \frac{1}{2}\, Tr\{[S].\chi\} \qquad \ldots\ldots(41)$$

Where χ denotes a set of 2x2 basis matrices (real and complex). In SAR polarimetry, commonly used sets of basis matrices are 1) Pauli basis matrices (χ_P), and 2) Lexicographic basis matrices(χ_L).

For bi-static acquisition, the set of four Pauli basis matrices (χ_{P_4}) is given by

$$\chi_{P_4} = \{\sqrt{2}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}, \sqrt{2}\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}, \sqrt{2}\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}, \sqrt{2}\begin{bmatrix}0 & -j\\j & 0\end{bmatrix}\} \qquad \ldots\ldots(42)$$

The four-dimensional (bi-static) Pauli scattering vector ($\underline{k}_{P_4}$) can be obtained by vectorization of scattering matrix.

$$\underline{k}_{P_4} = \frac{1}{\sqrt{2}}[S_{HH} + S_{VV} \quad S_{HH} - S_{VV} \quad S_{HV} + S_{VH} \quad j(S_{HH} - S_{VV})]^T \qquad \ldots\ldots(43)$$

In bi-static case, the set of four Lexicographic basis matrices (χ_{L_4}) is given by

$$\chi_{L_4} = \{2\begin{bmatrix}1 & 0\\0 & 0\end{bmatrix}, 2\begin{bmatrix}0 & 1\\0 & 0\end{bmatrix}, 2\begin{bmatrix}0 & 0\\1 & 0\end{bmatrix}, 2\begin{bmatrix}0 & 0\\0 & 1\end{bmatrix}\} \qquad \ldots\ldots(44)$$

This results into the bi-static Lexicographic scattering vector ($\underline{k}_{L_4}$)

$$\underline{k}_{L_4} = [S_{HH} \quad S_{HV} \quad S_{VH} \quad S_{VV}]^T \qquad \ldots\ldots(45)$$

The total backscattered power (SPAN) can be determined by scattering vectors $\underline{k}$ as

$$SPAN([S]) = \underline{k}.\underline{k}^{\dagger} = |\underline{k}|^2 \qquad \ldots\ldots(46)$$

These two scattering vectors can be transformed into each other by using a special unitary matrix as

$$\underline{k}_{P_4} = [U_{4T}]\underline{k}_{L_4} \quad using\ [U_{4T}] = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0 & 0 & 1\\1 & 0 & 0 & -1\\0 & 1 & 1 & 0\\0 & j & -j & 0\end{bmatrix} \qquad \ldots\ldots(47)$$

In monostatic case the set of Pauli basis matrices (χ_{P_3}) reduces to

$$\chi_{P_3} = \{\sqrt{2}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}, \sqrt{2}\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}, \sqrt{2}\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}\} \qquad \ldots\ldots(48)$$

Therefore, the monostatic Pauli scattering vector ($\underline{k}_{P_3}$) obtained after vectorization is

$$\underline{k}_{P_3} = \frac{1}{\sqrt{2}}[S_{HH} + S_{VV} \quad S_{HH} - S_{VV} \quad 2S_{XX}]^T \qquad \ldots\ldots(49)$$

In the monostatic case, the set of Lexicographic basis matrices (χ_{L_3}) is reduces to

$$\chi_{L_3} = \{2\begin{bmatrix}1 & 0\\0 & 0\end{bmatrix}, 2\sqrt{2}\begin{bmatrix}0 & 1\\0 & 0\end{bmatrix}, 2\begin{bmatrix}0 & 0\\0 & 1\end{bmatrix}\} \qquad \ldots\ldots(50)$$

This results into the monostatic Lexicographic scattering vector ($\underline{k}_{L_3}$)

$$\underline{k}_{L_3} = [S_{HH} \quad \sqrt{2}S_{XX} \quad S_{VV}]^T \qquad \ldots\ldots(51)$$

These two scattering vectors can be transformed into each other by using a special unitary matrix as

$$\underline{k}_{P_3} = [U_{3T}]\underline{k}_{L_3} \quad using\ [U_{3T}] = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 & 1 \\ 1 & 0 & -1 \\ 0 & \sqrt{2} & 0 \end{bmatrix} \qquad \ldots\ldots(52)$$

The polarimetric coherency matrix [T] and the covariance matrix [C] can be obtained by taking the outer product of the scattering vector (Pauli's or Lexicographic) and its adjoint vector together with an averaging operation. Thus, four-dimensional coherency matrix $[T_4]$ and covariance matrix $[C_4]$ are expressed as

$$\langle[T_4]\rangle = \langle\underline{k}_{P_4}.\underline{k}_{P_4}{}^{\dagger}\rangle \quad and\ \langle[C_4]\rangle = \langle\underline{k}_{L_4}.\underline{k}_{L_4}{}^{\dagger}\rangle \qquad \ldots\ldots(53)$$

The expansion of these is as

$$\langle[T_4]\rangle = \frac{1}{2}\begin{bmatrix} \langle|S_{HH}+S_{VV}|^2\rangle & \langle(S_{HH}+S_{VV})(S_{HH}-S_{VV})^*\rangle & \langle(S_{HH}+S_{VV})(S_{HV}+S_{VH})^*\rangle & \langle -j(S_{HH}+S_{VV})(S_{HV}-S_{VH})^*\rangle \\ \langle(S_{HH}-S_{VV})(S_{HH}+S_{VV})^*\rangle & \langle|S_{HH}-S_{VV}|^2\rangle & \langle(S_{HH}-S_{VV})(S_{HV}+S_{VH})^*\rangle & \langle -j(S_{HH}-S_{VV})(S_{HV}-S_{VH})^*\rangle \\ \langle(S_{HV}+S_{VH})(S_{HH}+S_{VV})^*\rangle & \langle(S_{HV}+S_{VH})(S_{HH}-S_{VV})^*\rangle & \langle|S_{HV}+S_{VH}|^2\rangle & \langle -j(S_{HV}+S_{VH})(S_{HV}-S_{VH})^*\rangle \\ \langle j(S_{HV}-S_{VH})(S_{HH}+S_{VV})^*\rangle & \langle j(S_{HV}-S_{VH})(S_{HH}-S_{VV})^*\rangle & \langle j(S_{HV}-S_{VH})(S_{HV}+S_{VH})^*\rangle & \langle|S_{HV}-S_{VH}|^2\rangle \end{bmatrix}$$

$$\langle[C_4]\rangle = \begin{bmatrix} \langle|S_{HH}|^2\rangle & \langle(S_{HH})(S_{HV})^*\rangle & \langle(S_{HH})(S_{VH})^*\rangle & \langle(S_{HH})(S_{VV})^*\rangle \\ \langle(S_{HV})(S_{HH})^*\rangle & \langle|S_{HV}|^2\rangle & \langle(S_{HV})(S_{VH})^*\rangle & \langle(S_{HV})(S_{VV})^*\rangle \\ \langle(S_{VH})(S_{HH})^*\rangle & \langle(S_{VH})(S_{HV})^*\rangle & \langle|S_{VH}|^2\rangle & \langle(S_{VH})(S_{VV})^*\rangle \\ \langle(S_{VV})(S_{HH})^*\rangle & \langle(S_{VV})(S_{HV})^*\rangle & \langle(S_{VV})(S_{VH})^*\rangle & \langle|S_{VV}|^2\rangle \end{bmatrix} \qquad \ldots\ldots(54)$$

The three-dimensional coherency matrix $[T_3]$ and covariance matrix $[C_3]$ are expressed as

$$\langle[T_3]\rangle = \langle\underline{k}_{P_3}.\underline{k}_{P_3}{}^{\dagger}\rangle \quad and\ \langle[C_3]\rangle = \langle\underline{k}_{L_3}.\underline{k}_{L_3}{}^{\dagger}\rangle \qquad \ldots\ldots(55)$$

The expansion of these is as

$$\langle[T_3]\rangle = \frac{1}{2}\begin{bmatrix} \langle|S_{HH}+S_{VV}|^2\rangle & \langle(S_{HH}+S_{VV})(S_{HH}-S_{VV})^*\rangle & 2\langle(S_{HH}+S_{VV})(S_{XX})^*\rangle \\ \langle(S_{HH}-S_{VV})(S_{HH}+S_{VV})^*\rangle & \langle|S_{HH}-S_{VV}|^2\rangle & 2\langle(S_{HH}-S_{VV})(S_{XX})^*\rangle \\ 2\langle(S_{XX})(S_{HH}+S_{VV})^*\rangle & 2\langle(S_{XX})(S_{HH}-S_{VV})^*\rangle & 4\langle|S_{XX}|^2\rangle \end{bmatrix}$$

$$\langle[C_3]\rangle = \begin{bmatrix} \langle|S_{HH}|^2\rangle & \sqrt{2}\langle(S_{HH})(S_{XX})^*\rangle & \langle(S_{HH})(S_{VV})^*\rangle \\ \sqrt{2}\langle(S_{XX})(S_{HH})^*\rangle & 2\langle|S_{XX}|^2\rangle & \sqrt{2}\langle(S_{XX})(S_{VV})^*\rangle \\ \langle(S_{VV})(S_{HH})^*\rangle & \sqrt{2}\langle(S_{VV})(S_{XX})^*\rangle & \langle|S_{VV}|^2\rangle \end{bmatrix} \qquad \ldots\ldots\ldots(56)$$

Special unitary transformation matrices ($[U_{4T}], [U_{3T}]$) can be used to relate the scattering vectors of two different basis as well as to transform the coherency and covariance matrix with each other.

Bistatic: $\langle[T_4]\rangle = [U_{4T}]\langle[C_4]\rangle[U_{4T}]^{-1}$ Monostatic: $\langle[T_3]\rangle = [U_{3T}]\langle[C_3]\rangle[U_{3T}]^{-1}$ $\ldots..(57)$

This study is limited to acquisition in monostatic only. The azimuthal scattering symmetry means the two symmetry properties namely reflection, and rotation symmetries have relevance and hence applied over the coherency matrix.

i) *Reflection symmetry:* In this type of symmetry, scatterers are considered to have an axis of symmetry in the plane defined by the line of sight (LoS) and the nadir line. The correlation terms among co-polarized and cross-polarized echoes are zero $(T_{13} = T_{31} = T_{23} = T_{32} = 0)$ under reflection symmetry -

$$\langle[T]\rangle_{ref} = \begin{bmatrix} T_{11} & T_{12} & 0 \\ T^*{}_{12} & T_{22} & 0 \\ 0 & 0 & T_{33} \end{bmatrix} \qquad \ldots\ldots(58)$$

Thus, a coherency matrix $\langle[T]\rangle_{ref}$ under reflection symmetry can be completely characterized by five parameters (four real and one imaginary).

ii) *Rotation Symmetry:* In this symmetry the scatterers remain invariant under rotations around the radar line of sight. It can be stated in terms of eigen-values $(\lambda_1, \lambda_2, \lambda_3 \text{ and } \lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0)$ of $\langle[T]\rangle_{ref}$

$$\langle[T]\rangle_{rot} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & (\lambda_2 + \lambda_3)/2 & j(\lambda_2 - \lambda_3)/2 \\ 0 & -j(\lambda_2 - \lambda_3)/2 & (\lambda_2 + \lambda_3)/2 \end{bmatrix} \qquad \ldots\ldots(59)$$

Therefore, the coherency matrix $\langle[T]\rangle_{rot}$ under rotation symmetry is characterized by only three eigenvalues. In addition, the correlation terms T_{22} *and* T_{33} are non-zero and equal in comparison to all other off-diagonal elements.

So, for azimuthal symmetry results are obtained by combining both reflection and rotation symmetries

$$\langle[T]\rangle_{azim} = \begin{bmatrix} 2\lambda_1 & 0 & 0 \\ 0 & \lambda_2 + \lambda_3 & 0 \\ 0 & 0 & \lambda_2 + \lambda_3 \end{bmatrix} \qquad \ldots\ldots(60)$$

Thus, coherency matrix $\langle[T]\rangle_{azim}$ with azimuthal symmetric is fully characterized by only two parameters (T11, T22 = T33) or by three Eigen-values, while all off-diagonal elements are zero.

6.13 Applications of microwave remote sensing

The principles of synthetic aperture radar (SAR) were developed in the 20th century and since then the successful operationalization of different SAR systems started at airborne and space-borne platforms. SAR imaging systems are an active microwave remote sensing system, which can capture data in all weather conditions and is independent of sun illumination. SAR systems are capable to image large coverage area with high spatial resolution. For this reason, SAR remote sensing techniques meet the requirements of diverse range of applications in the field of agricultural, soil science, forestry, glaciology, oceanography, hydrology, urban studies, geosciences, and many more. Selected applications of air borne/space borne imaging radar and radiometers in remote sensing are as summarized below.

Table 6.3 Various applications of microwave remote sensing systems

Radar Applications	
Major Field	**Sub-Fields**
Geology	Structure
	Lithology

Hydrology	Soil moisture
	Watershed mapping
	Flood mapping
	Mapping of surface water (ponds, lakes, rivers)
	Snow mapping
Agriculture	Crop mapping
	Agricultural-practice monitoring
	Identifying field boundaries
	Monitoring growth and harvest progress
	Identifying stress areas
	Rangeland monitoring
	Water problems–same as hydrology
Forests	Monitoring cutting
	Mapping fire damage
	Identifying stress areas
	Vegetation density
Cartography	Topographic mapping
	Land-use mapping
	Monitoring land-use changes, urban development, etc.
Polar regions (cryosphere)	Monitoring and mapping sea ice
	Detecting and tracking icebergs
	Mapping glacial ice sheets
	Monitoring glacial changes, including measuring
	Velocity

Ocean	Measuring wave spectra
	Monitoring oil spills
	Monitoring ship traffic and fishing fleets
	Wind speed and direction measurement
	Rain
	Clouds
	Measuring currents
	Undersea mapping

Applications of Radiometers	
Major Field	**Sub-Fields**
Hydrology	Soil moisture
	Watershed surface drainage
	Flood mapping
	Mapping of surface water (ponds, lakes, rivers)
	Snowcover extent, snow water equivalent, snow wetness
Agriculture	Soil moisture distribution for crop yield estimation and irrigation scheduling
	Delineation of freeze-thaw boundaries
Polar regions (cryosphere)	Monitoring and mapping sea ice and sea-ice type
	Mapping glacial ice sheets
	Monitoring ice-sheet melt conditions
Ocean	Measuring surface wind speed
	Measuring surface temperature
	Measuring surface salinity

	Monitoring oil spills
	Measuring and mapping rain
Meteorology and climatology (primarily over the ocean)	Temperature profile
	Integrated water vapor
	Water vapor profile
	Liquid water (rain)
Stratosphere, mesosphere, and lower thermosphere	Atmospheric temperature profile
	Magnetic field profile
	Abundance of atmospheric gases

Space borne non-imaging radars find applications in oceanography and polar ice, where altimeters and scatterometers are used.

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Chapter 7

THERMAL REMOTE SENSING

7.1 Introduction

Thermal remote sensing is a specialized field that involves the detection and analysis of thermal energy emitted by objects and surfaces. It utilizes sensors capable of measuring the infrared radiation emitted by these targets, which is directly related to their temperature. This technology provides a unique perspective by capturing thermal information that is not visible to the naked eye or detectable through other remote sensing techniques. By understanding the thermal behavior of objects and environments, thermal remote sensing enables a wide range of applications across various disciplines. The significance of thermal remote sensing lies in its ability to capture and interpret thermal information, offering valuable insights into diverse fields. In environmental studies, it allows for the monitoring and analysis of surface temperatures in water bodies, aiding in the assessment of aquatic ecosystem health and the identification of areas prone to pollution. Additionally, it assists in the detection and tracking of oil spills, volcanic activity, and the study of glacier dynamics. Thermal remote sensing plays a crucial role in understanding the Earth's energy balance and its impact on climate change.

In urban planning and infrastructure development, thermal remote sensing is instrumental in assessing the thermal performance of buildings, identifying areas with excessive heat or energy loss, and optimizing energy efficiency. It helps in identifying urban heat islands and guiding the placement of green spaces, contributing to sustainable and climate-resilient urban development. Furthermore, thermal remote sensing supports disaster management efforts by detecting and monitoring wildfires, assessing damage caused by natural disasters, and aiding in emergency response. Thermal remote sensing also holds great relevance in agriculture. It enables the assessment of crop health, water stress, and disease detection by analyzing thermal anomalies. Farmers and agricultural planners can optimize irrigation strategies, identify areas requiring intervention, and improve resource management based on the insights provided. This technology offers valuable information for maximizing agricultural productivity while minimizing environmental impacts. Thermal remote sensing is a powerful tool for capturing thermal information and analyzing the temperature patterns of objects and environments. Its significance spans various fields, including environmental studies, urban planning, disaster management, and agriculture. By providing unique insights into thermal behavior, thermal remote sensing contributes to a better understanding of our planet, supports informed decision-making, and aids in addressing pressing environmental challenges.

7.2 Principles of Thermal Remote Sensing

The principles of thermal remote sensing involve the fundamental concepts and processes underlying the capture and analysis of thermal information using remote sensing techniques. The thermal infrared region is a portion of the electromagnetic spectrum that falls within the longer-wavelength end of the infrared region. It corresponds to the wavelengths typically emitted by objects with temperatures above absolute zero. In this region, the wavelengths range from approximately 3 to 14 micrometers (µm). The thermal infrared region is of particular interest in thermal remote sensing because it captures the emitted thermal energy from objects and surfaces, allowing temperature analysis and monitoring.

Thermal radiation is the electromagnetic radiation emitted by objects due to their temperature. All objects with a temperature greater than absolute zero emit thermal radiation. The intensity and wavelength distribution of thermal radiation depend on the object's temperature. Hotter objects emit more intense radiation, and the wavelength distribution follows Planck's law, which describes the spectral distribution of thermal radiation. The physics behind thermal remote sensing follows two physical laws viz. Stefan-Boltzmann law and the Planck's law.

7.2.1 Stefan-Boltzmann law

The Stefan-Boltzmann law, also known as the Stefan-Boltzmann radiation law, describes the relationship between the total energy radiated by a perfect black body (an idealized object that absorbs all incident radiation) and its temperature. It is named after the physicists Josef Stefan and Ludwig Boltzmann, who made significant contributions to the understanding of thermal radiation. The Stefan-Boltzmann law states that the total power radiated per unit surface area (also known as the radiative flux) by a black body is directly proportional to the fourth power of its absolute temperature. Mathematically, it can be expressed as:

$$P = \sigma \times A \times T^4$$

Where:

- P is the total power radiated per unit surface area (in watts per square meter, W/m^2),
- σ (sigma) is the Stefan-Boltzmann constant, approximately equal to 5.67 x 10^-8 $W/(m^2{\cdot}K^4)$,
- A is the surface area of the object,
- T is the absolute temperature of the object (in kelvin, K).

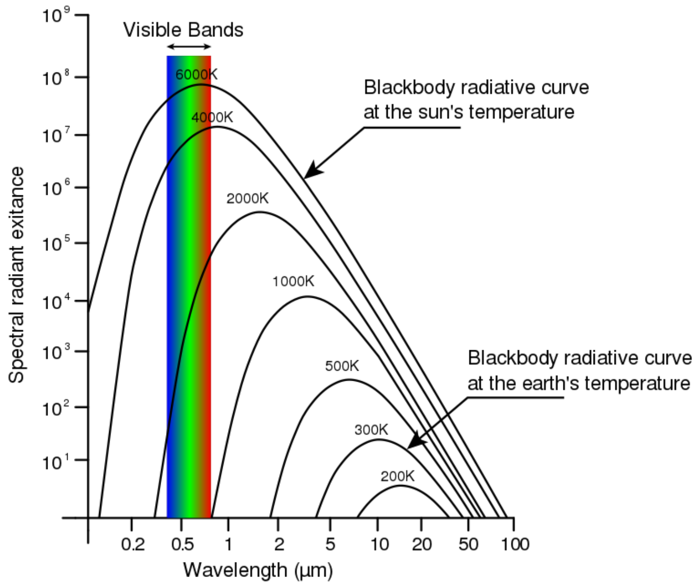


Fig. 7.1 Plot of spectral radiant existence vs wavelength representing the Blackbody emission curves

The Stefan-Boltzmann law implies that as the temperature of a black body increases, the rate at which it emits energy increases significantly. In other words, hotter objects emit more radiation per unit area than cooler objects. This relationship is fundamental to our understanding of thermal radiation and has applications in various fields, including astrophysics, climate science, and engineering.

It's worth noting that the Stefan-Boltzmann law is derived for ideal black bodies, which do not exist in reality. However, many real-world objects, especially those with high emissivity, can approximate black body behavior to a good degree.

7.2.2 Planck's Law

Planck's law, on the other hand, describes the spectral distribution of thermal radiation. Planck's law, formulated by the German physicist Max Planck in 1900, describes the spectral distribution of electromagnetic radiation emitted by a black body at a given temperature. It played a crucial role in the development of quantum mechanics and is considered one of the foundational principles of modern physics.

Planck's law states that the spectral radiance (or spectral intensity) of black body radiation at a specific wavelength λ and temperature T is given by:

$B(\lambda, T) = (2hc^2 / \lambda^5) * (1 / (e^{(hc / \lambda kT)} - 1))$

Where:

- ❖ $B(\lambda, T)$ is the spectral radiance (in watts per square meter per steradian per wavelength),
- ❖ h is the Planck constant (approximately 6.626 x 10-34 joule-seconds),
- ❖ c is the speed of light in a vacuum (approximately 3.00 x 108 meters per second),
- ❖ λ is the wavelength of the radiation (in meters),
- ❖ k is the Boltzmann constant (approximately 1.381 x 10-23 joules per kelvin),
- ❖ T is the absolute temperature of the black body (in kelvin).

Planck's law describes how the spectral radiance of black body radiation depends on both the wavelength and the temperature. It shows that as the wavelength decreases, the spectral radiance increases, meaning that shorter wavelengths carry more energy. Additionally, as the temperature increases, the peak of the spectral distribution shifts to shorter wavelengths, and the overall intensity of the radiation increases. Planck's law provides an accurate description of the radiation emitted by black bodies across the electromagnetic spectrum. It has important applications in various fields, such as astrophysics, quantum mechanics, and the study of thermal radiation. It provides the intensity of radiation emitted at different wavelengths by an object at a given temperature. Planck's law incorporates the temperature of the object, the speed of light, and fundamental constants to determine the distribution of thermal radiation across different wavelengths.

7.2.3 Infrared Radiation

Thermal remote sensing operates in the infrared portion of the electromagnetic spectrum. It is a technique that involves detecting and measuring thermal radiation emitted by objects in the infrared portion of the electromagnetic spectrum. The infrared spectrum spans wavelengths longer than those of visible light, typically ranging from approximately 0.7 micrometers to 1000 micrometers (or 0.7 to 1000 µm). Every object with a temperature above absolute zero (-273.15 degrees Celsius or 0 Kelvin) emits thermal radiation in the form of infrared energy. The amount of infrared radiation emitted by an object depends on its temperature. By detecting and analyzing this thermal radiation, remote sensing systems can gather valuable information about the temperature and thermal properties of objects or surfaces.

7.2.4 Temperature-Emittance Relationship

There is a direct relationship between an object's temperature and the amount of thermal radiation it emits. As the temperature increases, the intensity of the emitted infrared radiation also increases. This relationship enables the estimation of temperature based on the measured radiation.

7.2.5 Atmospheric Interference

The Earth's atmosphere interacts with thermal radiation, causing absorption, emission, and scattering. Some atmospheric gases, such as water vapor and carbon dioxide, can absorb and emit infrared radiation. To account for atmospheric interference, specific atmospheric correction techniques are applied to thermal remote sensing data to obtain accurate temperature measurements of the Earth's surface. Unmanned Aerial Vehicle (UAV) platforms have become increasingly popular for thermal remote sensing applications due to their flexibility, accessibility, and ability to capture data from aerial perspectives. These platforms, commonly known as drones, can be equipped with various types of thermal sensors to capture infrared radiation and gather valuable thermal information. UAV platforms equipped with thermal sensors offer advantages such as high spatial resolution, flexibility in flight planning, and cost-effective data acquisition. They are used in various applications, including agriculture, environmental monitoring, infrastructure inspection, and search and rescue operations. The combination of UAVs and thermal sensors has expanded the possibilities for thermal remote sensing and enhanced our ability to understand thermal dynamics and patterns from aerial perspectives.

7.3 Thermal Sensing Platforms

Thermal remote sensing can be conducted using various platforms, including satellite-based sensors, airborne sensors, and ground-based instruments. Satellites equipped with thermal sensors capture large-scale thermal information over broad areas, while airborne sensors provide higher spatial resolution and flexibility. Ground-based instruments, such as thermal cameras, are often used for localized and close-range observations.

7.4 Thermal Radiometric Calibration

Calibration is crucial in thermal remote sensing to ensure accurate and reliable measurements. Radiometric calibration involves the characterization and adjustment of thermal sensors to account for instrumental errors and variations. This process ensures consistency and comparability of thermal data acquired over time and across different sensors.

7.5 Thermal Indices and Analysis

Thermal remote sensing data can be analyzed using thermal indices or temperature-emissivity separation techniques. Thermal indices, such as land surface temperature (LST) or surface kinetic temperature (SKT), provide information on the temperature distribution of the Earth's surface. Temperature-emissivity separation techniques aim to separate temperature and emissivity information to derive more precise temperature values.

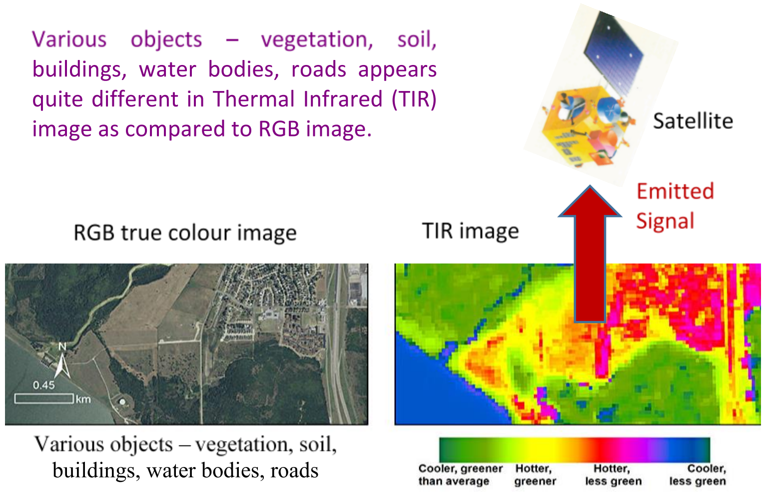


Fig 7.2 Schematic representation of the concept of thermal remote sensing

7.6 Types of Thermal Remote Sensing

Thermal remote sensing is a branch of remote sensing that focuses on the detection and measurement of thermal radiation emitted by objects and surfaces. It provides valuable information about temperature variations and thermal properties of targets. There are different types of thermal remote sensing systems, which can be classified based on their passive or active nature, as well as the type of sensors used.

7.6.1 Passive Thermal Remote Sensing

Passive thermal remote sensing systems detect the natural thermal radiation emitted by objects and surfaces without actively illuminating them. These systems rely on the temperature differences between objects and the background to capture thermal data. The main components of passive systems are thermal sensors, such as thermal cameras and radiometers. They measure the intensity of the emitted thermal radiation in different wavelength bands, typically in the longwave infrared (LWIR) or thermal infrared (TIR) regions. Passive thermal remote sensing is widely used in various applications, including agriculture, environmental monitoring, and building energy analysis.

7.6.2 Active Thermal Remote Sensing

Active thermal remote sensing systems, in contrast to passive systems, actively illuminate the target with a known source of thermal energy and measure the reflected or backscattered thermal radiation. Active systems are mainly used in specialized applications, such as thermal mapping of active volcanoes or monitoring the thermal signature of wildfires. Lidar systems, which use lasers to actively probe the environment, can also be utilized for active thermal remote sensing by measuring the temperature-dependent backscattered thermal radiation.

7.7 Thermal Sensors

Thermal sensors and detectors used in remote sensing are designed to capture and measure thermal radiation. These sensors can detect and quantify the infrared radiation emitted by objects and surfaces. They may use various technologies, such as thermopiles, microbolometers, or quantum detectors, depending on the specific wavelength range and sensitivity required for the application.

Thermal remote sensing systems typically consist of a thermal sensor or camera, data acquisition and processing components, and a platform for data collection. The sensor captures the emitted thermal radiation, which is converted into electrical signals. These signals are then processed to derive temperature information or generate thermal images. Thermal remote sensing can be conducted using satellite-based sensors, airborne sensors mounted on aircraft or drones, or ground-based instruments.

Thermal sensors play a crucial role in thermal remote sensing systems. Two commonly used types of thermal sensors are thermal cameras and radiometers.

Thermal Cameras: Thermal cameras are imaging devices that capture thermal radiation from a scene and generate thermal images. They use specialized infrared detectors to detect and convert the thermal radiation into visible images or data. Thermal cameras provide spatial information along with temperature distribution, allowing for detailed analysis of thermal patterns in a scene.

Radiometers: Radiometers are non-imaging sensors that measure the intensity of thermal radiation without generating images. They are used for quantitative measurements of temperature variations in a scene. Radiometers are commonly used in scientific research, climate studies, and thermal mapping applications.

7.7.1 Satellite-based Thermal Sensors

Satellite-based thermal sensors are deployed on satellites and provide a global perspective of the Earth's thermal properties. These sensors capture thermal data over large areas and enable the monitoring of temperature variations on a regional or global scale. Satellite-based thermal sensors often operate in the TIR region, as it offers better sensitivity for measuring thermal emissions from the Earth's surface. They are used for a wide range of applications, including weather forecasting, land surface temperature monitoring, and environmental studies.

7.7.2 Imaging Spectrometer

Imaging spectrometer can capture images for target or object of interest in hundreds of narrow contiguous spectral channels. Spectrometers operation in thermal infrared (TIR) range are known as infrared spectrometers. Imaging spectrometers have sub-systems similar to camera (with additional dispersive optical element on optical system) i.e., optics (including colour dispersion element), detector, electronics, mechanical system and thermal system. Fig. 7.4: Schematic of typical imaging spectrometer by making use of plane reflection diffraction grating as colour dispersive optical element.

Imaging spectrometer working is thermal infrared range usually makes use of cooled detector so as to have good sensitivity as signal from the target is less due to narrow bands as compared to broad band camera. Due challenging performance requirement for IR spectrometers there are few imaging IR spectrometer flown in spaceborne mission, instead many multispectral IR camera were flown. IR spectrometer will have unambiguous advantages over multispectral thermal camera, if competing sensitivity and performance requirement challenge is met by proper system configuration, design and development process.

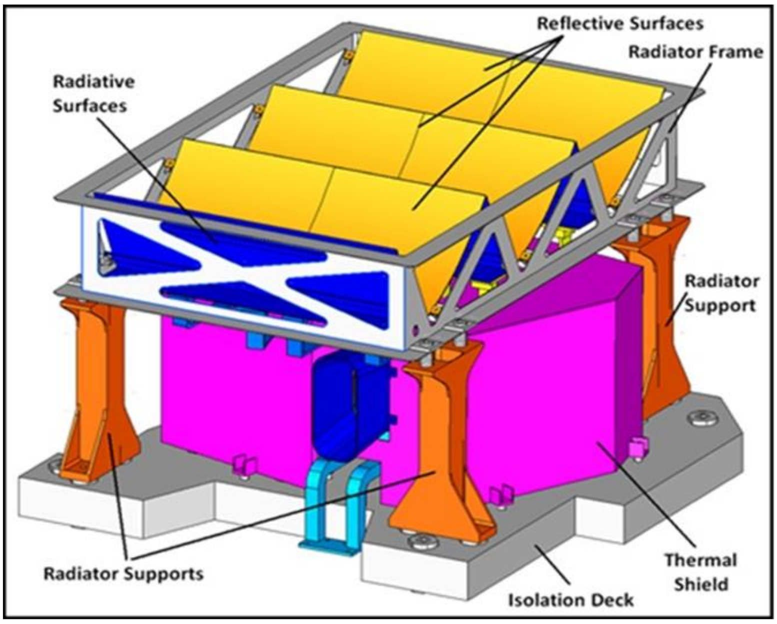


Fig. 7.3 CAD model showing various mechanical and thermal system parts (specifically a passive radiator used for thermal management of IR instruments or payloads)

Dispersive optical element / system can be either of diffraction grating, prism, tunable filters and interferometer. Grating is most common for imaging spectrometers operating in TIR range. For lab application various non-imaging IR spectrometers are based on optical interferometers (i.e., Michelson interferometer) along with Fourier Transform data processing. These IR spectrometers are called Fourier Transform IR (FTIR) spectrometers. FTIR spectrometers can of imaging type from spaceborne platform for remote sensing applications, where in imaging capability is due to the area array or by cross-track scanning system.

7.8 Data Acquisition and Processing

Thermal remote sensing systems acquire data by measuring the thermal radiation emitted or reflected by the target. The acquired data is then processed to extract meaningful information. Data processing techniques involve radiometric calibration, atmospheric correction, and temperature retrieval algorithms. These processes aim to remove sensor and atmospheric effects to obtain accurate temperature measurements and thermal maps.

7.8.1 Atmospheric Correction Techniques

Atmospheric correction is necessary in TIR imagery to account for the influence of the atmosphere on the measured thermal radiation. The atmosphere can attenuate, scatter, and emit its own thermal radiation, affecting the accuracy of temperature measurements. Several atmospheric correction techniques are employed to mitigate these effects:

Split-Window Algorithms: These algorithms utilize the differences in thermal emission between two or more spectral bands in the TIR region to estimate and correct for atmospheric effects. By comparing the observed brightness temperatures in different bands, atmospheric parameters such as water vapor content and atmospheric transmittance can be estimated and used for correction.

Radiative Transfer Models: These models simulate the interaction of thermal radiation with the atmosphere to predict the atmospheric effects on the observed thermal data. By inputting atmospheric parameters and meteorological data, radiative transfer models can generate synthetic thermal images, which are then compared with the observed data to estimate and correct for atmospheric influence.

Empirical Line Methods: These methods involve the collection of ground-truth data in the form of temperature measurements at specific locations in the scene. By comparing the ground-truth temperatures with the corresponding observed thermal values, empirical relationships are established to correct for atmospheric effects.

7.8.2 Preprocessing Steps

Preprocessing of TIR imagery involves several steps to enhance the quality and usability of the data:

Geometric Correction: Geometric correction is performed to remove distortions, such as sensor tilt, rotation, and terrain-induced displacements. This step ensures accurate spatial alignment and eliminates geometric errors in the imagery.

Radiometric Calibration: Radiometric calibration involves converting the raw sensor measurements into calibrated radiance or temperature values. Calibration procedures include correcting for sensor biases, dark current, and non-uniformity across the sensor array.

Image Enhancement: Image enhancement techniques can be applied to improve the visual interpretation of TIR imagery. These techniques include contrast adjustment, histogram equalization, and noise reduction.

7.8.3 Calibration Procedures

Calibration is a critical step in working with TIR imagery to ensure accurate and consistent temperature measurements:

In-flight Calibration: In-flight calibration involves using on-board calibration systems or known calibration targets to monitor and adjust the sensor response over time. This procedure accounts for variations in sensor performance, such as changes in detector sensitivity and response.

Laboratory Calibration: Laboratory calibration is conducted prior to the launch of a sensor and involves characterizing the sensor's radiometric response using controlled thermal sources. This calibration establishes a relationship between the sensor's output and the incident thermal radiation.

Cross-Calibration: Cross-calibration involves comparing the measurements of different sensors that observe the same targets. This procedure allows for the harmonization of data from different sensors, ensuring consistency and compatibility.

By applying atmospheric correction techniques, conducting preprocessing steps, and implementing calibration procedures, thermal infrared imagery can be interpreted accurately, providing valuable insights into temperature variations, thermal properties, and thermal patterns in the observed scene.

7.9 Applications of Thermal Remote Sensing

Thermal remote sensing systems are valuable for a wide range of applications. They enable the assessment of land surface temperatures, monitoring of vegetation health, identification of thermal anomalies in urban areas, detection of wildfires, analysis of energy efficiency in buildings, and support for disaster management and response efforts. By capturing thermal information from a distance, these systems provide valuable insights into temperature patterns and distributions, contributing to various fields of study and decision-making processes.

7.9.1 Thermal Remote Sensing Application in Agriculture

Thermal remote sensing plays a crucial role in agriculture by providing valuable insights into crop health, water stress, and overall agricultural management. Here are some key applications of thermal remote sensing in agriculture:

Crop Stress Detection: Thermal remote sensing helps detect and monitor crop stress conditions, such as water stress, nutrient deficiencies, and diseases. Healthy plants typically have a lower leaf temperature compared to stressed plants. By capturing thermal images of agricultural fields, temperature variations can be analyzed to identify stressed areas, enabling targeted interventions and optimized irrigation strategies.

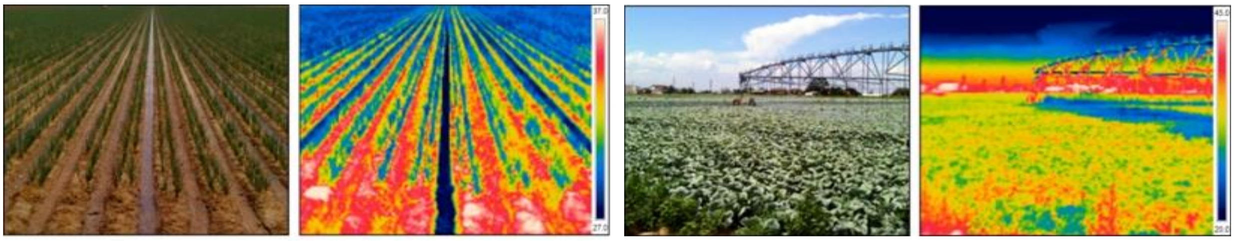


Fig 7.4 Plantation or vegetation in RGB and TIR (showing different features and may indicate their health status)

Irrigation Monitoring: Thermal remote sensing assists in irrigation management by monitoring soil moisture levels and assessing crop water stress. Thermal imagery helps identify areas with inadequate irrigation or overwatering, enabling farmers to adjust irrigation practices and conserve water resources while maintaining crop health and productivity.

Yield Estimation: Thermal remote sensing contributes to yield estimation by providing information on crop health, biomass, and growth patterns. By analyzing temperature variations and thermal patterns across a field, it is possible to assess crop vigor and predict yield potential. This information aids farmers in making informed decisions regarding harvesting schedules and optimizing crop management practices.

Disease and Pest Detection: Thermal remote sensing can help identify crop diseases and pest infestations. Infected or infested plants often exhibit temperature variations due to altered physiological processes. By analyzing thermal patterns and temperature anomalies in crop canopies, early signs of diseases or pest outbreaks can be detected, enabling timely interventions and targeted treatment. Fig. 7.5 shows the RGB and thermal IR images of plant leaves showing diseases and infected portion.

Crop Phenology Monitoring: Thermal remote sensing facilitates the monitoring of crop phenology, which involves tracking the various stages of crop growth and development. Thermal imagery helps identify key phenological stages, such as flowering and fruiting, by analyzing temperature changes associated with different growth phases. This information is valuable for crop management, including timing of fertilization, pest control, and harvesting operations.

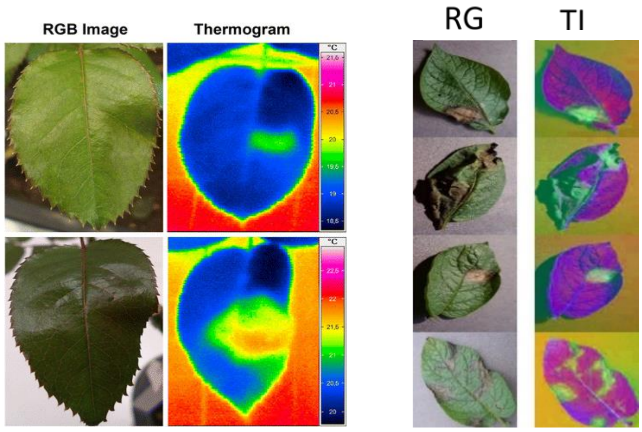


Fig 7.5. Plant leafs images in RGB and TIR (showing diseases or infected portion)

Precision Agriculture: Thermal remote sensing is an essential component of precision agriculture practices. By integrating thermal data with other remote sensing datasets (e.g., multispectral or hyperspectral imagery), farmers can create detailed crop maps, assess spatial variability within fields, and implement site-specific management strategies. This approach optimizes resource allocation, minimizes input waste, and maximizes crop productivity. Different levels of precision agriculture are shown in fig. 7.6.

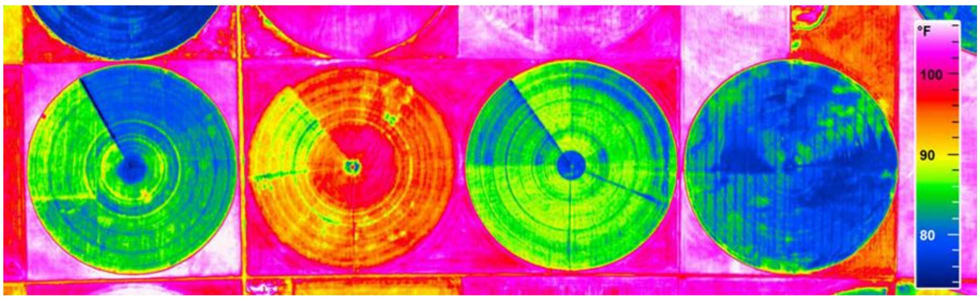


Fig. 7.6 Precision agriculture crop field showing different level of crop cover and soil moisture.

Stubble burning: Thermal remote sensing is a valuable tool for monitoring stubble burning, a practice that can have adverse environmental effects. By using thermal infrared cameras mounted on UAV platforms or satellites, thermal images can be captured to detect and assess areas with elevated temperatures associated with burning activities. Temporal analysis enables the tracking of burning incidents over time, while hotspot detection algorithms identify clusters of high-temperature pixels indicative of active burning. Integration with other data sources enhances the understanding of stubble burning's impact on air quality and allows for estimating the extent of burned areas. By employing thermal remote sensing, stakeholders can effectively monitor and manage stubble burning, implementing measures to mitigate its environmental consequences.

Overall, thermal remote sensing in agriculture enables farmers to make data-driven decisions, optimize resource management, and enhance crop productivity while minimizing environmental impact. It aids in early detection of crop stress, efficient irrigation management, disease and pest control, and overall precision agriculture practices.

7.9.2 Thermal Remote Sensing Application in Forestry and Ecosystem Studies

Thermal remote sensing has several applications in forestry and ecosystem studies. Some key applications are:

Forest Fire Detection and Monitoring: Thermal remote sensing is crucial for early detection and monitoring of forest fires. Thermal imagery can detect the high-temperature signatures associated with active fires, allowing for rapid response and fire management. It helps identify the location, extent, and intensity of fires, aiding in firefighting efforts and post-fire analysis.

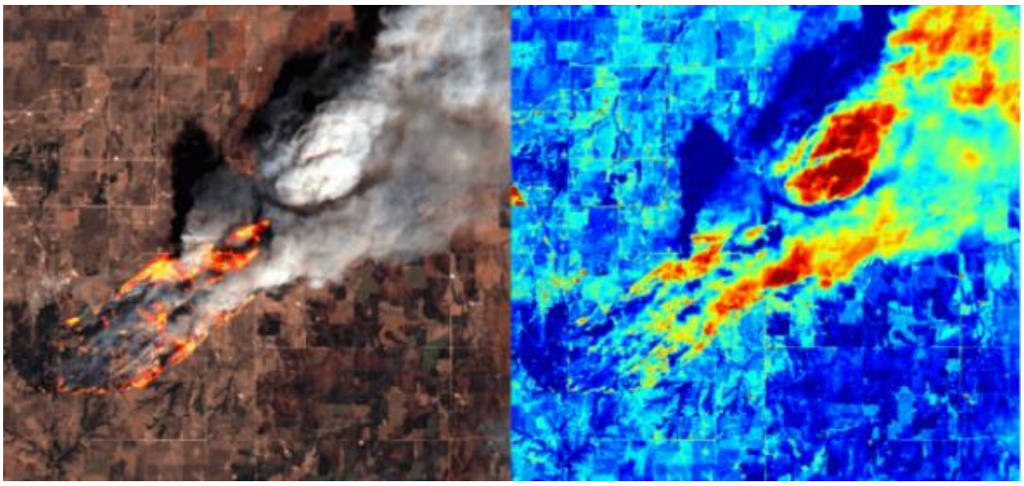


Fig. 7.7 True colour composite and TIR imagery of active fire and biomass burning

Burned Area Mapping: After a forest fire, thermal remote sensing can be used to map the extent and severity of the burned areas. By analyzing thermal signatures, post-fire temperature distributions, and thermal anomalies, it helps assess the impact of fires on vegetation, soil, and ecosystem dynamics. This information is vital for post-fire rehabilitation and restoration planning.

Fire Behavior Analysis: Thermal remote sensing enables the analysis of fire behavior and dynamics. By capturing thermal imagery during active fires, it helps characterize fire spread patterns, flame fronts, and heat release. This information contributes to understanding fire behavior, modeling fire spread, and assessing fire risk in forested ecosystems.

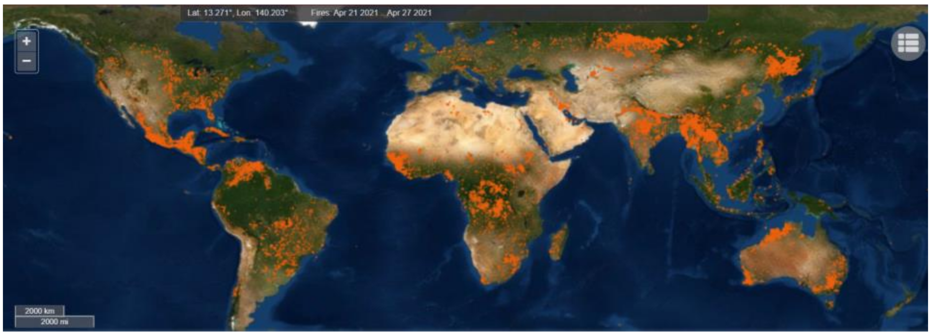


Fig. 7.8 MODIS Forest fire hotspots during 21-27 April, 2021 (FIRMS, 2021)

Vegetation Health Assessment: Thermal remote sensing aids in assessing vegetation health and stress in forests. By analyzing temperature variations and thermal patterns across forested areas, it helps identify areas with vegetation stress, disease, or pest infestations. This information is useful for targeted management interventions and monitoring ecosystem health. By analyzing temperature anomalies and thermal patterns, it enables the identification of areas affected by drought, insect infestations, or other stressors. This information supports forest management decisions and conservation efforts.

Ecosystem Functioning and Productivity: Thermal remote sensing provides insights into ecosystem functioning and productivity. By monitoring land surface temperature and assessing the thermal dynamics of vegetation, it helps estimate evapotranspiration rates, energy fluxes, and water use efficiency. This information contributes to understanding ecosystem processes, carbon dynamics, and water balance in forested ecosystems.

Biodiversity Mapping: Thermal remote sensing can assist in mapping and monitoring biodiversity in forests. By analyzing temperature variations associated with different habitat types and vegetation structures, it helps identify areas of high biodiversity or habitat diversity. This information aids in conservation planning and biodiversity assessments.

In summary, thermal remote sensing plays a crucial role in forestry and ecosystem studies. It aids in forest fire detection and monitoring, mapping burned areas, analyzing fire behavior, assessing vegetation health, understanding ecosystem functioning, mapping biodiversity, and monitoring forest health and stress. These applications contribute to effective forest management, conservation planning, and understanding the dynamics of forested ecosystems.

7.9.3 Application in Urban Heat Islands analysis and management

Thermal remote sensing has significant applications in the analysis of urban heat islands (UHIs). UHIs refer to the phenomenon where urban areas experience higher temperatures compared to the surrounding rural areas. Here are the key applications of thermal remote sensing in UHI analysis:

UHI Mapping and Characterization: Thermal remote sensing enables the mapping and characterization of UHIs by capturing temperature variations across urban areas. High-resolution thermal imagery helps identify areas with elevated temperatures, quantify temperature differences between urban and rural zones, and delineate the spatial extent of UHIs. This information is valuable for understanding the intensity and spatial patterns of UHIs.

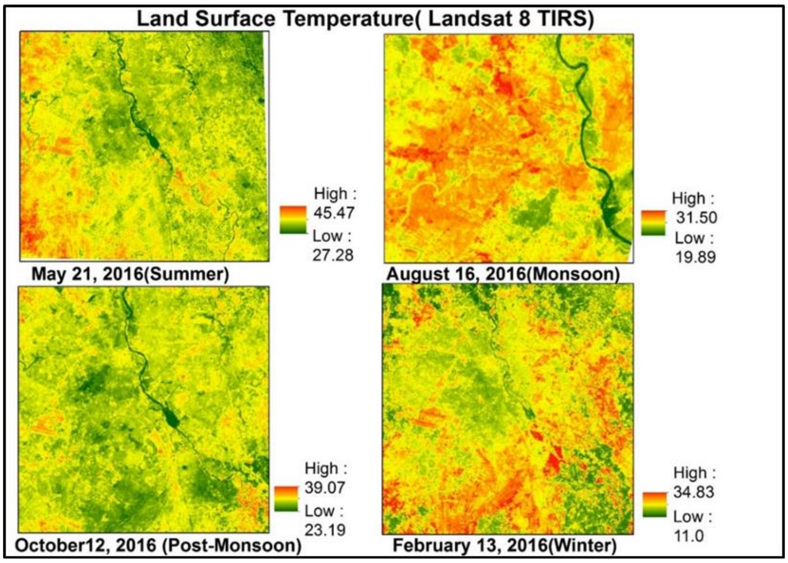


Fig. 7.9 Urban Heat Islands and their characterization from Space based thermal remote sensing

UHI Intensity and Temporal Analysis: Thermal remote sensing facilitates the analysis of UHI intensity and temporal variations. By comparing daytime and nighttime thermal images, it provides insights into the diurnal and seasonal patterns of UHIs. This analysis helps identify peak UHI occurrences, duration, and factors influencing UHI intensity, such as land cover, building density, and surface materials.

Urban Planning and Design: Thermal remote sensing data aids in urban planning and design by informing decision-making processes. It helps identify areas with high UHI intensity, guiding the prioritization of mitigation strategies, such as green infrastructure implementation, urban greening, and cool roof initiatives. Thermal remote sensing also assists in evaluating the effectiveness of urban planning interventions in reducing UHI intensity.

Energy Management: UHI analysis using thermal remote sensing contributes to energy management in urban areas. By identifying UHI hotspots, it helps target energy-efficient interventions and optimize energy consumption. For example, the identification of areas with high UHI intensity can inform the strategic placement of energy-efficient cooling systems and the implementation of heat mitigation measures in buildings.

Climate Change Impact Assessment for urban systems: Thermal remote sensing enables the assessment of the impact of climate change on UHIs. By analyzing historical thermal data and comparing it with recent imagery, it helps identify long-term trends in UHI intensity and understand the relationship between climate change and UHI dynamics. This information is crucial for climate change adaptation strategies and urban resilience planning.

Health and Well-being Studies: UHI analysis using thermal remote sensing supports studies on the health and well-being impacts of UHIs. By identifying areas with high UHI intensity, it helps identify heat-vulnerable neighbourhoods and inform heat mitigation measures to reduce heat-related health risks. It also aids in evaluating the effectiveness of heat mitigation interventions in improving the thermal comfort and well-being of urban residents.

Thermal remote sensing plays a vital role in mapping and monitoring UHIs, analyzing their intensity and temporal variations, guiding urban planning and design, facilitating energy management, assessing climate change impacts, and studying the health and well-being effects of UHIs. These applications contribute to sustainable urban development, energy efficiency, climate change adaptation, and the creation of healthier and more livable cities.

7.9.4 Application of thermal remote sensing in Building and Infrastructure

Thermal remote sensing has several applications in building and infrastructure analysis, particularly in identifying energy inefficiencies, conducting thermal inspections, and analyzing heat loss/gain. Here are the key applications:

Identification of Energy Inefficiencies: Thermal remote sensing helps identify energy inefficiencies in buildings. By capturing thermal images of building exteriors, it can detect areas with excessive heat loss or gain, inadequate insulation, and air leakage. Temperature variations on the building surfaces indicate areas of energy inefficiency, guiding energy audits and retrofitting efforts to improve energy performance.

Fig. 7.10 Monitoring energy efficiency using thermal remote sensing. Credit: Satellite Vu

Thermal Inspections: Thermal remote sensing enables non-destructive thermal inspections of buildings and infrastructure. By capturing thermal images, it helps detect hidden defects, structural issues, and malfunctioning components. It can identify areas with abnormal temperature patterns, such as electrical hotspots, moisture intrusion, or insulation deficiencies. Thermal inspections aid in preventive maintenance, minimizing downtime and optimizing asset management.

Heat Loss and Gain Analysis: Thermal remote sensing is used to analyze heat loss and gain in buildings. By comparing the temperature patterns of building surfaces, it helps quantify the amount of heat escaping or entering the building envelope. This analysis aids in evaluating the effectiveness of insulation, identifying areas of heat leakage, and optimizing heating, ventilation, and air conditioning (HVAC) systems for energy efficiency.

Roofing Analysis: Thermal remote sensing is valuable for roof inspections and analysis. It can identify areas of moisture infiltration, inadequate insulation, or damaged roofing materials. By detecting temperature variations on the roof surface, thermal remote sensing helps prioritize roof repair and maintenance activities, extending the lifespan of the roof and improving energy efficiency.

Solar Panel Efficiency: Thermal remote sensing assists in analyzing the efficiency and performance of solar panels. By capturing thermal images of solar arrays, it helps detect potential issues, such as malfunctioning cells, shading, or soiling. This information aids in optimizing solar panel performance, identifying areas for cleaning or maintenance, and ensuring maximum energy production.

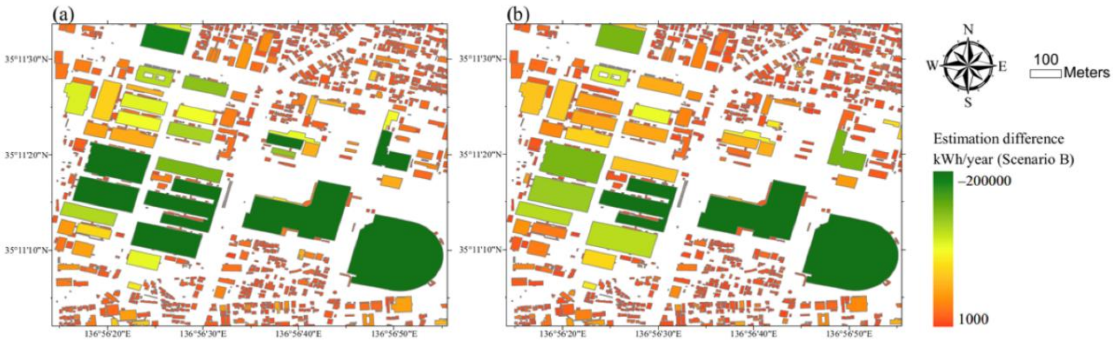


Fig 7.11 Rooftop Solar energy potential using thermal remote sensing

Infrastructure Monitoring: Thermal remote sensing is employed in the inspection and monitoring of critical infrastructure. It can detect thermal anomalies in bridges, dams, pipelines, and power lines, indicating potential structural issues, leakage, or electrical faults. Regular thermal monitoring helps identify areas requiring maintenance, preventing failures, and ensuring the safe operation of infrastructure assets.

Overall, thermal remote sensing in building and infrastructure analysis allows for the identification of energy inefficiencies, conducting thermal inspections, and analyzing heat loss/gain. These applications help improve energy efficiency, optimize maintenance efforts, ensure structural integrity, and enhance the overall performance and sustainability of buildings and infrastructure.

7.9.5 Application of Thermal Remote Sensing in Archeology

Thermal remote sensing has significant applications in archaeology, particularly in the detection of buried structures and archaeological sites using thermal anomalies. Some of the potential use of thermal remote sensing in archeological application are:

Site Discovery and Mapping: Thermal remote sensing aids in the discovery and mapping of archaeological sites. By capturing thermal images of the Earth's surface, it can detect temperature variations caused by buried archaeological features and structures. Thermal anomalies may indicate subsurface remains, such as walls, foundations, and buried artifacts, helping archaeologists identify potential excavation sites.

Soil Moisture Variations: Thermal remote sensing can detect variations in soil moisture content, which can indicate the presence of buried archaeological features. Moisture levels within the soil can differ due to variations in soil composition and water retention properties caused by buried structures. Thermal imagery helps identify areas with differential evaporation rates, suggesting potential subsurface archaeological remains.

Thermal Inertia Analysis: Thermal remote sensing utilizes the concept of thermal inertia, which is the ability of a material to store and release heat. Buried archaeological structures and features may have different thermal properties compared to the surrounding soil, resulting in variations in thermal inertia. By analyzing these thermal inertia variations, thermal remote sensing helps identify and delineate buried structures and archaeological sites.

Subsurface Anomalies: Thermal remote sensing can detect subsurface archaeological anomalies that are not visible on the surface. By capturing thermal images from airborne or satellite platforms, it can identify subsurface variations in thermal properties caused by buried features. These anomalies may include differences in thermal conductivity, heat storage capacity, or thermal emission, indicating potential archaeological remains.

Landscape Analysis: Thermal remote sensing aids in landscape analysis for archaeological purposes. It helps identify patterns and anomalies in the thermal characteristics of the landscape, such as variations in surface temperature and thermal gradients. By analyzing these patterns, thermal remote sensing can assist in understanding the historical land use, settlement patterns, and cultural practices of past civilizations.

Monitoring Excavation Sites: Thermal remote sensing can be used to monitor excavation sites and assess changes in temperature patterns during excavation. By capturing thermal images before, during, and after excavation, it helps identify new thermal anomalies that may indicate previously unknown buried features or provide insights into the excavation process itself.

The applications of thermal remote sensing in archaeology provide valuable tools for site discovery, mapping, and monitoring. By detecting thermal anomalies and analyzing temperature patterns, it assists archaeologists in identifying buried structures, delineating archaeological sites, and understanding past human activities. These applications contribute to the preservation and exploration of our cultural heritage

7.9.6 Application of thermal remote sensing in climate and weather monitoring

Thermal remote sensing plays a crucial role in climate and weather studies by providing valuable information on the Earth's energy balance, surface temperature, atmospheric composition, and weather patterns. It offers numerous applications and contributions in this field. One of the key applications is surface temperature monitoring, enabling the measurement and analysis of temperature patterns across vast regions. It helps in studying phenomena like urban heat islands, tracking land surface temperature changes, and identifying anomalies related to climate events such as El Niño and La Niña.

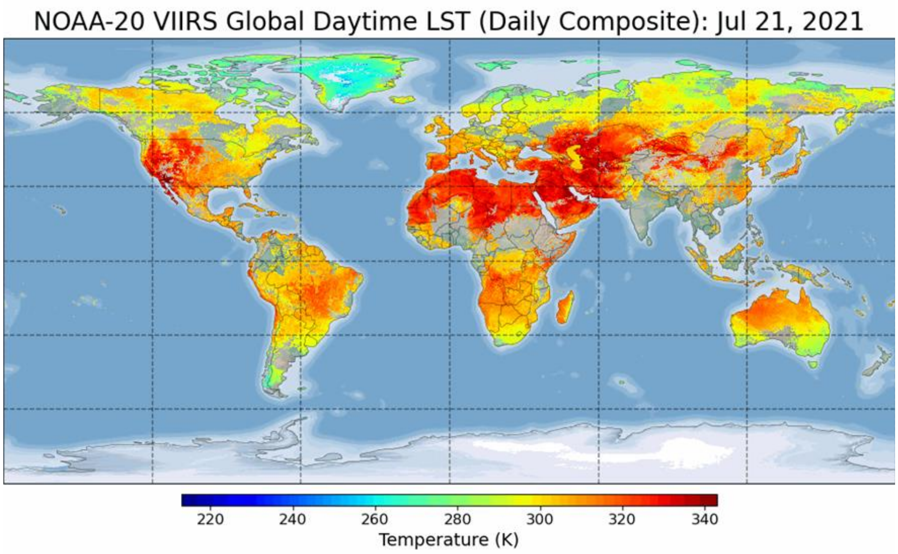


Fig. 7.12 Land surface temperature global map, useful for weather prediction and climate modeling

Thermal remote sensing also aids in estimating the Earth's energy balance by quantifying thermal radiation emitted by the surface and absorbed by the atmosphere. This data is essential for understanding climate dynamics, assessing the impact of greenhouse gases and aerosols, and studying the Earth's radiation budget. Furthermore, it contributes to the analysis of atmospheric composition, including greenhouse gases, ozone, and water vapor. These measurements assist in studying atmospheric chemistry, quantifying greenhouse gas emissions, and evaluating temperature and humidity distribution in the atmosphere.

In weather forecasting, thermal remote sensing data is crucial. It helps meteorologists track weather systems, monitor cloud properties, and analyze temperature gradients, facilitating accurate predictions and enhancing our understanding of weather dynamics. Moreover, thermal remote sensing supports climate change analysis by monitoring long-term surface temperature changes, sea surface temperature, and ice melt. These observations help quantify climate change impacts and track indicators such as rising global temperatures and shrinking polar ice caps. Additionally, it aids in analyzing extreme weather events like heatwaves, droughts, and wildfires. Monitoring surface temperature anomalies and identifying regions experiencing unusual thermal conditions contribute to understanding event dynamics and supporting early warning systems.

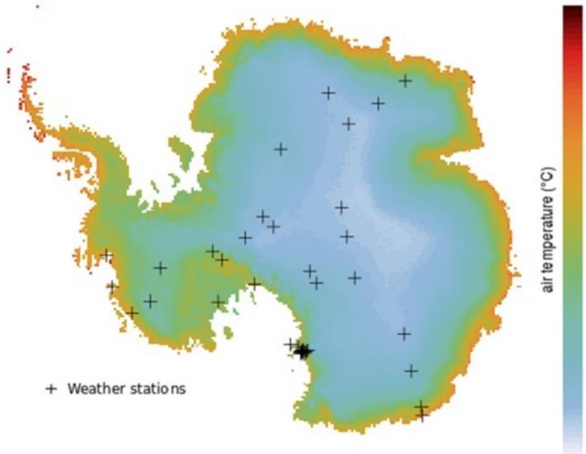
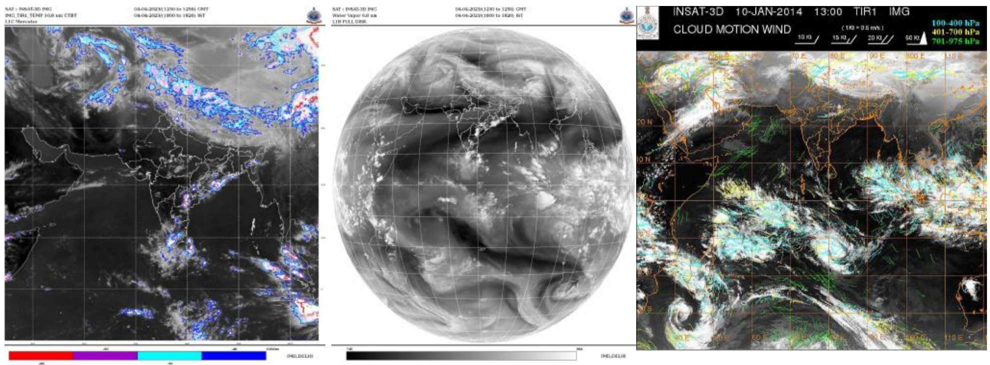


Fig. 7.13 Antarctica temperature map from satellite data and weather station locations

7.9.7 Cyclogenesis using SST through thermal remote sensing

Cyclogenesis, the process of cyclone formation, can be studied by utilizing thermal remote sensing techniques to monitor Sea Surface Temperature (SST). Specifically, in the case of SST measurement, thermal sensors focus on detecting the infrared radiation emitted by the ocean. Through the analysis of these thermal signatures, the temperature of the ocean surface can be estimated with a high degree of precision.



(a) (b) (c)

Fig 7.14 Thermal Imaging of Oceans for Cyclone monitoring. (a) Cloud temperature map from INSAT-3D data (using 10.8 µm channel); (b) water vapour map from INSAT-3D data (using 6.8 µm channel); (c) Wind vectors generated from INSAT-3D data (using TIR-1 channel)

Cyclone forecasting: SST plays a crucial role in cyclogenesis as it provides the necessary heat and moisture for the development of cyclones. Warmer ocean waters transfer thermal energy to the atmosphere above, causing the air to become buoyant and rise. This upward movement of warm air creates a low-pressure system at the surface, which is a key component in the formation of cyclones. By employing thermal remote sensing, meteorologists can identify areas with unusually high SST, which serve as potential breeding grounds for cyclones. Monitoring these SST patterns provides valuable insights into the progression and intensification of cyclones, facilitating more accurate forecasting and better preparedness for potential impacts.

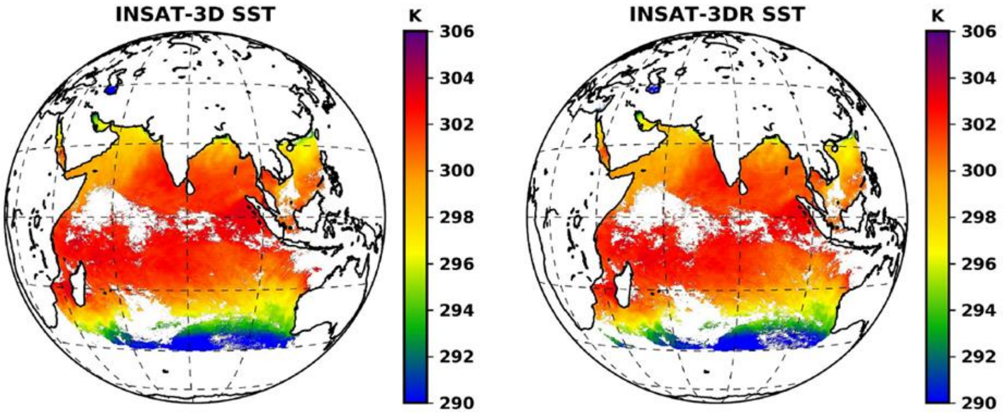


Fig 7.15 Sea surface temperature generated from INSAT-3D data (using TIR channels)

Cyclone modeling: Thermal remote sensing plays a crucial role in cyclone modeling by providing valuable insights into the thermal structure and characteristics of cyclones. Utilizing satellite-based sensors, researchers can capture and analyze the infrared radiation emitted by cyclones, enabling them to gather data on temperature variations and heat distribution within the cyclone system. This data helps in understanding the internal dynamics of cyclones, such as the development of eyewalls, the location and intensity of convection, and the distribution of warm and cold air masses. By integrating thermal remote sensing data into cyclone models, scientists can enhance the accuracy of predictions, deepen their understanding of cyclone behavior, and contribute to the development of effective strategies for forecasting and mitigating the impacts associated with these powerful weather systems.

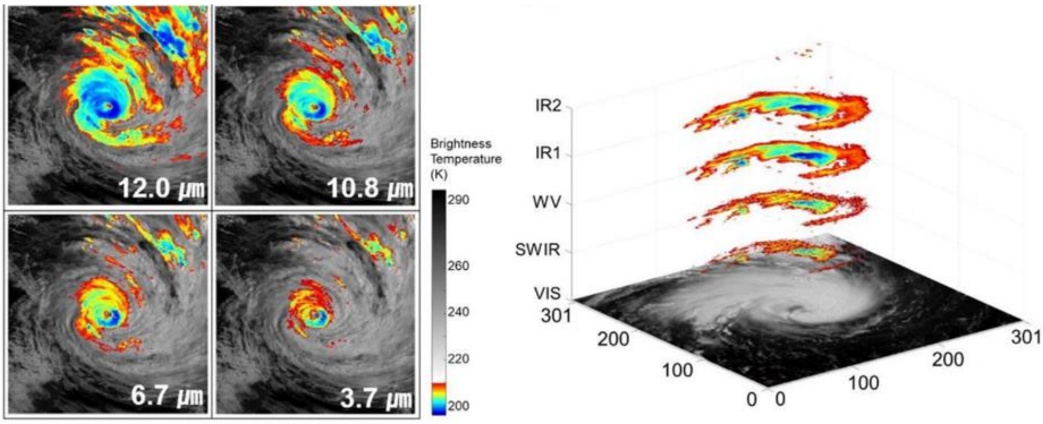


Fig 7.16 Cyclone dynamic modelling along with their vertical structure

7.10 Case Studies

7.10.1 Active Fire Detection using satellite remote sensing

Satellite-based active fire detection is a method used to identify and monitor fires by utilizing satellite sensors designed to detect and track fires from space. These sensors capture thermal infrared radiation emitted by active fires, allowing for the detection and mapping of fire hotspots over large areas. Specialized satellite sensors like MODIS (Moderate Resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imaging Radiometer Suite) are commonly employed for active fire detection. These sensors are equipped with thermal bands that measure emitted thermal radiation in specific wavelength ranges associated with fires. Orbiting the Earth, the satellite sensors acquire data by scanning the planet's surface. They capture images or measurements of the Earth's thermal radiation, including the radiation emitted by active fires.

Fire detection algorithms are applied to the satellite data to identify and differentiate fire signals from other thermal sources. These algorithms utilize techniques such as temperature thresholds, spectral analysis, and temporal analysis to distinguish fire signatures. The contextual fire detection algorithm developed by Giglio and colleagues incorporates various contextual cues to enhance the accuracy of fire detection from satellite imagery. The algorithm takes into account spatial, spectral, and temporal information to differentiate fire signals from other thermal anomalies. It utilizes neighbouring pixel analysis to assess the shape, size, and distribution of fire-related signals within the spatial context. Spectral analysis involves examining multiple spectral bands and indices to identify distinct fire signatures. Temporal analysis considers the persistence and growth of fire hotspots over time. Additionally, environmental factors such as weather conditions and topographic features are integrated to evaluate the likelihood and behavior of fires. By incorporating these contextual cues, the Giglio et al. algorithm improves the reliability and effectiveness of fire detection, facilitating timely and accurate monitoring of fire activity.

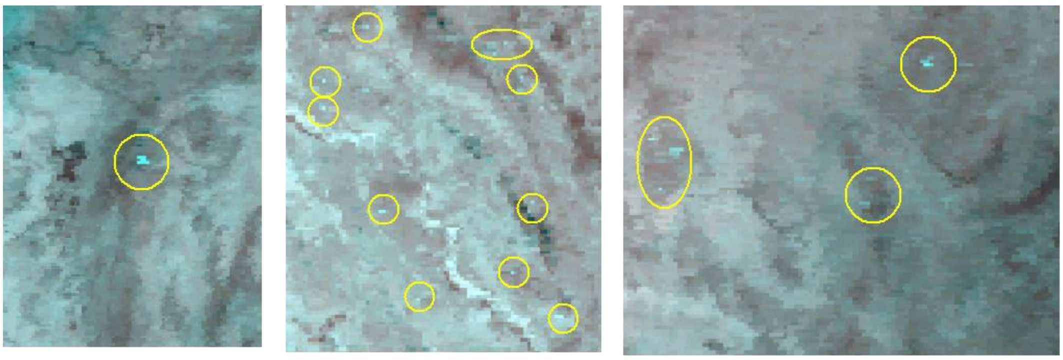


Fig 7.17 Thermal Anomaly images detected using contextual algorithm of Giglio et. al, (2023). Source: NRSA, 2005

The fire detection algorithms identify fire hotspots within the satellite images. Hotspots represent areas with elevated temperatures and significant thermal anomalies, indicating the presence of active fires. Each hotspot is typically represented by its geographic coordinates and associated fire characteristics, such as temperature and confidence level.

Fire Mapping and Monitoring: The detected fire hotspots are mapped and displayed using Geographic Information Systems (GIS) technology. This enables visualization and tracking of fire activity over time. Fire maps can be regularly updated to monitor fire spread and intensity, providing valuable information for firefighting efforts and assessing fire risks.

Satellite-based active fire detection is a valuable tool for monitoring and managing wildfires, particularly in remote or inaccessible areas. It enables timely detection, tracking, and mapping of fires on a global scale, supporting fire management agencies, researchers, and decision-makers in wildfire response and prevention efforts.

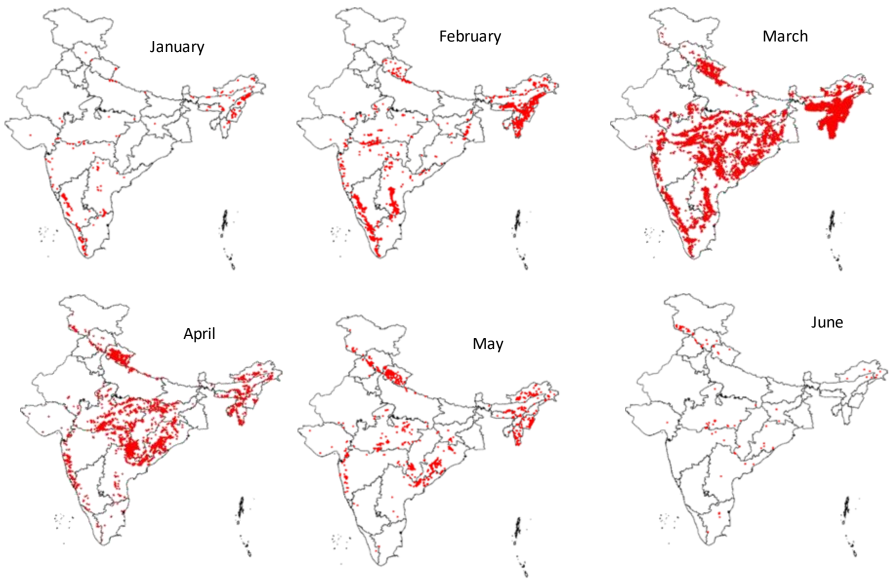


Fig 7.18 Forest fire distribution in Indian subcontinent during 2019 fire season using MODIS Terra and Aqua.

7.10.2 Spatio-Temporal Distribution of Heat Wave Risk and Vulnerability in Indo Gangetic Plains of India Using Modis LST

Heat Waves (HW) is one of the extreme weather events affecting human mortality in many parts of the world. Increasing frequency and duration of heat waves (HWs) is responsible for increasing health hazards like thermal stress in human and livestock, increasing mortality due to dehydration and adverse impact on the economy across the globe. Recent global HW events is found to have a significant impact on human health and mortality (Barriopedro et al., 2011; WMO, 2011). The impact is more profound in urban areas due to pre-existing urban heat island (UHI) effect, lack of vegetation cover and sheer density of population, which amplifies the impact of HW.

Lack of spatial variability in ground-based observations makes this data inadequate to study local scale HW conditions. Hence, in this study, large volume of analysis ready data of MODIS LST available on open-source platform of Google Earth Engine (GEE) has been employed to compute number of HW indicators in Indo-Gangetic Plains of northern India from year 2003-2019. Analysis Ready Data (ARD) of MODIS Land Surface Temperature (LST) pertaining to 91 days in a year and 5,669,300 grids were computed within 1 hour using GEE platform. GEE's parallel computing power is found to be highly efficient to process large volume of data for analysing spatio-temporal variability of HW conditions which would otherwise take weeks or even months of local computation efforts. Seven HW indicators pertaining to Duration, Frequency and intensity such as Average HW Duration, Max HW Duration, Cumulative HW Days, Max HW Events, Cumulative Warm Days, Max HW Temperature, Max warm day Temperature have been computed (Rao et al., 2021). Temporal trend of HW indicators revealed that year 2009-2019 has shown increased frequency, duration and intensity of HW conditions in the study area as compared to period 2003-2009 (Fig. 7.19).

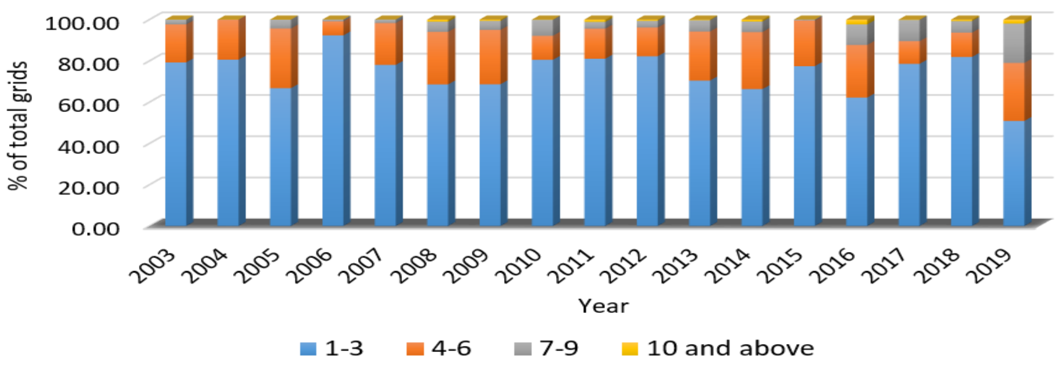
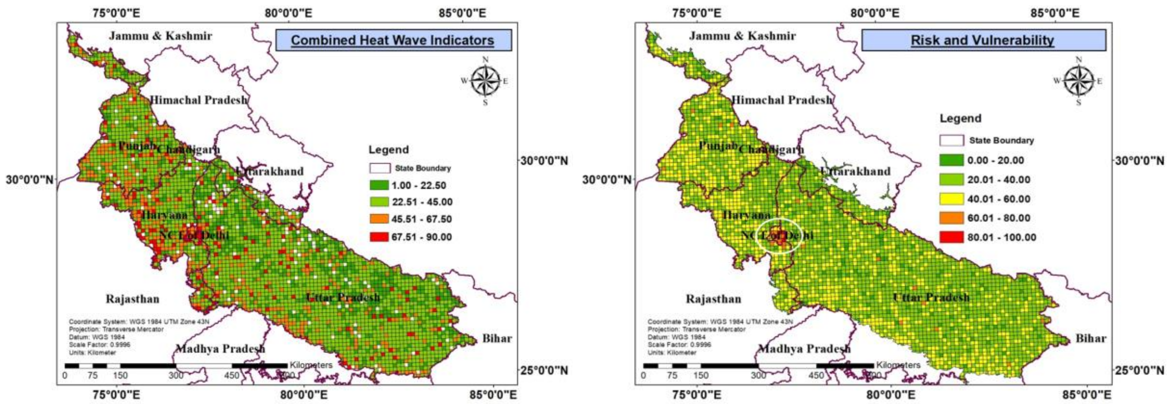


Fig. 7.19 Maximum Heat wave duration (2003-2019)

A cumulative HW indicator computed by integrating all seven HW indicators through Analytical Hierarchy Process (AHP) shows higher values of heat wave index in the region of NCT Delhi and the nearby area along with the neighbouring plains in the state of Haryana, India. Further, risk and vulnerability hotspot analysis by integrating cumulative HW indicator, GHSL population and LULC transformation (from year 2005-2006 to 2015-16) shows highest risk of HW events in NCT Delhi and its surrounding region. Some parts of Uttar Pradesh and Haryana regions also displayed high HW risk because of the concentrated urban centers. However, other than the NCT Delhi region, other pockets are either very small or show a scattered pattern of HW (Fig 7.20a). Analysis of change in built up area from year 2005-2006 to 2015-16 shows positive correlation of the growth in built-up with all seven HW indicators (Fig 7.21).



(a) (b)

Fig. 7.20 (a) Cumulative Heat Wave Indicator; (b) Risk and Vulnerability Hotspots in Indo-Gangetic Plains of India

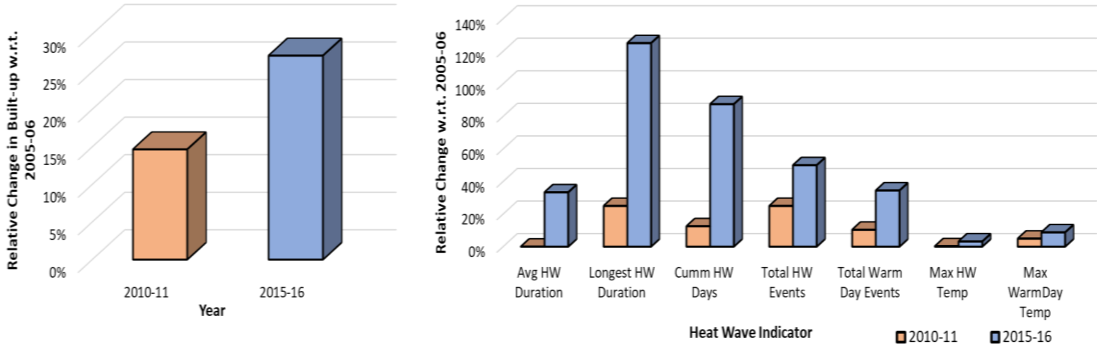


Fig. 7.21: Impact of Built-up change on Heat Wave

Thermal remote sensing has emerged as a valuable tool for analyzing heat waves and their impacts. By utilizing sensors mounted on satellites or airborne platforms, thermal remote sensing can capture detailed information about surface temperatures and thermal patterns over large geographic areas. This technology enables researchers and policymakers to monitor and assess the intensity, extent, and duration of heat waves, providing crucial insights into their spatial and temporal dynamics. By analyzing thermal data, scientists can identify hotspots, understand heat wave patterns, and evaluate the vulnerability of different regions to extreme heat events. These findings are instrumental in developing effective heat wave mitigation strategies, enhancing public health response, and informing urban planning decisions to create heat-resilient cities. Thermal remote sensing, therefore, plays a vital role in advancing our understanding of heat waves and supporting proactive measures to mitigate their adverse effects on human health, infrastructure, and ecosystems.

7.10.3 Monitoring Glacial retreat and Glacial Melting in Antarctic using Thermal Remote Sensing

Monitoring the retreat and melting of glaciers in Antarctica using thermal remote sensing is essential for understanding the effects of climate change. Thermal remote sensing techniques provide valuable data on temperature variations in glaciers and ice sheets. By utilizing satellite-based sensors that capture the thermal radiation emitted by the Earth's surface, scientists can analyze surface temperatures of glaciers and identify areas experiencing active melting.

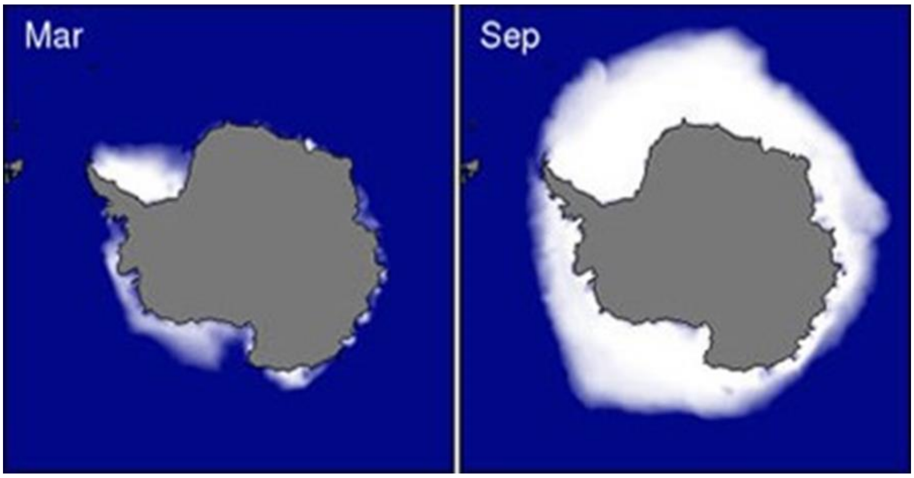


Fig 7.22 Variations in Ice cover over Antarctica in different season (long-term observation indicates the degree of climate change)

One approach involves using thermal infrared sensors to measure the heat radiated by the ice surface. By comparing temperature data from different time periods, researchers can assess the rate of glacial retreat and melting, providing insights into the overall stability and health of the ice mass. Thermal remote sensing is also useful for monitoring the presence of meltwater on glaciers. Meltwater forms as a result of glacial melting, and its existence indicates increased melting rates. By analyzing thermal images, scientists can identify and track the extent of meltwater ponds or streams on glaciers, helping to evaluate the intensity and duration of melting events.

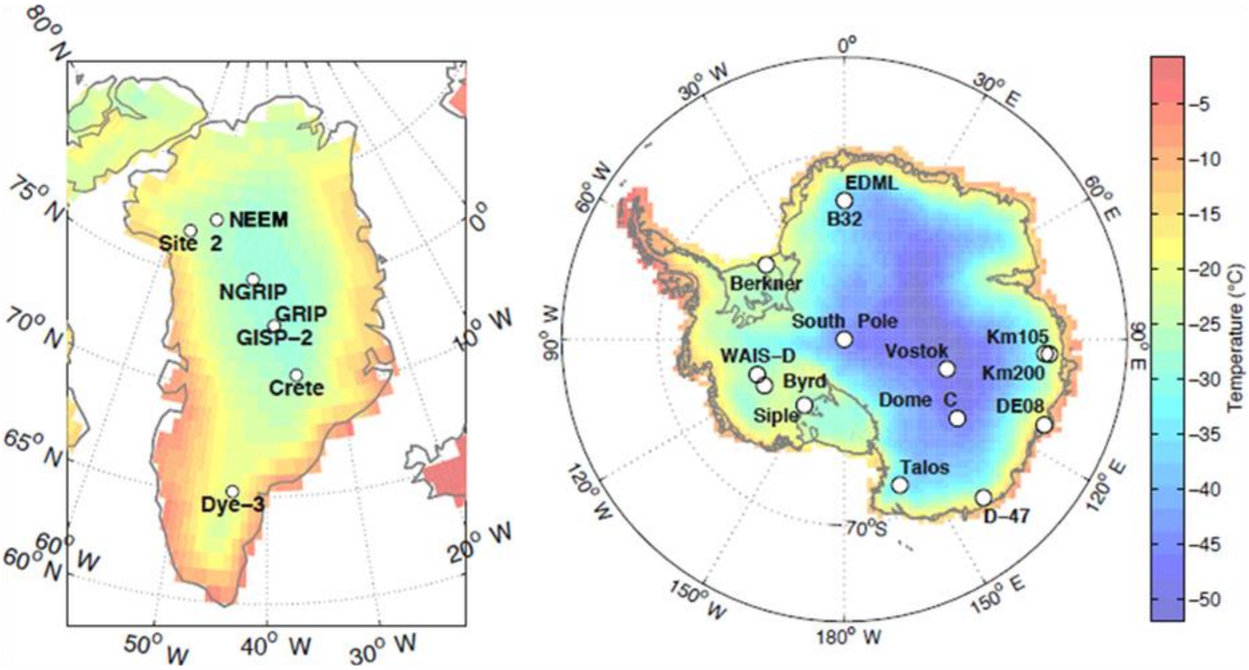


Fig 7.23 Surface / ice temperature over Antarctica and Greenland

Additionally, combining thermal remote sensing with other techniques such as satellite altimetry allows researchers to estimate changes in ice thickness. By measuring the surface temperature and elevation of glaciers, scientists can infer the thinning or thickening of ice masses over time, providing valuable insights into ice loss and accumulation. Thermal remote sensing offers a non-invasive and efficient method for monitoring glacial retreat and melting in Antarctica. By analyzing temperature variations, detecting meltwater presence, and integrating data from various sources, researchers can enhance our understanding of the changing dynamics of glaciers and their response to climate change in the Antarctic region.

7.11 Challenges and Future Directions

Thermal remote sensing, while a powerful tool, faces several challenges and limitations that can affect its application and data interpretation. These challenges include atmospheric interference, low spatial resolution, surface emissivity variability, surface and background complexity, weather and solar illumination constraints, and cost and accessibility. One significant challenge is atmospheric interference. The Earth's atmosphere interacts with thermal radiation, leading to absorption and emission of energy. Factors like humidity, aerosols, and water vapor content can introduce errors in temperature measurements. Correcting for atmospheric effects through advanced atmospheric correction techniques is necessary to obtain accurate and reliable thermal data. Another limitation is the relatively low spatial resolution of thermal remote sensing systems compared to other remote sensing techniques. This makes it challenging to capture fine-scale details and detect small-scale features accurately. Although higher spatial resolution thermal sensors exist, they often come at a higher cost, limiting their accessibility.

Surface emissivity variability poses another challenge. Different materials have different emissivity values, affecting the thermal radiation they emit. Variability in surface emissivity can introduce errors in temperature measurements, requiring accurate knowledge and correction of surface emissivity values to obtain precise temperature data. Surface and background complexity can also complicate thermal remote sensing analysis. Urban areas, dense vegetation, and heterogeneous landscapes can introduce complexity in thermal patterns, making it challenging to differentiate between natural and anthropogenic heat sources. Shadows, reflections, and variations in surface properties further add to the complexity of interpreting thermal data. Weather conditions and solar illumination affect thermal remote sensing data acquisition. Cloud cover, rain, and fog can hinder the acquisition of thermal imagery or reduce its quality. Thermal remote sensing is also limited to daylight or twilight conditions when there is sufficient temperature contrast between objects and the background. Cost and accessibility are significant limitations. High-quality thermal remote sensing systems can be expensive to acquire and operate, restricting their availability to projects with limited budgets. Additionally, accessibility to thermal remote sensing data may be limited due to data licensing and restrictions.

Addressing these challenges and limitations is crucial to improve the accuracy and usability of thermal remote sensing data. Advancements in sensor technology, data processing algorithms, atmospheric correction techniques, and calibration procedures are ongoing efforts to overcome these limitations. By addressing these challenges, thermal remote sensing can continue to be a valuable tool in various fields of study, enabling better understanding and analysis of thermal phenomena and their applications.

7.12 Potential advancements in sensor technology and data processing techniques

The exploration of potential advancements in sensor technology and data processing techniques for thermal remote sensing is an area of active research and development. These advancements aim to overcome the limitations and challenges associated with thermal remote sensing and enhance its capabilities. Here are some potential areas of advancement:

Sensor Technology: Advances in sensor technology can lead to improvements in spatial resolution, spectral range, and sensitivity of thermal sensors. Higher spatial resolution sensors would enable the detection of smaller-scale thermal features and provide more detailed thermal maps. Expanded spectral ranges could allow for better differentiation of thermal signatures from various materials, improving the accuracy of temperature measurements. Moreover, increased sensor sensitivity would enhance the detection of subtle temperature variations, enabling more precise analysis of thermal patterns.

Thermal Radiometry: Advancements in thermal radiometry techniques can improve the accuracy and calibration of thermal remote sensing data. Enhanced radiometric calibration procedures would help mitigate systematic biases and uncertainties in temperature measurements, ensuring higher data quality and reliability. Furthermore, developments in absolute radiometric calibration methods would enable more accurate temperature quantification, facilitating more rigorous comparative analysis between different thermal datasets.

Machine Learning and Artificial Intelligence: The application of machine learning and artificial intelligence (AI) algorithms holds immense potential for advancing data processing techniques in thermal remote sensing. These techniques can aid in automated feature extraction, classification, and anomaly detection, enabling more efficient and accurate interpretation of thermal data. Machine learning algorithms can learn patterns and relationships within thermal datasets, improving the identification and classification of thermal anomalies or buried structures.

Fusion with Other Remote Sensing Data: Integration of thermal remote sensing data with other remote sensing datasets, such as multispectral or LiDAR data, can provide complementary information and enhance the overall analysis. By combining thermal data with other data sources, it becomes possible to derive more comprehensive and precise insights into various phenomena, such as land cover classification, vegetation health assessment, or urban heat island analysis. The fusion of different remote sensing data can offer a more holistic view of the studied environment and enable synergistic analysis.

These potential advancements in sensor technology and data processing techniques for thermal remote sensing have the potential to significantly enhance its capabilities and overcome existing limitations. Continued research and development in these areas will contribute to improved data quality, higher-resolution thermal imagery, more accurate temperature measurements, and advanced analysis methods, enabling better understanding and application of thermal remote sensing in various fields, from environmental monitoring to infrastructure assessment and cultural heritage preservation.

7.13 Future research directions and emerging applications

Future research directions in thermal remote sensing are focused on pushing the boundaries of technology and expanding the range of applications. Some key areas of future research and emerging applications in thermal remote sensing are:

Future research will focus on developing more advanced thermal sensors with improved spatial and spectral resolution. Higher-resolution sensors will enable the detection of smaller-scale features and provide more detailed thermal maps, while expanded spectral ranges will allow for better differentiation of thermal signatures from various materials. These advancements will enhance the accuracy and precision of temperature measurements and expand the range of detectable thermal phenomena. This can open up new opportunities in fields such as urban planning, precision agriculture, and infrastructure monitoring. Improvement in the spatial resolution of thermal remote sensing to capture thermal information at a microscale level can enable the detection and monitoring of localized thermal patterns, such as heat anomalies at the building or street level in urban environments. Microscale thermal mapping can contribute to urban planning, energy management, and the mitigation of heat-related risks in cities.

Future research in data processing techniques for thermal remote sensing involves exploring advanced algorithms, machine learning, and artificial intelligence to extract more meaningful information from thermal data. This includes automated feature extraction, object recognition, and change detection methods to enhance data interpretation and analysis capabilities. The integration of thermal remote sensing with AI and machine learning techniques is an emerging research direction. AI algorithms can aid in automated feature extraction, classification, and anomaly detection, enabling more efficient and accurate interpretation of thermal data. Machine learning techniques can learn patterns and relationships within thermal datasets, improving the identification and classification of thermal anomalies and enabling predictive analysis.

The integration of thermal data with other remote sensing datasets, such as optical, radar, and LiDAR, holds promise for improved analysis and applications. Fusion of multiple sensors can provide a more comprehensive understanding of the environment, allowing for better characterization of complex phenomena, such as land cover classification, vegetation health assessment, and disaster monitoring. Fusion of thermal remote sensing data with other remote sensing datasets, such as multispectral, hyperspectral, or LiDAR data, holds great potential. Integrating multiple data sources can provide a more comprehensive understanding of the studied environment, enabling improved land cover classification, vegetation health assessment, and urban heat island analysis. This integration allows for synergistic analysis and enhances the overall interpretation of remote sensing data. Hyperspectral imaging in the thermal domain is also an emerging area of research. By capturing thermal data across a wide range of spectral bands, hyperspectral thermal imaging offers the potential to identify and characterize materials based on their thermal spectral signatures. This can have applications in mineral exploration, environmental monitoring, and detection of hidden objects or buried structures.

Use of UAS and drones equipped with thermal sensors is an emerging trend in thermal remote sensing. These platforms offer flexibility, cost-effectiveness, and the ability to acquire high-resolution thermal data over small to medium-sized areas. Future research will focus on optimizing UAS platforms, developing autonomous flight and data acquisition techniques, and integrating thermal sensors with other sensors on UAS platforms.

There is growing interest in applying thermal remote sensing in the field of health and medicine. Thermal imaging can provide valuable insights into human physiology, such as detecting anomalies in skin temperature, monitoring blood flow, and identifying thermal patterns associated with diseases. Development of non-invasive and real-time thermal imaging techniques for medical diagnostics, monitoring, and disease detection and can provide insights into human physiology by detecting anomalies in skin temperature, monitoring blood flow, and identifying thermal patterns associated with diseases.

Thermal remote sensing can play a vital role in climate change studies by monitoring changes in land surface temperature, heat fluxes, and urban heat islands. Future research will focus on using long-term thermal datasets to analyze and understand the impact of climate change on ecosystems, urban areas, and regional climate patterns. Future research will focus on using long-term thermal datasets to analyze changes in land surface temperature, heat fluxes, and urban heat islands. This information can contribute to understanding the effects of climate change on ecosystems, urban areas, and regional climate patterns.

These future research directions and emerging applications in thermal remote sensing offer exciting opportunities for advancements in technology, data analysis, and the expansion of its application domains. Continued research in these areas will contribute to improving our understanding of thermal phenomena, addressing environmental challenges, and enabling informed decision-making in various fields.

7.14 Conclusion

Thermal remote sensing is a valuable technique that utilizes satellite-based sensors to measure and analyze the thermal radiation emitted by the Earth's surface. It provides a non-invasive and efficient method to gather information about temperature variations, heat distribution, and other thermal properties of different objects and phenomena. Thermal remote sensing although has been in vogue for the past 4 decades, has immense potential with respect to its development, advancement and applications. In the recent years, thermal remote sensing has been used for numerous application The applications of thermal remote sensing are diverse and include monitoring glacial retreat, assessing land surface temperature, detecting thermal anomalies in volcanic environments, studying urban heat islands, and tracking changes in vegetation and ecosystems. This technique has proven to be essential in understanding the impacts of climate change, improving land cover classification, assessing environmental health, and aiding in disaster management and resource planning. By enabling us to gain valuable insights into Earth's systems, thermal remote sensing contributes to informed decision-making across various fields and sectors.

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Chapter 8

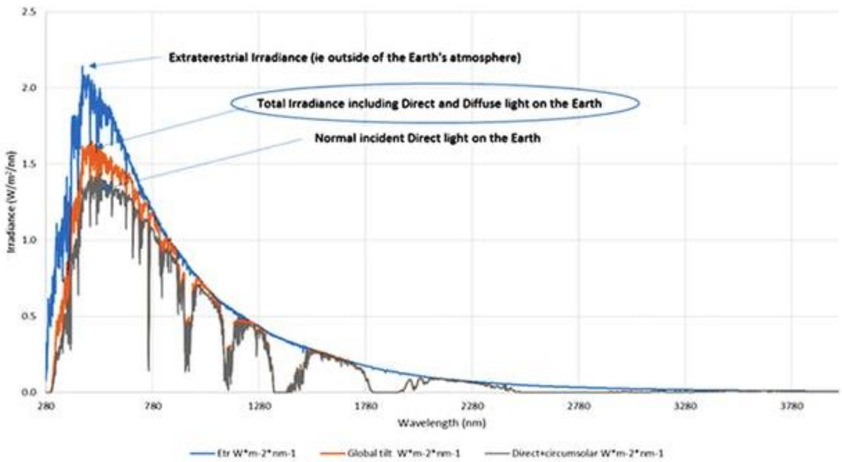
LIDAR REMOTE SENSING

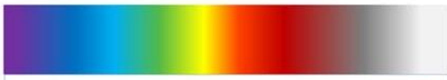
8.1 Introduction

Distance measurement using searchlight beam started in the 1930s and by 1938 cloud height measurement with light pulses was in place. With the invention of laser, Malcolm Stitch (Hughes Aircraft Company) introduced the first LiDAR in 1961. '**LiDAR'** was coined in 1963 by combining the words "LIght" and "raDAR" as **LI**ght **D**etection **A**nd **R**anging. **LiDAR** is an active optical remote sensing technology that measures properties of reflected and/or scattered light to find the range and/or other information of a distant target. Similar to radar technology, the reflected signals from a high-power light source provide target information like range, target characteristics, etc. This technology offers advantages over conventional methods of topographic data collection w.r.t. higher density, and higher accuracy.

8.2 Wavelength/s of LiDAR

Wavelengths of LiDAR instruments range from the infrared (10 μm) to the ultraviolet (250 nm) and can be applied to a variety of substances viz. rocks, rain, chemicals, air, clouds, and even single molecules. The optimum combination of wavelengths allows for the remote mapping of atmospheric contents by detecting wavelength-dependent changes in the returned signal intensity (echo). Wavelengths around 1500nm are not visible to the eye and hence 'Eye Safe'. Instruments with these wavelengths are good for large distances and computed precise distance of earth to moon. The choice of wavelength is important from science data and from performance. Fig. 8.1 shows the solar spectral profile while Fig. 8.2 shows the typical LASER wavelengths used for remote sensing.





Wavelength Range	Visible ~600 nm	Near Infrared ~905 nm	Shortwave Infrared ~1550 nm
Visible beam	Visible	Invisible	Invisible
Eye safety	By design	By design	By design
Emitter/Detector Components	Low cost Silicon detector and cost optimized laser diode		Higher cost III/V materials
Attenuation in water	Lowest	Moderate	Highest
Interference due to sunlight	Higher	Moderate	Lower

Fig. 8.1 ASTM G173-03 Solar Irradiance Model and some properties of wavelengths

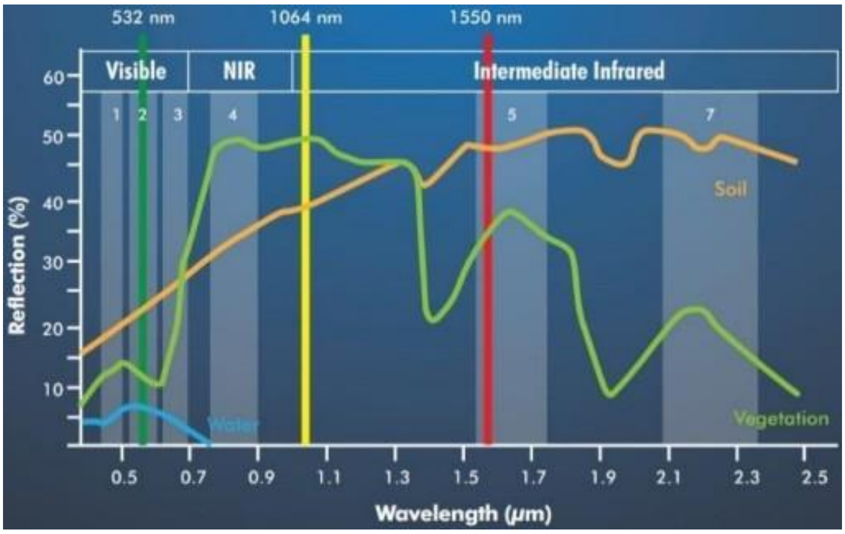


Fig. 8.2 Wavelengths used in LiDAR for remote sensing.

The peak of solar noise (light) is in the range of 500-600 nm. Noise at infrared (NIR around 905 nm) is half. SNR is better at the shortwave infrared range (around 1550 nm). NIR range is the best from price/performance. The strength of LiDAR returns varies with the composition of the surface object reflecting the return. The reflective percentages are the LiDAR intensity. Range, incident angle, beam, receiver, and surface composition influence return intensity. When the LiDAR tilts, the return energy decreases. Apart from direct reflection, different types of backscattering methods provide measurements, primarily from Rayleigh scattering, Mie scattering, and Raman scattering. Property of fluorescence, due to LASER excitation of target molecules provides substance constituents.

Science needs require four primary instrument types:

- Ranging: Measures the return beam's time of flight to retrieve distance.
- Backscatter: Measures beam reflection from aerosols and clouds to retrieve the optical and microphysical properties of suspended particulates.
- Laser spectral absorption: Measures laser absorption by trace gases from atmospheric or surface backscatter and volatiles on surfaces of airless planetary bodies at multiple laser wavelengths to retrieve the concentration of gas within the measurement volume.
- Doppler: Measures wavelength changes in the return beam to retrieve relative velocity.

LASER instruments have evolved more technologically in recent years due to application drive mainly from automobile and agriculture sectors. This has reduced the development cost and made functional components available in the commercial markets. There are three main classifications or types of LiDAR systems:

- Terrestrial LiDAR: Operations happen on the Earth's surface and can be either stationary or mobile.
- Airborne LiDAR: A laser scanner attached to an aircraft, such as helicopters, airplanes, or drone, creates a 3D point cloud map of the landscape. Airborne system LiDAR is currently the most detailed and accurate method of creating digital elevation models, replacing photogrammetry.
- Spaceborne LiDAR: Observations are made from orbits over the earth/ planets using satellites.

Fig. 8.3 below gives the features of LASER instruments used in common platforms.

Features	Satellite	Drones w/ Lidar	Helicopter w/ LiDAR
Resolution	12-inch High Resolution	VHR	VHR
Perspective	Overhead	Overhead	Overhead
Bands	MultiSpectral Mono, TriStereo, SAR, Hyperspectral	Visual, LiDAR, additional bands can be added	Visual, LiDAR, additional bands can be added
Speed of Data Acquisition	Instant	Very Slow	Fast
Geographic Coverage	Entire Planet	Localized	Regional
Regulatory Approval Needed	None	Required	Required
Historic Data	Available	Not Available	Not Available
Clearance Detection	Yes	Yes	Yes
Change Detection	Yes	No	No
Costs	$	$$$$	$$$$

Fig. 8.3 Features of LiDAR instruments used in common platforms

8.3 LiDAR Principle

The basic working of LiDAR is shown in Fig. 8.4. The measurement sequence is as:

- A LASER (pulse/ continuous wave) is fired from a transmitter
- Reflected energy is captured
- Round trip Time of Flight from the transmitted signal to the received signal is determined
- Using the speed of light, the distance is determined
- Distance = 3×10^8 x Time of Flight /2

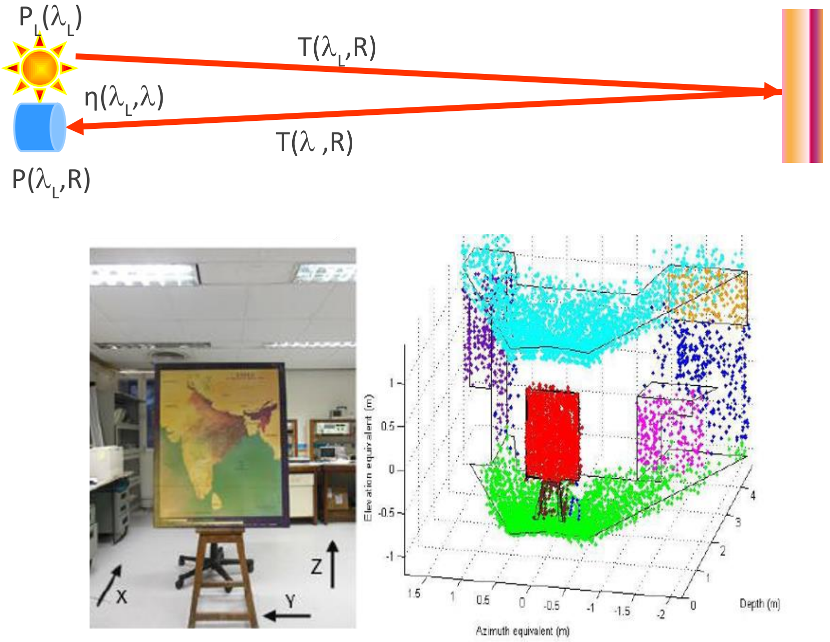


Fig. 8.4 LiDAR principle (Top) and echo map (Bottom right)

Generic LiDAR Equation

The received laser power from a surface is:

$P(\lambda_L,R)=P_L(c\tau_L/2)(A_0/R^2)\xi(R)\ \eta(\lambda_L,\lambda)T(\lambda_L,R)T(\lambda,R)\ \beta\ (\lambda_L,\lambda,\theta,R)\exp[-2\int_0^R\kappa(\lambda_L,r)dr]+P_B$

Where,

$P(\lambda_L,R)$ =Total scattered received laser power (W) at a time

R = Distance (m)

λ_L = Wavelength of LASER (m)

P_L = Average LASER output power (W)

c = Velocity of light (m/s)

τ_L = Effective Pulse duration (s)

$c\tau_L$ = Effective Pulse length (s)

A_0 = Effective Aperture of the telescope (m)

$\eta(\lambda_L,\lambda)$ = Optical Efficiency at λ_L,λ

$\xi(R)$ = Probability of radiation from position r at range R

$\beta(\lambda_L,\lambda,\theta,R)$= Volume backscatter coefficient ($m^{-1}sr^{-1}$)

$\kappa(\lambda_L,r)$ = Total atmospheric extinction factor (km^{-1})

$T(\lambda_L,R)T(\lambda,R)$ = extinction factors, $\exp[-\int_0^R\kappa\ (\lambda_L,r)dr + \int_0^R\kappa\ (\lambda,r)dr$

P_B = Background Noise

These parameters are involved in remote sensing as they affect the transmitted, reflected and the wavelength of the laser beam.

8.4 LiDAR Architecture

All laser rangefinders operate by emitting laser energy and measuring the time it takes for the energy to travel away from the sensor, strike a surface, and return. The following parameters can be determined from LiDAR return pulse.

- The time delay between the transmitted and returned pulses, which provides distance/ indication of the satellite altitude.
- The slope of the leading edge of the echo, which is related to the distribution of the heights of the surface reflectors, and thus to parameters such as significant wave height.
- The power level of the trailing edge of the echo pulse, which is used to an estimate of the backscatter coefficient and hence the small-scale roughness characteristics such as wind speed.
- The phase of the return signal (Modulated Pulses)

Fig. 8.5 shows the shape and properties of reflected signal of the LiDAR.

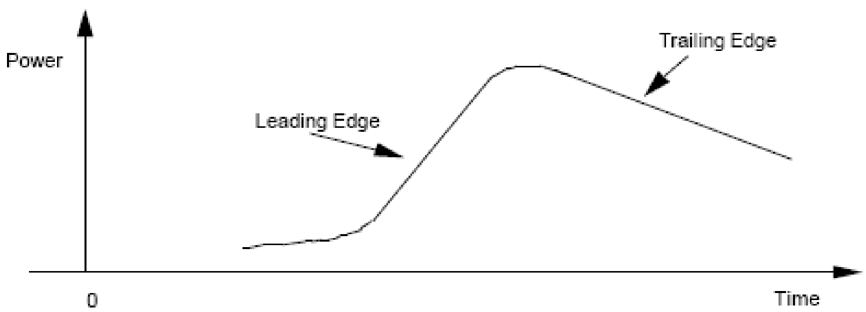


Fig. 8.5 Power Distribution of reflected signal

Depending on application-backed measurements, these lead to basic architectures as

- Non-modulated pulse
- Single tone modulation
- Frequency modulated
- Phase modulated

1) Non-modulated pulse (Time-of-Flight)

Here, a concentrated laser energy pulse emitted strikes a surface and returns to a detector. A timer measures the time elapsed between the leading edge of transmitted pulse and the return pulse (Fig. 8.6). The distance is

$$\mathbf{h = (c\,\Delta t\,/2)}$$

Where Δt is the roundtrip time of the laser energy, and **c** is the speed of light.

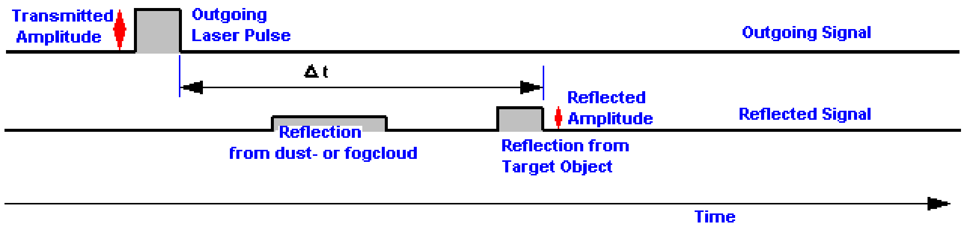


Fig. 8.6 Time-of-flight (TOF) method

Narrow pulses enable measurement of small distances. This method produces undesired backscatter clutter calling for gated receivers.

2) Single tone modulation

In this method, LASERs emit a single tone sinewave. Correlating transmitted signal with received signals gives the distance. This improves the discrimination from backscatter clutter. The Frequency modulated scheme is an improvement over this scheme.

3) Frequency modulated

Here, the LASER source is modulated with a chirp signal. The reflected light is incoherently detected and cross-correlated to get impulse waveforms (Fig. 8.7). Chirp signal has a bandwidth of ΔF. The Fourier transform of the frequencies establish the range to all scatterers along with respective magnitude and phase of the scatter's signal. Range to the target is:

$$\mathbf{h = c/2\Delta F}$$

Here, the optical aperture is artificially increased without loss of resolution and is called Synthetic Aperture LADAR (SAL). Digitized full waveform data is processed to extract information based on delay, amplitude and phase, which provides accurate assessment of surface, canopy and potential obstructions.

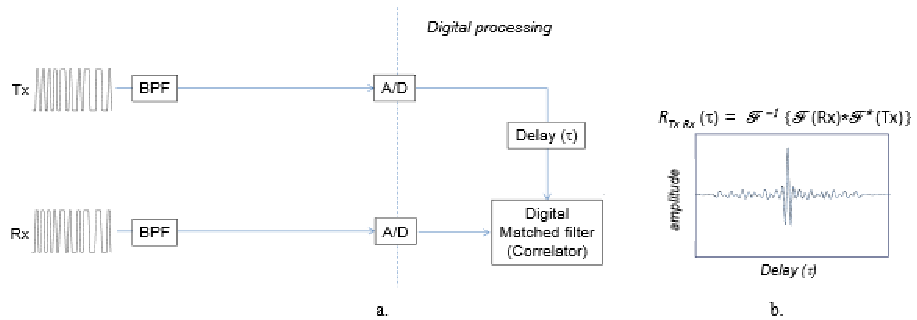


Fig. 8.7 Frequency modulated LiDAR (a) architecture and (b) co-relation output

4) Phase modulated

This scheme operates by modulating LASER **power** with a single tone sine wave (Fig. 8.8). The returned energy waveform, delayed by time **Δt,** is proportionately phase-shifted in comparison with the emitted energy.

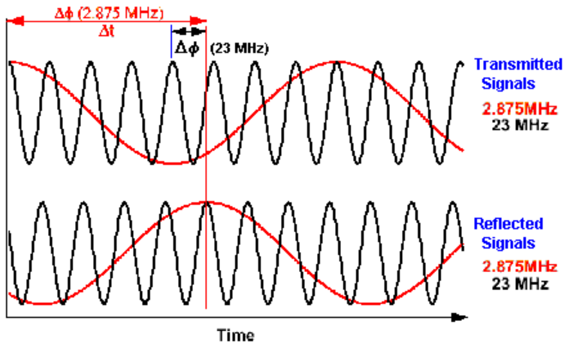


Fig. 8.8 Amplitude modulated continuous wave LiDAR

8.5 LiDAR - Basic Elements

LiDAR measures back-scattered signal along with its time information to extract range information. Time resolution of measurements defines the range resolution. The state-of-the-art LiDARs for remote sensing requires powerful source which is a LASER, telescope to receive reflected/ scattered light, photon level detection element, processing and computation elements along with secondary instruments for absolute parameters. Major sub-systems of a topographic LiDAR are laser module, optical transceiver, detection system, electronics module, mechanical and thermal system.

The function of the elements is described below.

- The laser is the active source, which emits energy that travels to the surface and subsequently reflected. Depending on the configuration, the signal may be pulsed, modulated or continuous. The laser source meets certain requirements depending on application needs e.g., wavelength, frequency accuracy, bandwidth, pulse duration time, pulse energy, repetition rate, etc.
- The optics consists of telescopes, spectral filters, scanners, collimating optics, beam splitters, wavelength control system, polarizers, etc. These determine the Angular resolution, detection range, etc.
- Detector and receiver electronics consist of photon detectors, amplifiers, discriminators, digitizers, processors, etc. Detectors commonly used are Si, InGaAs in either PIN diode or Avalanche photodiode configurations. The sensitivity of the receiver determines the range and accuracy.
- Data acquisition and control system record the returned data and corresponding range information; provide system control and coordination to transmitter and receiver. The system contains of very precise clock to record time, programmable filters, microprocessor and software. The second part of data acquisition is the GUI based corrected display, scientific tools, health monitoring, configuration control and thermal control.
- Position and navigation systems — Absolute position & orientation of the sensor - Global Positioning System (GPS) & Inertial Measurement Unit (IMU). Most topographic LIDAR's generate automated DEM with GPS receivers, IMU and scanner position information. Accurate geolocation of each laser spot requires knowledge of the aircraft attitude and geographic location in latitude, longitude, and altitude. Most GPS provide geographic location at 10 Hz. Precision GPS data requires kinematic differential GPS techniques that takes the difference of

received dual frequency (L1/L2) carrier phase-derived ranges. LiDAR data point accuracy is further improved with a ground-based GPS data (@ 10Hz) near the survey region. Instrument GPS is then relative to this ground GPS data.

- Cameras for information augmentation. Compatible RGB and/or IR cameras often augment LiDAR data.

Fig. 8.9-8.11 show the LiDAR instrument setup along with typical processing elements for airborne missions.

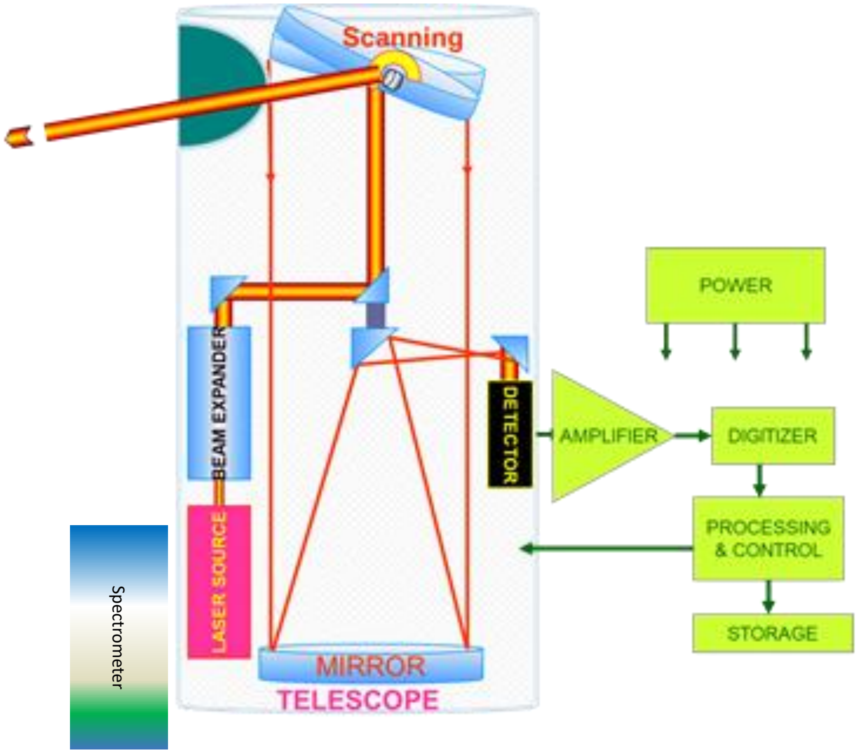


Fig. 8.9 Basic LiDAR instrument components

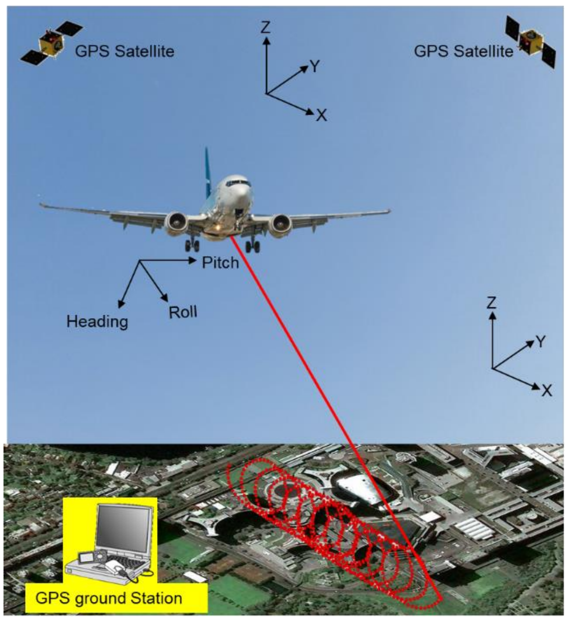


Fig. 8.10 IMU/GPS required for platform instability

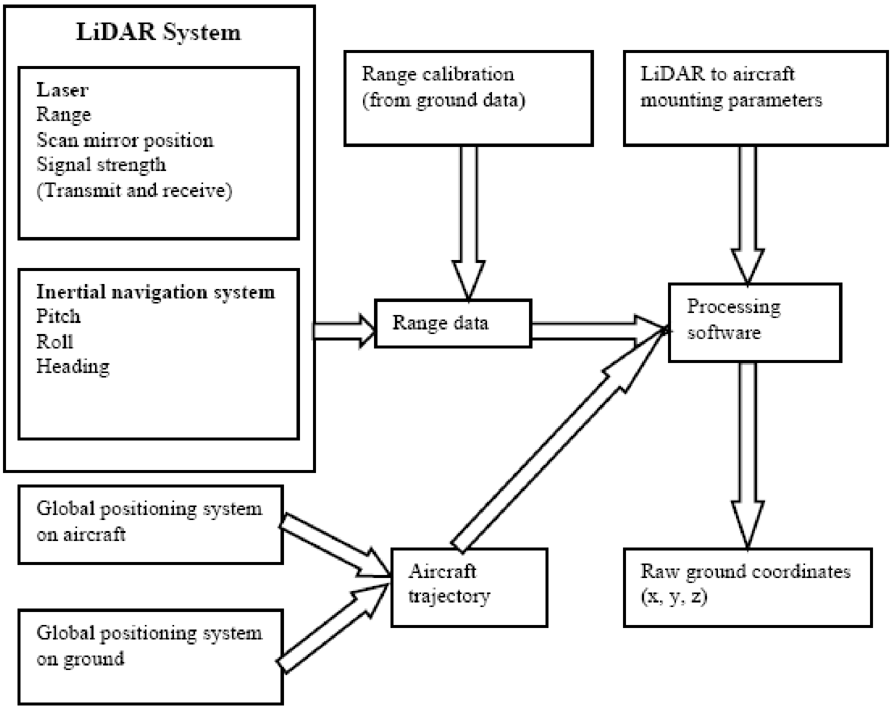


Fig. 8.11 LiDAR processing elements

Two configurations of LiDAR instrument affect optical and mechanical parts. If the transmit and receive apertures are two separate apertures, we call that a **bi-static LiDAR**. Here, transmit or illumination aperture does not have to be the same size as the receive aperture, nor at the same place. One reason for using **monostatic LiDAR** is to save weight and space by not having a second aperture for illumination; however, with bistatic illumination often you can have an illumination aperture that is much smaller than the receive aperture but needs alignment to see the same point in target (Fig. 8.12).

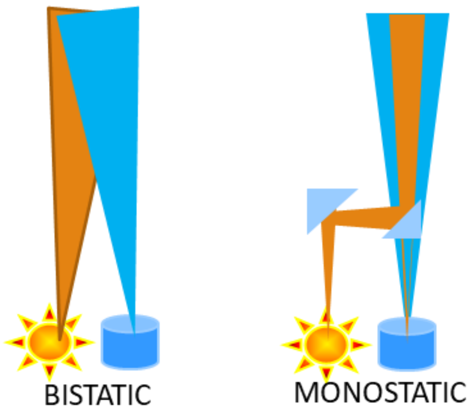


Fig. 8.12 LiDAR – Bistatic uses separate transmitter and receiver optics, monostatic uses common optics and does not require alignment

Scanner for Airborne/ mobile platform

LiDAR scanning is required to build a sparse cloud of points over a spatial area. LiDAR receiver, based on a single detector, covers only a point and hence scanning is required for covering a volume. The aircraft imparts scan in the flight direction, a scanning system provides data for the other direction/s. The challenges in a scanning system are field of view (FOV, swath), scan rate (Hz, rpm), optical aperture and element weights. Many types of scanning are possible. Common scanning systems are discussed here. Each system has its own advantages and disadvantages.

- Oscillating mirrors: Here, oscillating mirrors direct the laser pulses in two directions of the swath, creating a jagged pattern on the ground (Fig. 8.13 a). The swath width is given by the maximum angle of inclination of the mirror and is limited. The resulting point density is not uniform because the laser pulses tend to accumulate at the edges of the swath due to the deceleration of the mirror. The oscillation is from a galvanometer type system, which provides programmable FOV control.

- Rotating polygon mirror: This system creates a scan pattern composed of parallel lines oblique to the direction of the platform's progression (Fig. 8.13 b). The scan here is always in the same direction. The swath is dependent on the width of the polygonal mirror face and is limited. Many types of polygon shapes are possible which define the width and swath. Fig. 8.14 shows some types.

- Rotating mirror: Mirror axis of rotation is made collinear with the direction of the laser beam emitted by the source to allow 360°scan. The scanning pattern is composed of parallel lines oblique to the direction of the system's motion (Fig. 8.13 c). This time, the size of the swath is dependent on the maximum range of the LiDAR system. However, the scan efficiency is poor as only a small proportion is useful for ground scanning.

- Dispersive prisms or gratings: Dispersive prisms/ dispersive gratings rotate around the same axis to generate roses-like scanning patterns. For instance, the Risley prisms (wedge prisms) do circles (Fig. 8.13 d) or roses like scanning patterns (Fig. 8.16). The advantage of these patterns is that they do not repeat themselves so that even in static, the coverage rate increases over time, which allows the detection of more details in the field of view of the sensor. The size of the swath depends on the configuration and inclination of each wedge prism. Laser diffraction methods using optical pipes are also used as a scanner. Fig. 8.17 shows the same.

- Off-axis parabolic mirror: The mirror is tilted at an angle and rotates on a fixed axis. The scans are circular or parabolic similar to Fig. 8.15 d. This is also known as conical scanning (Palmer scanning). This is the simplest system to scan a periphery with a large FOV.

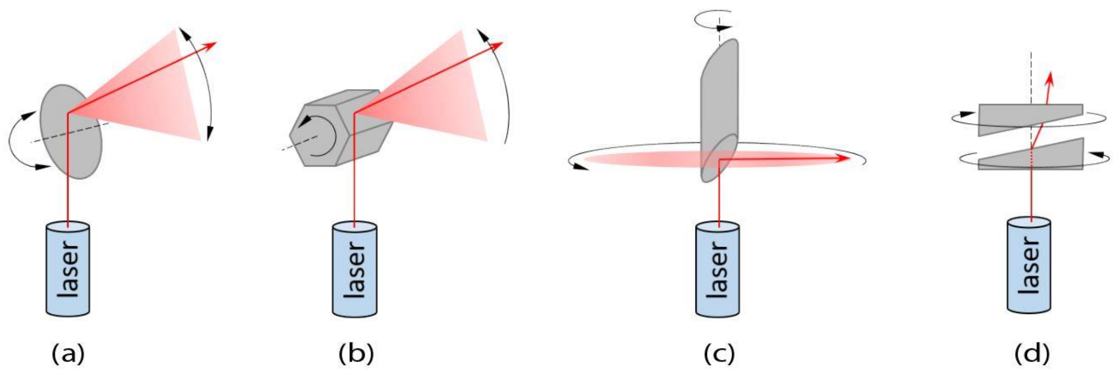


Fig. 8.13 Different scanning mechanisms: (a) oscillating mirror; (b) rotating polygonal mirror; (c) rotating mirror; (d) rotating wedge prism; (e) two rotating wedge prisms.

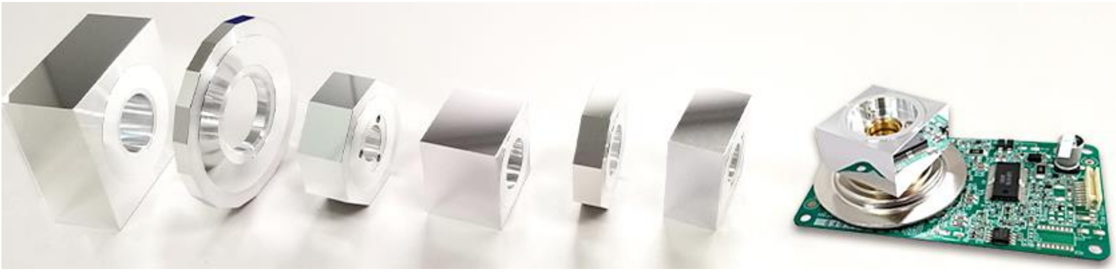


Fig. 8.14 Polygon mirror- multiple shapes possible.

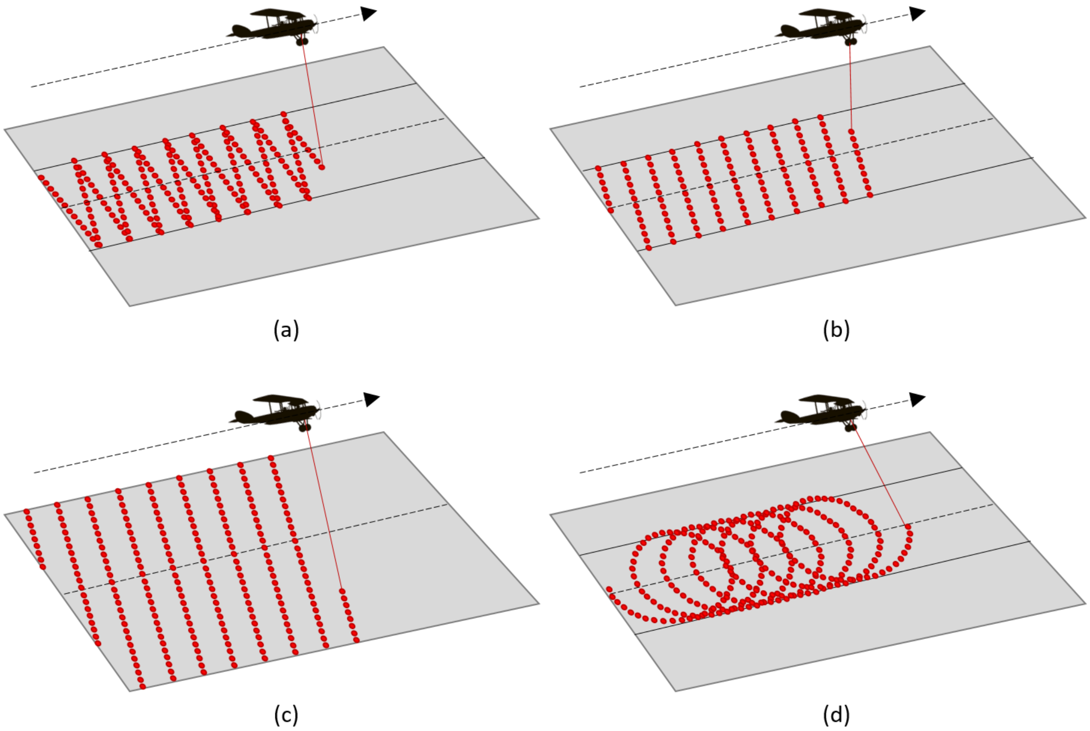


Fig. 8.15 Different scan patterns; (a) pattern generated by an oscillating mirror; (b) pattern generated by a rotating polygonal mirror; (c) pattern generated by a rotating mirror; (d) pattern generated by a rotating wedge prism.

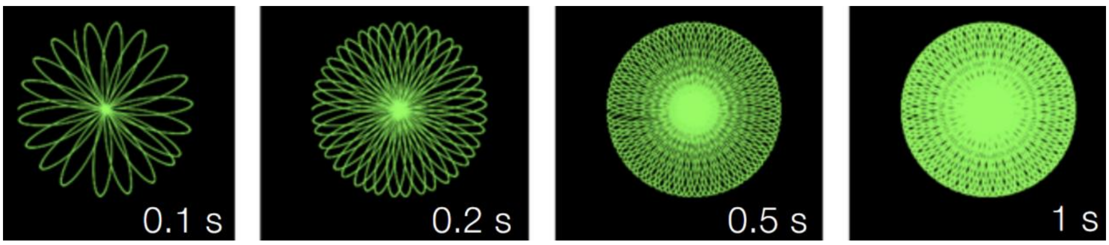


Fig. 8.16 Risley scan- roses like scanning patterns.

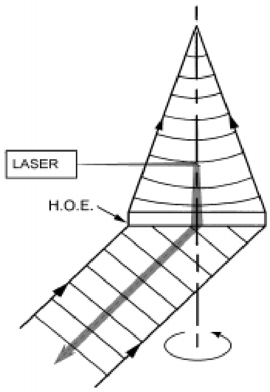


Fig. 8.17 Diffraction-based scanning.

8.6 LiDAR configuration

Application requirements drives the LiDAR instrument type and thus the system configuration (Table 8.1). Sub-system configuration varies largely based on the applications from continuous modulated laser to ultra-short pulsed laser, coherent to incoherent detection system, single pixels to linear/area arrays, APDs to SPADs, ADCs to TDCs etc. and so on. Thus, finalizing an application and thus a type of LiDAR is the first step towards system configuration.

Table 8.1 System requirements

Parameters	Configurations possible
LiDAR echo processing	Time-of-flight, Full waveform, Gating
Altitude (km)	As per application
Footprint (m)	Defines spatial resolution Small or large
Vertical sampling (m)	As per application, defines LASER pulse width
Sampling distance (Across track, m)	Defines spatial resolution, local slope determination
Sampling distance (Along track, m)	Defines spatial resolution
Swath (km)	Area coverage
Point density (pt/m2)	As per application Defines spatial resolution

The point density of LiDAR is the data density (d) is the number of points per unit area and is dependent on the configuration as:

$$d = N/(B*S), \quad N = F/Fs$$

Where,

B=1 for bidirectional scan or else 0

S – Swath

F – Data points generated per sec (PRF x digitization bits)

Fs –Scan frequency

v – Velocity of platform

H – Altitude

θ – Scan angle

1. Transmitter

The transmitter optics consists pulsed laser source, which feeds a beam expander optics with minimum coupling loss. The beam expander optics is a combination of lens elements. The transmission chain will also consist of beam splitter for generating a reference beam for reference detectors and fold mirrors for redirecting the beam to a common optics, as in monostatic configuration, shared by both transmitter and receiver for achieving compactness.

2. LASER

Light Amplification by Stimulated Emission of Radiation (LASER) produces a coherent beam of optical radiation by stimulating electronic, ionic, or molecular transitions to higher energy levels. When they return to lower energy levels by stimulated emission, they emit energy. LASER outputs are monochromatic, coherent and directional. The process involves:

- Absorption
- Spontaneous Emission
- Stimulated Emission
- Population inversion

Lasers can be 3 level or 4 level system. In 3 level systems, population inversion happens between lower ground state and a higher-energy metastable state. In 4 level system, inversion takes place between the metastable lower-level excited states. A summary of LASER principle and available LASER is given in Table 8.2.

Different LASER can be constructed based on the gain and pump medium. Gas LASER have gas (He-Ne laser) as the gain medium while a liquid dye-based medium provides dye laser and a Ruby medium give solid state LASER. The pump source can be a flash lamp or semiconductor LASER. These all define the wavelength and output power. Pulsed LASER are further Q-Switched or Mode locking type. Q-Switched LASER use opaque electro-optical device (Pockets cell) which becomes transparent when a voltage is applied. The light then builds up in the cavity by the excited atoms making the cavity quality 'Q' increases to a high level and emits a high peak power pulse. Mode locking LASER synchronize phases of different frequency modes to interfere with each other and generate a beat. The Laser outputs with regularly spaced pulses. These provide pulses of Picoseconds to nanoseconds with high peak powers. Tunable LASER use prisms, gratings, Fabry-Perot etalons and filters in the cavity to change wavelengths. Varying the oscillator cavity also tunes the wavelength. Other methods are population inversion for more than one transition, second harmonic, third harmonic, stimulated Raman scattering and parametric oscillation. Table 8.3 gives the LASER requirements for LiDAR instrument.

Table 8.2 LASER process

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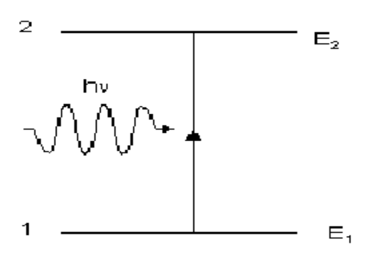
<td>
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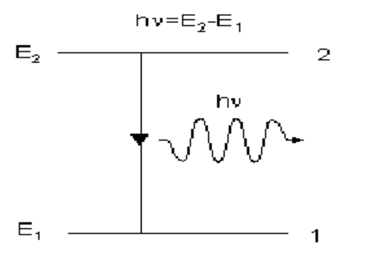
<td>
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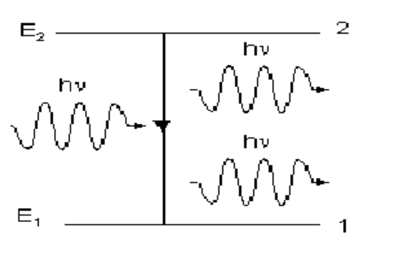
<td>
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<td>Absorption: Energy absorbed by an atom make the electrons excited into vacant energy shells</td>
<td>Spontaneous Emission-

Atom decays from level 2 to 1 by emission of a photon</td>
<td>Atoms at upper energy level is stimulated to be in same phase, direction and wavelength with an incoming pumped photon</td>
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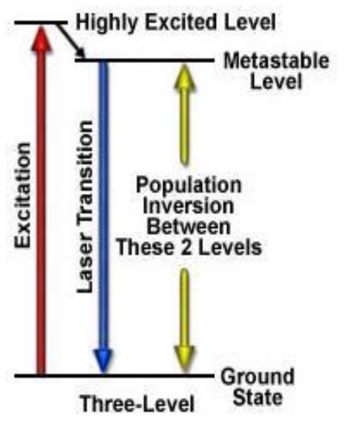
<td colspan="2">
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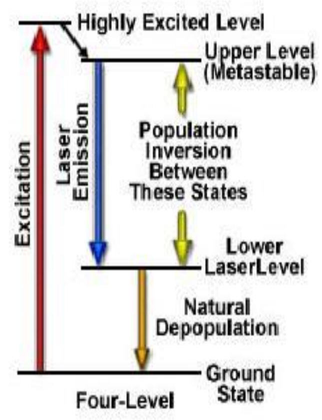
<td>
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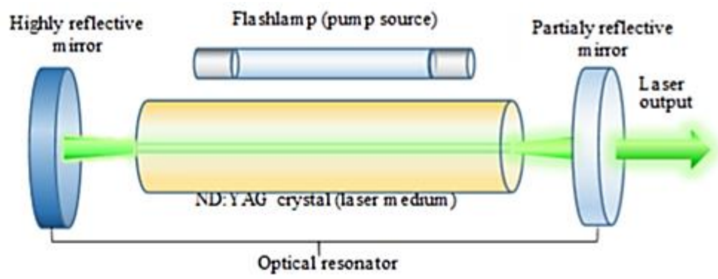
<td colspan="3">
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<tr>
<td>Flash lamp emits an intense burst of light, exciting ions in the crystal to higher energy levels.</td>
<td>At a specific energy level, some ions emit photons in all directions. Photons from one ion stimulate emission of photons from other ions to amplify the light.</td>
<td>Mirrors reflect the photons continuing this process of stimulated emission and amplification. Photons leave through the partially silvered mirror as laser light.</td>
</tr>
</table>

LASER TYPE	WAVELENGTH (nm)
Helium Cadmium	325 - 442
Rhodamine 6G	450 - 650
Copper Vapor	511 and 578
Argon	457 - 528 (514.5 and 488 most used)
Frequency doubled Nd:YAG	532
Helium Neon	543, 594, 612, and 632.8
Krypton	337.5 - 799.3
Ruby	694.3
Laser Diodes	630 - 950
Ti:Sapphire	690 - 960
Nd:YAG	1064
Hydrogen Fluoride	2600 - 3000
Erbium:Glass	1540
Carbon Dioxide	10600

Some LASER types available

Table 8.3 LASER parameters

Operating wavelength (nm)	As per application
Linewidth (nm)	Application dependent, background noise
Pulse width (ns)	Vertical resolution, energy transmitted, eye safety
Pulse energy (mJ) (per spot)	SNR, range, energy transmitted, eye safety
Pulse Repetition Frequency (Hz)	Spatial, vertical and radiometric resolution
Type	Gas, solid, hybrid, semiconductor – dependent on power and wavelength

The average LASER power is given as Power(peak) x Pulse duration x Pulse repetition rate. The state of the art in lasers for remote sensing instruments requires significant platform resources (primarily power and volume) while also suffering from low reliability and consequently short operational lifetimes. Mechanical vibrations and thermal expansion affect LASERs. The LASER beams suffer from divergence, atmospheric distortions, scintillation and beam wander due to hot air bubbles and transverse winds. These limit accuracy for distances > 1 km. Over distances > 365 m, the laser beam may undergo total internal refraction caused by temperature gradients in the air. Particles (dust, water) in air can limit the dynamic range. Opto-mechanical misalignments can cause severe error. Apart from the above, the LASER power has to meet 'eye- safe' limits (Fig. 8.18). All these factors are accounted in engineering.

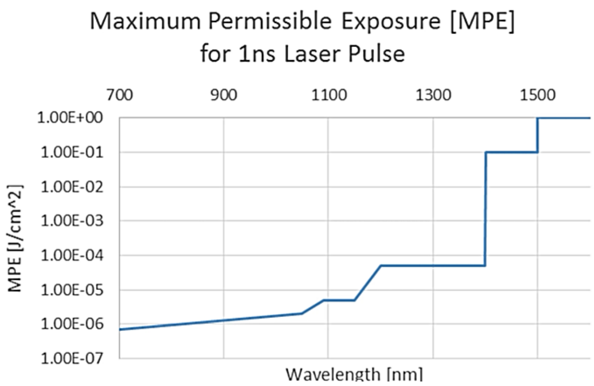


Fig. 8.18 LASER permissible limits - Standard - BS EN 60825-1:2014

Table 8.4 Transmitter optical parameters

Transmitter aperture (mm)	Dependent on SNR, range, laser power
Divergence (µrad)	Defines spatial resolution Footprint on ground
No. of transmission spots	Multiple spots, single spots define spatial resolution
Optical throughput	Efficiency

3. Receiver Optics

The receiver optics will be collecting the return signal from various application targets like forest Canopy, suspend particles, aerosols, clouds, etc. at varying altitudes. Due to inherent weak return signals reflected/ scattered from these targets, the receiver optics aperture is chosen sufficiently large. The receiver optics can be refractive or reflective depending on the telescope, range, detector optical window size and application.

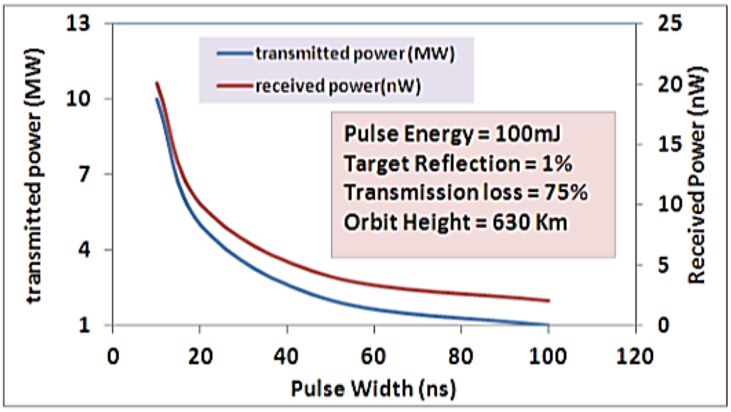


Fig. 8.19 Received power follows a log curve with pulse duration.

Table 8.5 Receiver optical parameters

Telescope	Cassegrain, Newtonian, etc.
Receiver aperture (mm)	Large aperture is preferred for higher photon collection
IFOV (µrad)	Angular resolution, co-registered to reflected beam spots
Filter bandwidth (nm)	Smaller for better SNR
Out of band blocking	This defines integrated background signal for SNR
Polarization	As per application
Spectroscopy	Grating, Prism, Interference filters to separate wavelengths
Optical throughput	Efficiency
Scanner type	Fig. 7.13 to 7.17, platform & application dependent
Scan rate (rev/s)	Platform speed, point density, swath

4. Detector & Electronics

LiDAR sends out laser pulses and a sensor like photodiode detects the reflected light from unknown objects. For low-light detection in the 200 to 1150 nm range, the designer has three basic detector choices - the silicon PIN detector, the silicon avalanche photodiode (APD) and the photomultiplier tube (PMT) (Fig. 8.20). APDs are widely used in instrumentation and aerospace applications, offering a combination of high speed and high sensitivity unmatched by PIN detectors, and quantum efficiencies at > 400 nm unmatched by PMTs. The advantage of a much higher angular resolution also gives APDs an outstanding role. The angular resolution of LiDAR systems makes it possible to identify the horizontal or vertical position of an object more precisely, and to distinguish different objects that are located in same distance and moving with the same speed. A matrix APD array enables a real-time LADAR imaging of moving targets with a single pulse. Within a single laser pulse, each channel of the array receives the reflected signal from the object in a timed sequence. APD arrays have a much higher sensitivity enabling detection and identification of objects hundreds or thousands of meters away.

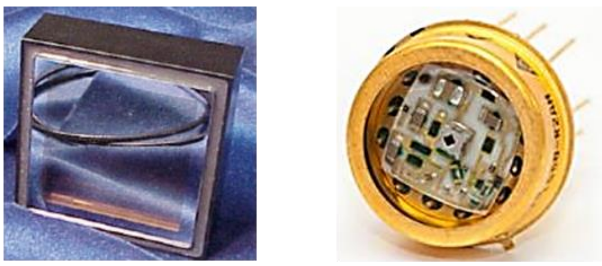


Photo Multiplier Tube **Si APD**

Fig. 8.20 Detector types

5. **APD**

The ideal APD would have zero dark noise, no excess noise, and broad spectral response, a gain ranges from 1 to 10^6 or more, and low cost. More simply, an ideal APD would be a good PIN photodiode with gain! In reality however, this is difficult to achieve because of the need to trade-off conflicting design requirements. Some trade-offs are optimized in commercial APDs. The basic structural elements provided by the APD designer include an absorption region 'A' and a multiplication region 'M'. An electric field E present across region A separates the photo-generated holes and electrons, and sweeps one carrier towards the multiplication region. The multiplication region M is designed to exhibit a high electric field to provide internal photocurrent gain by impact ionization. This gain region must be broad enough to provide a useful gain, M, of at least 100 for silicon APDs, or 10-40 for germanium or InGaAs APDs. In addition, the multiplying electric field profile must enable effective gain at field strength below the breakdown field of the diode. APDs are recommended for high bandwidth applications or where internal gain is needed to overcome high pre-amp noise.

The choice of detectors is based on:

1. Wavelength range to be covered.
2. Size of the detector
3. Electrical frequency bandwidth of the system; over specifying bandwidth will degrade the SNR of the system.

The detector output signal is amplified (AGC) and given to a high-speed digitizer. The bias of the detector and the front-end gain needs to be dynamically tracked and controlled for optimum SNR. The detectors usually operate in Geiger mode to have sub-ns single photon detection. The detectors need stabilized high voltage bias for operation. The detector also needs TEC for thermal stability. The output of a detector is given as:

$$Vo = Pr\ R\ Zt\ Av$$

Where, Pr is received optical power, R is the responsivity of detector, Zt is the trans-impedance gain and Av the amplifier voltage gain.

Table 8.6 Detector and Front-End Electronics Parameters

No. of detectors	One per band, more to cover multiple spots
QE (%)	Efficiency of photon conversion
Type of detector	Silicon, gallium, tube, etc.
Spectral Bandwidth	Large
Responsivity	Large
Analogue bandwidth (GHz)	Higher is better

Electronics convert the photons to digital values as 1 photon to 1 digital count. The digitized data further undergoes processing like digital filtering, cross-correlator, comparing, time stamping, formatting, etc., which removes unwanted signals. The range information may be stored. Storing of digital data, offline processing will require large high-speed memories. High-speed data acquisition and processing needs custom hardware for digitizer, DSP, memory and interfaces. Controlled temperature environment is required for detectors, optics and mechanical stability. Data from INS/GPS positioning and timestamping are added to the echo points. Noise reduction is vital and many processes like digital low pass filters, Kalman filter, etc. are used. Information filtering based on regions of interest (ROI), Gating of the echo, deriving context information are the high-level processing.

The basic functions are:

- Detector Bias generation
- Laser Drive Electronics
- Analog and digital Signal Processing
- Digitization
- Processing multiple echoes, full waveform digitization, and range-based data clustering.
- Thermal Control of Detector, Optical and Electronics subsystem
- Temperature, Analog and Digital telemetry acquisition and processing.
- Power supply generation for Laser Source and Electronics subsystem.
- Storage

Table 8.7 Major Electronics parameters

ADC Sampling freq. (GHz)	Higher for full waveform
ADC quantization bits	Radiometric resolution
Data processing	Data clustering (range based) and data selection, Different sampling for cloud and land targets
Thermal Control	To meet LASER power dissipation, thermal control of optics, optical filters, detectors, etc.
Position and accuracy	IMU, GPS

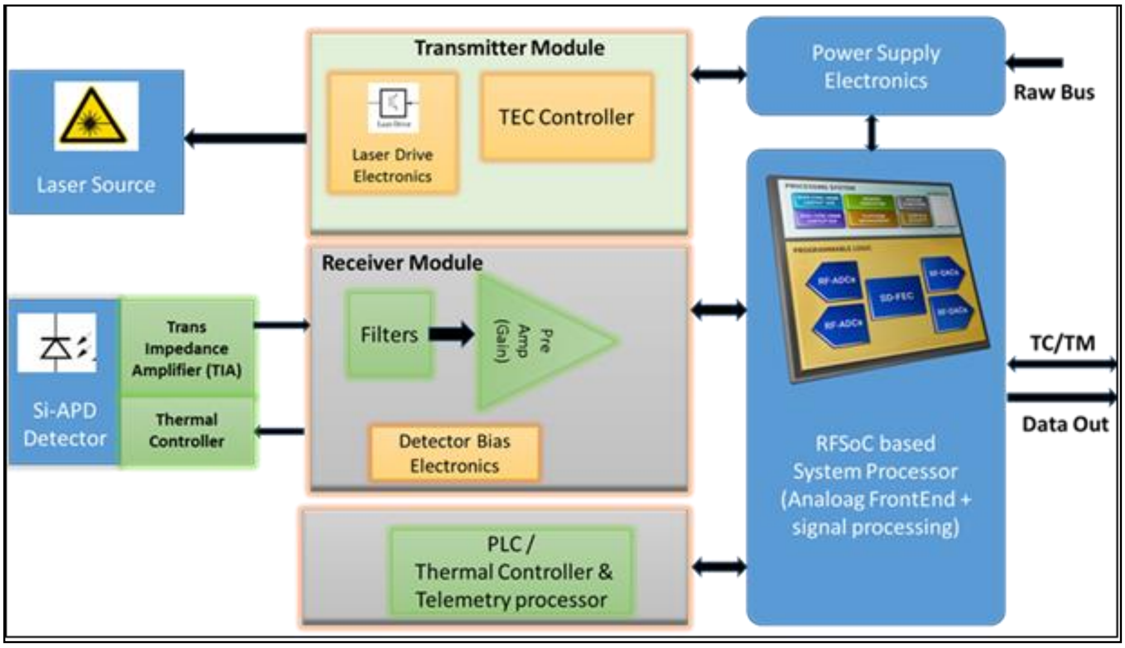


Fig. 8.21 Camera Electronics Block Diagram

8.7 Data Processing

Processing LiDAR data involves geometric rectification, calibration, absolute altitude and coordinate rectification, basic information derivation and custom information processing. The processing also adds aircraft trajectory datasets, and digital camera images and stores in a standard *.LAS or *.LAZ file. Though the processing is similar for most application, differences may arise depending on the user product. LIDAR system generates point cloud data. A point cloud is a set of data points in 3D space, which represent a 3D shape or object. These are referenced to the earth location by a process called Geo-location. There are two standard methods (a) Earth Centered earth fixed (ECEF) which are the Cartesian coordinate (x y z) of the earth (b) the ECEF are converted to latitude, longitude and height as per World Geodetic System (WGS)-84-reference system.

LiDAR data points in ECEF are defined by

- Laser scan beam position (η)
- Range information [0 0 z]
- Platform roll, pitch and yaw (α0 β0 γ0)
- Platform acceleration in roll, pitch and yaw
- GPS antenna coordinates (dx dy dz)
- INS (α β γ) & GPS (ϕ λ)
- WGS-84 (ax ay az) reference

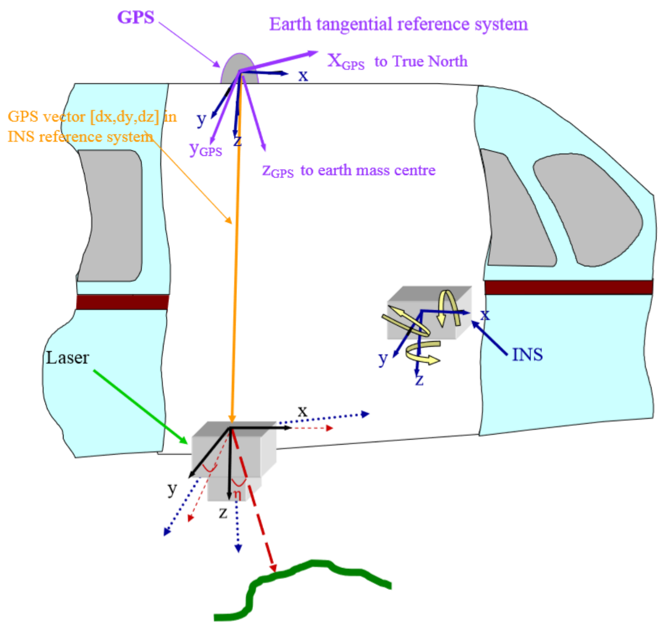


Fig. 8.22 LiDAR, INS, GPS positions on the platform

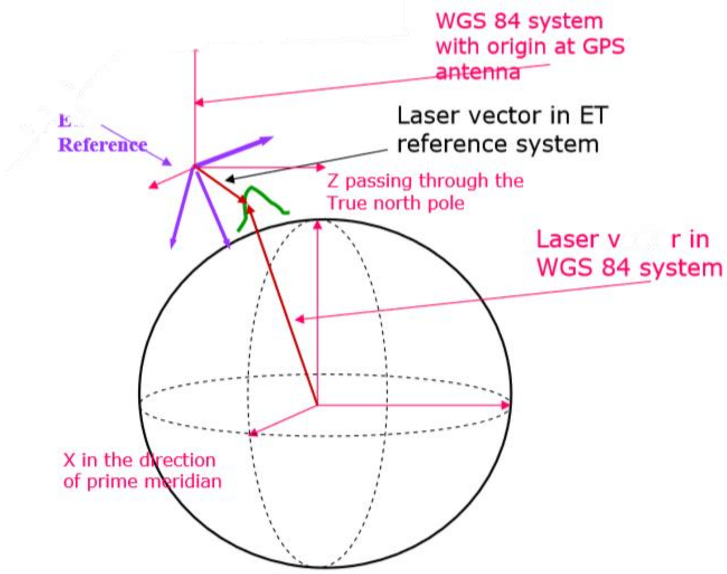


Fig. 8.23 WGS-84 reference standard

The positions of laser footprint on ground are translated by transforms using positional information from LASER pulse time, INS and GPS to absolute position on earth.

$[x',y',z'] = [0\ 0\ z]R_x(\eta)R_x(\alpha_0)R_y(\beta_0)R_z(\gamma_0)T(d_x\, d_y\, d_z)R_x(\eta)R_x(\alpha)R_y(\beta)R_z(\gamma)R_y(\varphi+0.5\pi)R_z(-\lambda)T(a_x\, a_y\, a_z)$

Each point position with its set of Cartesian coordinates (X, Y, Z) make the Point Cloud Data. Apart from conventional parametric processing requirements, LIDAR data require other kind of processing like Digital Elevation Model creation, classification of data and 3D visualization of point cloud data. These are handled with specialized software.

8.8 Calibration

Various factors lead to measurement errors. These are due to manufacturing tolerances, fabrication tolerances, temperature variation, vibrations, nonlinearity and measurement methods and assumptions. Instrument calibrations of detector dead time, instrument after pulse and instrument overlap remove errors from the data. Instrument errors are mainly due to

- Sensor position due to error in GPS, INS and GPS-INS integration
- Angle alignment of laser with platform axis
- Differential vibrations of laser & INS
- Scanner angle
- GPS antenna coordinates
- Time measurements, atmospheric correction, target surface property - range walk
- Footprint size
- Measurement method/s

Usually, an elaborate characterization of sub-system elements, integrated level alignments and calibrations reduce the errors. However, residual errors and time dependent error information have to be acquired and reduced through proper modeling. Many LiDAR instruments are in use. Some are listed in Tables 7.8 to 7.10.

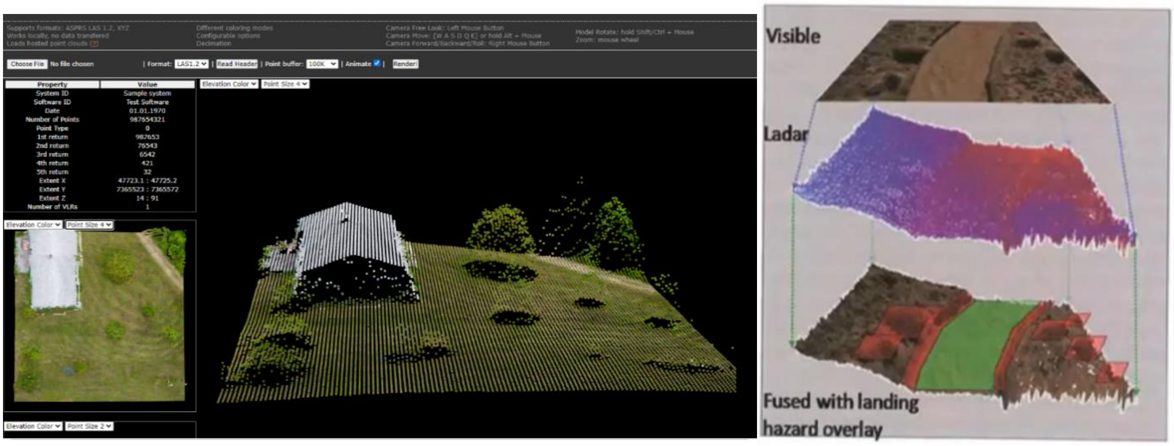


Fig. 8.24 (a) LIDAR 3D cloud point Visualization Software (b) Fusion of LIDAR points and visible scene image

Table 8.8 Commercial LiDAR specifications

Sensor	Mode	Scan Freq.	Pulse Freq.	Scanning Angle	Beam Div. $1/e^2$	Pulse Energy	Range Resolution	Pulse Length	Digitizer
Optech 2033	Oscillating	0–70 Hz	33 kHz	$\pm 20°$	0.2/1.0 mrad	N/A	1.0 cm	8,0 ns	N/A
Optech ALTM3100	Oscillating	0–70 Hz	33–100 kHz	$\pm 25°$	0.3/0.8 mrad	<200 μJ	1.0 cm	8,0 ns	1 ns
TopEye Mk II	Conic	35 Hz	5–50 kHz	14°, 20°	1.0 mrad	N/A	<1.0 cm	4,0 ns	0.5 ns
TopoSys I	Line	653 Hz	83 kHz	$\pm 7.15°$	1.0 mrad	N/A	6.0 cm	5,0 ns	N/A
TopoSys II	Line	630 Hz	83 kHz	$\pm 7.15°$	1.0 mrad	N/A	2.0 cm	5,0 ns	1 ns
Leica ALS50	Oscillating	25–70 Hz	83 kHz	$\pm 37.5°$	0.33 mrad	N/A	N/A	10 ns	N/A
Leica ALS50-II	Oscillating	35–90 Hz	150 kHz	$\pm 37.5°$	0.22 mrad	N/A	N/A	10 ns	1 ns
LMS-Q560	Line	160 Hz	<100 kHz	$\pm 22.5°$	0.5 mrad	8 μJ	2.0 cm	4,0 ns	1 ns

Table 8.9 Commercial LiDAR Instruments- A comparison

Model	OEM	Category	Laser wavelength [nm]	Scan rate [Hz]	Sampling rate [kHz]	FOV (deg)	Scan pattern	Typical alt.[m]	Footprint [cm]	Vertical acc. [cm]	Mass [kg]
Terrain Mapper	Hexagon Leica	topo	1064	25-150	2000	20-40	circular	1000	25	<5	40
VQ-1560i-DW	RIEGL	topo	1064/532	40-600	2x666	58	x-shaped lines	1000	20/100	2	65
CityMapper	Hexagon Leica	topo	1064	60-150	700	40	circular	1000	25	<5	54
SPL100	Hexagon Leica	topo	532	Up to 25	6000	20-40	circular	4000	32	<10	80
Titan	Teledyne Optech	multi-spectral	532/1064/1550	Up to 25	3x300	60	lines	1000	70/35/35	<10	120
VQ-880-G II	RIEGL	topo-bathy	1064/532	14-100	279/700	40	curved lines /circular	600	18/60	>2.5	65
HawkEye 4X	Hexagon Leica	topo-bathy	1064/532/532	-	500/140/40	28/40	elliptical	400	280	>5	-
CZMIL Nova	Teledyne Optech	topo-bathy	1064/532	-	70/10	40	circular	400	280	>7.5/15	287
VUX-1UAV	RIEGL	topo	1550	Up to 100	500	330	lines	100	5	1	3.5
Puck	Velodyne	topo	905	5 -20	600	360	fan of lines	50	10x5	3	0.8
miniVUX-1DL	RIEGL	topo	1064	75	100	46	circular	80	13x4	1.5	2.4
VQ-840-G	RIEGL	topo-bathy	532	10-100	50-200	40	elliptical	50	5	>2	15
EAARL	NASA	Topo-Bathy	532	25	10	45	Zig-zag	300	20	>16	113.4
SEDA	SAC	Topo-Bathy	1064/532	80 / 160	72	20	elliptical	1000	20	15 (inst.)	TBD

Table 8.10 Spaceborne LiDAR- Flown & planned

Payload	Year	Method	Applications	Vertical acc. (cm)
SLA-01/02	1996	TOF	Global Elevation Control Points	150
ICESat/GLAS	2003		Sea ice, atmosphere, land, vegetation, etc.	15
CALIOP, CALIPSO	2006	Doppler, TOF	Aerosol profile, cloud top height cloud, classification of aerosols' sub-types	3000
CATS, ISS	2015	HSRL, TOF	Pollution, dust, smoke, and aerosols, study daily changes in clouds and other parameters in the atmosphere	3000
ZY3–02	2016	TOF	Experimental altimetry	100
ATLAS, ICESat-2	2018		Polar ice sheet thickness, topography, cloud top height & aerosol, cloud type and its temperature	10
GEDI, ISS	2018		Topography, biomass, ecosystems & ice	100
ALADIN,ADM-Aeolus	2018	Spectrometers	Wind profiles, atmospheric backscatter & extinction coefficient profiles	200/s
GF-7	2019	TOF	Generalized Elevation Control Point	100
Terrestrial Ecosystem Carbon Monitoring Satellite	2022		Forestry carbon inventory monitoring, generalized elevation control points	100
MOLI, ISS	2022		Canopy & biomass	2500
ALTID, EarthCARE	Not Flown	HSRL, TOF	Aerosol profile, cloud top height	10000
LIDAR, ACE			Measure cloud type, aerosols, amount and cloud top temperature	TBD

8.9 LiDAR Application and Techniques

LiDAR instruments are diverse and the variability of spectral bands, spectral bandwidth are the key factors in remote sensing. With capabilities like multi-band LiDAR, broadband LASER, fine bandwidth tunable LASER, fine resolution spectrometers, tunable polarizers led to new applications rivalling present methods. The 'state of the art' near real time processing hardware, storage and synthetic visual mapping of the reflected/ scattered spectra are evolving at a rapid space to provide better information than that was possible. LiDAR has significant advantages over other methods of remote sensing:

- Higher accuracy
- Vertical accuracy 5-15 cm (1σ)
- Horizontal accuracy 30-50 cm
- Fast acquisition and processing -1000 km2 in 12 hours, DEM in 24 hrs.
- Minimum human dependence-most processes are automatic
- Mostly Weather/Light independence
- Forest Canopy measurements
- Collect data in 3D.
- Cost- Comparative studies show LiDAR data is cheaper in many applications in terms of speed, accuracy and density of data.

Fig. 8.25 compares one example application of LiDAR with other methods.

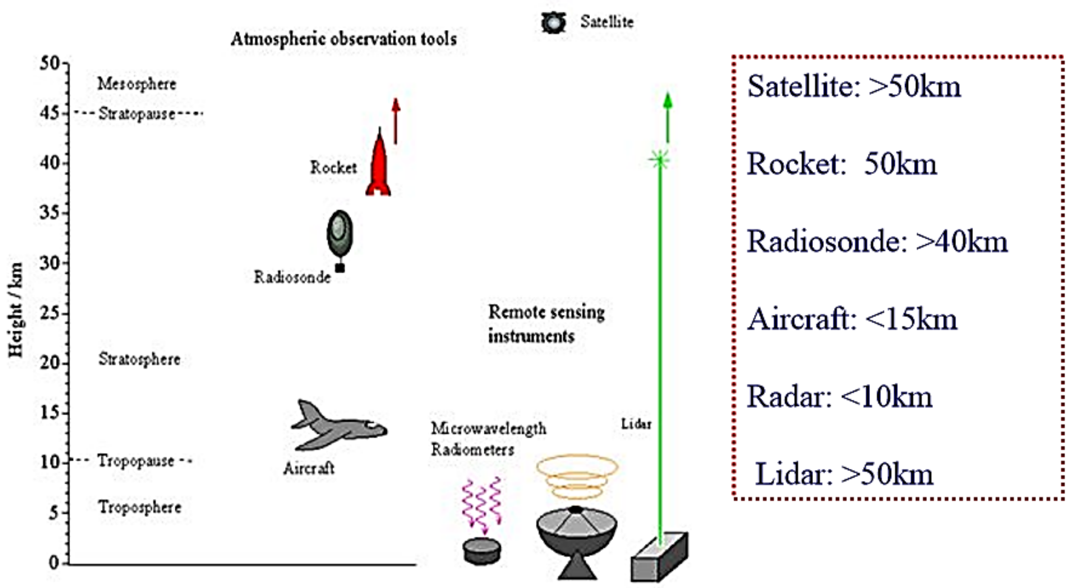


Fig. 8.25 LIDAR capability

8.10 LiDAR for Remote Sensing

Exploiting the atmosphere constituent properties, many types of LiDAR have been developed. Some of the popular LiDAR types are discussed in detail.

Table 8.11 Types of LiDAR

LiDAR Type	Techniques of Sensing	Measurements
DIAL	Absorption by Atoms & molecules	Gas concentrations, gas pollutants, ozone, water vapour
Mie/ Aerosol	Elastic scattering by aerosols & clouds	Aerosols, cloud geometry & thickness
HSRL (High Spectral Resolution)	Doppler broadening/ Spectral distribution	Aerosols from airborne system
Rayleigh (wavelength dependent)	Elastic scattering by air molecules	Stratosphere, mesosphere density, temperature
Resonance Fluorescence	Resonance scattering, Fluorescence by atoms, Elastic scattering by air molecules, Doppler shift	Stratosphere, mesosphere density, temperature, wind density, clouds in mid to upper atmosphere
Raman (wavelength dependent)	Inelastic scattering	Water vapor, Aerosols, cloud optical density, Temperature (lower atmosphere)
Fluorescence	Laser induced fluorescence, inelastic scattering	Marine, vegetation
Bathymetry	Reflection from water & floor surfaces	Seafloor, reverbed elevations
Wind/ Doppler	Doppler shift	Wind speed, turbulence, wind direction
Altimeter	Reflection from surfaces	Topography, ranging

1. **Elastic backscatter LiDAR** measure profiles of the extinction coefficient assuming conditionally 'constant' aerosol extinction to backscatter ratio, called the LiDAR ratio. In practice, the LiDAR ratio strongly depends on the size, morphology and chemical composition of the particles and hence not accurate. The detected signal intensity of the scattered light contains contributions from all constituents in the atmosphere including air molecules, aerosol particles and clouds. These LiDAR provide information on cloud base heights, aerosol optical depth, and structure of the atmospheric boundary layer.

2. A linear **polarized LiDAR** measures the ratio of perpendicular backscatter intensity and parallel backscatter intensity with respect to the transmitter polarization axis to give the linear particle depolarization ratio (δ). Liquid droplets in clouds give symmetrical scattering, while ice crystals are asymmetrical. Rain and large ice crystals are horizontally oriented. Liquid droplets in clouds return linearly polarized backscattered signal and $\delta = 0$. When $0 < \delta < 1$ the backscattered light has cross-polarized components indicating that the cloud contains ice crystals.

3. **High Spectral Resolution LiDAR (HSRL)** determines aerosols in the atmosphere. The unit works with the different spectral distribution of the reflected LiDAR signals to differentiate between pulses reflected by molecules from those sent back by aerosols. This processing approach measures the molecular only backscatter at the transmitted wavelength by blocking the spectrally narrow aerosol returns and passing the spectrally broad molecular returns.

4. **Raman LiDAR** can detect the signals at the LASER wavelength (elastic backscattering) and at different wavelengths due to inelastic scattering by molecules (nitrogen and/or oxygen). These signals emerge from scattering by molecules, which absorb a part of the photon's energy or add an amount of energy to the photon's energy (inelastic scattering). By inelastic scattering, these molecules change their vibrational and/or rotational state (Raman process). The backscattered light experiences a frequency shift $\Delta f = fL - f = \Delta E/hc$ caused by change of molecule energy levels (ΔE). Using this technique, the LiDAR can evaluate the presence of aerosols with optimum accuracy. The main advantage of a Raman LiDAR over elastic-backscatter LiDAR is that it measures the extinction coefficient rather than inferring it under assumptions. Raman scattering

cross sections are very small and therefore need high laser pulse energy, large telescopes, and efficient detectors.

A state-of-the-art multi-wavelength Raman LiDAR is 3 backscatter + 2 extinction configuration which emits at 1064, 532, and 355 nm wavelengths. A 7-channel receiver separates the elastically backscattered signals while a polarizer discriminates the parallel- and cross-polarized components. The system detects:

- elastic backscatter signals at 355, 532, 1064 nm
- vibration-rotation Raman signals of nitrogen at 387 and 607 nm
- vibration-rotation Raman signals of water vapor at 407 nm
- parallel- and cross-polarized components of the 532-nm signal

The depolarization ratio at 532 nm, the extinction coefficient and the LiDAR ratio at 355 and 532 nm, water-vapor mixing ratio and relative humidity can be determined. Pure-rotational Raman Effect measures the temperature profile in the atmosphere.

5. **Differential Absorption LiDAR (DIAL)** use a tunable laser or two wavelengths of laser pulses to record data from the peak of a gas absorption line and another in a low-absorption region. Here, the wavelength of one radiation is matched to a specific molecular transition such that it undergoes attenuation without change in wavelength ($\lambda L1 = \lambda$). The second wavelength is detuned from the molecule transition so that it is scattered back with less attenuation and without change in wavelength ($\lambda L2 = \lambda$). The differential attenuation of the backscattered signals show the presence/ concentration of target specimens. This LiDAR is useful for measuring gas concentrations and temperature profile.

6. A **Bathymetric LiDAR** works with green wavelengths, which penetrate the water surface and return to provide depth of the water bodies. The Fresnel reflection- returns a portion of the energy from the water surface and the remainder is reflected from the bottom. The depth penetration a function of water clarity and bottom reflection. This when combined with a topographic LiDAR is useful for identifying shorelines and elevations for coastal engineering and marine sciences.

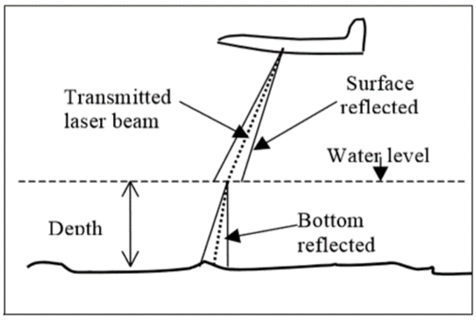


Fig. 8.26 Bathymetric LiDAR

7. **Doppler LiDAR** detects the molecule/ particle movements from wavelength shift of line-of-sight backscattered signals as vector $v\rightarrow = \Delta fc/2$. These are useful for monitoring wind turbulences, wind speed, and wind direction using multiple data points.

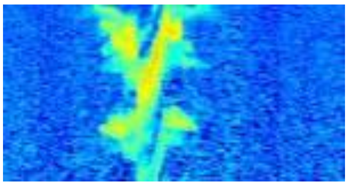
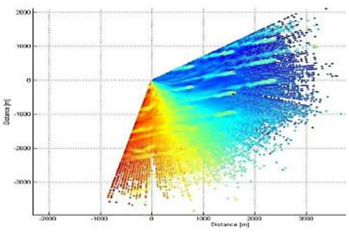
8. **RangeFinder/ Altimeter LiDAR** is based on the Time of Flight -Pulsed lasers, CW laser

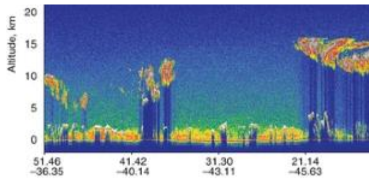
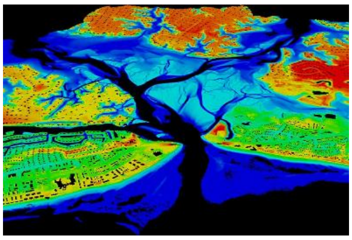
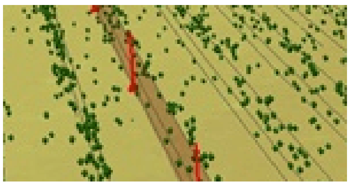
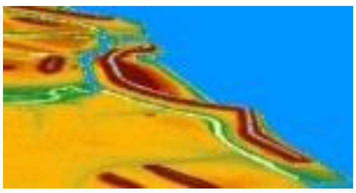
amplitude modulation or CW laser chirp / Chirp pulse compression. This gives the range information of targets. These are useful in topography, ground elevation, sea ice, vegetation, etc. studies.

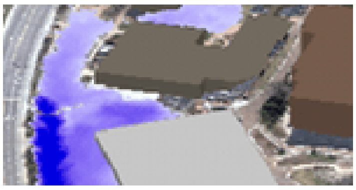
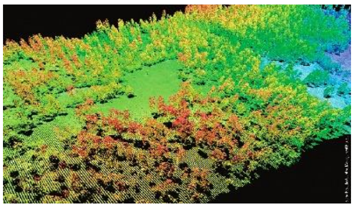
8.11 Applications

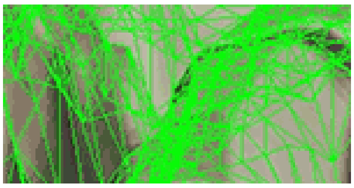
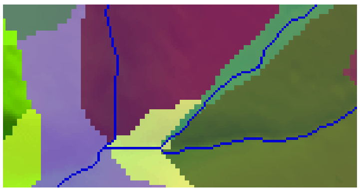
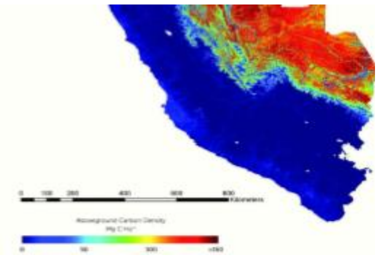
A LiDAR created a topographic map of Mars back in 1999. LiDAR can measure the elevation of a seashore and underwater. This feature is utilized for disaster management by predicting areas affected by tsunami and floods. Due to its shorter wavelength, Differential Absorption LiDAR (DIAL) can detect tiny molecules in the atmosphere. Molecular scattering decreases with increasing wavelength, allowing the system to build a 'density map'. The data collected by LiDAR is highly accurate, giving an exact estimation of the molecules comprising any form of matter. This technology is primarily useful for studying atmospheric gases, aerosols, clouds and locating new oil and gas deposits. Doppler LiDAR s measure wind speed, turbulence, wind direction, and wind shear accurately. Further applications in remote sensing are geography, geology, bathymetry, geomorphology, archaeology, forest biomass mapping, forest DEM (Digital Elevation Model) generation, monitoring of atmosphere constituents, weather, pollution, flood, coastal erosion, glacier, avalanche, route/corridor mapping, cellular network planning, seismology, etc. The list of applications are unlimited. Some interesting applications are summarized in Table 8.12.

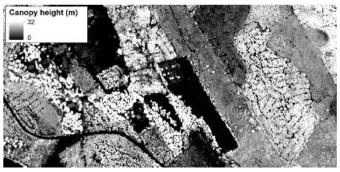
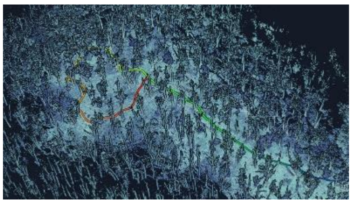
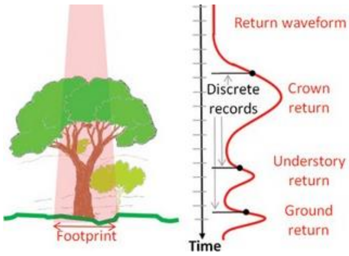
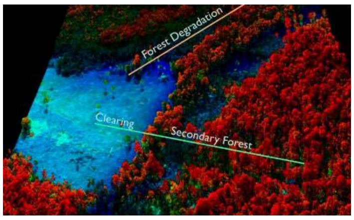
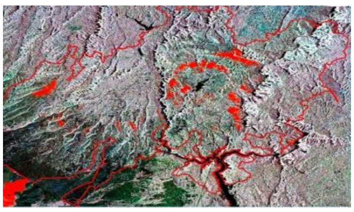
Table 8.12 LiDAR Applications

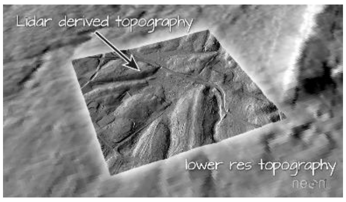
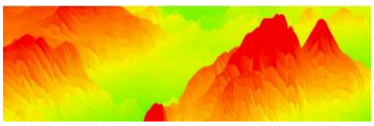
Sl.	Application	Measurements
1	Pollution modeling 	Monitor pollutants like carbon dioxide, Sulphur dioxide and methane (Greenhouse Gases) and Gases Related to Air Quality like tropospheric ozone, nitrogen dioxide, formaldehyde, etc.
2	Meteorology 	Study atmospheric composition, aerosols and clouds (Backscatter LiDAR), forms of gas in the atmosphere (Differential Absorption LiDAR or DIAL), Raman LiDAR measures gas concentration and Doppler LiDAR measures wind profile
3	Atmospheric physics	Measure atmospheric gases, aerosols, clouds, and temperature, as well as concentrations and fluxes of pollutants like volcanic sulphur dioxide, atomic mercury and hydrocarbons (DIAL)

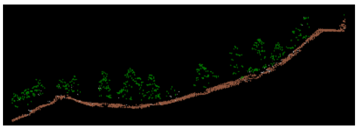
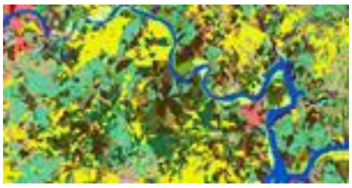
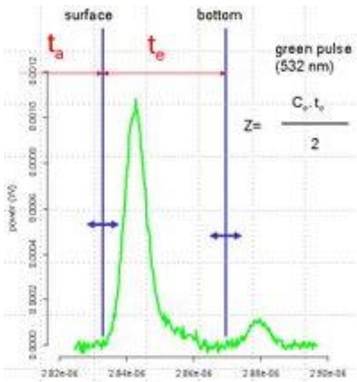
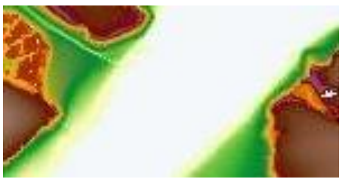
4	Cloud profiling 	LiDAR pulses are capable of penetrating the clouds and provide cloud statistics, such as heights and phases. Aerosol data provide understanding of the connection between clouds and climate change.
5	Aerosol distribution data	Measurements of concentration and distribution of atmospheric gases and aerosols gives air quality as well as forecast of the dispersion of trace gases and aerosols in the first layers of the atmosphere
6	Gas composition data	Particular gases in the atmosphere such as ozone, carbon dioxide or water vapor is measured to get gas composition for weather forecasting, climate modeling and environmental monitoring.
7	Biology and conservation 	Ecological research is aided by assessment of habitat quality for various species, as well as to map areas where flooding and drought might occur.
8	Biodiversity 	Monitoring habitat structure provides species diversity by deriving from factors crucial to survival, such as vegetation structure.
9	Coastline management 	Topographical and bathymetric LiDAR uses an infrared laser to map the land, while the latter uses water-penetrating green light. In tandem, they form coastal surveys.

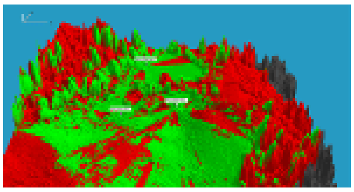
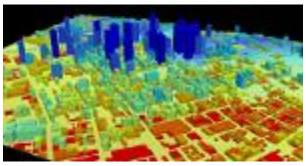
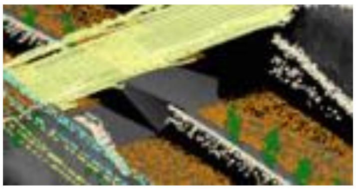
10	Flood modeling 	LiDAR data provides the advanced topographical information needed for flood relief modeling.
11	Earthquake damage	LiDAR data and imagery is useful for post-earthquake assessment of building damage, which can save lives and hasten rescues operations.
12	Morphology	LiDAR data is used for investigation of evolution and characteristics of morphology to forecast future patterns of change. This bio-geomorphic characterization of coasts allows coastal managements.
13	Glacier changes	LiDAR collects data around glacier level changes to provide inputs for climate changes.
14	Study of forest ecology 	LiDAR is able to collect vast amounts of detail on forest flora and fauna. Ecologists use this data to implement conservation strategies.
15	Oceanography	LiDAR provides details like ocean depth, composition, general biomass and phytoplankton fluorescence. These lead to quantitative information of species in the deep sea.
16	Dune monitoring	Dune activities like changes in size, shape and vegetation are important for morphology study.

17	Tsunami prediction 	DEM gives the elevation value of the seashore, while bathymetric data provides underwater elevation. These are used to model and forecast the severity of an oncoming tsunami and predict affected areas.
18	Watershed and stream delineation 	DEMs define watershed areas and streamline delineation. This allows modeling the likelihood of flooding.
19	Storm water management	LiDAR data provides an accurate and precise elevation map for Integrated Storm water Management Plan (ISMP) to balance land use planning, storm water engineering, flood protection and environmental protection.
20	Estimation of carbon absorption 	DIAL provides accurate data of carbon absorption within specific locations of forests, helping researchers make improvements.
21	Landslide analysis	High-resolution DEM has made it possible to obtain accurate regional landslide information at a higher frequency, improving safety and asset integrity.
22	Measurement of water surface roughness	LiDAR provides water surface mapping to detect and evaluate roughness and enable hydrology modeling.
23	Vulnerability studies	LiDAR enables tracking of disasters such as tornadoes, landslides, tsunamis, and enable storm surge modeling, hydrodynamic modeling and shoreline

		mapping. These lead to plans for human safety.
24	Forestry management 	LiDAR has the unique ability to measure forest canopy structure, as well as the ground underneath. This allows for cost-effective, large-scale surveys, calculate fuel capacity and root expanse.
25	Precision forestry 	Precision forestry involves the use of intelligent forestry systems to make data-driven decisions. LiDAR provides a detailed reading of forest dynamics, enabling organizations to collect meaningful data.
26	Forest canopy measurement 	LiDAR is used to determine both canopy density (ratio of vegetation to ground) and canopy height (how far above the ground the top of the canopy is). The data determines the exact quality of the trees.
27	Deforestation 	LiDAR identifies the forest areas affected by humans. Researchers measure the 3D structure of tree canopies, height and the diversity of canopy elements like leaves, twigs and branches. This data gives the tropical forest assets including lumber inspection
28	Forest fire management 	LiDAR data provide forest fire patterns and determine high-risk areas (fuel mapping), so proactive measures can be taken to circumvent a blaze.

29	Geology	LiDAR data is an essential tool for mapping, monitoring and managing natural hazards and resources, allowing geologists to study earth topology and its origin through a process known as geomorphology.
30	Micro-topography 	LiDAR captures high-resolution micro-topography of areas otherwise hidden by trees and greenery, penetrating through the forest canopy to detect the surface underneath. In 2012, it was used to find the legendary city of La Ciudad Blanca in Honduras.
31	Soil profiling	LiDAR determines the profile and roughness of different agricultural soil types, informing decisions about crop planting, tillage and which manure type to use for best results.
32	Oil and gas exploration	DIAL offers a new method of oil and gas exploration by detecting gases and particles along with the accurate 3D model of the terrain, minimizing the project's environmental impact.
33	Quarries and minerals	LiDAR is used to detect air pollutants, survey surrounding land and gauge environmental effects.
34	Calculation of ore volumes	LiDAR provides ore volumes by penetrating the Earth's surface to gather data.
35	Robotic mining	LiDAR determines minerals that lie beneath the surface of the earth, and analyses mine structure to prevent them from collapsing.
36	Terrain modeling 	LiDAR provides two types of elevation model: first return and ground. The first includes forest canopies and buildings (DSM), whereas the second topography (DEM). This allows detailed mapping of any given terrain, allowing scientists to

		study changes in slope and landform breaks.
37	Bathymetric mapping 	Water depths from 0.9m to 40m with a vertical accuracy of 15cm is achieved based on clarity of the water. Green laser pulse transmitted provides reflections from both surface and depth of water.
38	Ecological & land classification (ELC) 	ELC provides physical and biological information about a given landscape to help with sustainable management. LiDAR can map and provide accurate data for civil engineering works.
39	Hydrographic survey 	Bathymetric LiDAR captures geospatial data of the coastline and shallow waters, facilitating the efficient creation of hydrographic data.
40	River survey 	Bathymetric systems penetrate underwater and measure aspects of river data such as depth, length and flow. This helps in understanding the nature of the river, as well as planning to avoid potential floods.
41	Urban planning and surveying	LiDAR provides digital models of the earth's surface at relatively high speed. This is useful in land use planning and creating city models.

	 	
42	Viewshed analysis 	A viewshed dictates surrounding areas as visible or non-visible from an observer's POV. These analyses are a common function of GIS software. LiDAR technology can be used to create a DEM, from which one can conduct a viewshed analysis on any given piece of land to determine what will be visible from various different angles – helpful when planning new buildings or infrastructure.
43	Airport infrastructure	LiDAR technology can be used to map out airport infrastructure and features like the runway, terminal building and hangar – pinpointing their exact location. This information is essential to airport security, preventing infiltration and accidents.
44	Edge detection 	Using LiDAR data, we can detect and analyses objects and the edges of objects, such as bridges, buildings and roads. Edge detection is used in bridge or structure maintenance by identifying damages.
45	Transport planning/ Railway infrastructure/ Road design 	High spatial resolution LiDAR capture data over large areas, as well as in fine detail to plan transportation projects. It provides a fast, accurate and cost-effective solution to map complete railway networks, map out the exact road design and minimize the impact of new constructions and maintenance. This is particularly invaluable in high-risk areas with hilly, unstable terrain.

46	Archaeology	LiDAR has proved invaluable to archaeologists – such as the mapping of ancient features by observing patterns not visible from the ground. DEMs can also reveal micro-topography hidden by trees and shrubs.
47	Military	The military uses 3D data for detailed mapping of urban and non-urban terrain for air defense, air traffic control, ground surveillance, navigation, search and rescue, fire control radars, and identification of moving targets.
48	Mobile network planning	High-resolution data makes it ideal for cellular network planning; determining the line of sight and viewshed for prospective cellular antenna – reducing costs in the process.
49	Mapping of wireless signal	In wireless signal mapping, LiDAR makes it easier to plan wireless transmitters/ tower, assess the strength and radius of the signal.
50	Navigation	Automated Landing, Hazard Avoidance, and Docking—Technologies to aid spacecraft and lander maneuvering and safe operations.

Bibilographghy and further suggested readings

Elastic Lidar Theory, Practice, And Analysis Methods Vladimir A. Kovalev William E. Eichinger By John Wiley & Sons, Inc.

Diaz, J.C.F., Carter, W.E., Shrestha, R.L., Glennie, C.L. (2017). LiDAR Remote Sensing. In: Pelton, J., Madry, S., Camacho-Lara, S. (eds) Handbook of Satellite Applications. Springer, Cham. https://doi.org/10.1007/978-3-319-23386-4_44

100 Real-World Applications of LiDAR Technology https://levelfivesupplies.com/100-real-world-applications-of-lidar-technology/

Tools- **LightTools** illumination design software for modeling and analysing LiDAR systems

LiDAR Data resources:

Open Topography

USGS Earth Explorer

The United States Interagency Elevation Inventory

NOAA Digital Coast

National Ecological Observatory Network (NEON)

LIDAR Data Online

Elastic Lidar Theory, Practice, And Analysis Methods, Vladimir A. Kovalev William E. Eichinger By John Wiley & Sons, Inc.

Diaz, J.C.F., Carter, W.E., Shrestha, R.L., Glennie, C.L. (2017). LiDAR Remote Sensing. In: Pelton, J., Madry, S., Camacho-Lara, S. (eds) Handbook of Satellite Applications. Springer, Cham. https://doi.org/10.1007/978-3-319-23386-4_44

The Geolocation Accuracy of LiDAR Footprint, Gabriel Popescu, Daniela Iordan, DOI: 10.13189/ujar.2016.040405

Atmospheric Lidar Based Remote Sensing Techniques, Longlong Wang, University of Nova Gorica.

100 Real-World Applications of LiDAR Technology https://levelfivesupplies.com/100-real-world-applications-of-lidar-technology/

American National Standard for Safe Use of Laser- ANSI Z136.1 – 2022

What are the different scan patterns of LiDAR systems?, https://www.yellowscan.com

LiDAR Data resources:

- Open Topography
- USGS Earth Explorer
- The United States Interagency Elevation Inventory
- NOAA Digital Coast
- National Ecological Observatory Network (NEON)

- LIDAR Data Online
- Tools- LightTools illumination design software for modeling and analyzing LiDAR systems

Chapter 9

UAV REMOTE SENSING

9.1 Introduction

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have revolutionized the field of remote sensing in recent years. UAV remote sensing involves the use of drones equipped with sensors to collect data about the Earth's surface from above. This innovative technology has transformed the way geographic data is acquired, providing high-resolution imagery, topographic data, and other valuable information for various applications. UAV remote sensing involves the deployment of drones to capture aerial data, enabling detailed and accurate information about the Earth's surface. Drones are equipped with various sensors, including cameras, LiDAR (Light Detection and Ranging) devices, thermal sensors, and multispectral sensors. These sensors capture data from different parts of the electromagnetic spectrum, allowing for a comprehensive understanding of the environment.

In cartography, the applications of aerial photography have been used since many years. The applications vary in a wide range of areas. Its main aim is to minimalize work on the ground. Relatedly, photogrammetry is a tool that are mainly employed in huge applications. The main purpose of this method is to get hold of 3D data of the zone of interest. Towards the end, they may also use to bring out orthophotos. For smaller cartography, UAVs also used for photogrammetry. Drone is also used as an important device for tasks that require quick response. This may include the tasks of monitoring and inspecting building facades. The use of UAV began in the military operations. But, of late UAV is seen to be used in numerous civilian activities. An important advantage of using UAVs is that it assists in acquiring a close-range aerial photography operation in addition to the already acquired terrestrial image-based techniques. This process of survey, in addition to the developments of the high-end sensors and computing power, occupies a pertinent role to solve various issues.

In the field of remote sensing, the on-board sensor's optics offer a critical part. Many of the UAV manufacturers planned and integrated better-quality lenses. However, the vital issue is that of the payload. Contrary to this, classical photogrammetry is assisted and complemented by the computer vision techniques.

The Unmanned aerial vehicles are designed and assembled based on the requirements and can be classified into two categories- (i) fixed-wing and (ii) rotorcraft or multirotor or rotary wing UAVs. Fixed-wing UAVs have limitations in terms of complex designs, difficult stabilizing mechanism, requirement of a long runway and difficult to operate in hilly terrain. However, they have advantages in terms of long endurance and large payload capabilities. On the other hand, multirotor UAVs use vertical take-off and landing and have been found more appropriate in hilly and complex terrain. However, unlike most fixed wing models of UAVs, the rotary wing models generally have a much shorter flight time. In this chapter, we will explore UAV remote sensing, its significance, and the advancements it brings to geographic analysis.

9.2 Advantages of UAV Remote Sensing

UAV remote sensing offers numerous advantages over traditional remote sensing techniques. Here are some key benefits:

- **High Spatial Resolution**: UAVs can capture imagery and data at a much higher spatial resolution compared to satellite imagery. This allows for detailed analysis of smaller geographic areas, facilitating precise mapping, land cover classification, and feature extraction.
- **Flexibility and Accessibility**: UAVs provide flexibility in terms of flight planning, enabling data collection on-demand. They can access remote or inaccessible areas, such as dense forests, rugged terrains, or disaster-stricken locations, providing valuable information that was previously challenging to obtain.
- **Cost-Effectiveness**: UAVs offer a cost-effective alternative to manned aerial surveys or satellite imagery. They require lower operational costs and can be deployed quickly for targeted data acquisition, reducing the expenses associated with data collection.
- **Real-Time Data Acquisition:** UAVs enable real-time data acquisition and on-site data processing, allowing for immediate analysis and decision-making. This is particularly useful in emergency response situations, environmental monitoring, and time-sensitive applications.

9.3 Types of UAVs

There are several types of UAVs/drones are available with different configurations and specifications. The users are defining their own standards as per their requirements. Generally, UAVs can be categorized by their performance and characteristics. Features including weight, wing span, wing loading, range, maximum altitude, speed, endurance, and production costs, are important parameters that distinguish different types of UAVs/drones and classify them into several categories. Furthermore, UAVs can be classified based on their engine types, size, weight, range and endurance, applications, and also use a tier system that is employed by the military. The UAVs often vary widely in their configurations depending on the platform and mission. The classification according to size includes: Very small UAVs, Micro or Nano UAVs, Small UAVs, Mini UAVs, Medium UAVs, and Large UAVs. In general, there are two broad categories of UAVs; fixed-wing and multirotor drones. Both the types have their own advantages and disadvantages including their suitability for some applications. Fixed-wing UAVs normally have longer flight endurance capabilities, while multirotor can provide stable image capturing and easy vertical take-off and landing characteristics. The UAV classifications are further discussed below:

9.3.1 Fixed-Wing UAVs

Fixed-wing UAVs resemble traditional airplanes and feature wings that generate lift to keep them airborne. They typically have a longer flight endurance, higher payload capacity, and the ability to cover large areas efficiently. Fixed-wing UAVs are commonly used for mapping, surveying, aerial photography, agricultural monitoring, and environmental research. Their design allows for stable and controlled flight, making them ideal for tasks that require extended flight durations and wide coverage. The limitation of fixed-wing UAV includes the requirement of ground distance for take-off and landing, as well as long sweeping turns, however, the actual distance required will depend on the model and its configuration. The fixed-wing UAVs are unable to hover at one spot constantly, which makes them unsuitable for any general aerial photography work.

9.3.2 Multi-Rotor UAVs

Multi-rotor UAVs are the most recognizable type of drones and are characterized by multiple rotors or propellers. The most common configurations are quadcopters (four rotors) and hexa-copters (six rotors), although octocopters (eight rotors) are also used for specialized applications. Multi-rotor UAVs offer vertical take-off and landing capabilities, hover capabilities, and manoeuvrability, making them suitable for close-range inspections, aerial videography, real-time monitoring, and search and rescue operations. They are widely used in cinematography, infrastructure inspection, emergency response, and surveillance. The multirotor UAVs have disadvantages due to their reduced range and speed as compared to fixed-wing UAVs. The main disadvantage of multi-rotors is their limited endurance and speed, making them unsuitable for large scale aerial mapping, long endurance monitoring and long-distance inspection, such as pipelines, roads and power lines. Since, the multi-rotors can't take flight for longer time, therefore the area coverage is limited.

9.3.3 Single-Rotor Helicopter UAVs

Single-rotor helicopter UAVs, often referred to as rotorcraft drones, feature a large rotor on top and a tail rotor for stabilization and control. These UAVs offer vertical take-off and landing capabilities, as well as the ability to hover and manoeuvre in confined spaces. Single-rotor UAVs are commonly used for military applications, aerial surveillance, transport of goods, and complex aerial missions requiring precise control and stability. Their capability to hover and fly at various altitudes makes them suitable for tasks such as aerial mapping, geophysical surveys, and infrastructure inspection.

9.3.4 Hybrid UAVs

Hybrid UAVs combine the characteristics of fixed-wing and multi-rotor UAVs, offering the advantages of both designs. These drones typically have fixed wings for efficient forward flight and multi-rotor capabilities for vertical take-off and landing. Hybrid UAVs are often used for long-endurance missions that require extended flight range, such as aerial mapping, surveillance, and monitoring large areas. Their ability to transition between fixed-wing and multi-rotor flight modes allows for versatility and adaptability to different operational requirements.

9.3.5 Nano and Micro UAVs

Nano and micro-UAVs are the smallest categories of drones, designed for applications that demand compact size, lightweight construction, and manoeuvrability in tight spaces. Nano UAVs typically weigh less than 250 grams, while micro-UAVs weigh between 250 grams and 2 kilograms. These small drones are often used for indoor inspections, urban environments, research in confined areas, and close-range surveillance. Their size allows them to navigate through narrow spaces, capture high-resolution imagery, and perform tasks that require close proximity to objects or subjects.

Table 9.1 Comparison between fixed-wing and multirotor UAVs

Capability	Fixed-wing	Multirotor
Speed	High	Low
Flight time	High	Low
Coverage	Large	Small

Object resolution	Cm/inch per pixel	mm per pixel
Take-off and landing area	Large	Very small
Landing in case of power failure	Can land safely without power	Can result in complete damage of UAV
Wind resistance	High	Low
Skill required to fly	High	Low
Projects	Large area mapping	Small area mapping, Machine and industrial plant monitoring, Indoor inspection
Applications	Land surveying, Agriculture, Mining, Environmental, Humanitarian etc.	Inspection, Urban survey, Construction sites, Emergency response, Law enforcement, Transport of medicines and light goods, Cinematography and videography etc.
Advantages	• Long endurance • Large area coverage • Fast flight speed	• Accessibility • Ease of use • VTOL and hover flight • Good camera control • Can operate in a confined area
Limitations	• Launch and recovery needs a lot of space • No VTOL/hover • Harder to fly, more training needed • Expensive	• Short flight time • Small payload capacity

9.4 Applications of UAV Remote Sensing

With their versatility, agility, and accessibility, UAVs have found applications across various industries, transforming the way we gather and analyze geographic information. In cartography, the applications of aerial photography have been used since many years. The applications vary in a wide range of areas. Its main aim is to minimalize work on the ground. Relatedly, photogrammetry is a tool that are mainly employed in huge applications. The main purpose of this method is to get hold of 3D data of the zone of interest. Towards the end, they may also use to bring out orthophotos. For smaller cartography, UAVs (Unmanned Aerial Vehicles) also used photogrammetry. Drone is also used as an important device for tasks that require quick response. This may include the tasks of monitoring and inspecting building facades. The use of UAV began in the military operations. But, of late UAV is seen to be used in numerous civilian activities. An important advantage of using UAVs is that it assists in acquiring a close-range aerial photography operation in addition to the already acquired terrestrial image-based techniques. This process of survey, in addition to the developments of the high-end sensors and computing power, occupies a pertinent role to solve various issues.

In the field of remote sensing, the on-board sensor's optics offer a critical part. Many of the UAV manufacturers planned and integrated better-quality lenses. However, the vital issue is that of the payload. Contrary to this, classical photogrammetry is assisted and complemented by the computer vision techniques. As asserted by Remondino et al. 2012 and Chiabrando et al. 2015, the process of extraction and matching is very much a part of the typical workflow. After this process, a strong outlier detection and elimination and also the process of bundle block adjustment is a necessary step to achieve the correct orientation of each camera which is the external parameters.

The applications of UAVs/Drones based land survey and mapping has taken quantum jump in the recent years. Some of the popular applications domain includes agriculture and crop monitoring, environmental monitoring, infrastructure planning and management, disaster monitoring and management etc. The UAVs equipped with multispectral sensors can assess crop health, monitor vegetation indices, detect diseases, and optimize irrigation practices. This enables farmers to make informed decisions about crop management, improving yields and reducing resource usage. UAVs contribute to environmental monitoring by capturing data on deforestation, land degradation, wildlife habitats, and ecosystem dynamics. This information aids conservation efforts, habitat assessment, and environmental impact assessments. In infrastructure planning and management, UAVs assist in infrastructure planning by providing accurate topographic data, 3D modelling, and mapping of construction sites. This supports efficient project management, site analysis, and monitoring of infrastructure development. In disaster management, UAVs play a vital role in disaster management by rapidly assessing damages, identifying affected areas, and facilitating search and rescue operations. They provide critical situational awareness for emergency response teams, aiding in efficient resource allocation and decision-making. Some of the major applications of UAV remote sensing are discussed below:

9.4.1 Agriculture and Crop Monitoring

UAV remote sensing plays a vital role in modern agriculture, offering farmers valuable insights into crop health, growth patterns, and resource management. By capturing high-resolution imagery and utilizing multispectral sensors, UAVs can assess crop vigor, detect stress, identify areas with nutrient deficiencies, and monitor irrigation effectiveness. This data empowers farmers to make informed decisions about fertilizer application, irrigation schedules, and overall crop management, leading to optimized yields, reduced resource usage, and improved sustainability.

9.4.2 Environmental Monitoring and Conservation

UAV remote sensing has transformed environmental monitoring and conservation efforts by providing detailed and up-to-date information about ecosystems, habitats, and natural resources. Drones equipped with sensors can capture imagery, detect changes in land cover, monitor vegetation health, and assess the impact of human activities on sensitive areas. This data aids in the preservation of biodiversity, identification of deforestation or illegal logging, monitoring of protected areas, and understanding the effects of climate change. UAVs enable more accurate and efficient data collection, supporting evidence-based decision-making for conservation initiatives.

9.4.3 Infrastructure Planning and Inspection

UAVs are increasingly used in infrastructure planning, construction, and maintenance. By capturing high-resolution imagery and creating detailed 3D models, drones assist in site selection, surveying, and monitoring construction progress. They can quickly identify potential issues, monitor critical infrastructure elements (such as bridges and power lines), and provide accurate measurements for volume calculations and elevation analysis. UAVs reduce costs, increase safety, and improve efficiency in infrastructure projects, enabling better planning and timely maintenance.

9.4.4 Disaster Management and Emergency Response

UAVs have become invaluable tools in disaster management and emergency response situations. Rapid deployment of drones enables quick assessment of damage, identification of affected areas, and search and rescue operations. Thermal sensors on UAVs assist in locating survivors in disasters such as earthquakes or floods. High-resolution imagery and real-time data from UAVs aid in resource allocation, situation awareness, and decision-making for emergency response teams. UAVs enhance the effectiveness and efficiency of disaster management efforts, helping to save lives and minimize damage.

9.4.5 Urban Planning and Real Estate

UAV remote sensing contributes to urban planning and real estate development by providing detailed and accurate data for site analysis, land use planning, and infrastructure design. Drones capture aerial imagery, generate high-resolution maps, and create 3D models of urban areas. This information aids in assessing the impact of proposed developments, analyzing transportation networks, evaluating building heights, and visualizing urban growth patterns. Real estate professionals use UAVs to showcase properties through aerial photography and videography, providing unique perspectives to potential buyers.

9.4.6 Archaeology and Cultural Heritage Documentation

UAV remote sensing has transformed archaeological research and cultural heritage documentation. Drones equipped with LiDAR or photogrammetry capabilities can capture detailed aerial imagery and generate high-resolution 3D models of archaeological sites, monuments, and heritage structures. This data assists archaeologist in mapping ancient landscapes, identifying hidden features, and preserving cultural heritage digitally. UAVs allow for non-invasive and efficient documentation, supporting archaeological research, conservation efforts, and public outreach.

9.5 Payloads/ Sensors for Remote Sensing Applications

The on-board sensor's optics plays an important role in the field of remote sensing. Many manufacturers tried to bring together quality lenses. But the payload was a major issue. Some of the most commonly used sensors and payloads for different applications in Remote Sensing fields are:

- RGB (Red-Green-Blue) sensors/ camera

- multispectral sensors
- hyper-spectral sensors
- thermal sensors
- Li-DAR sensors

 RGB Sensor	 Multi-spectral sensor	 Hyper-spectral sensor	 Thermal sensor	 LiDAR sensor

Fig. 9.1 Various sensors used in remote sensing

In hyper spectral sensors, some disadvantages include large dataset size, complex image processing and high cost. In case of thermal imagery, thermal camera can be used along with any other system. Some problem may arise in this usage in the form of humidity. Many of the off-the-shelf multispectral cameras are highly effective. They can give image resolutions above 4200 pixels by 2800 pixels. They are also better than the thermal cameras which can give resolution of around 640 pixels by 480 pixels. For Remote Sensing, consumer-grade cameras are used in wide scale. Research is needed to examine these cameras to be effective in this field. These cameras need to be compared with hyper-spectral imaging systems and sophisticated multispectral in various remote sensing applications.

9.6 UAV Data Processing Software

Photogrammetry software can take overlapping images as data inputs. These are then combined to bring out point clouds, digital 2D or 3D models, etc. To give out more detailed 2D and 3D maps, these software brings together images which have similar points on the ground from multiple vantages. Some of the popular UAV data processing software are listed below:

- DroneDeploy 3D mapping mobile app.
- Pix4D Mapper photogrammetry.
- DroneDeploy Enterprise 3D Map.
- AutoDeskReCap photogrammetry.
- SimActive Correlator3D™ software.
- Maps Made Easy orthophoto and 3D models.
- 3DF Zephyr photogrammetry software.
- AgisoftPhotoScan photogrammetry.
- PrecisionHawk 3D map software.
- Open Drone Map photogrammetry.
- ESRI Drone2Map for ArcGIS.
- AgisoftMetashape 3D software.

The list presented above is not limited. The new and powerful software for UAV data processing are being developed by research communities and industry on regular basis. The selection of best suitable software for a user depends on many criteria such as cost, performance, complexity in learning the operations, computability etc.

9.7 Workflow for UAV Remote Sensing Applications

The workflow for UAV Remote Sensing involves three major steps, namely, UAV data acquisition, UAV data processing for the generation of the ortho products and deliverables of the ortho products. Before proceeding further, we need to understand the Orthorectification process in remote sensing.

The Orthorectification is a process used in remote sensing and geographic information systems (GIS) to correct aerial or satellite imagery for geometric distortions caused by terrain relief and sensor characteristics. It involves removing distortions such as scale variations, relief displacements, and image tilt, ensuring that the resulting image accurately represents the Earth's surface in a planimetrically correct manner. Aerial and satellite images are acquired from different perspectives and altitudes, resulting in geometric distortions due to the varying terrain topography and sensor characteristics. These distortions can lead to inaccuracies when using the imagery for mapping, measurement, or analysis purposes. Orthorectification is performed to transform the images into orthorectified images, which align with a map or coordinate system, allowing for accurate measurements and analysis.

The process of orthorectification involves several steps:

- **Ground Control Point (GCP) Collection**: GCPs are points with known coordinates on the Earth's surface. They are typically identified in both the imagery and a reference dataset (such as a digital elevation model or a map). The coordinates of GCPs are used to establish the relationship between the image and the Earth's surface.
- **Sensor Model Calibration**: The sensor characteristics, including the position and orientation of the sensor, are calibrated to account for distortions introduced during image acquisition. This calibration ensures that the image is transformed accurately.
- **Digital Elevation Model (DEM) or Terrain Data Integration**: A DEM or other terrain data sources are used to account for the relief displacements caused by the terrain. The DEM provides elevation information for each pixel in the image, allowing for the correction of terrain-induced distortions.
- **Image Transformation**: Using the GCPs and sensor model calibration, the image is transformed and resampled to remove distortions caused by terrain relief and sensor characteristics. The transformation aligns the image with a planimetric coordinate system, such as a map projection.
- **Image Mosaicking** (optional): In cases where multiple overlapping images are available, orthorectification can involve the mosaicking of individual orthorectified images to create a seamless, large-scale composite image.

Orthorectified imagery is widely used in various applications, including cartography, land cover mapping, urban planning, precision agriculture, environmental monitoring, and infrastructure development. The orthorectified images provide accurate spatial information and enable measurements and analyses to be performed with a high level of precision.

The three major steps in UAV remote sensing data processing are shown in Fig. 9.2.

Fig. 9.2 Stages of UAV remote sensing data processing

9.8 UAV data Acquisition for Survey

Based on the applications or project definitions, UAV data acquisition can be performed. For achieving quality and desired standards output/ data, some of the major parameters required are image overlaps, velocity, camera parameters and Ground Sample Distance (GSD). For automatically producing results with high accuracy and quality, a good dataset is needed. The process flow for UAV flight planning for data acquisition is shown in Fig. 9.3.

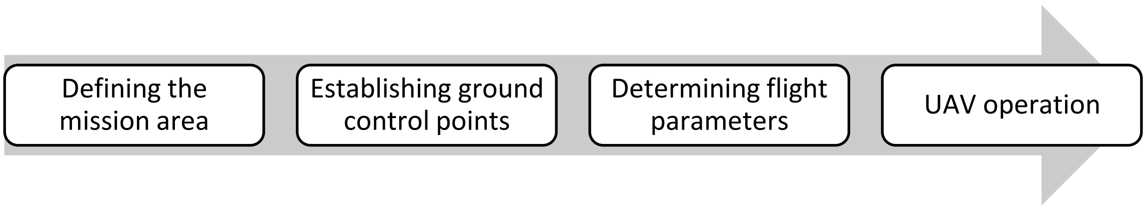


Fig. 9.3 Process flow for UAV flight planning

9.8.1 Defining the mission area

Based on the project definition, defining the mission area plays a very important role in selecting the specifications that are mostly favoured in UAV system required for data acquisition survey plan, such as UAV design/type, UAV payloads/sensors, etc. The selection of type of UAV platforms are based on literature available in market and experiences while carrying out few projects using UAV. The most widely used design is the multi-rotor and the VTOL fixed wing UAV for almost all surveying field. Additionally, it is also very important to consider the type of project (aerial/ terrestrial/ mixed), the type of terrain/ object, etc. (TCPO, MoHUA, 2020.) One of the important factors which affect the entire UAV cost is the payload weight. High end UAVs which can generate optimum thrust for effective lifting and controlling the payload for proper data acquisition need heavier payload. Following are some of the recommendations on the various types of payload/ sensors which can be used for enhancing quality of data:

i. Single Red-Green-Blue (RGB) sensors can be used for effective orthomosaic generation. It can be easily put up on cost effective UAVs and heavier UAV's like fixed wing.

ii. Multi-spectral 5 bands sensors as well as 10 bands Multi-spectral Dual mostly used for Studying Agricultural Crops. (mica-sense Dual Edge)

iii. Hyper-spectral sensor Camera

iv. Thermal sensor Camera

v. LIDAR is more effective to leverage the importance of photogrammetry. LIDAR technologies especially are in use for regions which require high quality.

vi. Multiple cameras (1 Nadir + 4 oblique) for photo realistic 3-D textured model.

For obtaining data goals of the particular field, UAV flight planning comprises of such categories like pattern, flight schedule, video or image capture specifications and weather-related requirements. If these aspects are not in the right direction, then it may lead to various problems like wasting of time and resources, damaging the UAV and also threatening the safety and well-being of others. So, before going out for Survey, proper flight plan should be crafted to get the desired result.

9.8.2 Establishing Ground Control Points (GCP)

Ground Control Points (GCPs) can be described as points on the surface of the earth of locations which are known. GCPs are points where the surveyor can point out accurately in the case of aerial mapping survey. This can be done through handful of known coordinates which can actually give the correct result in large map areas. They are easily recognizable in the images. GCPs usage are more into the demands of the projects and their accurate requirements. They are comprised to be of a part of conventional aerial mapping projects.

RTK, or Real-Time Kinematic, refers to a positioning technique used in drones to achieve centimeter-level accuracy in positioning data in real-time. When combined with a drone, it is often referred to as an RTK drone. RTK technology utilizes a base station and a rover to achieve highly accurate positioning by correcting for errors caused by atmospheric conditions and satellite signal delays. Some of the benefits of RTK Drones:

- High Precision: RTK technology enables centimeter-level positioning accuracy, which is essential for applications that require precise measurements, such as surveying, mapping, and construction.
- Efficiency: The high accuracy of RTK drones allows for faster and more efficient data acquisition. With precise positioning information, mapping large areas or conducting surveys can be done more quickly.
- Improved Data Quality: The increased accuracy provided by RTK minimizes errors and improves the quality of data collected by the drone. This is particularly important for applications that require high-quality and reliable data.
- Flexible Operation: RTK drones are capable of operating in various environments and terrains, including challenging or obstructed areas. Their accuracy and reliability make them suitable for complex tasks in diverse locations.
- Integration with GIS: RTK drones can be seamlessly integrated with Geographic Information Systems (GIS). The precise positioning data collected by the drone can be directly incorporated into GIS software, enabling accurate mapping and analysis.

By using RTK drone, it is observed through various literature that GCPs do not implicitly enhance accuracy of data acquisition. However, if the drone used is not RTK enabled, then the recommendation is to use GCPs. By skipping control points, it may give out effective results. But the reconstruction may not always favour to be on the correct scale, absolute position information or orientation. GCPs or RTK geotags can assists to confirm the accuracy of the reconstruction.

Fig. 9.4 GCP marker

9.8.3 Determining flight parameters

Flight parameters include the configurations of the camera settings; computing the image rate for a given frontal overlap, selecting the image acquisition plan type and computing the flight height for a given GSD.

1. **Selecting the image acquisition plan type**

UAV data processing software automatically finds thousands of common points between overlapping images. So, the characteristic point which are found in the image is termed as "keypoint". Matched keypoints are those when two keypoints are found to be similar on two distinct images. Correctly matched keypoints in each group will give one 3D point. A large number of keypoints can be matched together in conditions characterized by high overlap between two images which brings out a larger capturing of the common area. If the keypoints are more, then the computation of 3D can be more efficient and accurate. So, the need for a high overlap between the images. The importance of an effective design is required as the image acquisition plan with high impact give quality results. So, the ideal image acquisition plan is governed by the object to be reconstructed or the typed of terrain. Some of them are given as under:

a) **Grid pattern -**

This type of pattern is used mostly for flat surface. This is the most general case. Generally, 75 per cent minimum frontal overlap and 60 per cent side overlap is usually used. In the case of flat terrain with agricultural fields and forest and for dense vegetation areas, the minimum frontal and side overlaps should be made to 85 per cent and 70 per cent respectively. 2D outputs, viz., DSM (Digital Surface Model) and ORI (Orientation) are the important outputs of interest. A Digital Surface Model (DSM) is a representation of the Earth's surface that includes both the topographic features (such as buildings, trees, and terrain) and any other objects present on the surface. It provides information about the elevation or height of the objects above a reference datum, typically the mean sea level. Orientation (OR) refers to the process of determining the position and attitude (rotation) of an aerial or satellite sensor with respect to the Earth's surface.

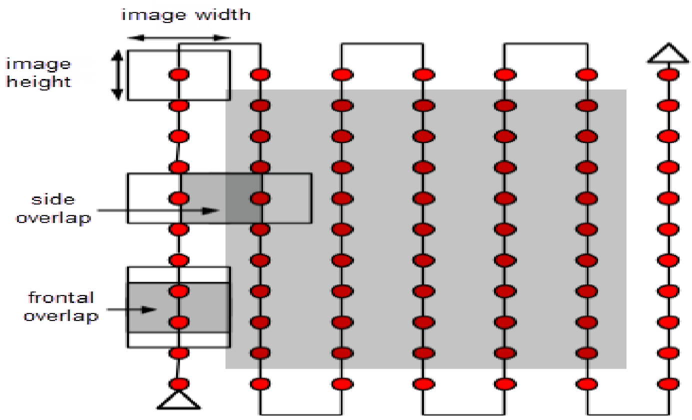


Fig. 9.5 Grid Pattern

b) Double grid pattern -

This is used for thickly populated regions where fluctuations of height can be seen. It helps in capturing images from different multiple sides and also with the requirement for optimal processing. 75 per cent minimal frontal overlap and 60 per cent side overlap should be used. The main outputs of interest are the 3D model outputs (point cloud, mesh) besides the 2D outputs, viz., DSM/ ORI.

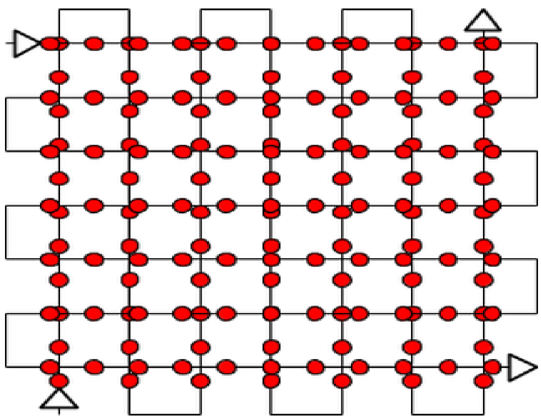


Fig. 9.6 Double grid pattern

c) Polygon pattern -

This pattern is mainly used when the environments are in need of flexible boundaries with a complex mapping shape or for flying.

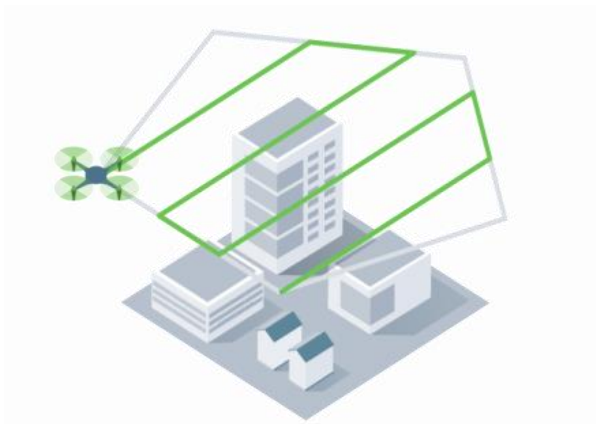


Fig. 9.7 Polygon mapping

d) Circular pattern -

This pattern is adopted for 3D reconstruction of isolated objects (e.g., specific tower, statue, and pylon) that are tall and slender requires a specific image acquisition plan. If the output of interest is a 2D object, this pattern is not required.

9.8.4 Computing the flight height for a given GSD

Ground Sampling Distance (GSD) is the distance which is observed between two consecutive pixel centers when measured on the ground. This effects the quality and the accuracy of the end results and also the details which can be seen in the final Orthomosaic. If the GSD value is bigger, the spatial resolution of the image is lower and vice versa.
Flight height (H) which is needed to get a given GSD can be calculated. It depends on:

- The camera focal length,
- The camera sensor width [mm],
- The image width [pixels]

It is given as:

$$\mathbf{H\,[m] = (imW * GSD * F_R) / (SW * 100)}$$

Where imW = image width [pixel]

GSD = desired GSD [cm/pixel]

F_R = real focal length

SW = real sensor width

2. Computing the image rate for a given frontal overlap

The image shooting rate to attain a required frontal overlap is determined by:

- the speed of the UAV/plane,
- the GSD and
- the pixel resolution of the camera

$$\mathbf{t = x / v = ((imW * GSD) / 100) * (1 - overlap) / v}$$

where imW = image width [pixel]

GSD = desired GSD [cm/pixel]

x = distance between two camera positions in the flight direction [m]

v = flight speed [m/s]

t = elapsed time between two images (image rate) [s]

Finally, as the flight parameters are determined, the UAV integrated with the sensor/ camera can be deployed for image/ data acquisition for the given region of interest.

9.9 UAV Data Processing

Research have observed that Remote sensing technologies which is based on satellite and aircraft platform are seen to continuously improve in the area of spatial and temporal resolution. This enhances the suitability for various applications of remote sensing (Matese et al. 2015). These technologies have various advantages and disadvantages involving operational, economic and technological factors. Satellite surveys has the capability of mapping large areas. However, they may suffer from conditions such as cloud cover and various other problems as they deal with fixed-timing acquisitions. Contrary to this, aircraft surveys can be designed and planned with flexible condition, but they can be costly (Berni et al. 2009). In the past, the development of light-weight sensors and low-cost unmanned air vehicles (UAVs) has resulted in valuable interest when using it in the research of RS fields (Everaerts 2008, Grenzdorffer et al 2008, Hung et al 2014, Zhang et al., 2002). UAVs can obtain imagery at centimeter resolution and their operations are far more environmentally friendly (generate less CO2 and noise) than any manned aircraft. The advantage of UAVs in RS surveys is due to high spatial and temporal resolutions, flexibility in terms of flying height and timing of data acquisition, less hindrance by weather conditions with lesser cost. UAVs are better appropriate for covering small areas with intensive observations, on the other hand, their few payloads and short flight endurance will always remain the weakness area to implement in wider scale UAV RS applications. Challenges in UAV data processing are mainly because of large data volume and the processing time involved. The general steps which should be followed in UAV data processing, starting from data acquisition to classification are described below.

For effective processing of data in UAV software like Pix4D, Agisoft, the enhancement quality of data is essential. For achieving high quality and ortho rectified images, the survey areas need to maintain accuracy and also, they should have sufficient number of Ground Control Points (GCPs). Flight planning is the pre-requisite to start the procedure of image acquisition and also to process the UAV data (Pix4D tutorial, Percivall et al 2015). These flight missions are generally planned in the lab which comprises of the required and efficient software, beginning from the knowledge and the resolution required (He et al 2012). Then, in this step, flying height and camera perspective centers are to be fixed. This will define the object details and the image scale. After the acquisition of the image, a process of camera calibration and image orientation is required. It is in need of images which has visible common features and these are termed as keypoints. They are followed by the adjustment of the bundle. Thereafter, orientation of the set images, orthorectification and feature extraction took place. The various features have to be considered to have a systematic image acquisition plan:

1. type of project (aerial, terrestrial, mixed).
2. aim and purpose of the project.
3. the path of the flight which is required for acquiring images.

The various steps involved in UAV data processing are presented in Fig. 9.8.

A high overlap in between the adjacent images is needed to acquire greater efficiency and accuracy. So, to have the required number of overlaps, the image acquisition plan has to be designed and chalked out in a crafted manner. At least, the suggested overlap is 75% frontal overlap (with respect to the flight direction) and at least 60% side overlap (between flying tracks). The suggestion is to get hold of the images with a regular grid pattern instead of following a very complex path. The camera is needed to maintain its stand at a constant height over the terrain/ object so as to achieve and deliver the required Ground Sampling Distance (GSD).

Today, technologically advanced UAVs are equipped with sophisticated software. This can plan and design the image acquisition plan, the required parameters which can be in the form of the percentage of overlap between the images, area of interest and the desired GSD, etc. For this case, the UAV took the images automatically in accordance to the selected images acquisition plan. This is done without any user intervention.

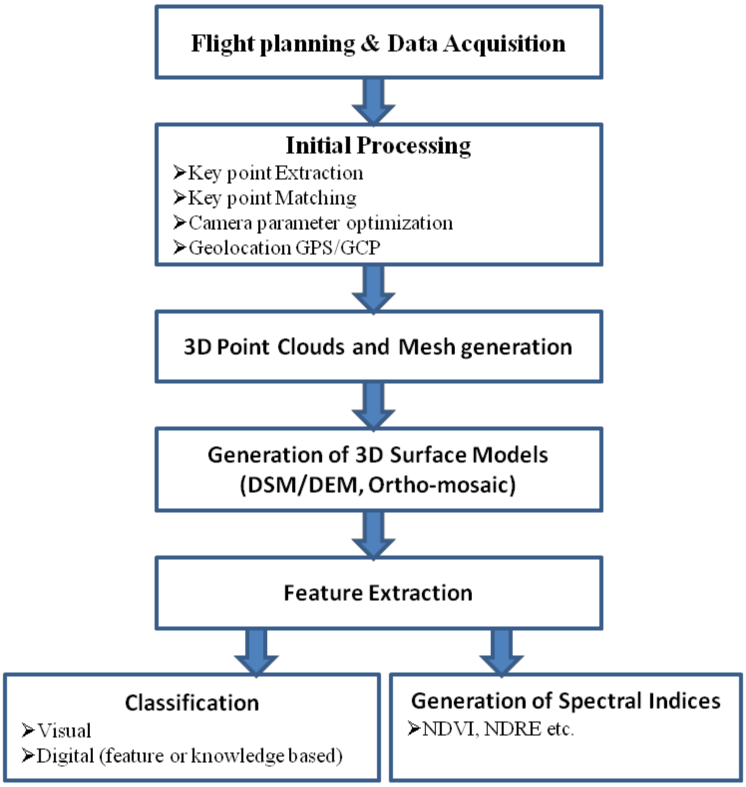


Fig. 9.8 UAV data processing workflow

9.9.1 Keypoint extraction

The keypoints are taken out from such areas of high contrast. Key point signatures are also designed by looking at the surrounding areas. The keypoints quality depends on the presence of buildings, rocks and urban features, etc. The camera quality also affects the keypoints. A 10 MP camera is generally sufficient to give a good quality image which can have the required number of keypoints. The required keypoints in an image are around 10,000 or more. Images with features such as overexposed, underexposed, fog, sand, camera with less than 3 Mega Pixel can produce lower number of keypoints to extract. This greatly affects the quality of the output.

9.9.2 Keypoint matching

The keypoints which is obtained from the individual images are coordinated with the similar keypoints in the neighbouring images (Fig. 9.9). High overlap images have large number of keypoints and are easier to match in the adjacent images, Images with low keypoints, which has reflecting surface like moving objects and water, for example vehicles show lower matching points. To acquire quality keypoints, to match a large overlap between images is needed. For images from low resolution camera resulting in low visual images and content, a large overlap of more than 75% is needed.

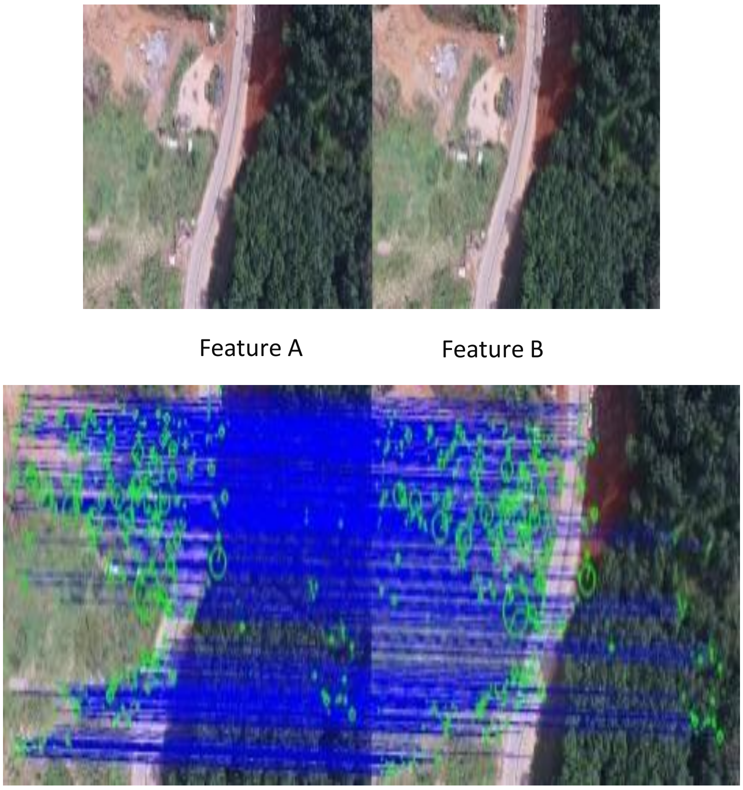


Fig. 9.9 Feature Matching. Blue line: Matching features from A to B

9.9.3 Camera parameter optimization

For the reconstruction of 3-D, the requirement is the position and exact camera model and position. The inbuilt GPS found in cameras and the resulting images are sometimes not always correct for the purpose to bring out the exact geolocation. So, in this context, for computation of the precise parameters of camera required from pixels, calibration is significant. The error in calibration of the images is lowered when the images are acquired with the right amount of the matching keypoints. This process plays a vital role in achieving high accuracy of the final required products. The initial parameters required for calibration have been taken from the software's database in which the information is stored. The user can choose the options for optimizing the internal and external camera parameters.

It is imperative that both internal and external orientation elements are needed to be calibrated "on-the-job" when commercial, low-cost cameras are used and mounted on lightweight drones. This is required to enhance the quality of adjustment as these types of cameras are temperature or vibrations sensitive than real photogrammetric cameras.

Further, optimized parameters can be used in a reconstruction model. It can be also taken to create undistorted images.

9.9.4 Geolocation GPS/GCP

If the Ground Control Points (GCPs) are acquired from the ground, they can be utilized to improve the geolocation accuracy. To achieve better accuracy, a minimum of three GCPs should be distributed throughout the image. After the initial processing is performed, the GCPs are imported. It is not necessary for the GCPs and photos to be the same, as the software handles the transformation between systems on the fly. When the geolocation of images is more accurate, the GCPs should be placed closer to the authentic position. It is crucial to indicate the exact location of the GCPs in the images to ensure a sufficiently high level of accuracy in the final location of the model. If a high-quality GPS system with built-in RTK/PPK is used in the UAV system, additional GCPs are not required.

9.9.5 Point cloud generation and 3-D Mesh

Based on the projected camera positions and matched keypoints, 3D dense point cloud and mesh are generated. In areas where a smaller number of keypoints are matched, the points densification may be less and generate holes in the point cloud. Areas such as ground under the tree, which while looking from the top is not visible produce holes in the imagery. Homogenous surface such as roof top, roads, water bodies generated fewer visual points thus points densification is affected. The correctness of the point clouds generated depends on the camera resolution. Camera with low resolution produces error up to 3-4 times of GSD at areas of low visual content. Using the point cloud, object characteristics such as length and elevation can be determined. The accuracy of the overall output depends on the calibration parameters of the camera, quality of the GCPs and GPS of the camera and the point cloud generated. To improve the quality of the results, filtering and smoothening of the point cloud is performed. It removes the redundant points and makes the point cloud easier to manage.

A mesh can be termed as a set of triangles. Triplets of integer indexes are used to represent triangles internally. These indexes are in relation to the combined cloud which is the mesh vertices. So, a mesh gets all the aspects which is related to a point cloud. A standard mesh can be seen to correspond to a single object. 3D texture mesh is generated by the point cloud. During the generation process of 3D texture, the triangles' vertices are described as it can reduce some points distances between Point cloud and the surface.

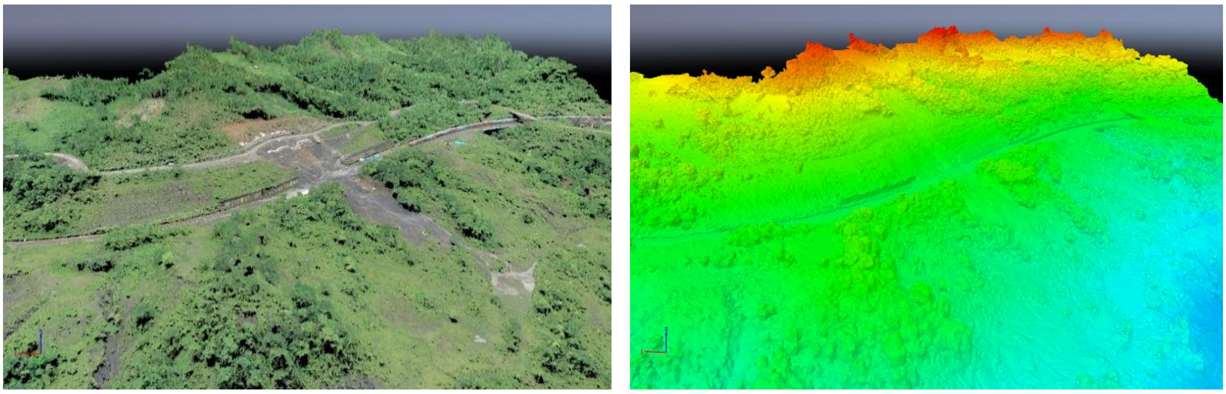


Fig. 9.10 (a) 3D Point cloud and (b) 3D Mesh

9.10 DSM and Orthomosaic

In this step, Digital Surface Model (DSM), Orthomosaic images (RGB or multispectral), Digital Terrain Model (DTM) are generated. Resolution for all the products can be selected according to the needs which is equal to the integer value of GSD or it can be arbitrary value.

DSM is a representation of the Earth's surface that includes both the topographic features (such as buildings, trees, and terrain) and any other objects present on the surface. It provides information about the elevation or height of the objects above a reference datum, typically the mean sea level. DSMs are generated by capturing and processing remote sensing data, such as aerial or satellite imagery, LiDAR (Light Detection and Ranging) data, or photogrammetric techniques.

DSMs are used in various applications, including urban planning, flood modeling, infrastructure design, and 3D visualization. They provide a detailed representation of the Earth's surface, enabling accurate measurements of terrain elevation and the identification of objects and features present on the surface.

Orthomosaic: An Orthomosaic is a geometrically corrected and orthorectified image created by stitching together multiple overlapping aerial or satellite images. It corrects for geometric distortions caused by terrain relief and sensor characteristics, ensuring that the resulting image represents the Earth's surface in a planimetrically correct manner. Orthomosaics combine the individual images' pixel information to create a single seamless and accurate representation of the area covered. Orthomosaics are widely used in various applications, including mapping, land surveying, agriculture, and environmental monitoring. They provide a detailed and geographically accurate visual representation of the area, allowing for precise measurements, feature extraction, and analysis.

Differences: The main difference between a DSM and an Orthomosaic lies in their purpose and data representation. DSM. A DSM focuses on capturing and representing the elevation or height information of the Earth's surface, including topographic features and objects present on the surface. It provides a three-dimensional representation of the terrain and objects. An Orthomosaic, on the other hand, is a two-dimensional image created by stitching together multiple images to create a seamless representation of the area. It corrects for geometric distortions and provides a planimetrically accurate representation of the Earth's surface, like a traditional map.

Accuracy: While a DSM emphasizes elevation information and 3D representation, an Orthomosaic emphasizes planimetric accuracy and visual representation. Both products serve different purposes and are used in different applications, but they can complement each other in providing comprehensive geospatial information.

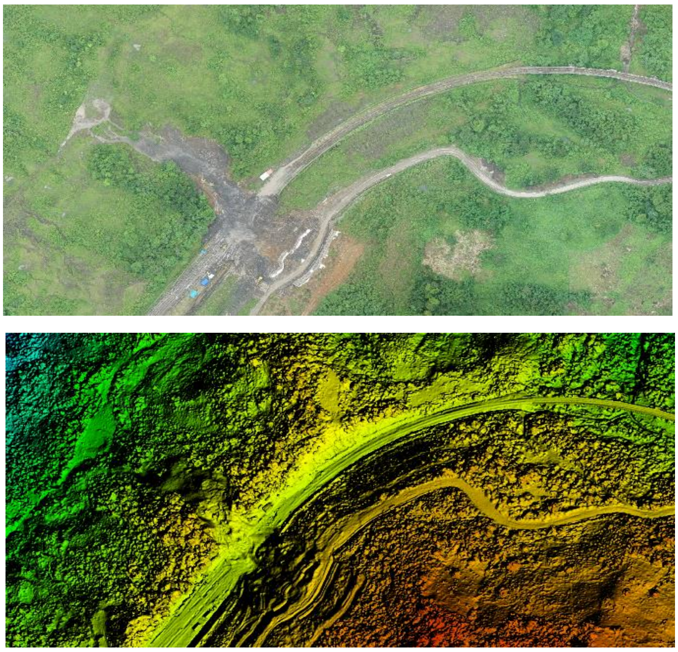


Fig. 9.11 (a) Orthomosaic generation and (b) Digital Surface Model

9.11 Feature Extraction

With all the processing carried out for the images for quality and accurate positioning, now the images are ready for feature extraction/classification. If on onboard UAV, additional multispectral sensor is used than the orthomosaic reflectance images are obtained individually for each band. The multiple bands can be imported in image processing software such as Arc GIS, ENVI, ERDA, QGIS, GRASS etc., and combined together to obtain a stacked image.

9.11.1 Classification

Image classification of ortho images in remote sensing is a fundamental technique used to analyze and extract information from aerial or satellite imagery. It involves categorizing the pixels within an ortho image into different classes or categories based on their spectral characteristics. This process enables the identification and mapping of various land cover types or features present in the image. Here are the key steps involved in the image classification of ortho images:

- **Image Preprocessing**: The ortho image is pre-processed to enhance its quality and remove any artifacts or noise. This may include radiometric correction, atmospheric correction, geometric correction, and image enhancement techniques.
- **Training Data Collection**: Training data is collected to represent different land cover classes present in the image. This data typically consists of sample pixels or regions of interest (ROIs) that are manually labeled or identified based on ground truth information. The training data should be diverse and representative of the various classes to ensure accurate classification.
- **Feature Extraction**: Spectral information is extracted from the ortho image for each pixel within the defined training data. This is typically done by computing the spectral reflectance values across different wavelengths or bands of the image. Additional features such as texture, shape, or contextual information can also be extracted to improve classification accuracy.
- **Classifier Selection**: A classification algorithm or model is selected to assign each pixel in the ortho image to one of the predefined classes. Commonly used classifiers include Maximum Likelihood, Support Vector Machines (SVM), Random Forest, or Neural Networks. The choice of classifier depends on the specific requirements of the classification task and the nature of the data.
- **Training the Classifier**: The selected classifier is trained using the extracted features and the corresponding labelled training data. This process involves optimizing the model parameters to minimize classification errors and improve accuracy. The training phase aims to establish the relationship between the spectral characteristics of the pixels and their corresponding land cover classes.
- **Classification**: Once the classifier is trained, it is applied to the entire ortho image to classify each pixel into the predefined classes. The classification process assigns a class label to each pixel based on the spectral similarity with the training data. This produces a classified image where each pixel is assigned to a specific land cover class.
- **Accuracy Assessment**: The accuracy of the classification results is assessed by comparing them with reference data or ground truth information. This evaluation helps determine the reliability and quality of the classification output. Measures such as overall accuracy, kappa coefficient, and user/producer accuracy are commonly used for accuracy assessment.

Accuracy is in relation with position accuracy in photogrammetry where it can be defined as the matching of the information on the map which is created from the data with that of the actual real world. Relative accuracy can be defined as the way to measure the position of the objects in relation to one another in a reconstruct model. While, absolute accuracy is the difference observed between the object location on the reconstructed model and their real position on the Earth which may be a geodetic coordinate system. It is imperative that the absolute accuracy of the survey is always lower than the GCPs' accuracy. It will also be in relation to the relative accuracy of the model. As observed from the literatures, relative accuracy is expected to an error of 1-3 times the size of the pixel when considering an accurate reconstructed model, vertically and horizontally. This means that if one considers a 2 cm GSD, a range of 2-6 cm accuracy can be achieved. For the correctly reconstructed model, to obtain absolute accuracy, an error of 1-2 GSD horizontally and 1-3 GSD vertically is expected. But this error cannot be considered global. The error may be more in a terrain with varied altitudes which has no identifiable characteristic objects like desert, forest and water. So, to lower errors, other than Ground Control Points, a good practice is to measure various check points in the field. These check points may lead to calculate the accuracy of the model when using the regular surveying calculation methods.

Applications of ortho image classification in remote sensing include land cover mapping, vegetation monitoring, urban planning, environmental assessment, and change detection analysis. The classified images provide valuable information for various industries and decision-making processes, enabling effective land management, resource planning, and environmental monitoring.

9.12 Limitation and Challenges in UAV Remote Sensing

UAV remote sensing, despite its numerous advantages, also faces certain limitations and challenges. Let's explore some of them:

1. **Limited Payload Capacity**: UAVs have limited payload capacity, meaning they can carry only a certain number of sensors or equipment. This restricts the type and quality of sensors that can be mounted on the UAV, limiting the range of remote sensing applications that can be effectively carried out.
2. **Limited Flight Endurance**: UAVs have limited flight endurance due to their battery life or fuel capacity. This restricts the amount of time they can spend in the air, limiting the coverage area and data collection duration. It may require multiple flights or careful planning to cover large areas or monitor dynamic processes adequately.
3. **Weather Dependency**: UAV flights are highly dependent on weather conditions. Adverse weather, such as strong winds, rain, or fog, can significantly affect the flight stability and the quality of data collected. Inclement weather conditions may restrict or postpone data collection, impacting the timeliness and reliability of the remote sensing data.
4. **Regulatory and Legal Considerations**: UAV operations are subject to regulations and legal restrictions imposed by aviation authorities in different countries. Compliance with these regulations, such as obtaining flight permits, respecting flight altitudes, and ensuring safety protocols, can be time-consuming and challenging. Additionally, privacy concerns and airspace restrictions in certain areas may limit the accessibility and feasibility of UAV remote sensing projects.
5. **Data Processing and Storage**: UAV remote sensing generates large volumes of data, which can pose challenges in terms of processing and storage. The data collected from high-resolution sensors can be massive, requiring powerful processing capabilities and sufficient storage

infrastructure. Efficient data management and processing workflows are necessary to handle and analyze the collected data effectively.

6. **Data Accuracy and Calibration**: Ensuring the accuracy and calibration of UAV remote sensing data can be challenging. Factors such as sensor calibration, geometric distortion, and atmospheric correction need to be carefully addressed to achieve reliable and accurate results. Calibration procedures and ground control points are essential for accurate data georeferencing and validation.

7. **Image Interpretation and Analysis**: Interpreting and analyzing UAV remote sensing data can be complex, particularly when dealing with large datasets and high-resolution imagery. Advanced image processing techniques, data fusion, and machine learning algorithms may be required for efficient data extraction, feature identification, and classification tasks. Skilled personnel with expertise in remote sensing and image analysis are necessary for accurate interpretation and meaningful analysis of the acquired data.

8. **Safety and Risk Management**: UAV operations involve potential safety risks, both to the UAV itself and to people and property on the ground. Proper risk management strategies, including flight planning, obstacle avoidance, and emergency procedures, need to be implemented to ensure safe operations and mitigate potential hazards.

9. **Making drone as aerial robot**: Installing of various electronic boards, sensors, antennas, wirings, batteries, etc. in a restricted space in the drone is once of challenging task. The limit payload to achieve better endurance and performance, a fluent air circulation is needed in the electronic boards, batteries and motor engine, design limitations like setting equipment parts in correct locations, to keep gravity center of UAV, communication antennas, OSD video camera, GPS insight, etc. and design limitations such as keeping gravity center of UAV in a correct position, setting are some of critical issues.

10. **Making an operational system**: The take-off of UAV by a launcher, hand or on an airstrip, the landing of UAV by parachute, skate, wheels or net, resistant to water, dust, stroke and temperatures, safety features such as parachuting in crash, return-to-home (RTH) planning in communication loss states, crashed drone finding by GSM messages and system services and reparations when in field operation are some of challenges in making an operational system.

11. **Pilot and Autopilot:** UAV flight requires skilled pilot in both practice and theory. Pilot should be effective especially in take-off and landing. Flight conditions, navigation data, solving the software and hardware problems and interruptions during flight for every moment needs to be monitored with awareness and concentration are some of the important considerations. Time to time check on the pre/post flight to check the accurate drone functioning which includes navigation, flight mechanical parts, data collection sensors and communication parts. When observing part failures, stopping of drone flight, grouping, data collection and backup of raw data and writing the problems and operation process in a diary booklet are some of important challenges in setting up an autopilot system.

12. **Flight limitations**: Study area reconnaissance to achieve ground station placement. Aerial and terrestrial direct insights are needed to UAV by taking care of various obstacles like landing/take-off and electric wires and towers for communication needs. Considering flight

limitations in flight design like flight height and endurance, topography, light, wind, site conditions and telecommunication limits.

13. **Flight security license and allowance**: No specified rules and instructions for UAV flight as can be seen in other manned planes. Attention to ICAO maps as it is required to know safe areas, heights, and period of flight. Extreme security issues in military and populated areas are also an important issue which needs to be addressed. The aerial imaging license differs from that of flight license and both should also be taken in consideration before planning the UAV based survey of any selected region.

Addressing these limitations and challenges requires ongoing technological advancements, regulatory developments, and operational improvements. With continuous innovation and improved capabilities, UAV remote sensing can overcome these challenges and offer valuable insights for various applications, including mapping, monitoring, and environmental assessment.

9.13 Conclusion

The evolution of UAV technology has resulted in a diverse range of unmanned aerial vehicles, each designed to cater to specific applications and operational requirements. From fixed-wing UAVs for large-scale aerial mapping to multi-rotor UAVs for close-range inspections and hybrid UAVs for extended endurance missions, the types of UAVs available provide immense versatility and flexibility. Understanding the characteristics and capabilities of different UAV types is crucial in selecting the most suitable drone for specific tasks, ensuring optimal performance and successful outcomes across various industries and sectors. As UAV technology continues to advance, we can expect further innovations and the emergence of new types of drones to cater to evolving needs and push the boundaries of aerial capabilities.

UAV remote sensing has opened up new possibilities for data acquisition and analysis in various fields. From agriculture and environmental monitoring to infrastructure planning, disaster management, urban planning, and cultural heritage documentation, UAVs offer valuable insights, efficiency, and cost-effectiveness. As technology continues to advance, we can expect further innovations in UAV capabilities, expanding their applications and contributing to advancements in numerous industries. UAV remote sensing is transforming the way we perceive and manage our environment, enabling data-driven decision-making for a sustainable future.

An aerial sensing system which is costs low has the advantage to achieve diverse large scale mapping operations. For very large-scale mapping, ability to obtain very high-resolution aerial images over a period of time and ease of ability and operation can prove to be a very efficient tool. In addition to this, high resolution aerial imaging can assist in providing a platform to explore novel applications which are currently not available.

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Chapter 10

EMERGING GEOSPATIAL TECHNOLOGIES

10.1 Introduction

In today's rapidly evolving digital world, the collection, analysis, and utilization of spatial data have become increasingly important across various industries and sectors. Geospatial technologies, which encompass a range of tools and techniques for gathering, storing, analyzing, and visualizing spatial information, have played a pivotal role in transforming how we understand and interact with our environment. As technology continues to grow at an unprecedented pace, new geospatial technologies are emerging, offering exciting opportunities for data analysis and informed decision-making. These technologies have immense potential to increase our understanding of the world around us and enable geo-intelligent decision-making across various sectors. With ongoing advancements, a new wave of geospatial technologies is emerging, offering unprecedented capabilities and opening up exciting possibilities.

In the recent past, Artificial Intelligence (AI) and Machine Learning (ML) have gained significant attention in the field of geospatial technologies. By harnessing the power of AI and ML algorithms, geospatial data can be processed more efficiently and accurately. These technologies enable the automatic extraction of valuable insights from satellite imagery, aerial photographs, and other geospatial datasets. For example, AI and ML algorithms can identify patterns in satellite imagery to detect changes in land use, monitor deforestation, or identify potential disaster risks. These advancements in AI and ML hold tremendous potential for applications such as urban planning, environmental monitoring, watershed development, disaster response etc.

Augmented Reality (AR) and Virtual Reality (VR) technologies are transforming the way we perceive and interact with geospatial data. AR overlays digital information onto the real world, while VR creates immersive virtual environments. When AR & VR are applied to geospatial technologies, it offers new ways to visualize, analyze and understand spatial data. For instance, AR can provide real-time information on points of interest, historical landmarks, or navigation instructions directly on a user's smartphone or smart glasses. VR, on the other hand, can create virtual simulations of real-world environments, allowing users to explore and analyze data in an immersive and interactive manner. These technologies have immense potential in fields like architecture, tourism, urban planning, disaster management, archaeology etc.

The Indoor Positioning Systems is yet another domain which has grab the attentions of researchers in advancing the location services. While Global Navigation Satellite System (GNSS) based navigation services such as GPS, GLONAS, NavIC etc., are widely used for outdoor positioning, there is increasing interest in accurate indoor positioning systems. Technologies like Bluetooth beacons, Wi-Fi, RFID, and Ultra-Wideband (UWB) are being leveraged to create indoor positioning solutions. These technologies enable applications such as indoor navigation, asset tracking, facility management, and location-based services within buildings and complex indoor environments.

Another important emerging technology which has great role to play in the advancements of geospatial technologies is Internet of Things i.e. IoT. The Internet of Things (IoT) refers to the network of physical devices embedded with sensors, software, and connectivity that enables them to collect and exchange data. When integrated with geospatial technologies, IoT can provide a wealth of real-time data about the environment, infrastructure, and human activities. For example, IoT sensors can monitor air quality, traffic patterns, or water levels in rivers and send the data to central server systems for data integration and analysis. This data can be used to make informed decisions regarding city planning, resource management, or emergency response. The combination of geospatial technologies with IoT is facilitating the development of smart solutions including development of smart cities and enabling more efficient and sustainable urban environments.

Unmanned Aerial Vehicles (UAVs) are commonly known as drones, have become increasingly popular in the field of geospatial technologies. Drones equipped with high-resolution cameras and sensors can capture aerial imagery and collect geospatial data with unprecedented detail and accuracy. These data can be used for applications such as land surveying, infrastructure inspection, precision agriculture, disaster monitoring and assessment. The use of drones significantly reduces the time and cost associated with traditional data collection methods, making it more accessible for various industries and researchers. However, regulations and privacy concerns surrounding drone operations remain an ongoing challenge that needs to be addressed for their widespread adoption.

Blockchain technology, known for its secure and decentralized nature, has the potential to address challenges related to data integrity, privacy, and interoperability in geospatial applications. By creating a distributed ledger of geospatial data, Blockchain technology ensures transparency, traceability, and trust in data sharing and collaboration. It can facilitate decentralized geospatial platforms, land administration systems, and supply chain management, empowering individuals and organizations with greater control and reliability.

The advancements in geospatial data creation and collection from earth observation satellites, drones, IoT devices, and other sources has created a need for efficient storage, processing, and analysis. Big data analytics and cloud computing technologies provide scalable and cost-effective solutions for managing and analyzing large volumes of geospatial data. Cloud-based platforms enable organizations to store, share, and collaborate on geospatial datasets seamlessly. These platforms also provide powerful computational capabilities for processing and analyzing complex geospatial data, such as running advanced algorithms or creating interactive visualizations. The integration of big data analytics and cloud computing with geospatial technologies is empowering businesses, researchers, and governments to extract meaningful insights and make data-driven decisions.

Another exciting advancement in geospatial technology is the proliferation of satellite imagery and remote sensing capabilities. With the launch of constellations of small satellites and advancements in satellite imaging resolution, access to high-quality imagery and data has become more accessible and affordable. This has opened up new possibilities for monitoring and managing our planet's resources. Governments can now monitor illegal deforestation, track changes in coastal areas, and detect illegal activities such as poaching and mining using multi-temporal earth observation imageries. Humanitarian organizations can leverage satellite imagery to respond to natural disasters, assess damage, and plan relief efforts. Businesses can use satellite data to analyze consumer behavior, optimize supply chains, and make informed location-based decisions.

The emerging technologies discussed above also imposed many challenges that need to be addressed before its effective and efficient utilizations. The concerns on privacy of data and information arise as more location-based data is collected and analyzed. Ethical considerations must be taken into account when using geospatial technologies for surveillance or data mining purposes. Additionally, ensuring data accuracy and quality remains crucial to avoid misinformation and flawed decision-making. In this chapter we will discuss about different emerging geospatial technologies, its applications, challenges and opportunities.

10.2 Artificial intelligence

Artificial Intelligence (AI), refers to the development and application of computer systems that can perform tasks that typically require human intelligence. It involves creating machines or computer programs that can exhibit intelligent behaviour, learn from experience, adapt to new situations, and perform tasks without explicit instructions. AI encompasses a broad range of techniques and methodologies, including machine learning, natural language processing, computer vision, robotics, expert systems, and many more. These approaches enable machines to analyze, interpret, and understand complex data, make decisions, solve problems, and even interact with humans in a more human-like manner. Machine Learning (ML), a subset of AI, focuses on training computer algorithms to learn from data and improve their performance over time. It involves feeding large amounts of data into algorithms, allowing them to identify patterns, correlations, and trends, and make predictions or take actions based on that information. Deep Learning (DL), a specific branch of machine learning, employs artificial neural networks with multiple layers to process complex data and extract meaningful insights. The conceptual flow of AI, ML and DL is presented in Fig. 10.1. Natural language processing (NLP) enables machines to understand and generate human language. It involves techniques such as speech recognition, text analysis, language translation, and sentiment analysis. NLP enables machines to interact with humans through speech or text-based interfaces, understand user queries, and provide relevant responses or perform specific tasks. Computer vision focuses on enabling machines to interpret and understand visual information from multimedia contents such as images or videos. Through techniques such as image recognition, object detection, and image segmentation, computer vision algorithms can analyze visual data, identify objects, extract features, and make sense of visual content. AI has a wide range of applications across various industries and domains. It is used in fields such as healthcare, finance, manufacturing, transportation, marketing, and many more.

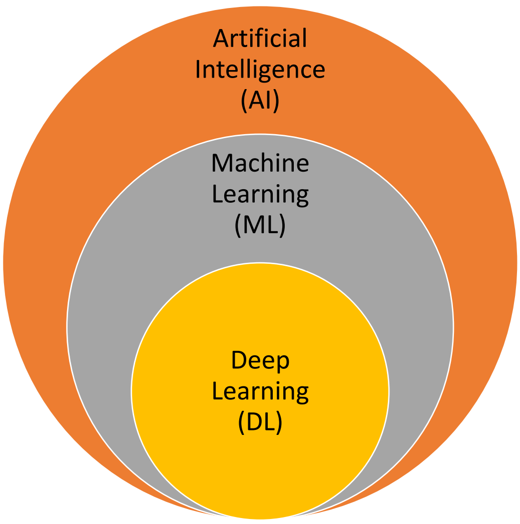


Fig. 10.1 Conceptual framework of AI, ML and DL

AI is playing a transformative role in the field of Geospatial technology, revolutionizing the way we collect, analyze, and interpret geospatial data. The integration of AI with GIS technologies is enabling more efficient and accurate data processing, advanced spatial analysis, and automated informed decision-making. Some of the major areas where AI is making significant impact in GIS are discussed below:

1. **Data Collection and Processing**: AI techniques are being employed to streamline and automate the collection and processing of geospatial data. For instance, AI algorithms can analyze satellite imagery to automatically identify and extract features like buildings, roads, or vegetation, eliminating the need for manual digitization. AI-powered image classification can classify land cover types, detect changes over time, and monitor environmental conditions. Additionally, AI algorithms can process large volumes of geospatial data, identifying patterns and relationships that might be difficult for humans to detect, thereby enhancing data quality and accuracy.

2. **Spatial Analysis and Predictive Modeling**: AI is revolutionizing spatial analysis by providing advanced tools for modeling and predicting spatial phenomena. Machine learning algorithms can analyze large geospatial datasets to identify patterns, correlations, and anomalies. For example, AI techniques can be used to predict land use changes, urban growth, or the spread of diseases based on historical data and various spatial factors. These predictive models help in making informed decisions for urban planning, resource management, and emergency response.

3. **Object Detection and Recognition**: AI algorithms, particularly computer vision techniques, are being utilized for object detection and recognition in GIS applications. For example, AI can automatically detect and identify specific objects or features in satellite imagery, such as buildings, roads, vehicles, or natural landmarks etc. This capability is valuable in various domains, including urban planning, infrastructure management, disaster assessment, and environmental monitoring. AI-based object recognition can also assist in automatically extracting information from aerial photographs, LiDAR data, or other geospatial sources.

4. **Spatial Decision Support Systems**: AI-powered spatial decision support systems (SDSS) leverage GIS capabilities along with AI algorithms to provide real-time insights and support decision-making processes. These systems integrate geospatial data, historical records, and real-time sensor data to analyze complex spatial problems. For example, in emergency response scenarios, SDSS can analyze multiple factors like proximity to hazards, population density, road networks, and available resources to optimize response plans and resource allocation.

5. **Geospatial Data Analysis and Visualization**: AI techniques contribute to enhancing geospatial data analysis and visualization, enabling more interactive and intuitive exploration of spatial data. AI-powered algorithms can automatically generate heatmaps, density maps, or thematic maps based on large datasets, allowing users to identify hotspots, trends, or patterns easily. Additionally, AI can assist in creating 3D visualizations, virtual reality experiences, or augmented reality overlays, providing immersive and interactive ways to understand and communicate geospatial information.

10.2.1 Machine Learning

Machine learning (ML) techniques are being increasingly applied in the fields of remote sensing and geographic information systems (GIS). ML algorithms have the capability to extract meaningful patterns and information from remote sensing data, automate analysis processes, and enhance the interpretation and utilization of geospatial data. The ML algorithms can extract valuable information from remote sensing imagery, classify land cover types, detect changes over time, and assist in various GIS tasks. A typical work flow of Machine learning process is shown in Fig. 10.5.

ML algorithms are widely used for image classification tasks in remote sensing. These algorithms can automatically categorize pixels or segments in an image into specific land cover or land use classes, such as forests, water bodies, urban areas, wastelands, agricultural fields etc. ML models, including convolutional neural networks (CNNs), are trained on labelled data to learn patterns and spectral characteristics associated with different land cover types. Object detection algorithms, such as the popular Faster R-CNN or YOLO, can identify and delineate specific objects or features of interest, such as buildings, roads, and trees, in remote sensing imagery.

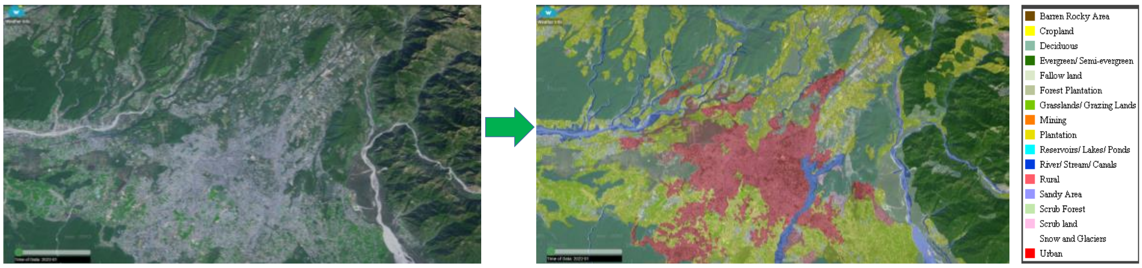
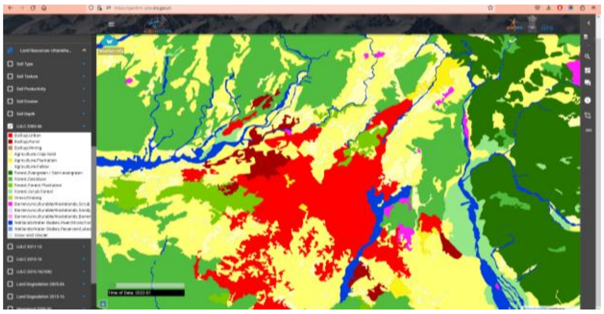
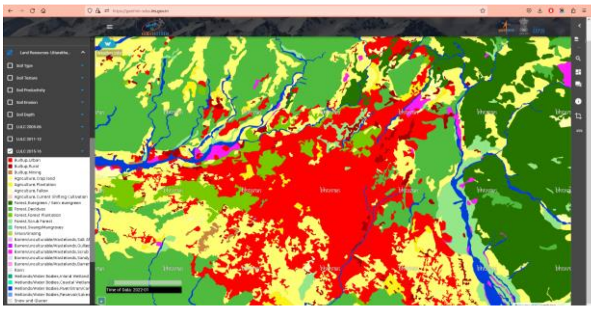


Fig. 10.2 Classification of Satellite image as Land cover map

Another important area in geospatial domain which has great applications of ML based algorithms is Change detection studies. The change detection is an essential task in monitoring and analyzing temporal changes in land cover or environmental conditions using remote sensing imageries. ML algorithms can detect and quantify changes by comparing multiple remote sensing images captured at different times. By training ML models on historical data with known change information, algorithms can identify and classify areas of change, such as deforestation, urban expansion, or agricultural transformations etc. This automated change detection approach significantly reduces manual effort and enables efficient monitoring of large areas. Recent automatic change detection algorithms, utilising methods like deep learning, unsupervised clustering, object-based analysis, and multi-scale approaches, have made substantial progress in a variety of disciplines. Convolutional neural networks (CNNs), in particular, have demonstrated potential in effectively detecting changes by learning pertinent characteristics from input image pairings. Change detection is made possible by unsupervised methods like clustering, which don't require training data or prior knowledge. Taking into account their characteristics and relationships, object-based change detection concentrates on higher-level picture objects or areas. By analysing images at various resolutions, multi-scale techniques enable the detection of changes of varying sizes. These improvements in automatic change detection algorithms improve our capacity to assess and keep an eye on dynamic situations.



Land use/Land Cover Map -2005



Land use/Land Cover Map -2015

Fig. 10.3 Land use/Land Cover Change Map of Dehradun region

One of the complex and challenging tasks in the process of information extraction from remote sensing imageries is the image segmentation for different geographical features. ML techniques are very effective to detect and segment specific objects or features within remote sensing imagery. This includes identifying buildings, roads, vehicles, or other objects of interest. Object detection algorithms, such as Faster R-CNN or YOLO, can locate and classify objects within an image, while segmentation algorithms, like U-Net or Mask R-CNN, can precisely delineate the boundaries of objects. Support Vector Machines (SVM) is a widely used ML algorithm for image segmentation in remote sensing. SVM aims to find an optimal hyperplane that separates different classes in the feature space. In remote sensing, SVM can be trained using labelled samples to identify the boundaries between different land cover classes or objects. SVM-based segmentation often involves the extraction of relevant spectral, textural, and contextual features from remote sensing imagery. It's important to note that the choice of ML technique for image segmentation in remote sensing depends on the specific requirements of the task, the availability of training data, and the characteristics of the remote sensing data being used. Additionally, data pre-processing steps, such as image normalization and feature extraction, play a crucial role in the performance of ML algorithms for image segmentation in remote sensing. One of example of image segmentation in a satellite imagery is shown in Fig. 10.4. The image segmentation techniques using ML have many applications, including urban planning, infrastructure monitoring, and disaster assessment.

Fig. 10.4 An example of image segmentation in satellite Imagery (Source-https://www.gsitechnology.com)

ML based algorithms are very effective in analysis of imageries from Hyperspectral remote sensing. Hyperspectral remote sensing data provides information about a wide range of spectral bands, enabling more detailed analysis and identification of materials and features on the Earth's surface. ML algorithms can leverage hyperspectral data to perform tasks like target detection, material classification, and anomaly detection. These algorithms can learn spectral signatures and patterns associated with specific objects or materials, allowing for accurate identification and classification of various features in the scene.

One of the most powerful capabilities of geospatial technology is spatial modelling for understanding future scenarios. ML algorithms can analyze geospatial datasets (raster and vector), to identify patterns, correlations, and relationships. These algorithms can extract valuable insights and make predictions regarding various phenomena, such as crop yield, air quality, urban growth, or flood susceptibility. ML models can incorporate diverse spatial variables and historical data to generate predictive models, assisting in decision-making processes related to resource management, disaster preparedness, and environmental planning.

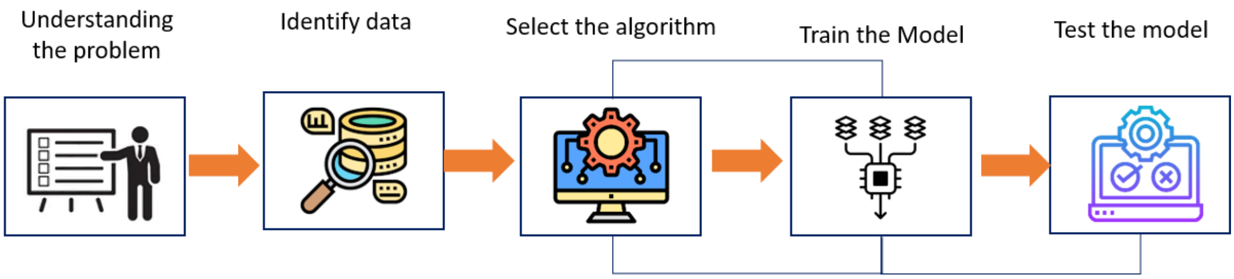


Fig. 10.5 Workflow of Machine learning process

The integration of machine learning techniques with remote sensing and GIS provides significant opportunities to extract valuable information from geospatial data and automate analysis processes. By leveraging the power of ML, researchers, scientists, and practitioners can enhance their understanding of the Earth's surface, enable more efficient data analysis, and support evidence-based decision-making in a wide range of domains.

10.2.2 Deep Learning

Deep Learning (DL) is a subset of Machine Learning (ML) that focuses on training artificial neural networks with multiple layers (hence the term "deep"). It aims to develop algorithms and models that can automatically learn and make intelligent decisions by extracting hierarchical representations from large amounts of data. At the core of deep learning are artificial neural networks, which are inspired by the structure and functioning of the human brain. These networks consist of interconnected nodes, called artificial neurons or units, organized into layers. Information flows through the network, with each layer processing and transforming the input to produce more complex representations. The deep learning models are typically trained using large datasets and a technique called *backpropagation*. During training, the model iteratively adjusts the weights and biases of the artificial neurons based on the discrepancies between the predicted outputs and the known or expected outputs. This process allows the model to learn and optimize its internal representations, making it capable of recognizing patterns, extracting features, and making accurate predictions or decisions. One of the key advantages of deep learning is its *ability to automatically learn representations from raw data, eliminating the need for manual feature engineering*. Deep neural networks can learn hierarchical features at multiple levels of abstraction, capturing complex patterns and dependencies in the data. This capability has led to significant breakthroughs in areas such as image recognition, object detection, speech synthesis, and language translation.

Deep learning has significantly impacted remote sensing and GIS by revolutionizing the analysis and interpretation of geospatial data. Its ability to automatically learn and extract complex patterns from raw data has led to improved accuracy and efficiency in various tasks. Convolutional Neural Networks (CNNs) are a popular type of deep learning architecture used for computer vision tasks. CNNs employ convolutional layers that can effectively capture spatial patterns in images. CNNs are designed to automatically learn hierarchical features from input images, making them well-suited for capturing spatial information and extracting meaningful features from remote sensing data. Fully Convolutional Networks (FCNs), U-Net, and SegNet are popular CNN architectures used for image segmentation in remote sensing. These models can be trained on annotated training data, where pixels or regions are labeled with the corresponding land cover classes or objects of interest. CNNs have demonstrated outstanding performance in image classification and segmentation tasks. These models can automatically classify pixels or segments within remote sensing imagery into predefined classes or delineate objects of interest. Deep learning-based approaches have enabled more accurate land cover mapping, object detection, and precise segmentation of features like buildings, roads, and vegetation.

Deep learning techniques have enhanced change detection in remote sensing by automatically identifying and analyzing differences between multi-temporal imagery. By training deep neural networks on historical data, these models can effectively capture temporal changes and identify areas undergoing transformations, such as land cover changes or urban growth. Deep learning-based change detection allows for more efficient and accurate monitoring of earth surface with respect to environmental changes, infrastructure development, climate change impact studies etc.

Deep learning algorithms, particularly region-based Convolutional Neural Networks (R-CNN) and their variants, have proven effective in detecting and recognizing objects within remote sensing imagery. These models can automatically locate and classify objects of interest, such as buildings, vehicles, or natural landmarks. Overall, R-CNN-based techniques have proven to be valuable tools for object detection and recognition in remote sensing, contributing to improved analysis, interpretation, and understanding of geospatial data. However, it's important to note that R-CNN approaches can be computationally expensive and require large amounts of training data and computation resources. Additionally, annotated training data, specifically labelled bounding boxes for the target objects, are essential for training accurate and effective R-CNN models in remote sensing applications.

The deep learning-based algorithms are also very effective in data fusion. It can be used to integrate and fuse data from various geospatial sources, such as satellite imagery, LiDAR data, and aerial photographs. Deep learning models can learn the relationships between different data layers and generate composite datasets that capture the combined information. Data fusion using deep learning enables more comprehensive analysis and enhances the understanding of complex geospatial phenomena.

Deep learning models have advanced scene understanding and analysis in remote sensing by capturing contextual and spatial relationships within imagery. These models can learn to recognize and interpret complex scenes, identify land cover patterns, and provide more detailed information about the environment. Deep learning-based scene understanding allows for more informed decision-making in urban planning, agriculture, environmental management etc.

Fig. 10.6 Deep learning use cases in Remote Sensing

The deep learning models often require a large amount of labelled training data and significant computational resources for training. Overfitting, where the model becomes too specialized to the training data and fails to generalize to new data, is also a common challenge. Addressing these limitations and developing techniques for interpretability, fairness, and robustness are active areas of research in the field of deep learning.

The integration of deep learning with remote sensing and GIS has opened up new possibilities for analyzing and interpreting geospatial data. These techniques offer improved accuracy, efficiency, and automation in tasks such as image classification, change detection, object detection, and scene understanding. As deep learning continues to evolve, it is expected to drive further advancements in remote sensing and GIS, enabling more precise and comprehensive analysis of geospatial information.

10.2.3 Generative AI

Generative AI, also known as Generative Adversarial Networks (GANs), is a branch of artificial intelligence that focuses on generating new data that resembles a given training dataset. It involves training a generative model to create new samples that are similar in distribution to the original data, allowing it to generate realistic and novel outputs. In a typical generative AI framework, there are two main components: a ***generator*** and a ***discriminator***. The generator tries to produce synthetic data samples from random noise, while the discriminator aims to distinguish between real and generated samples. The generator and discriminator are trained simultaneously in a competitive manner, with the goal of improving the generator's ability to generate data that is indistinguishable from real data. The training process of generative AI involves an iterative feedback loop. The generator initially produces random samples, which are evaluated by the discriminator. The discriminator provides feedback on the quality of the generated samples, and this feedback is used to update the parameters of both the generator and the discriminator. Over time, the generator learns to generate samples that closely match the characteristics of the training data, while the discriminator becomes more adept at differentiating between real and generated samples. Generative AI has found applications in various domains, including image generation, text synthesis, music composition, and more. Some notable examples include generating realistic images, creating new artworks, generating human-like speech, and even generating entire synthetic environments. One of the significant advantages of generative AI is its ability to produce novel and creative outputs. By capturing the underlying patterns and structures of the training data, generative AI models can generate new samples that exhibit similar characteristics. This can be particularly useful in scenarios where there is a need for generating new data for tasks like data augmentation, simulation, or creativity-driven applications.

Generative AI techniques have many innovative applications in the field of remote sensing and GIS. While the implementation of generative AI in remote sensing is still relatively new, it holds promise for generating synthetic remote sensing data, enhancing data augmentation techniques, and aiding in the interpretation and analysis of geospatial data. Some of emerging applications of generative AI in remote sensing and GIS are discussed below.

- **Synthetic Data Generation**: Generative AI can be used to generate synthetic remote sensing data that resembles real-world imagery. By training a GAN on a large dataset of labelled remote sensing images, the generator can produce new synthetic samples that capture the statistical properties and characteristics of the original data. This synthetic data can be useful for augmenting limited training data, creating diverse datasets for model training, and overcoming challenges related to data scarcity or privacy restrictions.
- **Data Augmentation**: Generative AI can contribute to data augmentation techniques in remote sensing. By generating new synthetic samples based on existing data, GANs can increase the diversity and quantity of training data, which can lead to improved model generalization and performance. This is particularly valuable in tasks such as land cover classification, object detection, and change detection, where a larger and more varied dataset can enhance the robustness of models.
- **Super-resolution and Data Enhancement**: Generative AI techniques, such as GANs, can be utilized to enhance the resolution and quality of remote sensing imagery. By training GAN models on pairs of low-resolution and high-resolution images, it becomes possible to generate high-resolution versions of low-quality or degraded remote sensing data. This can improve the visual clarity and detail of imagery, aiding in applications such as feature extraction, urban planning, and infrastructure monitoring.
- **Image in-painting and Completion**: Generative AI can assist in filling the missing or occluded regions within remote sensing images. By training a GAN on pairs of complete and incomplete images, the model can learn to predict and generate plausible content for missing areas. This capability is particularly useful in scenarios where data may have gaps due to cloud cover, sensor limitations, or data acquisition issues. By generating complete images, the model can provide more comprehensive and accurate information for analysis and interpretation.
- **Data Interpretation and Synthesis**: Generative AI can aid in the interpretation and synthesis of remote sensing data. By training GANs on labelled remote sensing imagery, the model can learn to generate synthetic samples that capture the characteristics of specific land cover classes or objects. This can assist in understanding and analyzing complex geospatial phenomena, supporting tasks such as land cover mapping, object detection, and scene understanding.

It's important to note that the application of generative AI in remote sensing is still an evolving field, and there are challenges to overcome, such as ensuring the quality and realism of the generated data, addressing biases, and validating the performance of models trained on synthetic data. However, generative AI holds promise for enhancing data augmentation, data interpretation, and data synthesis in remote sensing, offering opportunities to improve the efficiency and effectiveness of geospatial analysis and decision-making.

10.3 Augmented Reality (AR) and Virtual Reality (VR) & GIS

Augmented Reality (AR) and Virtual Reality (VR) are revolutionizing the way we interact with and visualize geospatial data in the field of Geographic Information Systems (GIS). These immersive technologies provide new avenues for exploring, analyzing, and understanding spatial information, offering enhanced capabilities for decision-making, planning, and communication. Augmented Reality (AR) combines real-world environments with computer-generated overlays to provide an augmented view of reality. By overlaying digital information onto the physical world, AR enables users to interact with and explore geospatial data in real-time. With the aid of AR-enabled devices such as smartphones, tablets, or smart glasses, users can visualize geospatial data directly within their environment.

AR in GIS opens up a range of possibilities. For instance, urban planners can use AR to visualize proposed buildings and infrastructure within the existing cityscape, allowing for better assessment of their impact on the surroundings. Field workers can overlay utility lines, land parcel information, or underground infrastructure onto the real-world environment, facilitating maintenance and repair tasks. AR can also enhance navigation by providing real-time directions and points of interest.

Virtual Reality (VR), on the other hand, immerses users in a computer-generated environment, completely replacing their physical surroundings. By wearing VR headsets or using VR systems, users can experience a fully simulated world, enabling them to explore and analyze geospatial data in a highly immersive manner. VR in GIS offers many advantages which enhance the power of GIS to make it more effective and closer to the reality. Some of the possible application areas of VR in GIS includes urban planning, environment management, disaster/emergency management etc. The urban planners and architects can use VR to create and experience virtual models of planned developments, enabling stakeholders to visualize and provide feedback on designs before construction begins. Environmental scientists can simulate and study landscapes, ecosystems, and climate change scenarios. VR can also facilitate virtual field trips, allowing students and researchers to explore remote locations without physically being there.

Fig. 10.7 VR Model of a city with integration of GIS maps (Source- SkylineGlobe)

A sample image of VR model with integration of GIS layer for a city is shown in Fig. 10.7. Both AR and VR have the potential to transform GIS in several ways. Some of important areas of Remote Sensing and GIS which have significant applications of AR and VR are discussed below:

- **Geospatial Data Collection**: AR and VR can revolutionize the way geospatial data is collected in the field. AR-based mobile applications can enable field workers to visualize and capture data directly within their physical surroundings. For example, utility workers can use AR to view underground infrastructure like pipes and cables, making it easier to locate and document assets. In VR, users can simulate field environments for training purposes, allowing them to practice data collection techniques and emergency response scenarios in a safe and controlled virtual environment.

- **Enhanced Visualization**: AR and VR technologies provide intuitive and immersive visualization of geospatial data. Users can observe and interact with data in a more engaging and realistic manner, leading to better understanding and analysis of data.
- **Spatial Analysis and Planning**: AR and VR enable users to overlay multiple layers of data onto real-world or virtual environments, supporting spatial analysis, decision-making, and planning activities. Users can assess the impact of proposed changes or evaluate alternative scenarios in a more comprehensive way.
- **Public Engagement and Communication**: AR and VR offer effective tools for communicating geospatial information to a wider audience. These technologies enable stakeholders to experience and interact with spatial data, fostering better public engagement and collaboration in planning processes.
- **Training and Education**: AR and VR provide immersive learning experiences for GIS training and education. Users can explore virtual environments, practice fieldwork, and gain hands-on experience without the limitations of physical constraints or risks.
- **Geo-visualization**: AR and VR can be used to create compelling geo-visualizations and immersive simulation experiences. Users can navigate and explore geospatial narratives, enhancing the understanding and communication of complex spatial information.
- **Environmental Monitoring and Simulation**: AR and VR can contribute to environmental monitoring and simulation efforts. In AR, real-time sensor data, satellite imagery, and climate models can be overlaid onto the physical environment, providing researchers and decision-makers with up-to-date information on environmental conditions. VR can simulate dynamic environmental scenarios, such as forest fire spread or coastal erosion, allowing stakeholders to witness and analyze potential impacts. These technologies aid in understanding environmental processes and support informed decision-making.
- **Tourism and Cultural Heritage**: AR and VR offer captivating experiences in the tourism and cultural heritage sectors. With AR, tourists can explore historical sites and landmarks, with relevant historical information and reconstructions overlaid on their view. VR can transport users to remote or inaccessible locations, allowing them to virtually visit archaeological sites, museums, or natural wonders. These immersive experiences enhance engagement, education, and preservation of cultural heritage.

While AR and VR in GIS offer exciting opportunities, there are many challenges to address. The accuracy and currency of underlying geospatial data, seamless integration with existing GIS platforms, and the development of user-friendly interfaces are areas that require attention. Furthermore, the hardware and computational requirements of AR and VR systems need to become more accessible and affordable for wider adoption. The integration of Augmented Reality (AR) and Virtual Reality (VR) technologies with Geographic Information Systems (GIS) is transforming the way we interact with spatial data. These immersive technologies enhance visualization, analysis, planning, and communication, opening up new avenues for decision-making and understanding of geospatial information. As AR and VR continue to advance, their integration with GIS will revolutionize various domains, from urban planning and environmental management to education and public engagement, offering unprecedented opportunities for spatial exploration and analysis.

10.4 Digital Twin

A digital twin is a virtual replica or representation of a physical object, system, or process that exists in the digital realm. It combines real-time data, simulation models, and advanced analytics to provide an interactive and dynamic digital counterpart of its physical counterpart. Digital twins enable organizations to gain a deeper understanding of their assets, optimize performance, and make informed decisions by leveraging insights from the virtual representation. They find applications in various industries, including manufacturing, healthcare, transportation, and smart cities, empowering organizations to improve operational efficiency, predict maintenance needs, and drive innovation.

Implementation of digital twin in GIS refers to a virtual replica or representation of a geographical object, system, or environment in the digital realm. It combines geospatial data, sensor data, and other relevant information to create a real-time, dynamic model that mirrors the characteristics and behaviour of its physical counterpart. In the context of GIS, a digital twin incorporates geospatial components, such as location, spatial relationships, and attributes, to provide a comprehensive understanding of the physical world. Digital twins in GIS enable a wide range of applications and benefits. They facilitate better decision-making, planning, and analysis by providing a detailed and up-to-date representation of the physical environment. For example, in urban planning, a digital twin can simulate the impact of proposed changes, such as new infrastructure or building developments, allowing stakeholders to visualize and evaluate the potential outcomes before implementation. Furthermore, digital twins can support real-time monitoring and management of assets and systems. By integrating sensor data, IoT devices, and GIS, organizations can create a digital twin that continuously updates and reflects the current state of the physical asset or system. This allows for proactive maintenance, predictive analytics, and optimization of operations. Digital twins also enhance collaboration and communication among stakeholders. They provide a common platform for sharing information, visualizing data, and facilitating interdisciplinary cooperation. This can be particularly valuable in complex projects or scenarios where multiple parties need to coordinate and align their activities.

Fig. 10.8 The city of Boston's digital twin (Source: ESRI)

The integration of GIS and digital twins is an emerging field with significant potential. By combining geospatial intelligence with the dynamic representation of physical objects and systems, organizations can gain valuable insights, improve efficiency, and optimize decision-making across various domains, including infrastructure management, smart cities, environmental monitoring, and asset performance optimization.

10.5 Indoor Positioning Systems (IPS)

Indoor positioning systems (IPS) have emerged as a critical technology for navigating and tracking objects and individuals within indoor environments. While Global Navigation Satellite System such as GPS, GLONAS, NavIC are widely used for outdoor positioning, IPS fills the gap by providing accurate location information in complex indoor spaces. The signals of GNSS based navigation system are not available inside a cemented roof or in dense forest. Due to this limitation, the development of IPS is very essential for many applications.

The Indoor positioning systems are designed to determine the position of objects or people inside buildings or enclosed spaces. They enable real-time tracking, navigation, and monitoring in environments where GPS signals are limited or non-existent. IPS utilizes a combination of hardware and software components to achieve precise indoor positioning. The navigation principle of IPS is similar to GNSS, however the different technological solutions are available for implementations.

10.5.1 Technologies Employed in IPS

The Indoor positioning systems are available with different technological solutions such as Wi-Fi based, Bluetooth based, ultra-wideband and RFID based IPS. All these technological solutions are their own pros and cons.

Wi-Fi-based IPS: Wi-Fi-based IPS utilizes Wi-Fi access points to estimate the position of devices or users. By measuring the signal strength and analyzing the received signal strength indication (RSSI), trilateration or fingerprinting algorithms can be used to calculate the location. Wi-Fi positioning is widely adopted due to the ubiquitous nature of Wi-Fi infrastructure.

Bluetooth-based IPS: Bluetooth-based IPS utilizes Bluetooth beacons or low-energy devices to transmit signals that can be received by compatible devices. Similar to Wi-Fi, the received signal strength is used to estimate the proximity and position of the target object. Bluetooth-based IPS is suitable for smaller areas and offers lower power consumption compared to Wi-Fi. Bluetooth Low Energy (BLE) beacons are small devices that transmit signals, allowing nearby devices to determine their proximity. By triangulating the received signal strength from multiple beacons, Bluetooth-based IPS provides accurate positioning within indoor spaces

Ultra-Wideband (UWB): UWB technology utilizes short-range radio waves to provide highly accurate positioning. UWB signals can penetrate obstacles and offer centimeter-level accuracy. UWB-based IPS relies on time-of-flight measurements to calculate the distance between the target device and multiple anchor nodes, enabling precise positioning.

RFID-based IPS: Radio Frequency Identification (RFID) technology uses tags and readers to identify and track objects within an indoor environment. RFID-based IPS is commonly used for asset tracking and inventory management in industrial settings or large facilities.

The most popular techniques used for navigation in IPS are Trilateration, Fingerprinting and Particle Filters. Trilateration calculates the position of a target object based on the distance measurements from multiple reference points. By knowing the distances from at least three anchor nodes, the target's location can be determined using geometric calculations. Fingerprinting is a technique where the received signal strength patterns at different locations within a building are pre-mapped and stored as reference fingerprints. When a user or device measures the received signal strength, it is compared with the stored fingerprints to estimate the location. Particle filters are commonly used in IPS to estimate the target's position based on sensor measurements and motion models. These probabilistic algorithms handle uncertainties and noise in measurements, making them suitable for real-time positioning.

IPS enables seamless indoor navigation for various applications, including airports, shopping malls, hospitals, hotels and museums. IPS enables the delivery of location-based services within indoor environments. Retailers can provide personalized offers and recommendations based on a customer's precise location within a store. Similarly, museums and exhibition centers can offer interactive and context-aware information to enhance visitor experiences. Users can receive turn-by-turn directions, locate points of interest, and find the shortest routes within complex indoor environments. IPS can also be used for the businesses to track and manage assets within indoor spaces. This is particularly valuable in industries such as warehousing, logistics, and healthcare, where real-time tracking and inventory management are critical. One of the important applications of IPS is indoor security and emergency response. By tracking the location of personnel and assets in real-time, security teams can respond swiftly to incidents, monitor restricted areas, and ensure the safety of occupants.

10.5.2 Challenges in IPS

The Indoor Positioning Systems are important for many applications. However, there are few challenges and limitations in IPS technologies. Achieving high accuracy in indoor positioning remains a challenge due to the complex indoor environments, multipath interference, and signal attenuation caused by obstacles. Calibration is crucial to account for environmental factors that affect signal propagation. Implementing IPS in large-scale environments requires robust infrastructure, scalability, and maintenance considerations is yet another challenging task. IPS involves the collection and processing of sensitive location data, necessitating robust privacy and security measures to protect user information needs to be addressed while implementing IPS. Integrating IPS with Geographic Information Systems enables the fusion of indoor and outdoor positioning data, providing seamless navigation across both environments. Indoor environments often suffer from signal interference, such as multipath reflections and obstructions, which can impact the accuracy and reliability of IPS systems. Advanced signal processing techniques and algorithms are employed to mitigate these challenges. Creating accurate indoor maps and calibrating IPS systems require extensive efforts. IPS technologies rely on battery-powered devices. Optimizing power consumption is essential to ensure long battery life while maintaining continuous positioning accuracy. Efficient algorithms and hardware design help achieve this balance.

Indoor positioning systems have immense potential in revolutionizing navigation, tracking, and monitoring within indoor spaces. With advancements in wireless technologies, sensor fusion, and algorithms, IPS is becoming increasingly accurate and reliable. As the demand for location-based services and indoor navigation grows, IPS will continue to play a crucial role in improving efficiency, safety, and user experiences in various domains.

10.6 Internet of Things (IoT) & Sensor Network

The Internet of Things (IoT) technology connects the different objects and devices to the internet, allowing them to collect, exchange, and analyze data. By enabling seamless communication and data sharing between physical and digital systems, IoT opens up new opportunities for automation, efficiency, and improved decision-making. IoT relies on a network of interconnected devices equipped with sensors and actuators. These devices collect and transmit data, enabling real-time monitoring and control of physical objects. IoT devices leverage various connectivity options, including Wi-Fi, Bluetooth, cellular networks, and Low-Power Wide Area Networks (LPWAN), to establish communication links between devices through Internet. IoT devices generates large amount of data which impose various technical challenges in data processing and analytics. Cloud computing, edge computing, and data analytics techniques are employed to process and analyze this data, extracting valuable insights and enabling intelligent decision-making.

Message Queuing Telemetry Transport (MQTT) is a lightweight messaging protocol designed for constrained devices and low-bandwidth networks. It enables efficient publish-subscribe communication between IoT devices and the cloud. It is designed for efficient communication between devices with limited resources, such as low bandwidth, low power, and intermittent connectivity. Constrained Application Protocol (CoAP) is a protocol specifically designed for resource-constrained devices in IoT applications. It facilitates simple request-response interactions between clients and servers. HTTP and RESTful APIs are widely used in IoT to enable communication between devices and web services. They provide a standardized way to access and manipulate IoT data.

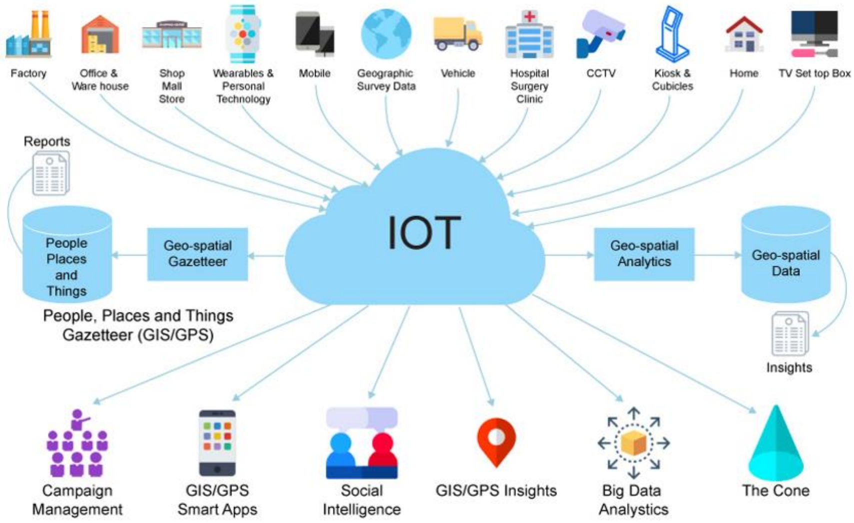


Fig.10.9 Conceptual diagram of IoT connectivity and data integration (**Source**-http://cloudsegue.com)

The integration of IoT with GIS has revolutionized the way we collect, analyze, and visualize spatial data. By combining real-time sensor data from IoT devices with the spatial capabilities of GIS, organizations and individuals can gain valuable insights, make informed decisions, and improve various aspects of their operations.

- **Real-time Data Collection and Visualization**: IoT devices equipped with sensors, such as environmental monitors, vehicle trackers, and infrastructure sensors, generate a continuous stream of real-time data. By integrating this data with GIS, organizations can visualize the collected information spatially, providing a dynamic and interactive representation of the physical world. Real-time data updates enable immediate insights and response to changing conditions, enhancing situational awareness and decision-making.
- **Enhanced Spatial Analysis**: The integration of IoT with GIS empowers spatial analysis by combining sensor data with geographic information. By overlaying sensor readings onto GIS maps, patterns,

trends, and correlations can be identified spatially, enabling more accurate analysis and prediction. This integration offers deeper insights into complex relationships between spatial variables, facilitating effective planning, resource management, and problem-solving.

- **Improved Asset and Resource Management**: Integrating IoT with GIS enables organizations to better manage their assets and resources. For example, sensors embedded in infrastructure assets can monitor performance, detect faults, and trigger maintenance notifications. By combining this information with GIS, asset managers can visualize the location, status, and health of assets, optimize maintenance schedules, and allocate resources efficiently. This integration supports proactive asset management, cost reduction, and enhanced service delivery.
- **Smarter Decision-Making**: The integration of IoT and GIS facilitates data-driven decision-making by providing a comprehensive understanding of the spatial context. Real-time data from IoT devices, when analyzed within a GIS framework, allows decision-makers to assess situations, identify trends, and predict outcomes with greater accuracy. This integration empowers organizations to respond swiftly, mitigate risks, and optimize processes across various domains, including urban planning, agriculture, transportation, and emergency management.

The application of IoT in GIS opens up new possibilities for collecting, analyzing, and visualizing real-time geospatial data. Another specific application of IoT in GIS is known as **sensor network**. Sensor network is a network of interconnected sensors that collect and transmit data about the physical environment and its spatial attributes. These sensors can be deployed in various locations, such as urban areas, agricultural fields, forests, or water bodies, to capture real-time information about temperature, humidity, air quality, noise levels, water quality, and other environmental parameters. The integration of sensor networks with GIS technology enables the collection, analysis, and visualization of geospatial data, providing valuable insights for decision-making and spatial analysis. Let us now discuss few specific use cases on applications of IoT and sensor network in GIS:

- **Smart Cities:** IoT devices can be deployed throughout cities to gather data on various aspects, such as transportation, energy consumption, waste management, and public safety. By integrating this data into GIS, city planners and administrators can gain insights into urban dynamics, optimize resource allocation, and make data-driven decisions for improving the quality of life in urban areas.
- **Environmental Monitoring**: IoT sensors can be used to monitor environmental parameters such as air quality, water quality, noise levels, and weather conditions. This real-time data, when integrated with GIS, allows for better spatial analysis and visualization of environmental trends and patterns. It enables environmental agencies and researchers to monitor changes, identify pollution sources, and take appropriate measures for mitigation and preservation.
- **Agriculture and Precision Farming**: IoT devices, including soil moisture sensors, weather stations, and remote sensing technologies, can provide real-time data on crop health, soil conditions, and weather patterns. Integrating this data with GIS allows farmers to monitor field conditions, optimize irrigation and fertilization, detect pest infestations, and make informed decisions for precision farming practices. Sensor networks in GIS are employed in precision agriculture practices. Sensors can monitor soil moisture levels, nutrient content, temperature, and other relevant parameters. By integrating this data with GIS, the users can create detailed spatial maps of their fields, make data-driven decisions about irrigation, fertilization, and pest management, and optimize crop yields while minimizing resource use.
- **Infrastructure Monitoring and Management**: IoT sensors can monitor the condition, performance, and maintenance needs of infrastructure assets such as bridges, buildings, and

utility networks. By integrating IoT data with GIS, infrastructure managers can visualize asset locations, track their health and performance, predict maintenance needs, and plan repairs or replacements effectively.

- **Emergency Management**: During natural disasters or emergencies, IoT devices can play a crucial role in collecting real-time data on factors such as temperature, humidity, air quality, seismic activity etc. GIS integration allows emergency responders to analyze and visualize this data spatially, enabling effective emergency planning, resource allocation, and situational awareness. Sensor networks are instrumental in disaster management and response. They can provide early warning systems for natural disasters such as earthquakes, floods, or wildfires. By integrating sensor data with GIS, emergency response teams can visualize and analyze real-time information about affected areas, assess the severity of the situation, and plan effective rescue and relief operations.
- **Transportation and Logistics**: IoT devices, including GPS trackers, vehicle sensors, and traffic monitoring systems, can provide real-time data on transportation movements, traffic conditions, and logistics operations. By integrating this data into GIS, transportation managers can optimize routes, analyze traffic patterns, manage fleet operations, and enhance overall transportation efficiency.

Above are just a few examples of how IoT can be integrated into GIS applications. The combination of real-time IoT data with geospatial analysis capabilities provides valuable insights and enables informed decision-making across various domains. As IoT technology continues to advance, the integration with GIS is expected to play an increasingly significant role in shaping smart cities, sustainable development, and efficient resource management. The integration of IoT with GIS represents a powerful convergence of technologies that enhances data-driven decision-making, spatial analysis, and resource management across industries. The real-time nature of IoT data combined with the spatial visualization and analysis capabilities of GIS opens up new opportunities for improved operations, enhanced situational awareness, and sustainable development. As IoT technology advances, the integration with GIS is poised to play an increasingly vital role in shaping our understanding of the world and driving innovation in various domains.

While the integration of IoT with GIS offers tremendous benefits, there are challenges to address. Some of the major challenges in IoT based applications are discussed here. Integrating data from diverse IoT devices with GIS systems requires careful consideration of data formats, standards, and protocols to ensure seamless data interoperability. The data volume and scalability is yet another challenge to handle the influx of real-time data streams efficiently in IoT based services. Ensuring the accuracy and reliability of IoT data is crucial for meaningful analysis and decision-making. Data validation, calibration, and quality control mechanisms are essential in maintaining data integrity. Protecting IoT-generated data from unauthorized access, ensuring data privacy, and implementing robust security measures are vital considerations in the integration of IoT with GIS. IoT networks are vulnerable to attacks such as denial-of-service (DoS), man-in-the-middle (MitM), and replay attacks. Implementing strong network security measures, including firewalls, intrusion detection systems, and secure protocols, is crucial for implementation of IoT based solutions.

10.7 Big Data

Big data refers to extremely large and complex datasets that cannot be easily managed, processed, or analyzed using traditional data management and processing techniques. It encompasses massive volumes of structured, semi-structured, and unstructured data that is generated from various sources such as social media, sensors (satellites and ground), transaction records, log files, and more.

Structured data refers to data that is organized and formatted in a predefined manner, making it easily identifiable and searchable. It follows a specific schema or data model, typically represented in tabular form with rows and columns. Structured data is highly organized, allowing for efficient storage, retrieval, and analysis. It often resides in relational databases or spreadsheets, where each data element has a well-defined data type and is associated with a particular field or attribute.

Semi-structured data refers to data that does not adhere to a strict tabular structure like structured data but still contains some level of organization. It possesses elements of both structured and unstructured data. Semi-structured data often includes tags, labels, or other metadata that provide a basic structure, making it easier to process and analyze compared to unstructured data. Examples of semi-structured data include XML files, JSON documents, log files, and HTML web pages. These data formats allow for flexibility and hierarchical organization, enabling data modeling and extraction of relevant information. Semi-structured data is commonly encountered in web scraping, data integration, and document management systems.

Unstructured data refers to data that does not have a predefined or organized format, making it more challenging to classify and analyze using traditional methods. Unlike structured data, unstructured data does not conform to a specific schema or data model and often lacks a clear structure. It can come in various forms such as text documents, emails, social media posts, audio recordings, images, videos, and sensor data. Examples of unstructured data include customer reviews, social media feeds, news articles, video footage, and voice recordings etc. Due to its lack of structure, unstructured data requires advanced techniques like natural language processing, text mining, image recognition, and sentiment analysis to extract meaningful insights. Analyzing unstructured data provides valuable information for sentiment analysis, trend detection, market research, content recommendation, and customer sentiment analysis.

The Big data consists of structures, semi-structured and unstructured data which have five major characteristics i.e., **volume, variety, value, velocity,** and **veracity** (Fig. 10.10**)**. Let us focus on the V's of Big data with more details. Big data involves a large amount of data that exceeds the capacity of conventional database systems. It encompasses terabytes, petabytes, or even exabytes of information, which requires specialized tools and technologies to store and process the large data sets. Big data is generated and collected at an unprecedented speed. It includes real-time or near-real-time data streams that need to be processed and analyzed in a timely manner to extract meaningful insights. The velocity of data flow poses challenges in terms of data capture, integration, and analysis. Big data comes in various formats and structures, including structured data (e.g., relational databases), semi-structured data (e.g., XML, JSON), and unstructured data (e.g., text documents, images, videos). This variety adds complexity to data management and analysis, as different data types require different processing techniques.

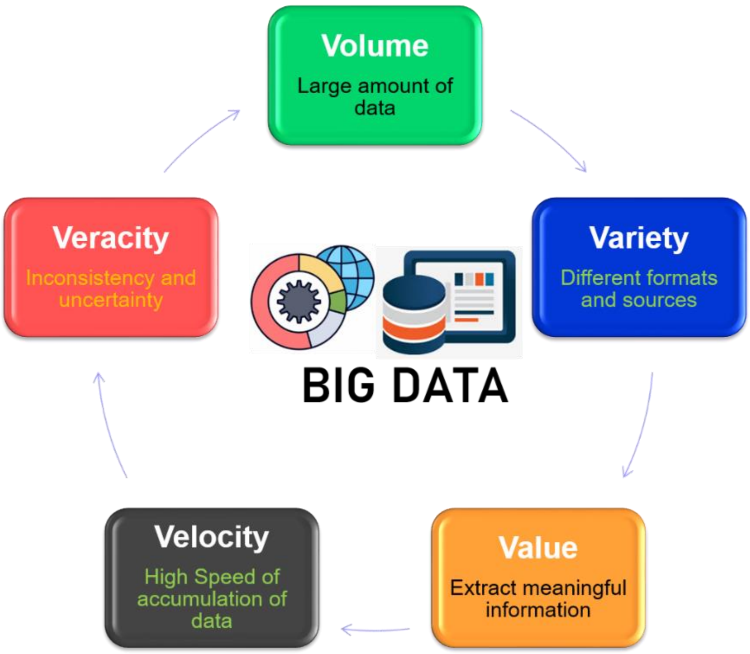


Fig. 10.10 Characteristics of Big data

10.7.1 Big Geo-data

Big data in GIS involves the utilization of large and complex geospatial datasets to gain valuable insights and make informed decisions. With the exponential growth of geospatial data, big data analytics techniques are crucial for processing and deriving insights from massive datasets. These techniques enable the analysis of complex spatial relationships, patterns, and trends, supporting informed decision-making. The term **Big Geo-data** is referring to the implementation of big data concept with respect to geo-spatial data.

Structured data in GIS refers to geospatial information that is organized and stored in a well-defined format. It typically consists of tabular data with predefined fields and data types. An example of structured data in GIS is a spatial database that contains attribute tables with columns representing specific characteristics of geographic features, such as roads, buildings, or land parcels. Each row in the table corresponds to a specific feature, and the columns store attribute information like names, addresses, area measurements, or classification codes. Structured data enables efficient querying, analysis, and visualization within GIS systems, supporting tasks such as spatial analysis, data integration, and decision-making processes. **Unstructured data in GIS** refers to geospatial information that lacks a predefined format or structure. It can encompass various types of data, including free-form text, images, videos, and documents. An example of unstructured data in GIS is social media posts with geotagged information. These posts may contain text, images, or videos related to specific locations, but they do not follow a standardized format. **Semi-structured data in GIS** refers to geospatial information that has a partial structure or contains elements of both structured and unstructured data. It contains some organizational characteristics but does not conform entirely to a rigid schema. An example of semi-structured data in GIS is data obtained from web scraping or web APIs. This type of data often comes in a structured format such as JSON (JavaScript Object Notation) or CSV (Comma-Separated Values), but it may have varying levels of structure within the dataset. For instance, when scraping data from websites, different web pages may have slightly different structures or contain optional fields. Similarly, when retrieving data from web APIs, the response may include additional optional parameters or nested structures based on the query. Semi-structured data in this context requires parsing and transformation to extract the relevant geospatial information while accounting for the varying structure and optional fields within the dataset.

10.7.2 Big Data Analytics

Big data analytics is the process of examining and analyzing large and complex datasets to uncover patterns, trends, correlations, and other valuable insights. It involves the application of advanced computational techniques, statistical models, and machine learning algorithms to extract meaningful information from vast amounts of data. The goal of big data analytics is to transform raw data into actionable insights that can drive decision-making, optimize processes, and support strategic initiatives. It involves processing and analyzing data from various sources, including structured, semi-structured, and unstructured data, to identify patterns and extract valuable knowledge. Big data analytics typically involves the following stages:

- **Data Collection**: Gathering data from multiple sources, which can include transactional databases, social media feeds, sensor networks, log files, and more. The data is collected and stored in a central repository for analysis.
- **Data Preparation**: Cleaning, transforming, and integrating the data to ensure its quality, consistency, and compatibility with the analytics process. This includes removing duplicates, handling missing values, and normalizing data.
- **Data Analysis**: Applying statistical techniques, data mining algorithms, and machine learning models to uncover patterns, trends, and correlations within the data. This step involves exploratory data analysis, descriptive statistics, predictive modeling, and other advanced analytics techniques.
- **Data Visualization**: Presenting the analyzed results in a visual format, such as charts, graphs, or interactive dashboards, to make the insights more accessible and understandable for stakeholders. Visualization enhances data exploration, facilitates communication, and aids in decision-making.
- **Interpretation and Decision-Making**: Interpreting the results of the analysis and using the insights gained to inform decision-making processes. The insights derived from big data analytics can guide strategic planning, optimize operations, improve customer experiences, and drive innovation.

Big data analytics is widely used across industries and sectors, including finance, healthcare, marketing, manufacturing, transportation, and many more. It enables organizations to gain a deeper understanding of their data, make data-driven decisions, identify new opportunities, mitigate risks, and improve overall performance. Key technologies and tools used in big data analytics include distributed computing frameworks (such as Apache Hadoop and Spark), data mining algorithms, machine learning libraries (like scikit-learn and TensorFlow), statistical analysis software, and data visualization tools. These technologies provide the computational power and analytical capabilities required to process and extract insights from large and complex datasets. Some of the most popular software tools used for big data analytics are shown in Fig. 10.11.

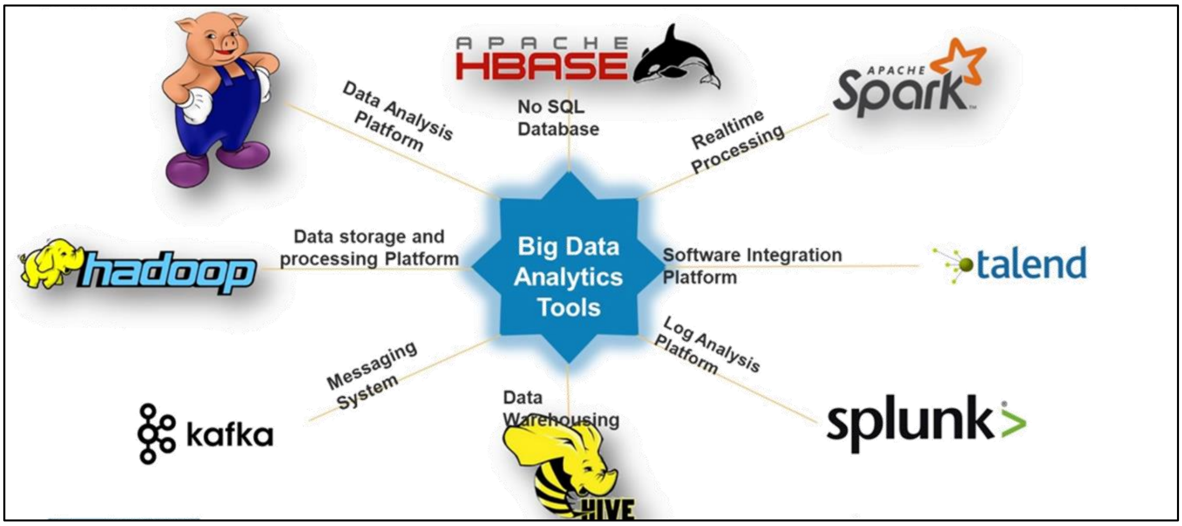


Fig. 10.11 Popular software tools for Big data analytics

Big data analytics have many applications in geospatial domain. Some of the typical examples of Big data in geospatial domain are discussed below:

- **Satellite Imagery Analysis**: With the availability of high-resolution satellite imagery and the increase in data collection frequency, big data analytics can be applied to analyze massive volumes of satellite imagery. This enables monitoring changes in land cover, identifying urban expansion patterns, assessing vegetation health, and detecting natural disasters like wildfires or floods.
- **Sensor Networks**: Sensor networks generate vast amounts of geospatial data from various sources, such as weather stations, environmental sensors, or IoT devices. By integrating sensor data with GIS, big data analytics can be used to analyze real-time information about weather conditions, air quality, noise levels, or water quality. This aids in environmental monitoring, resource management, and early warning systems for natural disasters.
- **Social Media Data**: Social media platforms generate enormous amounts of geotagged data. By analyzing social media posts, big data analytics can provide insights into people's behaviours, sentiments, and activities within specific geographic areas. This information can be useful for urban planning, marketing campaigns, and understanding social trends.
- **Transportation Analysis**: Transportation systems generate vast amounts of data, including GPS traces, traffic flow information, and public transportation schedules. Applying big data analytics to this data in GIS allows for real-time traffic monitoring, optimizing route planning, identifying traffic congestion patterns, and predicting traffic conditions to improve transportation efficiency.
- **Geospatial Simulation**: Big data analytics can be used to simulate and model complex spatial phenomena. For example, simulating the spread of infectious diseases within a population, predicting the impact of climate change on coastal areas, or modeling the behaviour of crowds in urban spaces. These simulations aid in understanding and planning for various scenarios and making informed decisions.
- **Emergency Management**: Big data analytics in GIS can support emergency response and disaster management. By analyzing real-time data from various sources such as satellite imagery, social media, weather forecasts, and sensor networks, emergency responders can gain insights into the affected areas, identify critical infrastructure, and allocate resources effectively.

These are just a few examples of how big data is applied in GIS. The integration of big data analytics with geospatial technologies enhances our ability to extract valuable insights, make informed decisions, and address complex challenges across various domains.

10.8 Cloud computing GIS

Cloud computing refers to the delivery of computing services, including storage, processing power, and software applications, over the internet. Instead of relying on local infrastructure, organizations can access and utilize these resources on-demand, paying only for what they use i.e. pay-as-you-go. The cloud offers scalability, flexibility, and cost efficiency, allowing businesses to leverage powerful computing capabilities without the need for extensive hardware investments or maintenance. It has become a transformative technology, enabling businesses to innovate, collaborate, and scale their operations effectively in a connected and digital environment. Cloud computing offers various service models, including Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). In the IaaS model, users have control over the operating systems, storage, and network infrastructure, while in the PaaS model, users can focus on developing and deploying applications without managing the underlying infrastructure. The SaaS model allows users to access software applications over the internet without the need for installation or maintenance. The typical architecture and services of cloud computing are shown in Fig. 10.12.

Cloud computing has revolutionized various industries by providing scalable, cost-effective, and flexible computing solutions. It has enabled businesses to leverage advanced technologies, such as big data analytics, artificial intelligence, and Internet of Things (IoT), while reducing the burden of managing infrastructure. With its immense computing power and accessibility, cloud computing has become an integral part of modern computing infrastructure, enabling innovation and driving digital transformation across diverse sectors. Cloud computing has revolutionized the field of GIS by providing a scalable and flexible platform for storing, processing, and analyzing geospatial data. This technical article explores the intersection of cloud computing and GIS, highlighting the benefits, challenges, and innovative applications of cloud-based GIS.

- **Scalability and Elasticity**: Cloud computing offers unprecedented scalability and elasticity in GIS. Traditional GIS systems often face limitations in terms of storage capacity and computational power. With cloud-based GIS, organizations can easily scale their resources up or down based on demand, enabling the processing of large and complex geospatial datasets without investing in costly infrastructure.

- **Data Storage and Accessibility**: The cloud provides a centralized and secure repository for storing geospatial data. Cloud storage solutions offer high availability, redundancy, and disaster recovery options, ensuring the safety and accessibility of valuable GIS data. Cloud-based storage also facilitates seamless collaboration and data sharing among distributed teams, enabling real-time updates and version control.

- **Distributed Geo-processing**: Cloud computing enables distributed geoprocessing, where computationally intensive GIS operations are performed across multiple virtual machines or containers. This parallel processing capability accelerates geospatial analysis, allowing for faster data processing, spatial modeling, and advanced analytics. Additionally, cloud-based geoprocessing provides the ability to dynamically scale resources to handle peaks in workload, ensuring efficient utilization of computing resources.

- **Geospatial Web Services**: Cloud computing facilitates the deployment of geospatial web services, making GIS data and functionality accessible via web browsers or application programming interfaces (APIs). Cloud-based GIS platforms offer scalable and responsive map services, enabling users to interact with and visualize geospatial data on various devices. This promotes the development of web and mobile applications that leverage GIS capabilities for decision-making, asset management, and location-based services.
- **Machine Learning and AI Integration**: The cloud computing paradigm seamlessly integrates with machine learning and artificial intelligence (AI) techniques, enhancing GIS capabilities. By leveraging cloud-based infrastructure and resources, organizations can apply machine learning algorithms for tasks such as image classification, object detection, and spatial pattern recognition. The combination of cloud computing and AI empowers GIS users with automated analysis, predictive modeling, and data-driven insights.
- **Cost Efficiency and Flexibility**: Cloud-based GIS offers cost efficiency by eliminating the need for upfront infrastructure investments and reducing maintenance overheads. Organizations can choose from a variety of pricing models, such as pay-as-you-go or subscription-based plans, based on their specific needs and usage patterns. The cloud's flexibility enables GIS users to experiment with new technologies, scale resources as needed, and rapidly deploy and update GIS applications without disruptions.

Cloud computing has transformed the field of GIS, providing unprecedented scalability, accessibility, and computational power for geospatial analysis and collaboration. By leveraging cloud-based infrastructure, organizations can unlock the full potential of their geospatial data, enabling advanced analysis, real-time decision-making, and innovative applications. Embracing cloud computing in GIS opens new horizons for spatial analysis, collaboration, and the integration of emerging technologies, paving the way for a more connected and data-driven geospatial future.

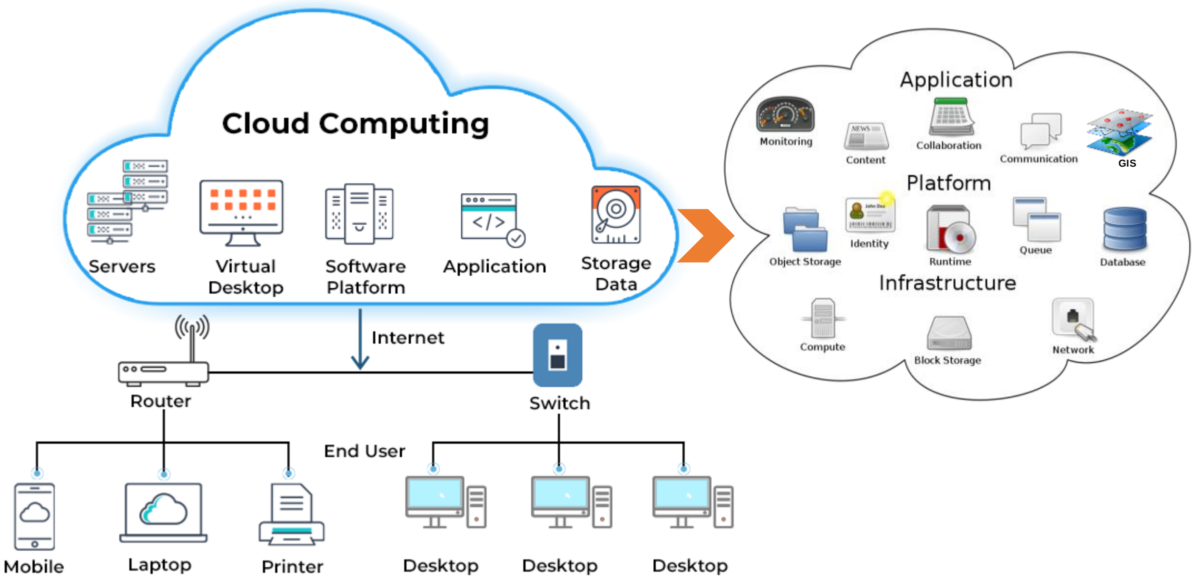


Fig. 10.12 Cloud computing architecture and services

10.9 Blockchain technology

Blockchain technology is a decentralized and immutable ledger system that enables secure and transparent transactions or data exchanges. It operates on a distributed network of computers, known as nodes, which collectively validate and record transactions in a chronological and tamper-resistant manner. Each transaction, or block, is cryptographically linked to the previous one, forming a chain of blocks. The decentralized nature of blockchain eliminates the need for intermediaries and offers benefits such as enhanced security, transparency, traceability, and trust. It has applications beyond cryptocurrencies, including supply chain management, smart contracts, identity verification, and decentralized applications, with the potential to revolutionize various industries by enabling efficient and secure data sharing and transactional processes. By combining cryptographic hashing, consensus mechanisms, and a distributed network, blockchain technology ensures a secure, transparent, and tamper-resistant system for recording and verifying transactions. It provides a foundation for building applications that require trust, data integrity, and decentralized control, revolutionizing various industries and domains.

Integration of Blockchain technology with GIS offers new opportunities to enhance data integrity, security, and transparency within the geospatial domain. By leveraging the decentralized and immutable nature of blockchain, GIS applications can benefit from increased trust and reliability in spatial data management and sharing. In the context of GIS, blockchain technology can be used to address challenges such as data provenance, data authenticity, and data sharing among multiple stakeholders. With blockchain, each geospatial transaction or data update can be recorded as a block in the chain, creating an auditable and tamper-proof history of changes. This ensures the integrity of spatial data by providing an immutable record of its creation, modification, and ownership. Furthermore, blockchain technology enables secure and transparent data sharing among different entities in the GIS ecosystem. It eliminates the need for a central authority or intermediary, allowing direct peer-to-peer data exchanges while maintaining data privacy and security. This decentralized approach enhances data collaboration, facilitates data integration across multiple sources, and promotes trust between stakeholders. The integration of blockchain technology in GIS can also support spatial data marketplaces or decentralized applications (DApps) where users can securely trade or exchange geospatial data using smart contracts. Smart contracts are self-executing contracts with predefined rules and conditions, enabling automated and trusted transactions. This can enable new business models for spatial data, such as data monetization and incentivized sharing. Additionally, blockchain technology can assist in geospatial data authentication and verification. It can provide a reliable mechanism to verify the authenticity and integrity of geospatial datasets, ensuring that the data has not been modified or tampered with throughout its lifecycle.

Overall, the integration of blockchain technology in GIS has the potential to revolutionize the way spatial data is managed, shared, and trusted. It brings transparency, immutability, and enhanced security to geospatial transactions, promoting collaboration, data integrity, and innovative applications in various domains such as land administration, supply chain management, urban planning, and environmental monitoring.

10.10 Challenges and Opportunities in emerging technologies

Emerging geospatial technologies are driving a transformative shift in the field of spatial analysis. These innovative tools and techniques leverage advancements in artificial intelligence (AI), remote sensing, and data processing to capture, analyze, and visualize geospatial data more efficiently. Integration of artificial intelligence (AI), machine learning (ML), Deep Learning (DL) and Generative AI in GIS enables automated image analysis, object detection, and classification, improving accuracy in tasks like land cover mapping and natural resource management. Additionally, the application of deep learning algorithms allows for complex pattern recognition and predictive modeling, enabling more advanced spatial analysis and decision-making. Advancing remote sensing technologies, including high-resolution satellite imagery and LiDAR sensors, UAV based observations provide detailed spatial data for disaster management, precision agriculture, and infrastructure planning. Augmented reality (AR) and virtual reality (VR) in GIS enhance visualization and decision-making, while the Internet of Things (IoT) enables real-time data collection for asset management and environmental monitoring. These emerging technologies revolutionize spatial analysis, offering new possibilities for data-driven insights, advanced modeling, and immersive visualization across various industries.

While emerging geospatial technologies offer tremendous opportunities, several challenges must be addressed to realize their full potential. These include:

1. **Data Quality and Standards:** Ensuring the accuracy, reliability, and interoperability of geospatial data remains a key challenge. Standardizing data formats and metadata, establishing quality assurance mechanisms, and promoting data sharing frameworks are essential.
2. **Ethical and Privacy Concerns**: As geospatial technologies gather vast amounts of personal and sensitive data, ethical considerations around data privacy, consent, and security become paramount. Robust legal and ethical frameworks are necessary to protect individuals' rights and maintain public trust.
3. **Skills and Capacity Building**: The adoption of emerging geospatial technologies requires a skilled workforce capable of leveraging their full potential. Investments in education, training, and capacity building programs are crucial to ensure a competent geospatial workforce.
4. **Infrastructure and Connectivity**: Reliable and affordable internet connectivity, particularly in remote and underprivileged areas, is critical for the widespread adoption and effective utilization of geospatial technologies.
5. **Data Privacy and Security**: With the rapid growth of emerging technologies, there is an increased need for robust data privacy and security measures. Protecting sensitive geospatial data and ensuring secure transmission and storage are significant challenges in the era of interconnected systems.
6. **Integration and Interoperability**: The integration of various emerging technologies, such as AI, remote sensing, and IoT, presents challenges in terms of interoperability and data exchange. Ensuring seamless integration and compatibility between different platforms and systems is crucial for maximizing the potential of these technologies.
7. **Scalability and Infrastructure**: Scaling up emerging technologies to handle large datasets and complex analysis poses challenges in terms of computational resources, storage, and infrastructure. Organizations need to invest in scalable and robust systems to harness the full potential of these technologies.
8. **Ethical Considerations**: Emerging technologies raise ethical concerns related to data privacy, bias in algorithms, and responsible use of geospatial information. Developing ethical

frameworks and guidelines is essential to ensure the responsible and ethical deployment of these technologies.

9. **Cost and Affordability**: Implementing and maintaining emerging technologies can be costly, especially for smaller organizations or those with limited resources. Finding cost-effective solutions and exploring collaborations can help overcome financial barriers and promote wider adoption.

10. **Regulation and Policy**: The fast-paced nature of emerging technologies often outpaces the development of regulations and policies. Developing appropriate regulatory frameworks to govern the use, sharing, and protection of geospatial data is crucial to address legal and ethical challenges.

11. **Data Governance and Standards**: Establishing data governance practices and standards is essential for managing and sharing geospatial data effectively. Creating frameworks for data sharing, interoperability, and standardization ensures consistency and reliability across different systems and platforms.

12. **Social Acceptance and Adoption**: The successful adoption of emerging technologies relies on social acceptance and user adoption. Addressing concerns, fostering awareness, and demonstrating the tangible benefits of these technologies to the broader community are vital for their widespread acceptance and adoption.

While emerging technologies offer tremendous opportunities, addressing these challenges is necessary to fully realize their potential in revolutionizing geospatial analysis, decision-making, and sustainable development. Through collaborative efforts, technological advancements, and strategic planning, these challenges can be overcome, leading to a future where emerging technologies become integral tools in harnessing the power of geospatial information.

10.11 Conclusion

In conclusion, emerging geospatial technologies are reshaping the landscape of spatial analysis and transforming how we perceive and interact with the world around us. The integration of artificial intelligence, remote sensing, augmented reality, virtual reality, and the Internet of Things has opened up new possibilities for data acquisition, analysis, visualization, and decision-making in the field of GIS. These technologies offer unprecedented opportunities for capturing and processing vast amounts of geospatial data, enabling more accurate and efficient analysis. They enhance our understanding of complex spatial phenomena, support proactive decision-making, and facilitate the development of innovative solutions across various sectors. From automated image analysis and object detection to real-time monitoring and simulation in virtual environments, emerging geospatial technologies provide valuable insights and facilitate informed decision-making. They empower organizations to optimize operations, improve resource management, enhance urban planning, and respond effectively to environmental challenges. However, the adoption and successful implementation of these technologies come with challenges. Addressing issues related to data privacy, integration, scalability, skill gaps, ethical considerations, and cost is crucial for their widespread acceptance and utilization. It is important for researchers, practitioners, policymakers, and stakeholders to collaborate and navigate these challenges to unlock the full potential of emerging geospatial technologies. Through ongoing innovation, training programs, policy development, and responsible use, we can harness the power of these technologies to drive sustainable development, improve quality of life, and address complex spatial challenges at local, regional, and global scales. The future of geospatial analysis holds immense promise, and as emerging technologies continue to evolve, they will play a central role in shaping our understanding of the world and driving positive change. With continued advancements, collaboration, and strategic planning, we can fully leverage the potential of emerging geospatial technologies to create a more sustainable, resilient, and informed society.

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