CHAPTER 1

Background of Remote Sensing

1.1 Modern Surveying

Surveying is a core subject for civil engineers, architects, and geographers. It is considered in the beginning of several developmental and infrastructural projects, such as roads, railways, canals, dams, bridges, buildings, townships, pipelines, transmission lines, and others (Schofield, 1984). Surveying is "*the technique of precisely determining the relative position (2D or 3D) of natural and man-made features above or below the surface of the Earth, by means of direct or indirect elevation, distance, and angular measurements*". The natural features include landscapes, rivers, mountains, etc., while man-made features are canals, buildings, bridges, etc. According to the American Congress on Surveying and Mapping (ACSM), Surveying is *"the science and art of making all essential measurements to determine the relative position of points or physical and cultural details above, on, or beneath the surface of the Earth, and to depict them in a usable form, or to establish the position of points or details"*.

The objectives of surveying are (Garg, 2021) many, such as collect the data about the relative positions of points/objects on the surface of Earth, prepare maps required for various engineering projects, establish horizontal and vertical controls required for accurate mapping and subsequently for construction, compute areas and volumes of earthwork in various projects, and layout of various engineering works on the ground. Surveying is also important in many other studies, such as archaeology, geology, geophysics, landscape architecture, meteorology, and seismology, including military engineering.

Surveying involves a lot of field work to collect data about all types of features/objects using surveying instruments and techniques. It also includes the establishment of control points on the ground, called Ground Control Points (GCPs), with the help of angular and linear measurements. Conventional surveying instruments take linear, angular or height measurements to derive the 3D coordinates (planimetry and height) of GCPs and various objects/targets. Today, modern instruments (e.g., GPS, LiDAR) are used to determine the 3D coordinates more precisely and faster. It is important to understand the basic features of these modern survey equipment for 3D data collection and creating various thematic maps, before these devices are used.

Field surveying equipment are used to collect the field data. These data/observations are represented graphically on a piece of paper, called 'Map', or digitally to create digital maps which could be used in Geographic Information System (GIS), along with the other data. The features/details may be represented in analogue form as a paper map, or in digital form, such as a Digital Terrain Model (DTM). For land development planning and designing to the final construction of infrastructures, and subsequently their maintenance and/or upgradation, the foremost requirement is to have an accurate map of the land. Therefore, the users must have a thorough understanding of the modern methods and instruments used, including the mapping and analysis of field data.

As the surveying technology advances, improved optics, sensors, communication devices, and software are introduced for field data collection and analysis with greater speed and accuracy (Garg, 2022). Surveying as a professional activity is continuously expanding to include many other technologies and skills, under one roof, known as, 'Geospatial Technology'. Surveying professionals are now using modern tools of data collection and analysis as well as mapping in a digital environment. The effective use of modern surveying tools and approaches would require a good working knowledge of modern field equipment, photogrammetry, remote sensing, laser scanners, Global Positioning Systems (GPS), Unmanned Aerial Vehicles (UAVs), computer cartography, Geographical Information Systems (GIS), and associated software to analyse the data, generate large-scale maps, visualize the terrain in 3D, and integrate multiple geo-referenced data for optimum results (Garg, 2019). Figure 1.1 presents various platforms (ground-based, UAV-based, aerial-based, and satellite-based) to collect Earth surface data at different heights and different resolutions.

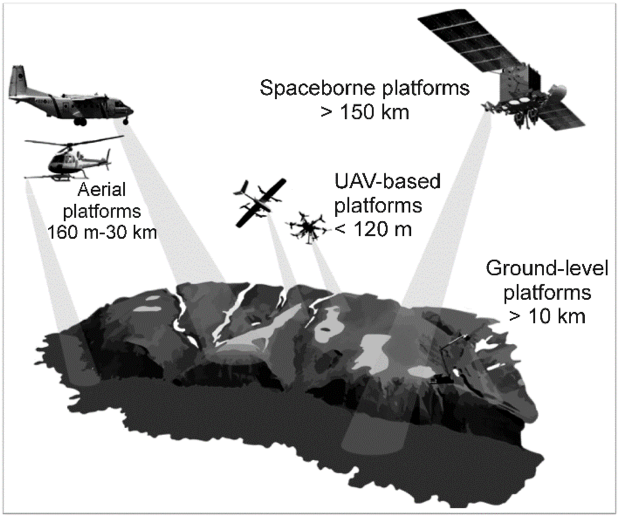

Figure 1.1 Various platforms used for remote sensing data collection.

1.1.1 Selected Technical Terms used in Surveying

It is necessary to understand the technical terms frequently used in surveying; some of them are given below:

(a) **Level surface**: A surface perpendicular to the direction of gravity at all points is called a level surface. The top of a still lake represents the level surface.

(b) **Datum**: A level surface that is used as a reference for computing the elevations of other points.

(c) **Mean Sea Level (MSL) datum**: It defines the average height of the sea tides for all stages. At a particular place, the MSL is established by finding the mean (free of tides) of tide heights over 19 years. In all important survey work, MSL has been used as a datum.

(d) **World Geodetic System 1984 (WGS-84) datum**: It is a 3D coordinate reference frame for establishing the latitude, longitude, and heights for navigation, positioning, and geodetic mapping. Presently, it represents the best global geodetic reference system for Earth that is used for practical applications of mapping, charting, positioning, and navigation.

(e) **Elevation:** It is the vertical distance of a point above the datum.

(f) **Bench Mark (BM)**: It is a point of known elevation above a datum. Generally, the BM is marked on the ground after fixing a small concrete pillar and marking the centre of the top surface on a fixed brass plate. There may be more than one BM established in an area to be surveyed.

(g) **Latitude:** Latitude is a measurement of a location on the Earth (in degrees, minutes, and seconds) north or south of the Equator.

(h) **Longitude:** Longitude is a measurement of a location on the Earth (in degrees, minutes, and seconds) east or west of the prime meridian at Greenwich (an imaginary north-south line that passes through both geographic poles and Greenwich, London, England, U.K.). Latitude and longitude together define the real-world coordinates of a place.

(i) **Ground control points (GCPs):** These are the points whose precise coordinates are known, before the start of any survey work. The number of GCPs required depends on the area to be surveyed as well application.

1.1.2 Types of Survey Based on Instruments

Depending on the instruments, methods, and purpose, survey work can be categorized into various classes (Table 1.1). Most of these instruments, although field-based, provide immense geospatial data for creating 2D or 3D maps and models, and are used along with LiDAR data as input to GIS for spatial analysis (Garg, 2021). The images of some of these instruments is shown in Figure 1.2.

Table 1.1 Classification of surveying.

Based on		
Instruments	**Methods**	**Purpose**
Chain and Tape	Levelling	Topographic mapping
Levels	Trigonometrical levelling	Geodetic mapping
Theodolite and Tachometer	Traversing	Engineering mapping
Magnetic Compass	Tachometry	Route survey
Plane Table	Triangulation	Cadastral survey
EDM	Trilateration	City survey
Total Station		Mine survey
Digital Level		Geological survey
GNSS		Underground utility mapping
Smart Station		Hydrographic survey
GPR		Forestry mapping
Laser Level		
LiDAR		

(a) Chain and Tape

In chain surveying, a metallic chain designated in feet (66 feet or 100 feet) or meter (20 or 30 m) is utilized to measure linear distances. The chain traversing is usually carried out by dividing the entire area to be surveyed into several smaller triangles. By measuring the sides of triangles with the chain, other sides or angles in a triangle are determined using trigonometrical relationships. With the availability of good quality measuring tapes, the chains, due to their inaccuracy, difficult of use, and wear & tear in the field, are discontinued. In addition, many corrections are required to be applied while measuring long distances with the chain. Measuring to distances tapes are available with different materials, and lengths. Most common types are fibre glass reinforced plastic tapes and stainless steel tapes. Steel tapes are very accurate as they don't stretch much, but these are expensive and get kinks easily if not handled properly. These tapes also get rusted quickly. Long-distance measurements over 30 m are generally not recommended with tape due to misalignment along the line and the sag present during measurements.

(b) Levels

Levels are used to determine the difference in elevation between the points. The instrument is used along with a graduated rod, known as the leveling staff/stave. The levelling observations are linked to a ground point of known elevation or Bench Mark, to compute the elevations of other unknown points. From these elevation data, contours can be drawn on a map to determine the slope or profile characteristics of the ground. With the developments of Digital levels, Total Stations, Global Positioning System (GPS), and Laser scanner devices, the use of conventional levels is no more in practice.

(c) Theodolite and Techeometer

A theodolite instrument is used to measure the horizontal and vertical angles of ground points. It is also used to carry out traverse surveying where angles and distances between traverse stations are measured simultaneously. Angles and distances are used to establish horizontal and vertical controls in the area. Theodolites can also be used for prolongation of a line, alignment work, and levelling work. With the availability of Total stations, the conventional theodolite is not used now-a-days.

A tacheometer instrument is similar to a theodolite in construction, but additionally, its telescope consists of an anallactic lens and a stadia diaphragm with three horizontal hairs. The readings taken on a levelling staff against all three cross hairs are used to determine the horizontal distance between the tacheometer and staff. The central wire reading is utilized to compute the elevation difference between the ground points where tacheometer and staff are kept. With the availability of Total stations and GPS, the tacheometer is not used in practice.

(d) Magnetic Compass

Magnetic compass consists of a freely suspended needle that indicates the magnetic north direction (reference direction) in a static position. The compass gives the direction of a line with respect to a reference direction. It is also used in area traversing along with a chain or tape or theodolite. The digital compass is now frequently used in the field. Many mobile apps related to digital compass are also available.

(e) Plane Table

A plane table is similar to a wooden drawing board, used in the field to prepare a map of the area at the chosen scale. In plane table mapping work, field measurements and plotting the objects proceed simultaneously. An alidade is used that provides the direction towards the objects to be plotted, while a tape, a tacheometer, or a total station is used simultaneously to measure the distances and elevations of those objects. The plane table survey is no longer carried out as total stations, GPS, and laser scanners, along with associated software are much faster and accurate for mapping works.

(f) Electronic Distance Measuring (EDM) Instrument

The EDM is used to measure the slope distance between two points on the ground (Garg, 2023). The instrument is kept at one point, and a prism (reflector) mounted on a pole is kept at another point. The EDM is aimed towards the prism pole. It generates either infrared (IR) or microwave wavelength which travels through the atmosphere and strikes the prism, and finally returns back to the EDM. The instrument measures the travel time of return beam, and computes the slope distance using the relationship (distance= velocity x time). Some EDMs measure the phase difference between the outgoing and incoming beam to the instrument, and compute the slope distance (Deloney, 2022). The EDM is inbuilt in a total station, so EDM in isolation is no more used.

(g) Total Station

A total station is an electro-optical instrument that is a combination of an electronic theodolite, an EDM, and a micro-processor (Figure 1.2a). It is a very popular instrument used in data collection for surveying and mapping. The instrument measures the slope distance and horizontal & vertical angles of the point where the reflecting prism is kept. Micro-processor processes the collected data and computes the average of multiple angles measured, average of multiple distances measured, horizontal distances, elevations of ground, and 3D coordinates of the observed points (Chekole, 2014). It computes very accurate 3D coordinates of points, which can be used as ground control points (GCPs) for georeferencing of LiDAR data or as reference points for controlling the accuracy of survey work. Total station is used in survey work where a high level of precision is required. The major advantages of using a total station over conventional surveying instruments are: saving time, ease of working, increased accuracy, and processing the data in digital form.

Total station is kept at one point and the reflecting prism at another point to take the measurements between these two points. The instrument is aimed at the prism. It sends out infrared waves that are reflected back by the prism. By taking the measurements of the prism's location, the instrument computes the coordinates and elevation of the prism point. Total station can be also used in reflectorless mode (without a prism) for measuring the distance and angles. In this approach, the instrument works with a laser (Light Amplification by Stimulated Emission of Radiation) beam to measure the distances (Beshr and Elnaga, 2011). Modern total stations have the ability to measure distances up to 2 km without a reflector with an accuracy of ±3 mm. Reflectorless total stations are used for several applications due to their high accuracy and fast measurements in an automated mode. These are more suitable to survey areas with difficult or impossible terrain, such as disaster-affected areas (e.g., landslides), snow-covered peaks, nuclear waste sites, forest fire regions, etc. The laser beam-based total stations are convenient to use at night or underground or in those locations where the prism cannot be kept, such as bottom of the bridge deck, underground mines, and detailed surveys of busy road intersections. In addition, structural deformation in infrastructure can be precisely measured with reflectroless total station. The key advantage of reflectorless total station is to take measurements of inaccessible points with greater speed and accuracy (Ferreira and Santos, 2020). Additionally, it requires less manpower and time as another person is not required to hold the prism at the target point.

The Robotic Total Station (RTS) is the next advancement in total station that can automatically track a prism in x and y directions using a servomotor in the instrument and a sensor. These equipment provide ease of working, and save manpower at the instrument side, but are expensive due to sensor-based devices and the requirement of a 360^0 reflecting prism. The servomotor automatically tracks the movement of prism as the sensor in the prism and the sensor in the instrument communicate with each other. The instrument from the prism pole side can be operated with a remote controller that is fitted to the prism pole. This equipment requires just one operator to carry out the measurements of entire area, thus saves time and money.

Most of the total stations provide a distance accuracy of 2-3 mm at short distances, which decreases to about 4-5 mm at 1 km distance. They offer high accuracy, even under low-visibility (night/poor) conditions. Although angles and distances are measured frequently with the equipment, the most common application is to derive the position of control points in survey tasks. Total stations are used for enhanced productivity in topographic surveying, as well as set out bridges, dams, stadiums, canals, houses, or boundaries. The robotic total stations are also used by archaeologists, police, crime scene investigators, insurance companies, for automated guidance of dozers, graders, excavators, harvesters, tractors and scrapers, and deformation studies, such as dams, towers and plant chimneys (Ferreira and Santos, 2020). Other applications include, such as stakeout of points, deformation monitoring, cadastral surveys, tunnelling, volume calculation, and construction. Its automatic tracking function is very useful, especially in surveying where the environment is dynamic.

Once the data for total stations are collected, various software can be used to post-process the data. Usually, manufacturers supply their own customised software which allows to export the survey results into other formats, such as CAD software, MX Roads, or GIS software (Garg, 2023). As an example, software, like Auto Civil and Auto Plotter along with AutoCAD can be used for plotting contours and cross-sections. Other survey tasks, such as plotting, traversing, mapping, and area & volume computation, are now available in all software modules.

(h) Digital Level

A digital level is an advanced version of an automatic level (Figure 1.2b). A pendulum compensator fitted in the level is used to automatically level the instrument, once rough levelling with a circular bubble (same as in automatic level) has been achieved. The instrument in auto mode employs digital image processing approach, but it could be used to take the measurements manually, just like an automatic level. It uses a special bar-coded rod in auto mode that is bisected after levelling the instrument. Using a functional button, the image of the bar code is captured in the field of view, and processed by an onboard computer. The captured image is compared with the levelling staff's pattern that is already stored in the memory, and the reading is displayed digitally after a correct match has been established (Mudhavat, 2018).

The bar-coded staff on the reverse side has English or metric graduations that can be used to manually read it, where the instrument fails to read from the bar code, such as heavy bushes or long grasses obstructing the part of the bar code. The readings are recorded automatically and stored in the instrument. Later, these readings are processed in a computer to get the elevations, ground profiles, or DEMs, as well as the distance from staff. Normally, in auto mode, the maximum distance range of the instrument is approximately 100 m, and its accuracy in staff readings is ±0.5 mm. Digital levels provide very accurate elevation of points which can be used with integration of LiDAR data while creating the Digital Surface Model (DSM).

Figure 1.2 Surveying based on equipment and tools.

(i) Global Navigation Satellite System (GNSS)

Ground-based radio-navigation systems were developed in the early 20th century. In 1973, the US Department of Defense launched space-borne GPS satellites, resulting in the NAVSTAR (Navigation Satellite Timing and Ranging) GPS. It was primarily developed for military applications, but over a period of time, it has gained popularity for various civilian applications. Looking at its potential, the US government made the system freely available for civilian use in the 1980s. The GPS is primarily used for real-time positioning, as shown in Figure 1.2c.

The GPS provides exact 3D position of objects, anytime (day and night), anywhere on the globe, and in any weather condition (Garg, 2019). The other benefit includes accuracy and speed of data collection in the field, thus offering improved productivity and speed. The GPS overcomes several limitations of conventional surveying methods, like the requirement of intervisibility of survey stations, dependency on good weather, difficulties in taking night observations, heavy computational work to determine 3 coordinates, etc. With high accuracy of positioning data and the ease of operations, GPS is a preferred surveying technique for many applications. Surveying and mapping work is greatly benefitted from the use of GPS, such as highways, rails, mining/geology, agriculture, power, telecommunication, health, law enforcement, emergency, crustal movement, etc. It brings a revolution in applications where the exact position of any object or activity is to be determined, such as locating a facility, restaurant, institute, etc.

With the development of technology and applications, several countries have designed their own navigation system. For example, the GLONASS (Global Navigation Satellite System), a satellite-based navigation system, is owned and operated by the Russian Federation. The European Union developed a system that is known as GALELIO. Indian system is known as the IRNSS (Indian Regional Navigation Satellite System), which will use its seven satellites to send accurate navigation signals over India and up to 1,500 km from its surroundings. India's own GPS NavIC ('Navigation with Indian Constellation, whose Hindi meaning is 'sailor' or 'navigator') is the operational name of IRNSS. China has developed the BeiDou navigation satellite system. With the availability of signals from various satellites' constellation in recent years, the term GPS has been replaced by the Global Navigation Satellite System (GNSS). The GNSS is a general term for providing the position, navigation, and timing services from any of the satellite constellations. Thus, GPS is a type of GNSS that was developed by the US in the 1970s for military use. It is now frequently used in LiDAR systems. The GNSS is considered as a global leader in navigational systems.

The GNSS measurements are normally taken if four or more satellites are visible at a given time. Each satellite regularly transmits the data about its location and time. These signals travel at the speed of light and are captured by the GNSS receiver to compute the distance of each satellite from the receiver's position (using distance = velocity*time) by measuring the time of arrival of the signal. The GNSS uses the principle of trilateration and computes 3D coordinates of the point where the receiver is kept. These points can be used as ground control points (GCPs) for integration with the LiDAR data. The accuracy of GNSS-based measurements depends on several factors, including the method used. Higher accuracy within a few centimeters can be achieved when GNSS is used in combination with the augmentation systems. These 3D coordinates can be processed to generate a map or a DEM.

There are several approaches used to carry out GNSS surveys, like Static method, Real-time Kinetic (RTK) method, Stop and Go method, and Differential GPS (DGPS) method (Chekole, 2014). Each method provides a different accuracy. Table 1.2 presents a summary of methods as well as their level of application standards which can be useful to readers to make an appropriate selection of GNSS unit for an application.

The DGPS method makes use of two identical receivers, one is static kept at the base station, and the other receiver is in movement, called the rover receiver. The rover is moved to multiple points to get their positions during the survey work. In Continuously Operating Reference Stations or CORS, the base station is installed at a permanent known location. With a CORS-based system, the user can place the receiver anywhere in the local area to collect precise data. After completion of data collection, the users combine the collected data with data from the CORS to correct any anomalies and obtain accurate positions. The CORS are commonly used for major engineering projects that require continuous surveying over a long period.

Table 1.2 Various methods used by GPS survey (GPS Guidebook, 2004).

Method	Requirements	Application	Horizontal Accuracy	Comments	
Static L1 (Post processing)	-L1 GPS receiver -Computer for post processing -Minimum 45 minutes or more	Control surveys (High-accuracy)	1 cm + 2ppm	For giving, tolerates cycle slips, needs single frequency geodetic receiver.	-Relatively long occupations; -Lines limited to approx. 15 km due to ionosphere
Static L1/L2 (Post processing)	-Dual frequency GPS receiver -No P-code required -Need L1/L2 antenna	Control surveys (High-accuracy)	0.5 cm + 1ppm	For giving, tolerates cycle slips, works out effects of ionosphere	-Relatively long occupations
Fast-Static (Post processing)	-Dual frequency GPS receiver with either P2 or P1/P2 configuration -Need L1/L2 antenna -5 to 45 minute observation time, depending on number of SV's	Control surveys (Medium to high accuracy)	2 cm + 2ppm	-Short occupations, very efficient -No requirements for maintaining lock between points -	-Requires high-end receivers -More susceptible to multipath problems -Requires very careful planning or good communicat ion in field

Table 1.2 *Contd…*

Method	Requirements	Application	Horizontal Accuracy	Comments	
Kinematic Including stop & go and continuous (Post processing)	-L1 receiver with Kinematic option -Need kinematic antenna (L1) -Data collector with survey controller software recommended 5-30 seconds average for stop & go kinematic 0.5-5 seconds average for continuous kinematic	Continuous topographic surveys Feature mapping surveys	4 cm + 2ppm for stop & go 5 cm + 2 ppm for continuous	-Very short occupations -Most efficient data collection -One person can be the complete topographic crew	-Requires initialization -Must maintain lock to 4 SV's while moving between points -Most susceptible to multipath effects -Recommended max. distance between base and rover is 10 km
Kinematic Real time Kinematic (RTK) On-the-fly	-L1 receiver with RTK option (includes RTCM in/out) -Need kinematic antenna (L1) -Need data links -Need data collector with survey controller software -5-30 seconds average, depending on user requirements	Hydrographic surveys (real-time, high accuracy) Location surveys	4 cm + 2ppm	-No post-processing of data required -Provides real-time coordinates -Logs vector information for network adjustment, if desired -Very efficient for both location and layout	-Radio links between base and rover must be maintained (up to 5 repeaters okay) -Lines limited to 10 km
DGPS Resource Grade	L1 receiver with differential beacon, WAAS, or other broadcast signal	Mapping & location of resource features	1 m –L1 DGPS 2 m –WAAS 5 m –CA		-Not to be used for any boundary or regulatory line
Autonomous GPS	L1 receiver or CA code single frequency hand held	Orienteering Navigation	5 m-L1 30 m –CA code		

(j) Smart Station

Total station and GPS equipment are complementary to each other, and thus both may be required in the field for efficient survey work of a large area. Horizontal clearance of line of sight is required with the total station, while vertical clearance of satellite signals is needed with the GPS. Field measurements may discontinue if one of the clearances is not available. This problem is overcome by using a combination of both total station and GPS, called *Smart Station*. This combination significantly improves the efficiency and accuracy of survey measurements (Figure 1.2d). In case of obstructions in horizontal visibility, GPS antenna communicates with the total station, and all operations of GPS observations are performed through the keyboard of the total station. In situations, where GPS is not receiving good signals from the satellites due to vertical obstructions, total station is used effectively. The work thus continues in the field.

A smart station can be used as a total station and/or as a GPS on the same system, so the benefit is that instead of carrying the total station and GPS equipment in the field, survey measurements can be made much faster using the smart station alone. The device can also provide data for building information modeling (BIM) and virtual design and construction (Garg, 2023). It also provides very accurate 3D coordinates of ground control points (GCPs) which can be used for LiDAR survey work. Although the use of GPS is fast growing, total station is one of the popular instruments in surveying and will be used more in the future along with other surveying equipment to provide accurate data.

(k) Ground Penetrating Radar (GPR)

The GPR provides information about the types of objects and their depth below the ground. It is a geophysical technology that emits radar beams which penetrate into the ground to a certain depth depending on the wavelength and frequency of antenna of radar beam. These beams use the principle of electromagnetic theory and display the return signals from the objects (Garg, 2021). The GPR consists of two antennas; transmitter and receiver (Figure 1.2e). It generates radio waves by a transmitter antenna that penetrates through the subsurface. The receiver antenna estimates the depth and properties of the subsurface materials by measuring the strength (i.e., amplitude) of the reflections off the subsurface features and time, as depicted in Figure 1.3.

The GPR profiles may be used for the detection and identification of subsurface objects, such as plastic conduits, gas pipes in sandy soil, metallic pipes, lithology, and buried objects (Baker et.al., 2007). It can be used for mapping all the underground utilities, buried structures & objects, groundwater table, etc. Since the GPR does not need any physical digging or drilling, it does not disturb the site conditions. It provides high-resolution data of the subsurface, and the depth of penetration is limited by the ground conditions, material below ground and the frequency of the antenna used. Lower frequency antenna penetrates deeper but with less resolution, whereas the higher frequency antenna provides better resolution data but with shallower depth penetration. In addition, highly conductive materials, such as heavy clay soils and wet areas can absorb radar waves, thus lowering the depth of penetration and the quality of output.

Sometimes, ground surface features/landscape can provide an important clue about the objects below ground. The GPR requires expertise to interpret the data due to the complexity of subsurface conditions. The LiDAR data of the ground surface can be integrated with the subsurface GPR data to optimize the information contents.

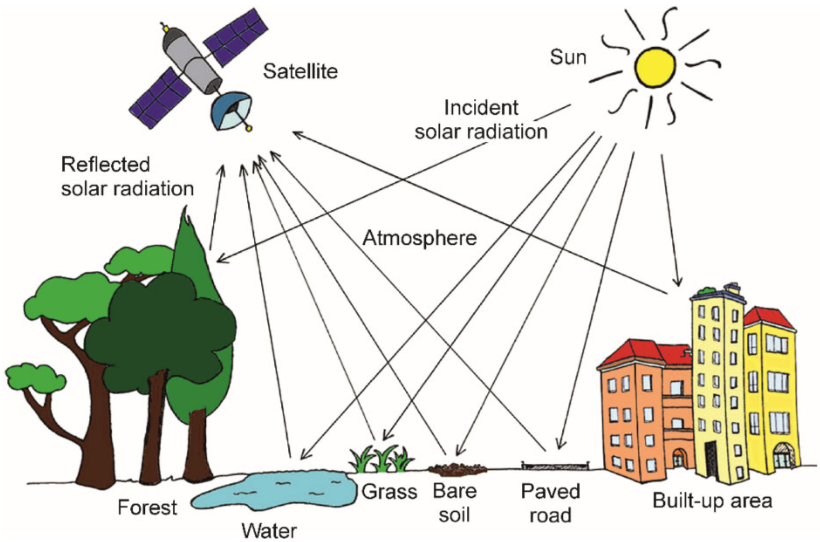

Figure 1.3 Working of a GPR.

(i) Laser level

A laser level is an electronic device that can emit a laser beam toward an object. The laser light is visible as a bright red or green, or completely invisible for working sites with high movement of people and traffic, such as busy roads. A laser beam will strike the sensor of levelling staff, and this sensor displays the measurements. The laser level brings automation to work, and provides precise elevations with faster data collection (One Point Survey, 2019).

The laser levels operate in three modes; manual-levelling, auto-levelling and self-levelling modes. Another advancement in laser level is the Rotary laser level (Figure 1.2f) which, instead of emitting a single unidirectional line, emits laser in 360º direction, scanning both vertical and horizontal planes. In Rotary level, the continuous rotation of the laser beam about its vertical axis determines the projection of the beam, therefore the laser level is kept accurately levelled. They are used along with a laser detector mounted to a graduated rod (Figure

1.1e), which detects the laser beam during outdoor surveys. These levels provide a greater range than the line levels and are preferred for larger and exterior workplaces (Johnson, 2020). The use of laser levels in construction industry has increased as it reduces the time to leveling.

Of late, laser levels have been frequently utilized for levelling, plumbing, machine control, excavation work, landscaping, construction, measuring elevation, alignment, grading of sites, construction stakeout, concrete levelling, drainage design, etc. (Ali and Al-garni, 1996). These are also very useful devices to locate the objects/ground situated at the same elevation; a property of elevation that is used to draw a contour on a map. The architects have benefited extensively from the use of laser-based levels in monitoring the interior height of buildings, and decorations, setting out individual walls and suspended ceilings, and controlling elevator guide rails. It helps engineers and contractors check the perfect angles and levels of a building/structure during construction.

1.2 Photogrammetry

The term photogrammetry is defined as "*the art, science and technology of obtaining reliable information about physical objects on the earth's surface and its environment, through processes of recording, measuring, and interpreting photographic images"*. It extracts information from the photographs and transforms it into useful results and thematic maps. Aerial photographs are considered one of the forms of remote sensing data. Photogrammetry has grown with the developments in digital data products, computer software, and digital photogrammetric methods. Photogrammetric images are captured from a special (metric) camera, or digital sensors, mounted on aerial platforms or drones. The end products from aerial photographic analysis can be the coordinates of individual points, a map of the ground surface (topographic map, thematic map, etc.), or a rectified image with map-like characteristics (ortho-photos), or a DEM or digital data.

The aerial photographs are commonly used for the generation of thematic maps, selection of ground control points (GCPs), and ground truth verification. Large-scale mapping using photogrammetry is cost-effective and faster for applications, like urban planning, forestry, agriculture, natural resources, terrain analysis, road alignment, infrastructural development, and many more. Digital aerial photography is used for commercial, industrial, agricultural, governmental, and private applications. These photographs have also been successfully used to generate 3D models of terrain for various planning purposes, visualization, and land measurement. The 3D mapping requires stereo-images (i.e., viewing the area from two different camera angles) that recreate similar conditions for generating 3D models by software. Photogrammetry saves time and costs to derive useful results, which can be used as input into another analysis system, such as GIS (Hassani and Carswell, 1992). The 3D coordinates/3D model can also be used to complement LiDAR point cloud data.

Broadly, the aerial photographs are of two types; vertical photographs and oblique photographs (Figure 1.4). Vertical photographs with at least 60% forward overlap between two successive photographs are mostly used for 2D or 3D creation, while oblique photographs are mainly useful to army/defence. When the photographs are recorded from a camera mounted on a tripod on the ground, these are called *terrestrial photographs* or *close-range photographs* (Garg, 2019). Terrestrial photographs are needed for a detailed mapping of the feature/object, as the camera is set very close to the object. Close-range photographs have been used for a large number of industrial and engineering applications, such as monitoring deformations dams, buildings, structures, towers, architectural restoration, preserving cultural heritage, medical imaging for forensic sciences and reconstructive surgery, facial reconstruction studies, structural stability studies of bridges and hydro-electric dams, earth-works, stock-piles, automobile industry, shipping industry, antenna calibration, study of traffic accidents and crime scenes by police departments, etc.

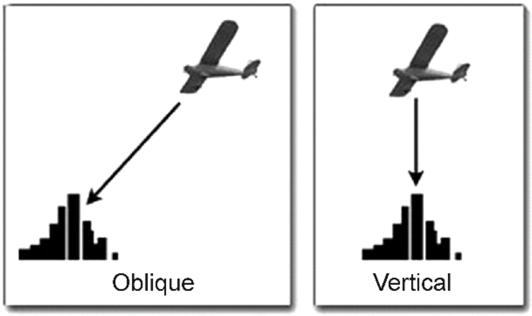

Figure 1.4 Taking vertical and oblique aerial photographs.

Two successive photographs taken from two different camera exposure stations with more than 60% forward overlap, are called a *stereo-pair*. The 3D model created for the common overlap area in a stereo-pair is called a *stereoscopic model* or *stereo-model*. The 3D view can be created from a stereo-pair using stereoscopic principle, using simple equipment, like stereoscopes, or costly equipment, like stereo-comparator, or digital photogrammetric workstations. The 3D model may be useful for identifying many features, such as slopes, low ridge and valley, topography, small depressions, and elevations. One of the important applications of stereo-photographs is the determination of elevations of various points in the overlap region. A parallax bar, also known as a *stereo-meter*, is used for this purpose to take the parallax measurements. If the elevation of at least one control point is known in the common area, the elevations of unknown points in the overlap region may be computed.

In reality, an aerial photograph has a non-uniform scale throughout the entire image due to undulation present on the ground. Therefore, its measurements can't be used directly like a topographic map. In a photograph, except at the principal point (centre), all other points may have variation in scale due to undulations present in the terrain. For example, a feature, such as a tall building, will also have shape distortion because the top of the feature will have a larger scale than its bottom. To overcome this problem, an orthophoto is created from an aerial photograph, which is a rectified photograph having characteristics similar to a map. An orthophoto is also known as the *map substitute*, as it can be used directly to create a map of the area. For analyzing a large area, a mosaic, which is an assembly of overlapping aerial photographs, is created. The overlap between photographs allows them to be merged to form a seamless mosaic that can be used for interpretation work or map creation.

There are a large number of open-source software available in photogrammetry that can be used to analyse digital aerial photographs. Some of them are given below:

(i) **MicMac:** MicMac can use close-range and aerial photos for works involving environmental protection, cultural heritage imaging, and preservation or forestry.

(ii) **Meshroom:** It is a photogrammetric computer vision framework that is easy to use for 3D reconstruction of images. It can be used to create textured mesh automatically using a node-based workflow.

(iii) **3DF Zephyr Free:** It is a free version of the software *3DF Zephyr*; a complete and efficient software for photogrammetric work. It is a good software for beginners to carry out 3D processing, 3D reconstruction, and basic editing.

(iv) **Visual SFM:** Visual SFM is a 3D reconstruction tool using Structure from Motion (SfM). It is a graphical user interface (GUI) application-based photogrammetry software for matching and making the automatic reconstruction.

(v) **Colmap:** Colmap is a general-purpose SfM software. It has a GUI, which has all the basic tools required to create a 3D model using several aerial photographs.

(vi) **Regard3D:** Regard3D is a SfM software used to generate 3D models from a series of aerial photographs. This program provides powerful tools with tutorials available on the website to understand its various functions.

1.3 Satellite Remote Sensing

The word "remote" means "from a distance", and "sensing" in this case means "to record." So remote sensing can be defined as the "*art of science & technology of obtaining reliable information about the physical objects and* *environment through the process of recording, measuring & interpreting images/data obtained from remotely distant sensor systems*". Sensors are required to gather the information as the human eye is sensitive to a very small part of the total electromagnetic spectrum (EMS), i.e., visible light (Garg, 2022). In remote sensing, Sun energy falling on the Earth interacts with the targets/objects and records the reflected /emitted energy from the objects with the help of sensors/cameras. The process is shown in Figure 1.5. Various devices and sensors on-board satellites may be used to record the electromagnetic radiation (EMR) reflected/emitted from the objects/targets in the visible, near-infrared, middle infrared, thermal infrared, and microwave range. The amount of radiation, emitted and reflected from the features/objects, depends on the physical and chemical properties of objects or material, surface roughness, angle of incidence, intensity, and wavelength of striking energy. Various objects/features are detected on images captured by these sensors, and variations in recorded energy that have been reflected or emitted by objects/features in several wavelength regions help identify the features (Gibson, 2000). Sensors therefore, are very important in data capture and discrimination of various objects/targets. These images provide a broader view of the area to make quicker decisions as well as help a deeper understanding of Earth.

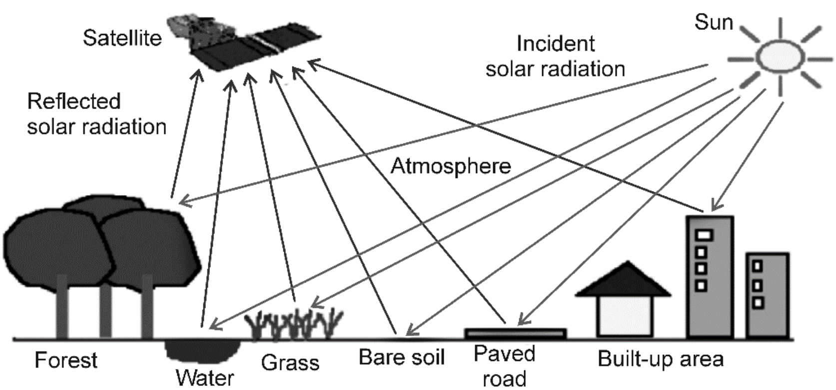

Figure 1.5 Remote sensing image acquisition.

Remote sensing offers spatio-temporal images of the Earth surface ranging from local to global scales. These images can be applied in a range of disciplines, like surveying and mapping, geography, geology, computer science, agriculture, forestry, meteorology, soil science, urban planning, military, oceanography, and civil engineering. Information, like land use, vegetation types, urbanization, soils, water, geology, forest, surface elevation, and snow, can be derived accurately from these images. Temporal images are utilized in monitoring land use change, flood monitoring, water pollution study, deforestation, forest fire, snow cover, urban sprawl, crop damage, disaster monitoring, etc. Applications of remote sensing well also depend on spatial, spectral, and temporal resolution of the images. For example, high spatial resolution images are required for large-scale topographic mapping, infrastructure mapping, and local urban mapping for smaller areas. High spectral resolution images may be crucial for precisely differentiating the conditions of objects (e.g., diseased crops from healthy crops). High temporal resolution images are important for taking repetitive observations, like flood monitoring, and urbanization monitoring.

Optical and radar/microwave images are the two most common types of satellite data used in mapping. The optical sensors or passive sensors work only during daylight since they measure reflected Sun energy coming from the objects. Whereas, radar/microwave sensors or active sensors can take images of the area day and night, in nearly all kinds of weather. Radar/microwave images can penetrate through clouds, and thus are useful to map soil moisture, stressed vegetation, submerged vegetation, water contamination, biomass, etc. As an example, passive sensors include a photographic camera, electro-optical sensor, and passive microwave sensor, while active sensors include laser, radar, active microwave, etc. Various parts of EMR that are used in remote sensing data acquisition, ranging from visual part to microwave part, are shown in Figure 1.6.

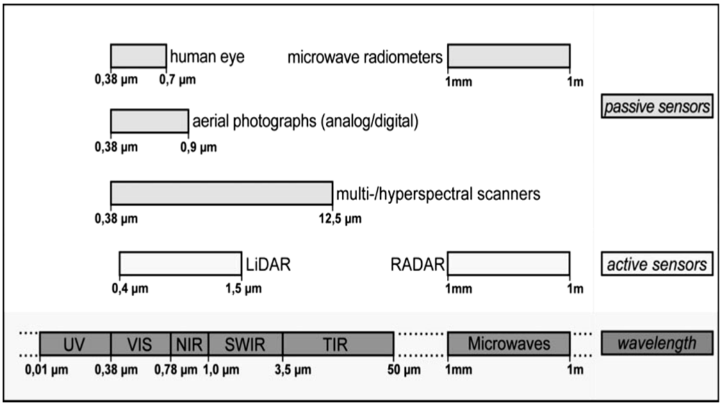

Figure 1.6 Various parts of EMR used by various sensors in remote sensing.

First remote sensing satellite was launched on July 23, 1972, called Earth Resource Technology Satellites (ERTS). Later it was renamed as Landsat-1 (Land satellite). It has been widely used for land use and land cover mapping and monitoring. With the passage of time, nine satellites in Landsat series were successfully launched, which have/are provided/providing an important source of remote sensing data for land use and land cover analysis (Gibson, 2000). The Landsat-9 was launched in September 2021. The Landsat-5 was the longest-operating satellite that continually collected data for nearly 28 years till January 2013 from its launch in March 1984. The summary of Landsats is presented in Table 1.3.

Table 1.3 A summary of Landsat satellites.

Mission	Landsat-1		Landsat-2		Landsat-3		Landsat-4		Landsat-5		Landsat-6	Landsat-7	Landsat-8		Landsat-9	
Period	1972-1978		1975-1982		1978-1983		1982-2001		1984-2012		1993, failed	April 1999 -	Feb 2013 -		Sept 2021-	
Altitude (km)	917		917		917		705		706			705	705		705	
Repeat cycle	18		18		18		16		16			16	16		16	
Swath width	185		185		185		185		185			185	185		185	
Sensors	RBV	MSS	RBV	MSS	RBV	MSS	MSS	TM	MSS	TM	ETM	ETM+	OLI	TIRS	OLI	TIRS
Bands	1-3	4-7	1-3	4-7	1-4	4-8	1-4	1-7	1-4	1-7	1-8	1-8	1-9	1-2	1-9	1-2
Spatial resolution (m)	80	82	80	82	80	82 B8:240	79	30 B6:120	79	30 B6:120	B1-B5, B7: 30 B6: 120 B8: 15	B1-B5, B7: 30 B6: 60 B8: 15	30 B8:15	100	30 B8:15	100
Radiometric resolution (Bits)	6	B1-B3:7 B4: 6	6	B1-B3:7 B4: 6	6	B1- B3:7 B4: 6	B1-B3:7 B4: 6	8	B1-B3:7 B4: 6	8	8	8	12	12	12	12

Landsat has been a successful mission that provided the largest depository of Earth's images to users for carrying out mapping work at local, regional, and global scales. Data of the entire globe from Landsat satellites is archived in the US and at various Landsat receiving stations, which provide free images to users for global research and applications, such as agriculture, cartography, geology, forestry, regional planning, surveillance, and education. The data can be downloaded free of cost through the United States Geological Survey (USGS) EarthExplorer website.

The SPOT (Satellite Pour l'Observation de la Terre), a series of satellites, the first one was launched in 1978 by France in collaboration with Belgium and Sweden. SPOT-1, 2 and 3 carried two identical High Resolution Visible (HRV) imaging systems (Garg, 2022). Each HRV was capable of operating either in the panchromatic mode or in the multispectral mode. HRVs used along-track, push-broom scanning methods. Due to the off-nadir viewing capability, HRV was also used for stereoscopic imaging with which the stereo models can be created. The SPOT-4 carried the High-Resolution Visible and Infrared (HRVIR) sensor and the Vegetation Instrument (VI). HRVIR also includes two identical sensors, both capable of giving 120 km swath width at the nadir. SPOT-5 carried two High-Resolution Geometric (HRG) instruments, a single High-Resolution Stereoscopic (HRS) instrument, and a VI. SPOT-6 mission employed two New AstroSat Optical Modular Instruments (NAOMI). The instrument operates in 5 spectral bands, including one panchromatic band. Pointable optics enable off-nadir viewing of area which increases the frequency of viewing. Due to the off-nadir viewing capabilities, stereo images were acquired, and used for relief and elevation determination as well as creating DEMs. SPOT-7 provided 2 m panchromatic and 8 m multispectral data on a daily revisit. The SPOT images are used to map and monitor the Earth's resources, infrastructure mapping, urban monitoring and oceanography. The summary of SPOT satellites is given in Table 1.4.

India launched its first remote sensing satellite as Indian Remote Sensing Satellite (IRS)-1A in March, 1988, and continued as IRS series, including CARTOSAT and RESOURCESAT series for varied land applications. India has launched state-of-art multispectral high resolution remote sensing satellite, RESOURCESAT-2A in 2016 and CARTOSAT-2E in 2019 with very high resolution panchromatic sensor. The multispectral sensor offers spatial resolution of around 5 m, whereas panchromatic sensor provides data at <1m resolution. CARTOSAT-3 was launched in 2019 with high spatial and temporal resolution for wider land applications. It has a panchromatic resolution of 0.28 m and multispectral of 1.12 m. India launched a Hyperspectral Imaging Satellite (HySIS) in Nov 2018 for land surface mapping, vegetation cover, land cover, land surface topography, using SWIR, VNIR Hyperspectral Solar Disk Imager (ESP-MACCS). RESOURCESAT-3 and 3A are planned for 2025 with 10 m resolution data. A summary of IRS satellites is presented in Table 1.5.

Table 1.4 A summary of SPOT satellites.

Mission	SPOT-1	SPOT-2	SPOT-3	SPOT-4		SPOT-5			SPOT-6	SPOT-7
Period	1986-2003	1990-2009	1993-1997	1998-2013		2002-			2012-	2014-
Altitude (km)	822	822	822	822		822			694	694
Sensors	HRV			HR VIR	VI	HRG	HRS	VI	NAOMI (2)	NAOMI (2
Bands	PAN and B1-B3			B1-B4	B0 B2-B4	PAN B1-B4	PAN	B0 B2-B4	PAN B1-B4	PAN B1-B4
Spatial resolution	PAN:10 m , MSS: 20 m			B1- PAN: 10m B1-B4 MSS: 20 m	1000	PAN: 2.5- 5m MSS: 10m B4: 20m	10m	1000	PAN: 2 m MSS: 8 m	PAN: 2 m MSS: 8 m
Radiometric resolution	8 bit			8 bit	10 bit	8 bit	8 bit	10 bit	12 bit	12 bit

Table 1.5 A summary of IRS satellites.

Satellite	IRS-1A	IRS-1B	IRS-1C	IRS-1D	IRS-P2	Cartosat-2	Resourcesat-2
Period	1988-1996	1991-2003	1995-2007	1997-2010	2003-	2007-	2011-
Altitude (km)	904		817		817	630	822
Repeat cycle (days)	22		24		24 LISS-4 and AWiFS : 5	310 Revisit: 4	24
Sensors	LISS-1, LISS-2A and 2B		PAN, LISS-3, WiFS		LISS-3 and LISS-4, AWiFS	PAN camera	LISS-3 and LISS-4, AWiFS
Bands	B1-B4		PAN, LISS-3 B1-B4 WiFS B1-B2		LISS-3 B1-B4 LISS-4 B1-B3 AwiFS B1-B4	PAN (0.5-0.85μm)	LISS-3 B1-B4 LISS-4 B1-B3 AwiFS B1-B4
Spatial resolution	72.5 m	36.25 m	PAN:5.8 m LISS-3: 23 m (B4:70 m)		LISS-3: 23.5 m LISS-4: 5.8 m AWiFS: 56 m	0.81 m	LISS-3:23.5 m LISS-4: 5.8 m AWiFS: 56 m
Radiometric resolution (Bits)	7	7	7	7	LISS-3 and 4: 7 AwiFS: 10	10	LISS-3 and 4: 10 AwiFS: 12

The ASTER (Advanced Spaceborne Thermal Emission and Reflectance Radiometer), launched in December 1999, provides data in three systems: Visible and Near-Infrared (VNIR), Shortwave Infrared (SWIR), and Thermal Infrared (TIR), to derive maps of land surface temperature, reflectance, and elevation. Its images are used for many applications, such as monitoring vegetation, hazards, geology, land surface, hydrology, and land-cover change.

The IKONOS is the first civilian fine-resolution sensor, launched in September 1999. It employs linear array technology and collects data in four multispectral bands at 4 m resolution and one panchromatic band at <1 m spatial resolution. IKONOS was the first successful commercial satellite to collect sub-meter resolution images. It provides high-resolution images useful for applications, such as urban planning, land use, agriculture, and natural disaster management (Garg, 2022).

GeoEye-1, launched in September 2008, is a high-resolution commercial remote sensing satellite for ground observation. It is equipped with a panchromatic resolution of 0.50 m and multispectral data at 1.65 m. It can collect images off-nadir up to 60^{o}.

QuickBird was launched in 2001 and acquired images in panchromatic and multispectral modes with very fine resolution. QuickBird sensors consist of linear array detectors to offer a spatial resolution as 0.61 m in the panchromatic mode and 2.4 m in the multispectral mode. It supports applications, like large-scale map making, land and asset management, and risk assessment.

WorldView-1, launched in 2007, provides very fine-resolution images with a short average revisit time. It provides panchromatic images with the finest resolution of 0.50 m. WorldView-2, launched in 2009, is capable to capture data in 8 spectral bands. WorldView-3, launched in 2014, offers fine-resolution imagery in 16 multispectral bands. It gives 31cm panchromatic, 1.24 m multispectral, and 3.7 m SWIR spatial resolution data every day. WorldView-4, launched in 2016, offers fine-resolution panchromatic band data and 4 multispectral band data.

Pleiades are the first French dual observation satellites designed for both military and commercial users with applications in disaster mapping, urban development, hydrology, geophysics, volcanic activity, etc. The Pleiades 1A was launched in December 2011; and Pleiades 1B in December 2012. This constellation is able to provide ortho-rectified color images up to 50 cm resolution with a daily revisit of any point on Earth. These satellites can capture high-resolution stereo-images in one step. Since these were designed primarily for emergency management, the images on request can be supplied within six hours of the event.

The salient features of some very high-resolution remote sensing satellites are presented in Table 1.6.

Table 1.6 Salient features of very high resolution remote sensing satellites.

	QuickBird	IKONOS	GeoEye-1	WorldView-1	WorldView-2	Pleiades-1 and 2
Swath width (km)	16.5	11	15	15	16.4	20
Pan data spatial resolution (m)	0.6	0.8	0.5	0.5	0.5	0.5
Multispectral						
Temporal resolution (days)	3-4	2-3	2-3	3-4	3-4	1-3

Thermal remote sensing measures the thermal radiations emitted from objects to detect temperature differences. It uses specialized thermal sensors on satellites to detect ground objects. All materials having a temperature above absolute zero (-273°C or 0°K), both day and night, emit infrared energy. Thermal IR imagery is usually obtained in the wavelength regions 3 to 5.5 µm and from 8 to 14 µm because of atmospheric absorption at other wavelengths. IR radiation at wavelengths 3 to 14 µm is called the *thermal IR region* (Garg, 2022). IR radiation at wavelengths larger than 14 µm is not utilized in remote sensing as the radiation is absorbed by the Earth's atmosphere. Applications of thermal infrared images can be broadly classified into two categories; one in which surface temperature is governed by man-made sources of heat, and the other in which it is governed by solar radiation. In the former case, the technique has been used from airborne platforms for determining heat losses from buildings and other engineering structures. In the latter case, thermal IR images have been used for identifying the crop types, soil moisture, measuring water stress, etc. A summary of satellites offering thermal IR images is given in Table 1.7.

Table 1.7 A summary of satellites offering thermal IR images.

Platform	Band	Wavelength (µm)	Spatial resolution (m)	Return time	Coverage
AVHRR	Bands 4 and 5	10.3–11.3 11.5–12.5	1100	4 times/day	Global
TM 5	Band 6	10.4–12.5	120	16 days	Global
ETM+	Band 6	10.4–12.5	60	16 days	Global
MODIS	Bands 31 and 32	10.78–11.28 11.77–12.27	1000	1 day	Global
ASTER	Bands 10–14	8.125–11.65	90	16 days	Selected areas
CBERS02	Band 9	10.4–12.5	156	3 days	Global
HJ-1B	Band 8	10.5–12.5	300	4 days	Mainly China

Microwave remote sensing offers better observation capabilities as the microwave images are unaffected by the weather conditions (rain or fog). Passive microwave sensors can operate day-night in all-weather conditions, and penetrate through the clouds to provide valuable information. The SMMR on Nimbus-7, ASCAT, SMAP, SSM/I on DMSP, TRMM TMI, AMSR-E on Aqua, ESA-CCI, SMOS mission by ESA, NASA-HYDROS mission and SMAP mission are major passive microwave radiometers (Wang and Qu, 2009). These sensors, such as radiometers, measure emitted microwave energy from 19 to 200 GHz, and are useful for soil moisture, vegetation cover, crop inventory, crop yield, biomass, flood inundation, water-logged surface geomorphology, topography, and geology (Varotsos and Krapivin, 2020). Emissivity is directly related to brightness temperatures and is used to estimate soil moisture, but at coarse spatial resolution. Global Precipitation Measurement Mission (GPM), launched in 2014, is follow-on of TRMM satellite in another satellite with a passive radiometer sensor. European SM and Ocean Salinity (SMOS) mission is the first satellite (launched in 2009) with L-band (1.4 GHz) dual-polarized multi-angular observations that give data every 3 days at a global scale with 50 m resolution (Zhao et al., 2014). The low-frequency microwaves penetrate more into the canopy, therefore low-frequency data are more valuable for soil moisture retrievals (Zhao et al., 2014), and high-frequency data (37 GHz) for vegetation studies.

Active microwave sensors, such as synthetic aperture radar (SAR), transmit microwave between 1-10 GHz to illuminate the land surface, and measure the backscattered radiations from the land surface to generate high spatial resolution (10-100 m) images. These data are available in wavelength regions; X-band (2.4-3.75 cm), C-band (3.75-7.5 cm), S-band (7.5-15 cm), L-band (15-30 cm), and P-band (30-100 cm) (Solberg, 2012). The X-band data is useful for military purposes, terrain mapping, and surveillance. The penetration capability of C-band is limited and restricted to the top layer of the atmosphere, whereas L-band penetrates into soils and vegetation (Woodhouse, 2017), and the P-band (30-100 cm) is used for research and experimental applications. SAR images can penetrate into the crop and vegetation canopies and soil surface and are used to generate sub-surface information. Today, several microwave remote sensing satellites, such as IRS-RISAT, ENVISAT, Sentinel-1A and 1B, ALOS, ALOS-2, RADARSAT-2, TERRASAR-X, etc., are providing valuable information for applications, such as soil moisture estimation, kharif crop inventory and monitoring, multi-crop discrimination and mapping, crop bio-physical characterization, forest vegetation biomass estimation, snow cover area and glacial characterization, sea and coastal land characterization and monitoring (Singh et al., 2011; Srivastava et al., 2008). A summary of microwave missions is given in Table 1.8.

Table 1.8 A summary of microwave missions.

Year	Mission	Sensor	Wavelength/FREQ.	Purpose
1978	Seasat	SAR Scatterometer Altimeter SMMR	23 cm 2.15 cm 2.22 cm 4.54, 2.8, 1.66, 1.42, 0.81 cm	Sea, land surface imaging, sea surface, wind speed and direction, Sea surface topography, sea surface temperature, wind speed water vapour/liquid water.
1979	Bhaskara -1	SAMIR	1.55, 1.35 cm	Sea surface wind speed atmospheric water vapour
1990	JERS	SAR	L-band	Ocean
1990	Radarsat	SAR	C-band	Sea ice/ocean
1991	ERS-1	ESCAT	5.3GHz	Ocean wind surface speed and direction, ocean wavelength and direction, and high-resolution radar-mapping of land, ocean, ice, and coastal zones
1992	JERS-1	SAR	L- 0.275GHz	Ocean
1992	OceanSat-1	MSMR	6.6, 10.65, 18 and 21GHZ	Atmospheric Prediction, Sea State Monitoring, Monitoring of Antarctic Sea
1997	TRMM	TRMM-PR	13.796 GHz, 13.802 GHz	Determining rainfall in the tropics and subtropics of the Earth through the use of a precipitation radar and radiometer
1999	QuickSCAT	SeaWinds Scatterometer	13.4 GHz	Acquire accurate, high-resolution, global measurements of sea-surface wind vectors in 1 to 2 day repeat cycles and fast delivery of its data
1999	SSM/I	DMSP Block 5D-3 Satellite Series	19.35 GHz (2), 22.24 GHz, 37 GHz (2), 85 GHz (2)	Provides low-resolution-temporal/high-resolution-spatial sounding of the atmosphere and surface. Measures sea surface winds, rain rates, cloud water, precipitation, soil moisture, ice edge, and ice chronological age.

Table 1.8 *Contd…*

Year	Mission	Sensor	Wavelength/FREQ.	Purpose
2002	AMSR-E	Microwave Radiometer	6.925,10.65,18.7, 23.836.5, 89 Ghz 36.5Ghz	Sea surface temperature (SST), wind speed, atmospheric water vapor, cloud water, and rain rate.
2005	EnviSat	ASAR	5.331 GHz	Ocean waves, sea ice extent and motion, snow and ice extent, surface topography, land surface properties, Earth's biomass (especially deforestation in equatorial zones), surface soil moisture and wetland extent.
2006	ALOS-1	ALOS-1 PALSAR	1270 MHz	Day-and-night and all-weather land observation
2006	MetOp	ASCAT	5.225 GHz	Wind velocity over the world's oceans using radar
2007	TerraSAR-X	TerraSAR-X	9.65 GHz	Hydrology, geology, climatology, oceanography, environmental and disaster monitoring, and cartography (DEM generation)
2009	Oceansat-2	OSCAT	13.5156 GHz	Oceanographic measurements
2010	TanDEM-X	TerraSAR-X	9.65 GHz	This mission flies near TerraSAR-X to perform interferometric SAR (InSAR) observations
2011	HY2A	Altimeter and Scatterometer	5.25 GHz, 13.58 GHz [altimeter]; 13.2555 GHz [scatterometer]	All weather observations, marine wind setup (wind vector), marine surface height, and SST (Sea Surface Temperature), along with aeromarine forecasts
2011	Megha Tropiques	Radiometer	18.7GHz, 23.8GHz36.5GHz, 89GHz and 157GHz	Atmospheric water cycle, All-weather capability
2012	RISAT-1	SAR	5.35GHz	Imaging of the surface features

Table 1.8 *Contd…*

Year	Mission	Sensor	Wavelength/FREQ.	Purpose
2013	SARAL	Altimeter, Radiometer	35.75 GHz , 23.8 GHz and 37 GHz	Operational oceanography, Coastal altimetry, Continental waters, Inland ice sheet monitoring, Light rainfall and clouds climatology, Mean sea level, Sea state observation and forecasting Geodesic reference system determination
2014	ALOS-2 PALSAR-2	SAR	1236.5/1257.5/ 1278.5 MHz (selectable)	Day-and-night and all-weather land observation.
2014	Sentinel-1A	SAR	5.405 GHz	Monitoring of Forest, Agriculture, Sea-ice, Oil spill, Sea vessel and Climate monitoring
2014	Sentinel-1B	SAR	5.405 GHz	Monitoring of Forest, Agriculture, Sea-ice, Oil spill, Sea vessel and Climate monitoring
2015	SMAP	Microwave Radar and Radiometer	1.4 (Radiometer) and 1.22-1.30 (Radar)	Hydrological Hazards Applications: Drought and Flood, Ecosystem Services Applications, Agricultural Productivity
2016	SCATSAT-1	Scatterometer	13.515 GHz (Ku band)	Day and night weather forecasting
2018	Sentinel-3	SRAL MWR Ku/C Band	23.8/36.5GHz	Mapping of Sea surface topography, Sea surface Temperature
2019	RISAT-2B	Radar	X-Band	Agriculture, Forestry, Disaster management

Hyperspectral imaging uses a much broader EMS to obtain both imaging and spectroscopic data simultaneously. Generally, hyperspectral imaging is a combination of modern imaging system and traditional spectroscopy technology (Garg, 2022). It collects detailed spectral information for every single pixel. Hyperspectral imaging produces multi-spectral color images with high resolution by taking contiguous wavelengths in the visible, near-infrared (NIR), short-wave infrared (SWIR), and mid-wave infrared (MIR) spectra with each representing a narrow spectral band (nm). The hyperspectral sensor collects about 200 or more spectral bands, with each about 10 nm wide, which collects continuous spectral reflectance signatures, while the very narrow bandwidth of hyperspectral data enables in-depth examination of Earth surface characteristics that would be missed from multispectral data due to their relatively coarse bandwidths.

When the reflected light strikes the hyperspectral imaging system, it is broken down into a large number of spectral bands. The wavelength ranges however depend on the type of hyperspectral camera used. Image resolution depends on the number of spectral channels and their interval. The full spectrum of interest of a scene thus creates a hypercube; a three-dimensional image set with two spatial dimensions and a third spectral dimension. Spatial scanners read the spectral data over time, which is slow but very detailed, while imagers take the images, thus providing the unique spectral signature of imaged objects within the EMS.

Compared to multispectral imaging, hyperspectral imaging provides more information, allowing for more accurate analysis, identification, and separation of materials and substances. Hyperspectral imaging can differentiate between materials with similar physical or visual characteristics that the human eye cannot see, such as different minerals. The common applications of hyperspectral imaging include:

Agriculture, where spectral images with infrared data can be used to assess the health and yield of crops, monitoring the soil moisture and nutrient content to optimize crop management practices and improve crop yields.

Environmental monitoring to assess changes in land use, vegetation health, and water quality over time. This allows for detecting early signs of ecological degradation and tracking the effectiveness of conservation efforts.

Mineral exploration and mapping mineral deposits, detecting the mineral composition and grade.

Non-destructive inspecting and grading of food products, detecting contaminants and defects in industrial products for quality control.

Military surveillance for detecting and identifying hazardous materials.

Details of some satellite mounted and aircraft mounted hyperspectral imaging systems along with their wavelength regions and number of bands are provided in Table 1.9.

There are a large number of satellites that provide thermal infrared images, microwave images, and hyperspectral images at 0.25 cm to more than 1000 m spatial resolution. In general, as the resolution becomes better, the frequency of temporal data becomes larger. With the availability of very high resolution images from CARTOSAT-3, SPOT-7, Sentinel, IKONOS, WorldView, QuickBird, GeoEye, AMSR, TRMM, SSM/I, RADAR, SAR, etc., remote sensing applications are growing rapidly. Today, remote sensing images have become an integral part of many national level government schemes or projects.

Integration of remote sensing data with other thematic layers in a Geographic Information System (GIS) provides additional benefits and flexibility to be used in a variety of applications requiring spatial modeling.

Table 1.9 Some hyperspectral imaging systems along with their wavelength regions and number of bands.

Sensors	Number of bands	Spectral region (μm)
Satellite mounted hyperspectral sensors		
FTHSI on MightySat II	256	0.35–1.05
Hyperion on EO	242	0.40–250
Aircraft-mounted hyperspectral sensors		
AVIRIS (Airborne Visible Infrared Imaging Spectrometer)	224	0.40–2.50
HYDICE (Hyperspectral Digital Imagery Collection Experiment)	210	0.40–2.50
PROBE-1	128	0.40–2.50
CASI (Compact Airborne Spectrographic Imager)	Over 22	0.40–1.00
HyMap	100 to 200	Visible to Thermal Infrared
EPS-H (Environmental Protection System)	VIS/NIR (76), SWIR1 (32), SWIR2 (32), TIR (12)	VIS/NIR (0.43–1.05), SWIR1 (1.50–1.80), SWIR2 (2.00–2.50), TIR (8–12.50)
DAIS 7915 (Digital Airborne Imaging Spectrometer)	VIS/NIR (32), SWIR1 (8), SWIR2 (32), MIR (1), TIR (12)	VIS/NIR (0.43–1.05), SWIR1 (1.50–1.80), SWIR2 (2.00–2.50), MIR (3.00–5.00), TIR (8.70–12.30)
DAIS 21115 (Digital Airborne Imaging Spectrometer)	VIS/NIR (76), SWIR1 (64), SWIR2 (64), MIR (1), TIR (6)	VIS/NIR (0.40–1.00), SWIR1 (1.00–1.80), SWIR2 (2.00–2.50), MIR (3.00–5.00), TIR (8.00–12.00)

In addition, the remotely sensed data and software available on open-source platforms have popularized it to be used in various disciplines. Table 1.10 shows some open-source software used in remote sensing. Landsat series, ASTER, Sentinel-2 and 2A, MODIS and AVHRR satellites provide 10 to 1000 m spatial resolution data in multispectral bands as "open source" which is freely available for wide land applications to various users. Using the USGS browser, users can find the last 40 years of free satellite images as well as data from other NASA remote sensing sensors (e.g., Terra and Aqua MODIS, ASTER, VIIRS, etc.). It also provides free satellite datasets in collaboration with ISRO, India (e.g., Resourcesat-1 and 2), ESA (Sentinel-2), and some commercial high-resolution space-based images (IKONOS-2, OrbView-3, historical SPOT data). The ESA offers open access to multispectral data from Sentinel-1 and 2 (Drusch et al., 2012). It launched multispectral remote sensing satellite Sentinel-2C in Sept 2024 to provide continuity of Sentinel data to its users. Remote sensing is recognized as an interdisciplinary tool that is being applied in various disciplines. Figure 1.7 shows images taken from various passive sensors. These images provide a wealth of information for various applications. For, example, a high-resolution IKONOS image in Figure 1.7a can be used for regional planning.

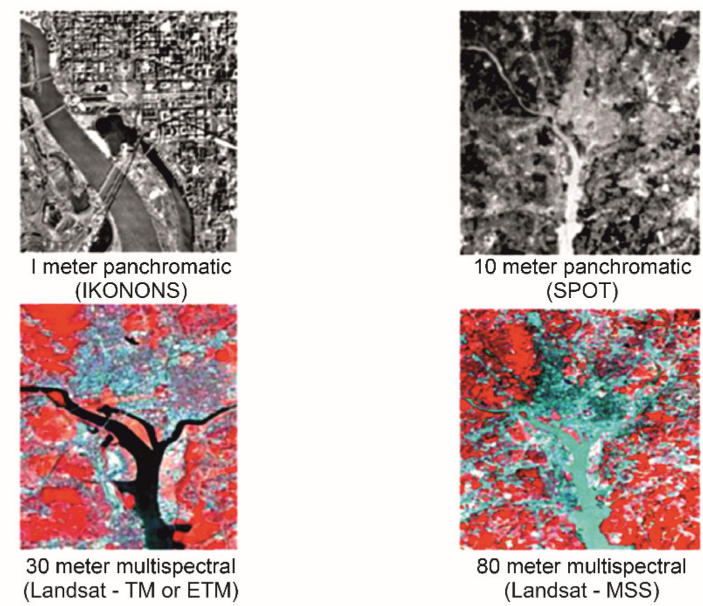

Figure 1.7 Satellite images taken from different sensors.

Satellite images are now available from various satellites, which can be analyzed using the capabilities of image processing software or GIS to create maps in 2D and 3D, at different scales (Garg, 2021). A change scenario can be generated using temporal satellite images, and this information can be used in GIS for planning, designing, and monitoring various civil engineering projects and natural resources. In addition, output from remote sensing data analysis (e.g., thematic maps) can be integrated with the LiDAR point cloud data to either develop accurate contours or precise 3D models. Several operational satellites are immensely contributing to generating reliable land information, such as crop inventory and crop yield estimation, forest types and cover mapping, mapping and monitoring of water resources, soil resource mapping, wasteland mapping, land degradation mapping, coastal mapping, geological and geomorphological mapping, monitoring watershed development planning, urban planning, disaster management support, environmental applications, etc. Some open-source software used in remote sensing are given in Table 1.10 (Pope et.al., 2014)

Table 1.10 Some open-source software used in remote sensing (Pope et.al., 2014).

Name	Description	Source
ESA Toolboxes	A set of software packages developed by the European Space Agency specifically to handle data from ESA instruments, as well as a wide range of other remote sensing data.	https://earth.esa.int/web/guest/pi-community/toolboxes
CIAS	An image cross-correlation tool built on top of the free IDL virtual machine. It can be used for feature tracking of surface displacement, e.g., to study sea ice movement, permafrost slump, or glacier flow.	http://www.mn.uio.no/geo/english/research/projects/icemass/cias/
GDAL Libraries	A powerful translator library for raster and vector geospatial data format.	http://www.gdal.org/
Generic Mapping Tools (GMT)	An open source collection of about 80 command-line tools for manipulating geographic and Cartesian data sets.	http://gmt.soest.hawaii.edu/
GRASS GIS	Used for geospatial data management and analysis, image processing, graphics and maps production, spatial modeling and visualization.	http://grass.osgeo.org/
ImageJ	Java-based generic raster editor with extensive plugin capabilities.	http://rsb.info.nih.gov/ij/
Multispec	Simple, lightweight geographical/multispectral raster viewer and editor.	https://engineering.purdue.edu/~biehl/MultiSpec/
PROJ.4	A library (often implemented in other programs, such as MATLAB, R, QGIS, etc.) used for a wide variety of cartographic reprojection.	http://trac.osgeo.org/proj/
Quantum GIS (QGIS)	A GIS software to view and edit a range of raster and vector data; programmable with python; integrates with GRASS, GDAL and R.	http://www.qgis.org/
R project	A software environment for statistical computing, data analysis and graphics.	http://www.r-project.org/

With the development in technology, high spatial, spectral, and temporal resolutions satellite images are available frequently. India in collaboration with NASA-JPL (USA) is developing microwave remote sensing satellite, namely NISAR, that is scheduled to be launched by June 2025. It is expected to provide L- and S-bands data with high spatial resolution that will measure the Earth's changing ecosystems, dynamic surfaces, and ice masses. It will provide information about biomass, natural hazards, sea level rise, groundwater, hydrological applications, kharif crop inventory and crop yield modeling, multi-crop inventory, and monitoring soil moisture. Landsat-10 with improved spectral bands is planned to be launched in 2030-31. The ESA is planning to launch its Sentinel-2D in 2028. With the availability of data from these future satellites, it is expected that remote sensing-based applications will further grow, and these data can be fused with LiDAR data for improved accuracy.

1.4 Unmanned Aerial Vehicle (UAV)/Drones

A drone is an unmanned aircraft that is guided remotely or autonomously. The UAV stands for Unmanned Aerial Vehicle; which means something that can fly without a pilot onboard. The terms drone and UAV mean the same thing and can be used interchangeably. Drones were initially used in the military. Later, the technology has been used for civilian applications. The UAVs/drones are low-flying aircrafts that are used for collecting very high-resolution images or laser point cloud data (Garg, 2020). These data are excellent sources of information for large-scale mapping and generating detailed DEMs of the terrain.

In land surveying, the measurement of 3D coordinates of points on the land surface is an essential step. Civil engineers, real estate, construction companies, oil and gas, renewable energy, mining, and government agencies, are using the latest tools of land surveying in order to understand the characteristics of land surface for planning and development. Land survey by a UAV/drone offers several advantages over the traditional land survey approaches. For example, the use of UAV/drone is flexible and can operate even in cloudy conditions. The UVAs/drones employ various sensors, cameras, and laser scanners, offering an economical approach to collect lots of data for smaller areas that can be used for 3D mapping/modeling. In addition, the transportation cost of a drone system and its mobilization time are lower. The UAVs are being used in a large number of applications, such as mapping, monitoring, and management of civil engineering and other projects.

There are two main types of UAVs/drones; multirotor and fixed-wing. Multirotors drones are very common, but mapping a large area may be done faster with a fixed-wing drone. Multirotor drones are easier to fly vertically up, but fixed-wing drones glide through the air and move in the air longer than multirotor drones. The multirotors commonly have rotors, propellers, or wings and a light-weight frame. These drones with propellers typically have four double-bladed propellers, but one, three, and four-bladed are also available. The blades with the help of motors generate lift to spin the propellers at high speed. Fixed-wing drones move the aircraft to forward direction and push the wings through the air to generate lift.

Figure 1.8 Multirotor and fixed-wing UAV/Drone.

The UAV/drone has a controller, which the operator uses on the ground station to control the launch, navigate, and land the drone. The controller all the time communicates with the drone using radio waves. Some drones can fly in automatic mode but they use a combination of obstacle avoidance sensors and GPS. The UAV/drones commonly have a camera onboard, which sends the view of drone to the operator. The UAV/drone also requires a power source, such as a LiPo (lithium polymer) battery. Figure 1.9 shows various components of a UAV, such as a camera, battery, flight controller, motor, propeller, GPS, propeller, and radio system.

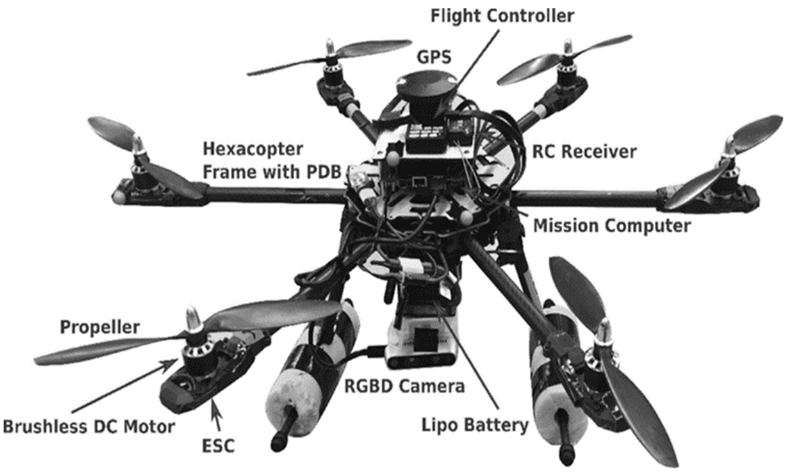

Figure 1.9 Components of a UAV system.

The GPS plays an important role in UAVs, and works through a network of satellites orbiting the Earth, which transmit signals to the UAV's GPS module. Several GPS satellites are moving around the Earth that continuously send out signals. These signals contain information about the satellite's location and the exact time the signal was transmitted. The GPS module inside the UAV acts as a receiver for these signals, which picks up signals from multiple satellites simultaneously. The more signals it gets from multiple GPS satellites, the more accurate the positioning is. The GPS module calculates the time it takes for each signal to travel from the satellite to the UAV. By measuring this time, the module can determine the distance to each satellite. Using the distances from at least four satellites, the GPS module computes the UAV's exact location in 3D space (latitude, longitude, and altitude) using trilateration.

The GPS technology has enhanced the capabilities of UAVs, making them more reliable and efficient in various tasks. The GPS provides UAVs with greater accuracy in navigation, ensuring precise movement, which is very important, particularly where high-quality aerial photos and videos are required for precise mapping. Another outstanding features of GPS in UAVs is to execute autonomous flights along pre-programmed routes. This functionality is of paramount importance in tasks, such as inspection, crop monitoring, and search or rescue operations, enhancing the effectiveness and efficiency of UAVs in completing the tasks successfully. In situations where UAVs lose connection with the remote controller or have low battery levels, GPS technology enables UAVs to automatically navigate back to their take-off point (Return to Home), and thus not only ensures a safe return in challenging situations but also protects costly equipment from being damaged. The GPS helps creation of virtual boundaries, known as *geofencing*, which restrict a UAV's flight to enter in the area, being a restricted zone or sensitive area, as per the flying regulations.

Despite of many advantages, there are several limitations of using GPS on UAVs. The UAVs typically use consumer-grade GPS modules, which are generally less accurate than the high-precision systems used in surveying equipment. The accuracy of location data is affected by the number of satellites a UAV can track at a given time, as signals from fewer satellites can lead to low precision. Dense and taller objects, like buildings, trees, indoor objects or even strong winds can interfere with the GPS signal, and thus affect the accuracy. While GPS is a common navigation tool for UAVs, but it is clear from above that it is not always reliable. Some onboard optical sensors gather information on altitude, attitude, and location, allowing the UAV to hover and maneuver as if it were receiving GPS signals. Additionally, LiDAR (Light Detection and Ranging) sensors enhance the UAV's navigation capabilities through SLAM (simultaneous localization and mapping) technology.

The UAVs/Drones equipped with sensors and cameras can quickly capture images and data on the terrain below it. UAVs/drones may have RGB and multispectral cameras or Light Detection and Ranging (LIDAR) sensors to collect high-resolution images of the area (Corrigan, 2016). With an RGB camera, the ground is imaged from different locations of UAV/drone, and each image is tagged with its real coordinates. Photogrammetric techniques are then used to create detailed 2D and 3D maps. The LiDAR technology uses lasers to measure distances, day and night. The resulting high-density 3D point cloud gives an accurate representation of the site. The point cloud data can be used to create digital elevation models (DEMs), digital terrain models (DTMs), and digital surface models (DSMs) (Nixon, 2019). Very accurate maps/models can be created by using photogrammetric data and LiDAR point cloud data.

The UAVs/Drones fly much lower altitude than aircrafts or satellites, and the data collected is of very high quality giving centimeter-level accuracy. To ensure absolute accuracy, ground control points (GCPs) with known coordinates are used. These GCPs are used along with the drone and GPS data in post-processing. The data collected can be georeferenced with geographical coordinates collected by in-house GPS. Since UAVs/drones complete data collection works faster with less manpower, these are cost-effective for land surveys. UAVs/Drones can be operated remotely from the ground to collect data of dangerous terrain or in adverse weather conditions without any risk of completing the job. UAVs/drones can be launched from almost anywhere to reach inaccessible areas.

Several key features can significantly enhance the capabilities of the UAV, and these are to be considered when procuring a UVA. A built-in GPS integrates seamlessly with the UAV's flight controller, offering features, such as return to home, geofencing, and stable flight. The GPS tracking can monitor the UAVs location in real-time, and helps locating the UAV in case of signal loss. The Return to Home (RTH) feature is an essential safety feature which automatically instructs the UAV to return to its take-off position in case of signal loss, or low battery, with the help of GPS. The UAV should have geofencing capability so as to prevent it entering a restricted zone by defining the coordinates of the boundary with the help of GPS. The Follow Me feature in UAV allows it to autonomously follow you, capturing aerial images as you move to different locations. The desired resolution and features, like live streaming or gimbal stabilization for smooth footage are to be considered. Higher resolutions provide sharper details, while live streaming allows for real-time viewing of flight path. A gimbal counteracts shake and vibrations, ensuring smooth video capture. The brushless motors in UAVs deliver superior efficiency, quieter operation, and longer lifespans as compared to brushed motors, so for longer flight times and maneuvers, brushless motors are preferred. A compact and folding designs makes them ideal for travel, and storage, as these UAVs can easily be put into backpacks. Advanced UAVs incorporate sensors and software that help detect and avoid obstacles during the flight, reducing the risk of collisions with other flying objects, such as big birds.

Table 1.11 presents various commercial drones and their salient features. This Table might help in selecting a particular UAV for some defined application.

Table 1.11 Various commercial UAVs/Drones and their salient features (Chen et.al., 2016).

UAV/Drone	Company	Country	Flight Time/ Payload	Camera/ Operation Range/Features
AR Drone 2.0	Parrot	France	12 min/100g.	Built-in 720p Cameras/200m/ Supports multiple controlling devices
Bebop 2	Parrot	France	22 min/20g.	Stabilised 1080p Cameras/180° vision HD 2000m/ Supports multiple controlling devices
Iris+	3D Robotics	US	22 min/400g.	GoPro Camera/1000m/ Supports multiple controlling devices
Solo	3D Robotics	US	25 min/420g.	GoPro Camera/805m/Powered by twin computers Ballistic parachute system
HEXO+	Squadrone System	US	15 min/200g.	GoPro Camera/100m/2-second battery swap
Phantom 4	DJI	China	28 min/300g.	Built-in1080p Camera, 4K resolution video/5000m/ Automatically avoid obstacles.
Inspire 1 Pro	DJI	China	18 min/1700g.	Built-in1080p Camera, 4K resolution video/ 2000m/ Independent camera controller
MATRICE 100	DJI	China	40 min/1000g.	External camera stabilization gimbal/ 5000m/ Independent camera controller
QR X900	Walkera	China	25 min/3000g.	External camera stabilization gimbal/1000m/ Parachute protection device

Table 1.11 *Contd…*

UAV/Drone	Company	Country	Flight Time/ Payload	Camera/ Operation Range/Features
Typhoon H	Yuneec	China	25 min/600g.	Built-in1080p Camera/ 800m/ Integrated autonomous flight models
Tornado H920	Yuneec	China	25 min/5000g.	Gimbal for PanasonicLumix GH4/ 2000m/ Integrated autonomous flight models
MD4-1000	Microdrones	Germany	45 min/1200g.	External camera stabilization gimbal/500m
eXom	SenseFly	Switzerland	22 min/1200g	Built-in HD camera and thermal camera/2000m
eBee	SenseFly	Switzerland	50 min/150g	Sony WX or thermoMAP/3000m

The mapping software processes the data and produces it into high-resolution 3D maps and models that accurately represent the land surface. The software uses photogrammetry techniques to create orthomosaics and 3D models from georeferenced UAV/drone images which can be uses to measure distances and compute volumes. The mapping software can automate the data collection and processing which makes drone surveys much faster and economical.

When free and open source software are used, we save some money, as the commercial mapping software can be very expensive. Applications that are free may not be as capable, updated, or user-friendly as the paid software. The paid ones are very sophisticated and serve the needs of larger industries ranging from engineering to construction and real estate. Free drone mapping software may not have all the features needed but these are good for initial learning. Alternatively, we can also try the trial versions of some of the more sophisticated drone mapping software. However, free software may not be a long-term solution if we want to establish a career as a professional in the drone technology. Some free and open source software to collect and process the UAV/Drone data are given in Table 1.12, along with their operating system and source.

Table 1.12 Some free and open source software to process UAV/Drone data (Olson et.al., 2022).

Software	Operating system	Source	Open source
AirMap	Android & iOS	https://www.airmap.com	Free
DroneDeploy	Android & iOS	https://www.dronedeploy.com	Application and basic processing free; advanced processing and support for cost
DroneMapper	Window	http://www.dronemapper.com	Free
GeoNadir			Free
Meshlab	Window,Apple, and Linux	http://www.meshlab.net	Free
Open Drone Map	Window,Apple, and Linux	https://opendronemap.github.io/odm/pages/about.html	Free
Open Aerial Map	Window	http://openaerialmap.org	Free
PHOTOMODUS	Window	http://www.racurs.ru/	Free
Pix4D	Android & iOS	https://pix4d.com/product/pix4dcapture	Cloud and desktop processing available for cost
Precision Mapper	Window	http://www.precisionmapper.com	Free
Precision Flight	Android & iOS	http://www.precisionhawk.com	Application free; cloud processing for cost
WebODM	Window and Linux	http://www.webodm.org	Free
3DF Zephyr	Window	https://www.3dflow.net	Free

UAVs/Drones equipped with AI and machine learning have achieved greater autonomy and the ability to complete more difficult tasks. Drone and IoT technology combined together can be used to share data in real-time with other drones and ground station. The drone movement can be coordinated with increased intelligence and connectivity for many applications, such as topographic mapping, healthcare, energy, construction, disasters, search & rescue, weather forecasting, aerospace, entertainment, etc.

According to Grandview Research (2024), the revenue from the commercial drone market is expected to reach $57.16 billion in 2030, up from US $22.98 billion in 2023. While, MarketsAndMarkets predicts that the drone services market will increase from US $17 billion in 2023 to US $57.8 billion by 2028. The emergence of complementary technologies, like 5G, AR (augmented reality) and computer vision, is expected to drive drone market growth and improve drone communication and intelligence. Some companies have already started services, like delivering food, mail and medicine. The future innovations in the drone technology include increased flight times and battery power, better AI-based and IoT network integration, and design of smaller drones (Gillis, 2024).

1.5 Laser Remote Sensing

Laser-based remote sensing, of-late, has created a revolution not only in geospatial data collection but also in 2D and 3D mapping of earth surface features. The word 'Laser' is an acronym for Light Amplification by Stimulated Emission of Radiation. The primary wavelengths used for lasers include the ultraviolet between 180 and 400 nm, visible between 400 and 700 nm and infrared regions between 700 nm and 1 mm. In this book, the word laser will be limited to mainly electromagnetic radiation-emitting devices at wavelengths from 180 nm to 1 mm.

The terms laser scanning and LiDAR (Light Detection And Ranging) scanning are often used interchangeably, but there is a significant difference between the two. The term 'laser scanning' refers specifically to the process of capturing detailed 3D shapes and geometry of objects or environments, usually with terrestrial equipment. While, 'LiDAR scanning' is a broader term that refers to the use of laser technology to measure the distances, and is used in terrestrial and airborne applications both. So, LiDAR scanning is a much broader term than the laser scanning.

In the 1960s, first 3D scanning technology was developed. LiDAR was first used in year 1961 to track the satellites by measuring the time a laser signal takes to return back from the object. In 1971, a LiDAR altimeter was used to map the Moon's surface, but the device was large, heavy and expensive, and not so accurate in present day context. The 3D laser scanning technology has been evolving since then, and now more accurate and photo-realistic scans can be obtained. Recent developments have emerged LiDAR as a key photonic technology using UV, Visible, or NIR lasers, depending on the objects and environment being surveyed (Weschler, 2020). A modern laser scanner can gather detailed point clouds, which may be used to construct digital 3D representations of the scanned area using point cloud processing software. It is used in numerous applications, such as creating maps and identifying archaeological sites, guiding driverless vehicles. crop monitoring, forest management, etc. The LiDAR technology is used for geospatial data acquisition which has made significant progress over the last three decades.

Lasers operating between 600-1000 nm are used for non-scientific applications; as these wavelengths can damage the human eyes, so these need to be used very carefully. The LiDARs mainly use laser emitters with wavelengths of 905 nm and 1550 nm, as laser light with a wavelength of 1550 nm does not affect the human eye. Such LiDARs with 1550 nm laser can produce high power without causing retinal damage. Higher the power, longer is the detection distance, and longer the wavelength, easier is the penetration to dust and haze. The fiber lasers working at 1550 nm are popularly used in topography mapping, measuring distance, and obstacle avoidance. These are also used in many military applications, as they are relatively safe to the human eye and not visible in night vision goggles. However, these lasers use InGaAs sensors, and therefore are costly than the lower-wavelength lasers. Manufacturers prefer to use silicon materials to manufacture LiDARs close to the visible wavelength of 905 nm and strictly limit the power of the emitter to avoid permanent damage to the eyes.

Diode-pumped YAG lasers at 1064 nm are deployed for airborne topographic mapping. Lasers with good transmission in pure water and limited backscattering from seawater particles are required for underwater and bathymetry applications. For such applications, 534 nm frequency-doubled diode-pumped YA lasers are preferred, as they can penetrate water with minimal attenuation. Apart from wavelength, other important parameters to a LiDAR setup include pulse repetition rate, laser power consumption, and beam divergence. Users can select between a flash LiDAR, in which the entire field of view is illuminated at once, or more conventional scanning LiDAR, which passes over the field of view, point by point.

1.5.1 Laser Theory and Operation

A laser is a device that causes atoms or molecules to emit light at specific wavelengths, and then amplifies that light to produce an extremely narrow beam of radiation. When electrons in the atoms and nuclei of photonic materials, such as glass, crystal, or gas absorb energy from an electrical current or light, a laser is produced. The extra energy excites the electrons enough to move them from a lower-energy orbit around the nucleus to a higher-energy orbit.

A laser generates a beam of very intense light that is monochromatic, directional, coherent and intense or bright. Monochromatic means that all the light produced by the laser is of a single wavelength. Directional means that the light beam has a very low divergence. Coherent means that the light waves are in phase with each other (Weschler, 2020). Laser light is much brighter than the regular light. For example, a 1mW He-Ne laser is more powerful than the Sun, which is due to the laser's coherence and directionality. Conventional light source (such as a light bulb) is a combination of all visible wavelengths (400-700 nm) that diverges and spreads light in all directions, as illustrated in Figure 1.10. A light bulb produces many wavelengths, making it incoherent. In this case, the intensity may be large at the source, but it decreases rapidly as an observer moves away from the source.

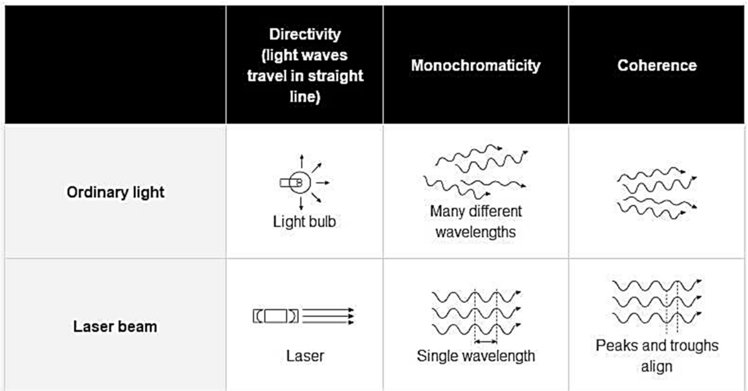

Figure 1.10 Comparison of conventional light source and laser beam.

The output from a laser has a very small divergence, as shown in Figure 1.10. It can maintain high beam intensities over long distances. Thus, relatively low power lasers are able to project more energy at a single wavelength within a narrow beam, as compared to more powerful conventional light sources.

1.5.2 Laser- the Key to LiDAR Technology

LiDAR uses the laser technology to emit light (photons) with greater consistency, in terms of its wavelength, polarisation and direction. As already mentioned, the laser beam operates in a very narrow wavelength range, with a distinct, singular (monochromatic) color (if visible light) having a long and narrow beam. The short wavelength of a typical LiDAR will produce laser beam of a very small diameter, which produces very high-resolution and dense data. The power of the laser is very important in LiDAR surveying work, which can be correlated to the maximum distance so that distant objects can easily be detected from LiDAR data (Figure 1.11). The higher the output power of laser, the greater is the distance measurement capability of LiDAR from objects. Thus, in UAV surveying, a higher-powered LiDAR system can be used at a reasonable height to collect dense data.

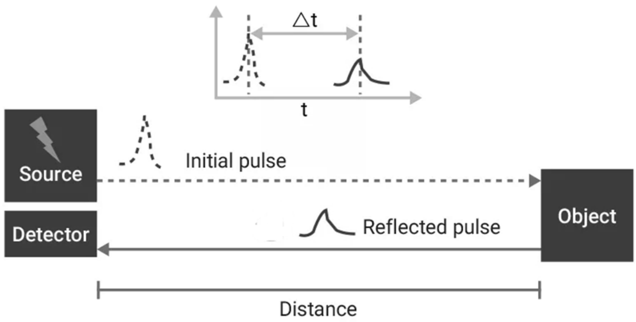

Figure 1.11 Laser pulse to get the distance between source and object.

This data, which is essentially the range information for each emission/reflection, is known as point cloud data. It presents precise 2-3D structural information of the target/object by determining the propagation distance between the LiDAR transmitter and the target/object, and analyzing the reflected energy magnitude, amplitude, frequency and phase of the reflected wave from the surface of the target/object.

It is important to choose a laser source that is safe to the human eye, and the laser intensity and power must remain within the safe limits. The laser must emit short pulses (a few nanoseconds) that have a high peak power. A narrow bandwidth is always preferred, as it allows the beam to act in a uniform manner, which produces a higher peak power and intensity. In addition, a narrow bandwidth filter will filter out the background illumination light during the LiDAR measurement. These together with beam motion, its diameter and divergence, allow maximum permissible exposure of the laser. Considering the above, the most popular wavelengths used for LiDAR lie in the infrared light range, e/g., 1550 nm, 850 nm, 1300 nm, and 905 nm.

In a LiDAR system, laser plays an important role in the overall system performance. Hence, when determining data acquisition requirements for a LiDAR system, the laser specifications usually control the system cost, performance, and the feasibility of an application. As LiDAR systems are also mounted on UAV and aircraft, therefore, it is crucial to keep the laser unit compact, and lightweight. It also needs to be robust enough to perform efficiently under constantly changing environmental conditions, e.g., temperature, humidity, vibrations, shocks, repeated take-off and landings. This makes the fiber lasers a better choice. The modularity, scalability, high efficiency, and inherent robustness of fiber lasers make them the preferred choice for LiDAR applications over bulk solid-state laser systems. The critical laser parameters that contribute to the performance of a LiDAR system are discussed below (MKS Instruments Handbook, 2024).

1. Laser wavelength

Three different wavelength regions are used in LiDAR systems: NIR excitation at 1064 nm using either DPSS or Yb-doped fiber lasers, VIS excitation at 532 nm produced by frequency-doubling a 1064 nm laser, and SWIR excitation at 1550 nm using Er-doped fiber lasers. Each wavelength has some merits and demerits, depending on the target reflectance and absorbance, background radiation, atmospheric transmission, and eye safety issues.

For airborne topographic mapping, 1064 nm is the most commonly used wave length. A major advantage of this wavelength is the abundance of commercially available laser sources and light detectors. Another advantage is that the detectors can be Si-based, and therefore offer higher gain and lower cost than alternative GaAs-based photodetectors. Furthermore, this wavelength generates high reflectance from the most commonly mapped targets, e.g., vegetation and snow. A major disadvantage is that wavelength is hazardous to the eyes. This limits the radiance that can be used for the laser beam requiring either laser power reduction or beam expansion to reduce the hazard. Another disadvantage is the large background noise experienced in this part of the spectrum, particularly from the spectral irradiance of the sun. For bathymetry applications, i.e., high-resolution mapping of the sea bottom and coastal areas, a 532 nm laser source is often used because it represents the best compromise between high transmission in pure water and limited backscattering from submarine particulates. Eye-safe lasers are becoming increasingly popular in high-performance compact LiDAR systems for civil and commercial applications. SWIR lasers operating at 1550 nm are generally more eye-safe at higher power levels and are typically used when solid bodies need to be detected, e.g., in topography mapping and obstacle avoidance. Furthermore, atmospheric transmission is quite good at this wavelength. Military applications also utilize these sources, as night vision devices are relatively insensitive to this wavelength. However, detection at 1550 nm requires the use of InGaAs or Ge photodetectors, which are more expensive and have lower detectivity than Si detectors. Another disadvantage of this wavelength is that it experiences strong water absorption. This significantly reduces the reflectance from certain objects, such as snow and vegetation, and limits LiDAR usage.

2. Pulse repetition rate

The pulse repetition rate and pulse energy determine the sampling rate of a LiDAR system, and in turn will determine the spacing of a dense network of geo-referenced elevation points produced by the system. A high pulse repetition rate means faster acquisition of data with higher point cloud density, and ultimately better resolution of a LiDAR system. Faster scanning can allow an aircraft/UAV to fly at higher altitudes, and thus yielding higher swath widths, and reducing time and flight costs. Early LiDARs were capable of operation at 10 kHz (10,000 points per second), but modern systems can process multiple laser returns, allowing for pulse rates to exceed 1 MHz. Multiple return LiDARs significantly increase the amount of collected data and enhance 3D structures, such as forest canopy, tree crowns, and other vegetation features.

3. Laser pulse width

Laser pulse width determines the range or vertical target resolution (dR) which can be determined as dR = $c\tau/2$, where c is the speed of light in vacuum and τ is the pulse width (duration). For instance, if we take τ = 2 ns, then dR = 30 cm, which means that the distance between two objects/targets must exceed 30 cm so that they are accurately identified as separate objects/targets. The vertical target resolution can be significantly improved by using full-waveform (FW) LiDAR systems, which emit laser pulses in a particular direction and capture the entire temporal envelope of each echo. However, the collected datasets are very large as they record the entire digitized backscattered laser pulses with a very high sampling rate (1-2 GHz).

4. Laser power and beam divergence

Factors affecting the maximum range from which data can be measured are laser peak power, target surface diffuse reflectance, and the amount of ambient light coming from the target surface. The reflected laser power must be sufficient to overcome the detector's SNR and trigger the pulse detector. Detectors typically have some limiting threshold that is set to mask out noise from ambient light. Therefore, there is a need for lasers that can generate high peak power pulses (in the tens of kW range) over a wide range of repetition rates (hundreds of kHz range) for high altitude mapping applications. The LiDAR footprint size at the target is directly related to the flying height above the ground and the laser beam divergence. The higher elevation requires larger pulse repetition rates (to maintain spatial resolution), but this may result in low pulse energy which reduces system SNR. Moreover, lower divergence values require larger beam expansion optics due to the laser brightness limitation. Modifying the LiDAR transmission optics provides control over the target spot size and the laser radiance on the target surface. The latter affects the SNR because of the amount of reflected signal compared to the ambient sunlight illumination.

5. Laser spectral width

The 1064 nm is the most common wavelength for airborne LiDAR systems due to the laser/detector availability and high reflectance from common targets. One major limitation of this wavelength is the background noise created by the spectral irradiance of the sun. To improve the SNR in this wavelength regime, LiDAR receivers employ a narrow (e.g., < 0.1 nm) bandpass filter.

1.5.3 Why LiDAR Surveying?

The advancements in sensors and other technologies for data acquisition have increased the need for huge, accurate and real-time data collection for better understanding and analysis in real-world applications (Chekole, 2014). The LiDAR surveying is used to remotely collect, detect, and measure objects/targets, automatically. LiDAR technology captures information about objects or areas in the form of point cloud data with 3D coordinates. LiDAR scanner is an 'active sensor' that acquires point clouds of millions of reflected laser points during a single survey. In point cloud data, each point is accurately referenced to its absolute position (i.e., longitude and latitude) on the ground. Thus, these millions of points can produce a very detailed and accurate 3D model of the site. This information can be very useful to analyze and determine various characteristics of the surveyed area. The point cloud maps and 3D models produced by LiDAR survey will represent variations in reflected light typically as color gradients, which makes human interpretation very easy (Weschler, 2020). The LiDAR data for some of the countries are available for free download, as given in Table 1.13.

Table 1.13 Open source LiDAR data.

Name	Source	Locations
University of Queensland	http://tern-auscover.science.ug.edu.au	Australia
Open Canada	https://open.canada.ca/data/en/dataset/957782bf-847c-4644-a757-e383c0057995	Canada
Virtual Terrain Project	http://terrain.org/locations/eu/	Europe
European Data	https://data.europa.eu/data/datasets?query=lidar	Europe
GEOSUD (French)	http://www.eguipex-geosud.fr/web/guest/	Europe, Asia, Africa and South America
LiDAR Data Online	http://www.lidar-online.com/tools/maps/	Europe, North and South America and Africa
National Land Survey of Finland	https://asiointi.maanmittauslaitos.fi/karttapaikka/tiedostopalvelu?lang=en	Finland
Jacobs University (Institute of Computer Science)	http://kos.informatik.uni-osnabrueck. de/	Germany

Table 1.13 *Contd…*

Name	Source	Locations
Open Topography Data Viewer	https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=b7c4b0e763964070ad69bf8c1572c9f5	Ireland
Land Information	https://data.linz.govt.nz/layer/104252-nz-elevation-survey-index/data/	New Zealand
Slovenia Geoportal	http://gis.arso.gov.si/evode/profiIe.aspx?	Slovenia
North of Spain	ftp://ftp.geo.euskadi.net/lidar	Spain
SwissSURFACE3D	https://www.swisstopo.admin.ch/de/hoehenmodell-swisssurface3d	Switzerland
Centre for the Environmental Data Archival	http://catalogue.ceda.ac.uk/list/?return_c	UK
Open Topography	http://www.opentopography.org/	USA
USGS Earth Explorer	http://earthexplorer.usgs.gov/	USA
NOAA Digital Coast	http://www.coast.noaa.gov/dataviewer/#	USA
lnteragency Elevation Inventory	http://coast.noaa.gov/inventory/	USA
National Lidar Dataset	http://en.wikipedia.org/wiki/National Lidar_Dataset	USA
National Ecological Observatory Network (NEON)	http://www.neonscience.org/data-resources	USA
State of Zurich	http://maps. zh.ch/	Zurich

1.5.4 Difference between LiDAR, SONAR and RADAR

The term LiDAR actually originates from Sonar (Sonic Navigation And Ranging) and Radar (Radio Detection And Ranging) technologies. The primary purpose of all these technologies is to detect and measure the distance of objects or surfaces through wave reflection. Each technology measures the time of travel of reflected energy to and from the object or surface, be it sound or electromagnetic radiation, and using half the time duration and the speed of light, the range can be derived. However, it is essential to understand the basic difference between these technologies.

LiDAR technology uses electromagnetic radiations in the visible part and infrared of spectrum, which have much higher frequencies than that of radio waves or microwaves to locate objects and measure distances. Sonar and Radar use acoustic (sound) and electromagnetic waves in the radio or microwave frequency spectrum. The wavelength of Radar is between 30 cm and 3 mm, while LiDAR has a smaller wavelength range (e.g., 903 and 905 nm). Radar uses the same principle for distance measurement, and emits a radio wave with a much higher frequency than the frequency used in Sonar. Both systems, however, give poor image resolution.

The Radar transmits radio waves from a rotating or fixed antenna and measure the time of flight of the reflected signal. The Radar can detect long distance objects, through fog or clouds, but its lateral resolution is limited by the size of the antenna. The resolution of standard Radar is several meters at a distance of 100 m. While, at a distance of 100 m, the LiDAR systems have a resolution of a few centimeters. That is the reason, LiDAR is used for laser altimetry, contour mapping, topographical and vegetation mapping. contributing to the creation of precise digital elevation models.

Figure 1.12 shows the difference between transmission and reflection of Lasers and Radar waves on various trees. Synthetic Aperture Radar (SAR) which is also popular in remote sensing, emits pulses at an angle, and as SAR moves along its flight path, its side-looking geometry allows the Radar to capture a wider area on the ground. The motion of SAR's platform simulates a larger antenna or aperture, and thus provides higher resolution images. With good lighting and atmospheric conditions, good quality and better contrast aerial photographs can be acquired for various mapping purposes, but if vegetation or high-rise structures are present in the area, LiDAR data may be an excellent source of input data for detailed and accurate interpretation below the vegetation cover.

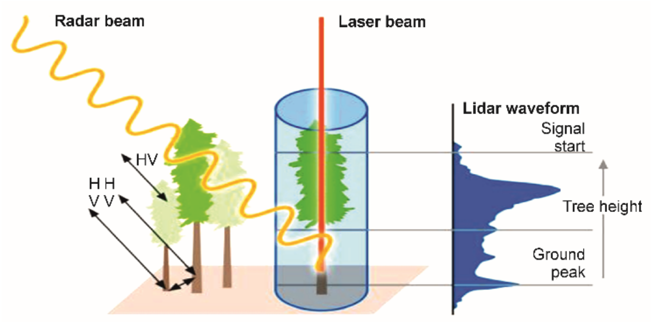

Figure 1.12 Behaviour of laser beam and radar beam (GISGeography, 2024).

In mobility applications, where high precision and reliable data is required, LiDAR technology is gaining popularity due to its varied applications. LiDAR is also used for autonomous vehicles, environmental monitoring, forestry, and inspecting various utilities, such as high-voltage power lines, dams, water supply pipelines, buildings, roads, etc. By having a LiDAR with a 360° viewing angle (e.g., using a rotating mirror), it is possible to get a point cloud of the area/terrain visible from that location. However, the choice between Radar and LiDAR often depends on the application. Radar, with its longer range, is more suitable for surveillance, while LiDAR, with its precision and detailed mapping capabilities, provides accurate data for object recognition and distances. Figure 1.13 shows the capabilities of LiDAR, Radar and camera systems for various stages of data acquisition.

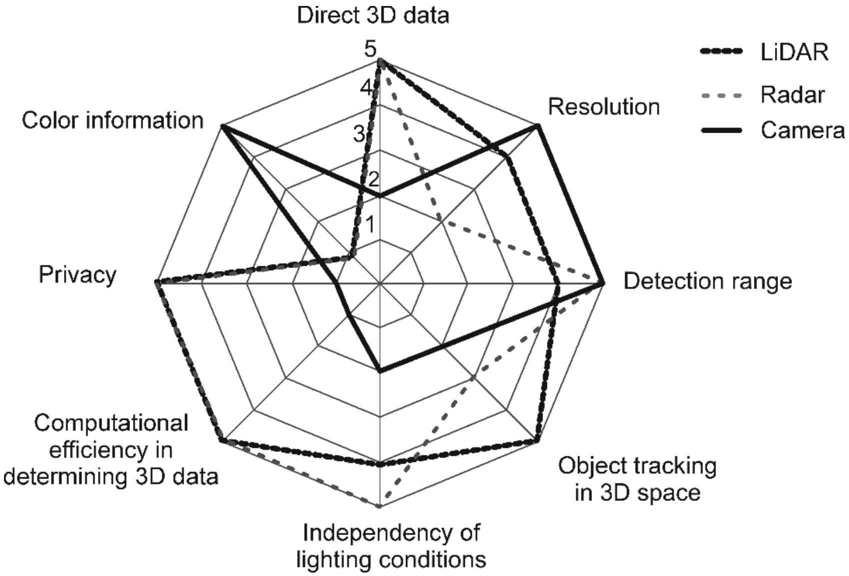

Figure 1.13 Performance comparison of LiDAR sensor vs radar and camera (Florian, 2020).

Sonar is typically used for underwater applications as acoustic waves can travel long distances through water. It measures the distances by emitting a powerful sound pulse and measuring the time it takes for the pulse to return from the object. By moving the Sonar to different locations, the entire environment can be mapped. As Radar waves cannot penetrate through water, it is typically used for airborne applications, such as air traffic control, aircraft anti-collision systems, defence, weather forecasting, and even detecting underground objects. Radar systems are typically expensive.

LiDAR is capable of providing high-resolution 3D model by generating millions of data points in real-time, which is not possible by using Radars or ultrasonic sensors. A distance accuracy of a few centimeters allows LiDAR to detect even the smallest objects precisely. LiDAR's high-precision data and ability to create detailed 3D maps make it most suitable where accurate distance measurements and mapping are critical. Due to the adoption of solid-state technology, the cost of high-resolution LiDAR sensors has come down, making them ideal for a variety of applications.

1.5.5 Area of Interest of LiDAR Remote Sensing

- Astronomical (Telescopes, Very Large Array)
- Climate Change (Environmental monitoring)
- Medical
- Military (surveillance, target detection, mapping, etc).
- Communication systems (free-space optical communications, wireless)
- Geoscience (natural hazards, earthquake and volcano monitoring)
- Transportation systems
- Archeology
- Mining
- Planetary Boundary Layer detection
- Aerosol-cloud (particle) detection
- Water vapor distribution
- Meteorological visibility
- Ozone, SO_2, CO, CO_2, N_2O, and other gases detection
- Wind velocity and direction
- Temperature profiles
- Metal atoms and ions detection
- Ranging and imaging
- Topography and bathymetry

1.6 Smartphones

There are now more mobile devices than humans on Earth. Mobile phones, particularly programmable smartphones, are proliferating very fast for data collection and mapping. Mobile phone sensing is emerging as a new area of research to explore the capabilities of smartphones. Smartphones are generally used in isolation, but these can now equipped with devices and used that have utility in many different sectors, such as business, healthcare, social networks, environmental monitoring, road safety, and transport. These are powerful research and working tools for collecting technical data in the field as they are equipped with many built-in sensors, including accelerometers, gyroscopes, compasses, GPS, RFID, Wi-Fi systems, microphones, and cameras. These sensors are utilized to gather data about the environment, such as coordinates, images, videos, air quality, temperature, humidity, and many more. For example, the data from smartphones can be used for health monitoring of civil structures by determining vibrations and capturing images, as well as monitoring the road conditions using GPS, gyroscope, and accelerometer (Das et.al., 2010). Some data can be analyzed using smartphone's software.

Smartphone is a good tool for participatory map-making in places where global datasets (e.g., Google Earth) lack spatial fidelity, and where community tools (e.g., OpenStreetMap) are used for sharing open-source spatial information amongst individuals. The smartphones connected to Web can be used to record and upload new location frequently to a secured server. Based on tracking and tagging the activities (such as walking, biking, driving, etc.), the system can provide environmental information to the users.

Some smartphone-based apps for remote sensing activities are available. These are primarily for citizens' applications where ground-based data are needed to validate and improve the quality of products, such as global land use and land cover maps. Two such apps are 'Field Photo' and 'GeoWiki Pictures', where the users are required to trigger the camera on their smartphones. The app then records various metadata depicting the conditions and locations of the photographs (Anderson et.al., 2016). Recently, the University of Exeter has created an app that can convert any Android smartphone into a self-contained remote sensing device. The data collected can be used to aid humanitarian rescue work in disaster-struck regions by creating maps of the landscapes. To use this app, the smartphone is suspended from lightweight aerial platforms, such as drones or kites, which gather the data/images autonomously, according to the user's specifications. As free/open source software, the app can be downloaded freely from the Google store by searching for 'UAV toolkit' (UAV toolkit 2016), and used wherever an Android smartphone and aerial platform are available to deliver rapid spatial data. All of the codes that support the generation of Geo-TIFFs are freely available from GitHub (Anderson et.al., 2016).