Microwave sensors can be used for study of crops, agriculture, urban, land use and land cover, geology and hydrology, forest cover, snow and ice, soil moisture and soil types, snow studies, hydrocarbons, etc., (Calla, 2010). Its potential has been established in various sectors, like discrimination of crop types, crop condition monitoring, soil moisture retrieval, delineation of forest openings, fire scar mapping, monitoring wetlands and snow cover, coastal wind, wave slope measurement, ship detection, substrate mapping, and slick detection (Kasischke et al., 1997). Many studies have demonstrated the use of SAR remote sensing to retrieve biophysical characteristics from forest targets (Richards et al.,1993), and established useful relationships between the backscattering coefficients and the above-ground biomass (Imhoff; 1995). Microwave sensors are being used for planetary exploration. The planets, like Mars and Venus, and satellites, like Moon, have been explored to detect presence of frozen water on Moon (e.g., very successful Chandrayan Mission of India) and presence of buried channels under sand dunes on Mars (Calla, 2010).

4. Hyperspectral Imaging Systems

Multispectral images are usually taken in 3 to 10 bands, where each band is obtained using a scanner/sensor/radiometer, whereas the hyperspectral images consist of much narrower bands (10-20 ηm) to record the images in more than hundred bands. In general, it comes from an imaging spectrometer. Hyperspectral sensors (also known as *Imaging Spectrometers*) collects images of a scene in tens to hundreds of narrow spectral bands, nearly simultaneously. The hyperspectral sensors have two key component technologies. One is the spectral filtering technique by which the observed scene radiance is divided into narrow distinct bands. The other key is the detector array technology which allows multiple spatial and/or spectral samples through one- or two-dimensional arrays.

The NASA successfully launched the Hyperion imaging spectrometer (part of the EO-1 satellite) which gives 30 m resolution images in 220 spectral bands (0.4-2.5 μm) with a 30 m resolution. The data collected are often termed an "image cube" where the two spatial dimensions are joined by the third spectral dimension (Figure 5.23). The Hyperion instrument provides a new class of observation data for improved characterization of Earth surface. The instrument can image a 7.5 km by 100 km land area per image, and provides detailed spectral mapping with high radiometric accuracy to map complex land eco-systems. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is another example of NASA's hyperspectral airborne sensor. For example, AVIRIS collects data in 224 contiguous channels with wavelengths from 0.4-2.5 μm.

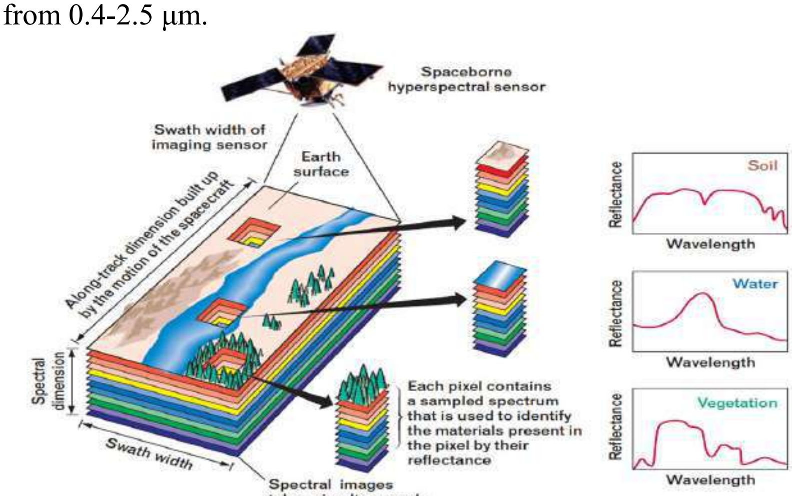

Figure 5.23 Hyperion imaging spectrometer (Plaza et al., 2009)

Hyperspectral images are being used in vegetation studies (species identification, plant stress, productivity, leaf water content, and canopy chemistry), soil science (type mapping and erosion status), geology (mineral identification and mapping) and hydrology (snow grain size, liquid/solid water differentiation). Lake, river and ocean applications include biochemical studies (phytoplankton mapping, activity), and water quality (particulate and sediment mapping). Processing techniques generally identify the presence of materials through measurement of spectral absorption features. Often the hyperspectral data are post-processed to derive surface reflectance through the use of atmospheric radiative transfer models. One of the drawbacks with hyperspectral images is that it adds a level of complexity to reduce the redundancy from 200 narrow bands to work with. Hyperspectral images have many real-world applications, and give higher level of spectral detail and better capability to analyse minute information. For example, hyperspectral imagery has been used in mineral exploration.

5.14 Some Remote Sensing Satellites and Sensors

Different satellites are designed and launched based on their intended uses. Satellite imagery employed in various application ranges from 1000 m to <1 m in spatial resolution.

1. Landsats

Landsat, launched by US in July 1972, is the longest running satellite program for acquisition of earth observation imagery. The Earth Resources Technology Satellite (ERTS) was renamed as Landsat in 1975. Since then, the Landsats have provided vast amount of images at medium resolution required to study and analyse the land use/land cover, vegetation and agricultural crops, urban, water, soils, geology and other Earth resources. Landsat has been one of the most important and demanding sources of medium resolution multispectral images globally.

The launch of Landsat-2 and Landsat-3 followed in 1975, and 1978, respectively. The first three satellites were identical and their payloads consisted of a Multispectral Scanner (MSS) and two video cameras, called *Return Beam Videcons* or (RBVs). One scene covered an area of 170 km x 185 km, as the satellites operated at an altitude between 907-915 km in sun-synchronous polar orbit with 103 minutes of orbital period and revisit time of 18 days.

Landsat-4 was launched in 1982. Then, Landsat-5 was launched in 1984, and it continued to deliver high quality, global data of Earth's surfaces for more than 28 years. Landsats-4 and 5 were equipped with two multispectral sensors, i.e., a MSS and a Thematic Mapper (TM). The altitude of the orbit was 705 km with 99 minutes' orbital period, and revisit time of 16 days. Other parameters were same as earlier satellites.

Landsat-6 was launched October 5, 1993, but was lost during launch. Thereafter, Landsat-7 was successfully launched in April 1999 which has 8 separate spectral bands with spatial resolutions ranging from 15-60 m, and a temporal resolution of 16 days (Figure 5.24). It was equipped with a multispectral sensor known as the *Enhanced Thematic Mapper Plus* (ETM+). The ETM+ provides data in one panchromatic band and 7 multispectral bands. Other parameters were same as Landsat-4 and -5 satellites.

Landsat-8 was launched in 2013, which continued to provide daily global data. It was launched in sun-synchronous orbit at an altitude of 705 km, circling the orbit every 98.9 minutes, covering the entire globe every 16 days. It consisted of two sensors. The Operational Land Imager (OLI) operates in nine spectral bands, including a pan band with resolution of 30 m in multispectral and 15 m in pan, while Thermal Infrared sensor (TIR) operates in two spectral bands: (10.6-11.19 μm) and (11.5-12.51 μm) with 100 m spatial resolution.

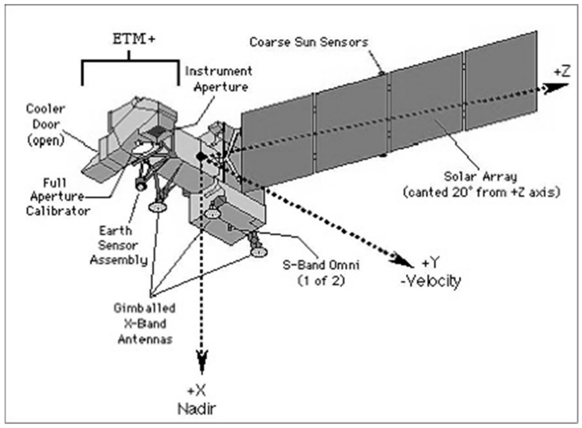

Figure 5.24 A view of Landsat-7 *(https://landsat.usgs.gov/)*

Landsat-9 is launched on 27, September 2021. It carries the Operational Land Imager-2 (OLI–2), and the Thermal Infrared Sensor-2 (TIRS–2), The OLI–2 captures images of the Earth's surface in visible, near-infrared, and shortwave-infrared bands, and TIRS-2 measures thermal infrared radiation, or heat, emitted from the Earth's surface. Landsat 9 improvements include higher radiometric resolution for OLI-2 (14-bit quantization increased from 12-bits for Landsat 8) allowing sensors to detect more differences, especially over darker areas such as water or dense forests. With the higher radiometric resolution, Landsat 9 can differentiate 16,384 shades of a given wavelength. The TIRS-2 enables improved atmospheric correction and more accurate surface temperature measurements. The spatial resolution is same as of Landsat-8. The date-wise history of Landsats is given in Figure 5.25. For other details, refer to Table 5.4 and Table 5.5.

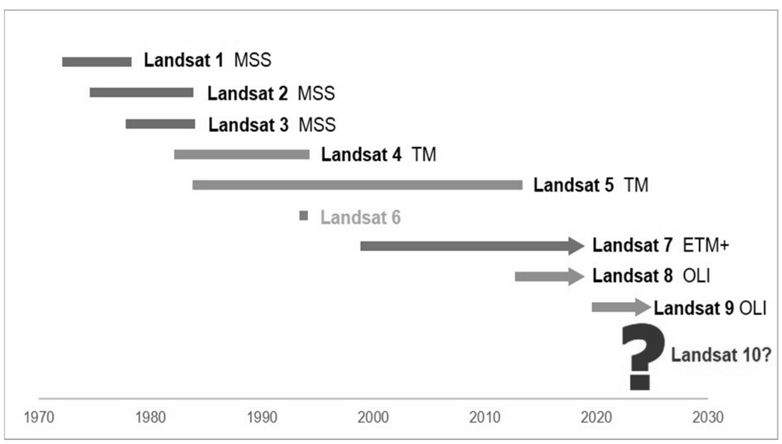

Figure 5.25 Date-wise history of Landsats (Source: https://landsat.usgs.gov/landsat-missions-timeline)

Table 5.5 Details of some satellites and their sensors (Garg, 2022)

Satellite	Launch date	Sensors	Spatial resolution (m)	Swath width (km)
Landsat-1	23. 07.1972	RBV MSS	80 80	185
Landsat-2	22.01.1975	RBV MSS	80 80	185
Landsat-3	05.03 1978	RBV MSS	40 80	185
Landsat-4	16.07.1982	MSS TM	80 30 and 120	185
Landsat-5	01.03.1984	MSS TM	80 30 and 120	185
Landsat-6	05.10.1993	ETM	could not achieve the orbit, and hence failed	

Landsat-7	15.04.1999	ETM+	30, 60 and 15	185
Landsat-8	11.02.2013	OLI TIRS	30 and 15 100	185
Landsat-9	27-09-2021	OLI TIRS	30 and 15 100	185
SPOT-1	21.02.1986	HRV PAN	20 10	60
SPOT- 2	22.01.1990	HRV PAN	20 10	60
SPOT-3	25.09.1993	HRV PAN	20 10	60
SPOT-4	24.03.1988	HR-VIR	20	60
SPOT-5	04.05.2002	HRG	10 and 5	60
SPOT-6	08 .09.2012	HRG	1.5	60
SPOT-7	30.06. 2014	HRG	8.0	60
IRS-1A	17.03.1988	LISS-I, LISS-II A/B	72.5 LISS-I 36.25 LISS-II	148 74 x 2 (148 km)
IRS-1B	29.08.1991	LISS-I and LISS-II A/B	72.5 LISS-I 36.25 LISS-II	148 74 x 2
IRS-P2	15.10.1994	LISS-II M	32 x 37	66 x 2 (131 km)
IRS-1C IRS-1D	28.12.1995 29.09.1997	LISS-III	23.5 and 70	142 and 148
		PAN	5.8	70
		WiFS	188	804
IRS-P3	21.03.1996	WiFS	188	804
		MOS-A MOS-B MOS-C	1500 520 550	195 200 192
IRS-P4 (Oceansat-1)	26.05.1999	OCM MSMR	360 x 236 105x68, 66x43, 40x26, 34x22 (km for frequency sequence)	1420 1360
IRS-P6 Resourcesat-1	17.10.2003	LISS-IV	5.8	70
		LISS-III	23.5	140
		AWiFS	70	740
IRS-P5 Cartosat-1	05.05.2005	PAN-F PAN-A	2.5 2.5	30 30
Cartosat-2	10.01.2007	PAN camera	< 1	9.6
Cartosat-3	27.11.2019	PAN camera Multispectral	0.25 4.0	16
Oceansat-2	23.09.2009	OCM SCAT ROSA	360 x 236 25 km x 25 km	1420 1400
RISAT	26.04. 2012	SAR instrument	< 2 to 50	100 - 600
RADARSAT-1	04.11.1995		9-100	50-100
ADEOS-1	17.08.1996	POLDER	6000-7000	1440-2200
Terra and Aqua	18.12.1999	MODIS	250, 500, 1000	2330
NOAA	1978	AVHRR	1100 at nadir	3000
	1975	GOES	8000	40
Sentinel-1	03.04.2014	C-Band (SAR)	5-40	80-400
Sentinel-2	23.06.2015	MSI	10, 20 and 60	290
Sentinel-5P	13.10.2017	Tropomi	3500, 7000	2600
Sentinel-3 A	16.02.2016	OLCI	300	1270
Sentinel-3 B	25.04.2018	SLSTR	500, 1000	1470
ERS-1	17.07.1991	ATSR-1	1000	80
ERS-2	21.04.1995	ATSR-2	1000	100
ENVISAT	01.03.2002	MERIS	300, 1200	1150

ALOS-2	24.05.2014	PALSAR-2	1-100	25-490

Various Landsats have employed various sensors, including Return Beam Videcon (RBV) Camera, Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM), ETM+, Operational Land Imager (OLI), etc. The details can be found in Garg, (2022). Landsat TM images taken in seven spectral regions are shown in Figure 5.26.

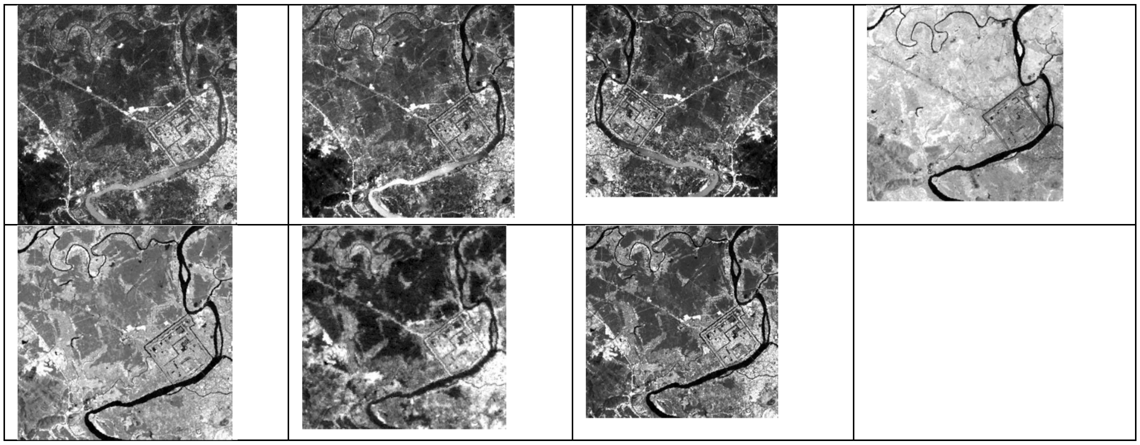

Figure 5.26 Landsat TM images, April 21, 2003, (a) band 1 (0.45-0.52 µm), (b) band 2 (0.52-0.60 µm), (c) band 3 (0.63-0.69 µm), (d) band 4 (0.76-0.90 µm), (e) band 5 (1.55-1.75 µm), (f) band 6 (10.40-12.50 µm), (g) band 7 (2.08-2.35 µm) (Garg, 2019)

2. SPOT

The SPOT (Système Pour l'Observation de la Terre) (System for Earth Observation), a high-resolution optical imaging Earth observation satellite system, was initiated by the CNES (Centre National d'études Spatiales- the French Space Agency). The SPOT-1 was launched by Ariane-2 on 21 February 1986, in sun-synchronous orbit with an inclination of 98.7° from equator and an altitude of 832 km. The inclination of the orbital plane combined with the Earth's rotation around the polar axis allows a satellite to cover entire Earth every 26 days. It provides data in panchromatic at10 m and multispectral bands at 20 m spatial resolution. The satellite was designed to explore the Earth's resources, detecting and forecasting phenomena, such as climatology and oceanography, and monitoring human activities and natural phenomena. The SPOT satellites provided images with improved resolution over the Landsat images. The SPOT satellites also had the capabilities to collect stereo-images for 3D study of Earth. Refer to Table 5.4 and Table 5.5 for additional details.

The SPOT-2 was launched in 22 January 1990, and SPOT-3 on 25 September 1993 which has ceased operations, due to problems with stabilization. Sensors in SPOT 1-3 were identical, including two identical optical imaging instruments High Resolution Visible (HRV) which operated in 2 modes (panchromatic and multispectral), either simultaneously or individually. The panchromatic band has a resolution of 10 m, and the multispectral 3 bands, operating in Green, Red and NIR wavelengths, have a resolution of 20 m covering an area of 3600 km^2 in a single scene The satellites can offer an oblique viewing capability up to angles of $\pm 27^0$ from the satellite's vertical axis. In this way, the temporal resolution is shortened from 26 to 4-5 days for the temperate zones. Images of the same area are captured on successive days by the same satellite viewing off-nadir.

In March 1998, the SPOT-4 satellite was launched which carried two identical optical sensors; Visible & Infrared High-Resolution (HR-VIR) sensors. This sensor had all bands of HRV sensor plus one additional band in MIR region (1.58-1.75 µm) with 20 m ground resolution. The SPOT-4 also had onboard the first VEGETATION instrument, developed for observations of vegetation cover at global level.

The SPOT-5, launched in May 2002, has 2 High Resolution Geometrical (HRG) instruments offering a higher resolution of 2.5-5 m in panchromatic mode and 10 m in multispectral mode. It was designed to have shortwave infrared band (1.58-1.75µm, essential for VEGETATION data) at a resolution of 20 m, in addition to first three multispectral bands of SPOT-4 HR-VIR sensor. A view of SPOT-5 is shown in Figure 5.27. The SPOT-5 also features an imaging instrument HRS (High-Resolution Stereoscopic) operating in panchromatic mode, pointing forward and backward of the satellite so that it takes stereo-images near simultaneously to create 3D relief. Figure 5.28 presents a multispectral colour image taken by SPOT-5 sensor.

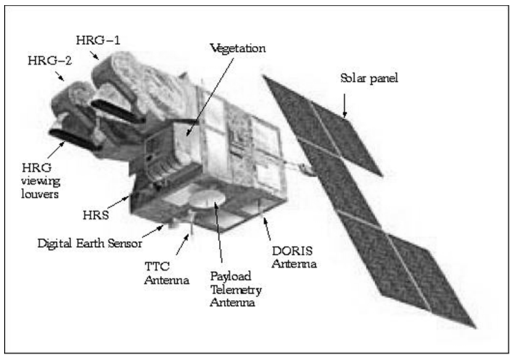

Figure 5.27 A view of SPOT-5 satellite (https://www.eoportal.org/satellite-missions/spot-5)


Figure 5.28 Rome as seen from SPOT-5 image (https://www.esa.int/ESA_Multimedia/Images/2005/12/Rome_seen_by_France_s_Spot_5_satellite)

The SPOT-6 and SPOT-7 were launched on 08 September 2012 and 30 June 2014, respectively, providing panchromatic (0.45–0.75) at 1.5 m resolution, and multispectral in Blue (0.45–0.53), Green (0.53–0.59), Red (0.62–0.69), NIR (0.76–0.89) µm at 8 m resolution, covering an area 60 km x 60 km, as well as color merged products at 1.5 m, resolution. Figure 5.29 shows a panchromatic band image taken by SPOT-6. The SPOT-6 and SPOT-7 have identical sensors and operating characteristics, and are capable to provide a daily revisit everywhere on Earth. The off-nadir viewing capability is shown in Figure 5.30 where from 4 different times, the satellite captures the images of the same area. These images are very useful for creating 3D model of the area. The disadvantage is that those days the satellite will miss the images of areas down below it. The availability of stereo imagery is limited, as their collection requires special control on the satellite. Traditional photogrammetric techniques can be used to successfully create topographic 3D data of inaccessible areas of the world.

Figure 5.29 SPOT-6 panchromatic image, August 2016 (https://innoter.com/en/satellites/spot-6-7/)

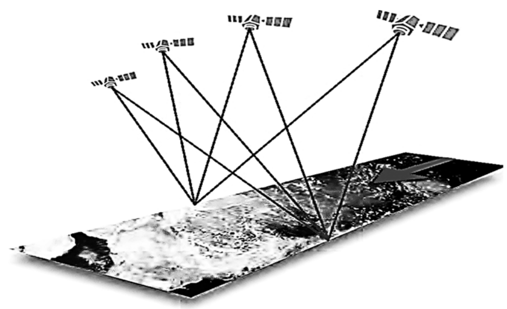

Figure 5.30 Off-nadir capabilities of SPOT to collect images
(https://crisp.nus.edu.sg/~research/tutorial/spot.htm)

3. The Indian Remote Sensing (IRS) satellite

India's first civilian remote sensing satellite IRS-1A was launched in March 1988. The first generation satellites IRS-1A and -1B were designed, developed and launched successfully during 1988 and 1991 with multispectral cameras LISS-I (Linear Imaging and Self Scanning sensor) and LISS-II at spatial resolutions of 72.5 m and 36.25 m, respectively. It was launched in a sun-synchronous orbit, at a nominal altitude of 904 km. It had an orbital period of 103.2 minutes with a repeat cycle of 22 days, crossing the equator around 10:26 AM. The IRS-1B provided better repetivity. Figure 5.31 shows the IRS satellite. Refer to Table 5.4 and Table 5.5 for additional details.

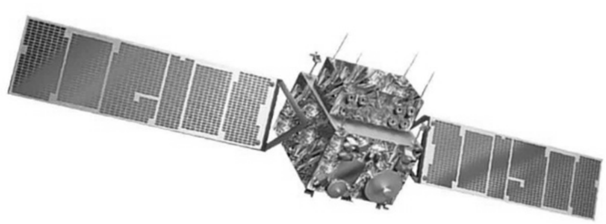

Figure 5.31 The IRS satellite (https://www.isro.gov.in/saga-of-indian-remote-sensing-satellite-system)

The IRS-1A and -1B carried LISS-I and -II; each with a multispectral camera providing images in 4 bands (0.46-0.52 µm blue, 0.52-0.59 µm green, 0.62-0.68 µm red, and 0.77-0.86 µm NIR) at 7 bits radiometric resolution. The LISS-I camera provides 76 m resolution images with a swath of about 150 km, while the LISS-II provides images at 36.25 m resolution. Four LISS-II scenes cover the area of one LISS-I scene. Figure 5.32 shows a FCC of IRS-1B image.

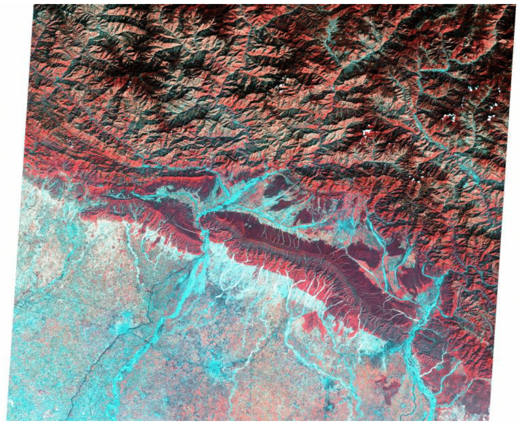

Figure 5.32 The IRS-1B image of Himalaya and lower region (Pradhan et al., 2010)

The second generation satellites, IRS-1C and -1D with improved spatial resolutions have been successfully launched in 1995 and 1997, respectively. The PAN, LISS-III and WiFS (Wide Field Sensor) sensors on IRS-1C and -1D provided the increased coverage required for application areas, such as resources survey and management, forest studies and disaster monitoring, environmental studies, cartographic and town planning. The panchromatic band data was captured (0.5-0.75 μm) at 5.8 m resolution.

The IRS-1C and 1D employed LISS-III scanner, and provided 7 bits multispectral image with 23.5 m ground resolution in Green 0.52–0.59 μm, Red 0.62–0.68 μm, Near-Infrared 0.77– 0.86 μm, and Short-wave Infrared 1.55–1.7 μm band at 70.5 m resolution. It carried another sensor called, WiFS sensor, which provided 7 bits data at 188 m resolution in two spectral band (0.62-0.68 μm and 0.77- 0.86 μm). The third sensor provides Pan data in 6 bits at 5.8 m resolution in 0.5 - 0.75 μm wavelength region, covering 70 km swath. Figure 5.33 (left image) shows a PAN image of IRS-1D at 5.8 m resolution.

Resourcesat-1 (IRS-P6), the tenth satellite in IRS series, was launched in October 2003 to provide both multi-spectral and panchromatic imagery of the Earth's surface. It was placed in 820 km high polar Sun synchronous orbit. It has three sensors on-board: a LISS-III, an AWiFS (Advanced Wide Field Sensor) and a high resolution multi-spectral camera LISS-IV, working on 'pushbroom scanning' mechanism. Resourcesat-3, a medium resolution, planned to be launched in 2023, will carry Advanced Linear Imaging Scanning Sensor-3 (ALISS-3) payload consisting of VNIR and SWIR bands. It would also carry Atmospheric Correction Sensor (ACS) for quantitative interpretation and geophysical parameter retrieval and to improve the data products. The ground sampling distances is expected to be 20 m for VNIR and SWIR bands.

The IRS 1C and 1D employed a Wide Field Sensor (WiFS) having 188 m resolution and providing images in 0.62-0.68 μm (red), 0.77-0.86 μm (near IR) with a swath of 774 km. RESOURCESAT employed Advanced Wide Field Sensor (AWiFS) with 56-70 m ground resolution, providing four images in 0.52-0.59μm (green), 0.62-0.68 μm (red), 0.77-0.86 μm (near IR), and 1.55-1.70 μm (mid-IR) with 370-470 km swath. The AWiFS data with improved spatial and spectral resolution helped in better classification accuracy of agricultural related applications, flood inundation, vegetation stress etc.

The IRS-P6 carried LISS-IV scanner to provide data with 5.8 m resolution. This scanner can be operated in two modes: mono and multi-spectral. In the multispectral mode, data is collected in three spectral bands *viz*, 0.52 to 0.59 μm (Green band 2) 0.62 to 0.68 μm (Red band 3), and 0.76 to 0.86 μm (NIR band 4) with 23.5 km swath. In mono mode, the data is available corresponding to a swath of 70 km. The LISS-IV scanner an off-nadir viewing capability by ± 26^0, thus providing a revisit of 5 days for any given ground area.

OCEANSAT-1 (IRS-P4) was launched in May 1999 to study physical and biological aspects of oceanography. It carried an Ocean Colour Monitor (OCM) and a Multifrequency Scanning Microwave Radiometer (MSMR). The OCM operates in 0.402-0.422, 0.433-0.453, 0.480-0.500, 0.500-0.520, 0.545-0.565, 0.660-0.689, 0.745-0.785 and 0.845-0.885 μm bands with 360 m spatial resolution and 1420 km swath. OCEANSAT-2, launched on Sept. 23, 2009, carried three payloads: OCM, Ku-band Pencil Beam Scatterometer (SCAT), and Radio Occultation Sounder for Atmosphere (ROSA). OCEANSAT-3, planned to be launched in September 2022, will carry Thermal IR sensor, 12 channel OCM, Scatterometer and Passive Microwave Radiometer for simultaneous measurement of ocean color and SST, improvements in signal to noise ratio. The IR sensor and OCM data would be used for the analysis of operational potential fishing zones.

CARTOSAT-1 carried two advanced Panchromatic (PAN) cameras with 30 km swath width and a spatial resolution of 2.5 m. The cameras are mounted on the satellite in such a way that near simultaneous imaging of the same area from two different angles is possible to generate DEM. The cameras are steerable across the direction of the satellite's movement to facilitate the imaging of an area more frequently. CARTOSAT-1 data provided enhanced inputs for large scale mapping applications, such as urban and rural development, land and water resources management, disaster assessment, relief planning and management, environment impact assessment and updating topographic maps.

CARTOSAT-2, launched in January 10, 2007, is capable of providing scene-specific images. It carried a single panchromatic camera providing better than 1 m spatial resolution image, with a swath of 9.6 km. Due to its along track and across track feature up to $\pm 45^0$, it can take frequent images at revisit periods of 4 days and 1 day. CARTOSAT-2A, launched on 28 April 2008, can also provide scene specific PAN imagery with better than 1 m resolution. CARTOSAT-2B was launched on July 12, 2010, with a camera of spatial resolution of about 0.8m. CARTOSAT-3, launched on 27 Nov. 2019, provided images with 0.25 m resolution in Panchromatic and 1 m in 4 bands of multispectral modes with a swath of 16 km. Images from these satellites would be useful for cadastre, infrastructure mapping and analysis, disaster monitoring and damage assessment, cartographic applications, mapping urban and rural areas. Figure 5.33 (right image) shows a PAN image of CARTOSAT-3 at 0.25 m resolution.

Figure 5.33 (Left image) IRS-1D panchromatic image at 5.8 m resolution (http://www.swisstopo.ch/NPOC/Products/kosovo/irsp_sarajewo.html), and (right image) CARTOSAT-3 panchromatic image of Palm city area, Qatar, at 0.25 m resolution, dated 28-Dec-2019 (https://www.isro.gov.in/high-resolution-panchromatic-and-multi-spectral-images-observed-cartosat-3-calibration-validation-of)

National Remote Sensing Centre (NRSC), Hyderabad, a sole agency of Department of Space, Govt. of India, distributes the satellite data to its users in India. The NRSC has an Earth station at Shadnagar, about 55 km from Hyderabad, to receive data from almost all contemporary remote sensing satellites. The National Data Centre (NDC) is a one-stop-shop for procuring a range of data products with a wide choice of resolutions, processing levels, product media, area coverage, revisit, season and spectral bands. Data products can be supplied on a wide variety of media and formats.

4. IKONOS

GeoEye Inc. (formerly Orbital Imaging Corporation or ORBIMAGE) provides very high-resolution images from IKONOS, Orbview-2, Orbview-3, GeoEye-1, GeoEye-2, which are today an important source of large scale mapping. The IKONOS, derived its name from the Greek eikōn for image, is a commercial Earth observation satellite. It was launched on 24 September 1999 in an altitude of about 680 km to collect high-resolution multispectral imagery with 3375 pixels and panchromatic (PAN) imagery with 13500 pixels, providing a swath width of 11.3 km. It provides 1 m (0.82 m) panchromatic image, and 4 m multispectral (Blue, Green, Red, and NIR 0.45–0.90 µm) image and 1-m Pan-sharpened image. The revisit time for IKONOS is 3-5 days off-nadir and 144 days for true-nadir, with a swath width of 11 km × 11 km (single scene). The IKONOS-2 developed by the DigitalGlobe, was launched in September 1999 in a sun-synchronous orbit at an altitude of 681km. It provides multispectral data in B, G, R, and NIR bands with 4 m resolution and a panchromatic data with 1 m resolution. It provides 11 bits (2048 grey levels) radiometric resolution image, covering 11 km swath. Figure 5.34 shows an IKONOS image of the Rio de Janeiro Port, Brazil.

5. QuickBird

QuickBird-1, a very high resolution satellite, developed by DigitalGlobe, was launched in November 2000. It was lost due to launch vehicle failure. QuickBird 2, was launched on 18 October 2001. It was placed in Sun-synchronous polar orbit, at an altitude of 470 km, with 1-5 days' temporal resolution with up to 25^0 of viewing angle along-and cross-track covering 16.5 km swath. The satellite has 4 multispectral bands (B, G, R and NIR) with 2.4 m resolution and a panchromatic band with 0.61 m resolution with 11 bits radiometric resolution. Figure 5.34 shows a QuickBird image Houston Reliant Stadium.

6. WorldView-1

WorldView-1, was launched on September 18, 2007 by DigitalGlobe, providing the panchromatic images at 0.5 m resolution. It has an average revisit time of 1.7 days, and is capable of collecting in-track stereo. Operating at an altitude of 496 km, WorldView-1 can cover up to 750,000 km^2 per day. WorldView-2 was successfully launched on October 8, 2009, collecting up to 975,000 km^2 of imagery per day. WorldView-2 was the first very high resolution satellite to offer 8-band multispectral imagery with sub-metre resolution, along with increased agility, accuracy and stereo capability. With the additional four spectral bands, WorldView-2 offers unique opportunities for remote sensing analysis of vegetation, coastal environments, agriculture, geology, environment, tourism and many others.

WorldView-3 was launched on August 13, 2014, in a Sun-synchronous orbit, at an altitude of 617 km, with orbital period of 97 minutes. It provides 31 cm resolution in panchromatic, 1.24 m resolution in multispectral, 3.7 m resolution in SWIR, and 30 m resolution in CAVIS (Clouds, Aerosols, Vapors, Ice, and Snow). The CAVIS monitors the atmosphere and provides correction data to improve haze, soot, or dust. WorldView-3 has an average revisit time of <1 day and is capable of collecting up to 680,000 km^2 per day. WorldView-3 offers unique opportunities for remote sensing analysis of vegetation, coastal environments, agriculture, geology, environment, tourism and many others. It provides highly detailed imagery for precise map creation, and change detection studies in telecommunications, infrastructure planning, mapping/surveying, civil engineering, mining & exploration, oil & gas, and DEM generation.
WorldView-4 (formerly GeoEye-2) was launched on November 11, 2016 in a Sun-synchronous orbit, at an altitude of 617 km, with 97 minutes' orbital period. It has an effective revisit time capability of ≤ 3 days. The satellite provides 31 cm resolution in panchromatic at nadir, 0.34 m at 20º off-nadir, 1m at 56º off-nadir, and 3.51 m at 65º off-nadir, as well as 1.24 m resolution in multispectral at nadir, 1.38 m at 20º off-nadir, 4 m, at 56º off-nadir, 14 m at 65º off-nadir in 4 bands (B, G, R and NIR) in 13.1 km wide swath with 2048 (11 bits) radiometric resolution. Figure 5.34 shows a WorldView-2 image of downtown Oakland, California.

Figure 5.34 (left) IKONOS image of the Rio de Janeiro Port, Brasil (https://seos-project.eu/world-of-images/world-of-images-c04-p06.html), (middle) Quickbird image Houston Reliant Stadium (http://www.usgsquads.com/digital-map-products/aerial-and-satellite-imagery/satellite-imagery/digitalglobe quickbird), and (right) WorldView-2 image of downtown Oakland, California (https://www.eoportal.org/satellite-missions/worldview-2).

Summary of some of the very high resolution satellites are given in Table 5.6.

Table 5.6 Characteristics of high resolution satellites (Garg, 2022)

Sensor	Resolution/Band*		Stereo-capability	Swath (km)
	Panchromatic	**Multispectral**		
IKONOS	0.82 m 445-900 nm	4 m (Blue, green, red, NIR) bands	Yes	11.3
IKONOS-2	1.0 m 445-900 nm	4 m (Blue, green, red, NIR) bands	Yes	11
QuickBird	Failed after launch			
QuickBird-2	61cm 450-900 nm	2.4m (Blue, green, red, NIR) bands	Along track	16.5
OrbView-3	1 m	4m (Blue, green, red, IR)	No	8
GeoEye-1	41 cm 450-800 nm	1.65 m Blue: 450-510 nm Green: 510-580 nm	Along track	15.2

		Red: 655-690 nm Near IR: 780-920 nm		
WorldView-1	50 cm 400-900 nm	Not applicable	Along track	17.6
WorldView-2	50 cm 450-800 nm	2.0 m Coastal: 400-450 nm Blue: 450-510 nm Green: 510-580 nm Yellow: 585-625 nm Red: 630-690 nm Red Edge: 705-745 nm Near Infrared 1: 770-895 nm Near Infrared 2: 860-1040 nm	Along track	16.4
WorldView-3	31cm 450-800 nm	Multispectral bands (1.24 m resolution) Coastal: 400-450 nm Blue: 450-510 nm Green: 510-580 nm Yellow: 585-625 nm Red: 630-690 nm Red Edge: 705-745 nm Near Infrared 1: 770-895 nm Near Infrared 2: 860-1040 nm SWIR bands (3.7 m resolution) SWIR-1: 1195-1225 nm SWIR-2: 1550-1590 nm SWIR-3: 1640-1680 nm SWIR-4: 1710-1750 nm SWIR-5: 2145-2185 nm SWIR 6: 2185-2225 nm SWIR-7: 2235-2285 nm SWIR-8: 2295-2365 nm CAVIS bands (30 m resolution) Desert Clouds: 405-420 nm Aerosol-1: 459-509 nm Green: 525-585 nm Aerosol-2: 635-685 nm Water-1: 845-885 nm Water-2: 897-927 nm Water-3: 930-965 nm NDVI-SWIR: 1220-1252 nm Cirrus: 1365-1405 nm Snow: 1620-1680 nm Aerosol-3: 2105-2245 nm Aerosol-4: 2105-2245 nm	Yes	13.1
WorldView-4 (formerly GeoEye-2)	31 cm 450-800 nm	1.24m Blue : 450 - 510 nm Green : 510 - 580 nm Red : 655 - 690 nm NIR : 780 - 920 nm	Yes	13.1
Pleiades	0.5 m	Panchromatic: 480-830 nm Blue: 430-550 nm Green: 490-610 nm Red: 600-720 nm Near Infrared: 750-950 nm	-	20 km
SkySat-C by Planet Labs	50 cm 0.81 cm	Panchromatic: 480-830 nm Blue: 430-550 nm Green: 490-610 nm Red: 600-720 nm Near Infrared: 750-950 nm	-	5.5 km

PlanetScope	3 m	Blue 440 – 510 nm Green 520 - 590 nm Red 630 - 685 nm Red Edge 690 - 730 nm NIR 760 - 850 nm	-	16 km x 24 km
Rapideye	5 m	Blue 440 – 510 nm Green 520 – 590 nm Red 630 – 685 nm NIR 760 – 850 nm	-	77 km
Cubasats	2-3 m	Blue 440 – 510 nm Green 520 – 590 nm Red 630 – 685 nm NIR 760 – 850 nm	-	147 m to 1.1 km

**Note: All data are 11 bit (2048 grey levels) radiometric resolution*

5.15 Types of Remote Sensing Images

Remote sensing images are available in two broad forms: hard copy or photographic products (B &W, colour), and soft copy (digital) product. The original product from the sensor is digital data acquired in individual band as B &W image. Human eyes have the limitations in identifying not more than 8-10 grey shades from B&W images, while up to 16 categories (colours) may be identified by the human eyes on a colour image. Therefore, colour images are preferred as compared to B&W images, which can be produced from three individual B&W images, taken in different spectral regions. Depending upon the range of wavelength used for capturing them, the images are classified into three main types.

1. B &W (Panchromatic) Images

A Panchromatic image, consists of a B&W image taken by the sensor a slightly larger range of visible part (refer to Figure 5.32). A panchromatic image may be interpreted and analysed in a similar way as B &W aerial photograph.

2. Multispectral Images

A multispectral image may consist of several bands of data (3-10 bands), such as from Landsat TM, where each band image has a specific utility. Human eyes can't appreciate the grey level variation of objects in each image, but there is variation which can be detected by the software. For visual colour display, each band of B&W image is displayed in one of the primary colours and superimposed. Thus, a colour composite image is much appreciated by human eyes for identifying many features/objects, as compared to individual B &W images. The interpretation of a colour composite image however will require the knowledge of the spectral signature of the objects present in the scene. A multispectral image in shown in Figure 5.35 (left image).

3. False Colour Composite (FCC) images

In displaying a colour composite image, basically three primary colours (red, green and blue) are used. When the three primary colours are mixed in various proportions, they can produce different colours in the visible spectrum. As we know that each spectral band in visible part is associated with a colour, so three images taken in three different wavelength regions are superimposed after passing them through three colour filters to obtain a colour composite image. If the colour of an object in the colour composite image may not have any resemblance to its actual colour, the output image is known as a *False Colour Composite* (FCC). There could be many possible combinations of producing a FCC image, however, a common scheme for displaying a multispectral image is NIR band in red, red band in green, and green band in blue colour (Figure 5.35, right image).

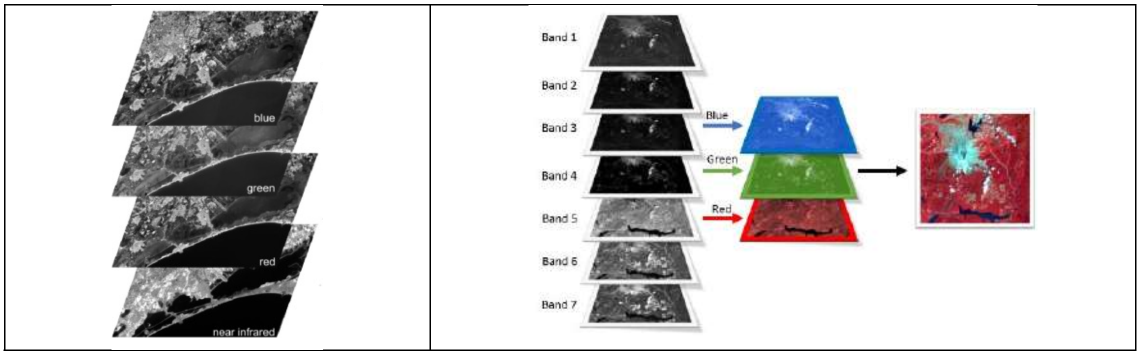

Figure 5.35 (Left image) Multispectral images (Ose et al., 2016), and (Right image) False colour composite from multispectral image (https://gsp.humboldt.edu/olm/Courses/GSP_216/lessons/composites.html)

In a FCC, vegetation would appear in different shades of red/orange colour, depending on the types and conditions of the vegetation. These shades of colours help identification of various vegetation types from FCC image. The vegetation types will have high reflectance in the NIR band as compared to the Red band. Clear water will appear as dark-bluish due to higher reflectance in green band. Bare soils, roads and buildings may appear in various shades of blue, yellow or grey, depending on their composition.

4. True Colour Composite (TCC) images

In a multispectral image, when the three primary colour bands are combined in a different way, the resultant image is called a true colour composite image (Figure 5.35, left image). For example, bands 3 (red band), 2 (green band) and 1 (blue band) of LANDSAT TM images are assigned R, G, and B colours, respectively for displaying the TCC. The TCC image resembles closely what is normally observed on Earth surface by the human eyes, e.g., vegetation would appear in different shades of green colour. Figure 5.36 shows a comparison of a TCC and a FCC.

Figure 5.36 (Left) True colour composite, and (Right) False color composite (Kurnaz et al., 2020)

5. Hyperspectral images

Hyperspectral image consists of more than 100 of narrower bands (10-20 ηm) where images are recorded by an imaging spectrometer, such as AVIRIS. Hyperspectral remote sensing combines the imaging and spectroscopy in a single system which often includes large data sets, about 100 to 200 spectral bands of relatively narrow bandwidths. Hyperspectral imagery is typically collected (and represented) as a data cube with spatial information collected in the x-y plane, and spectral information represented in the z-direction, as shown in Figure 5.23. Hyperspectral remote sensing is used for detection and identification of minerals, vegetation, water vapor, cloud properties, aerosols in the atmosphere, chlorophyll, phytoplankton, dissolved organic materials, suspended sediments, agriculture and forest production, snow cover fraction, grain size, leaf water, pigments, etc. Some hyperspectral satellite sensors and platforms along with their year of operation is given in Figure 5.37.

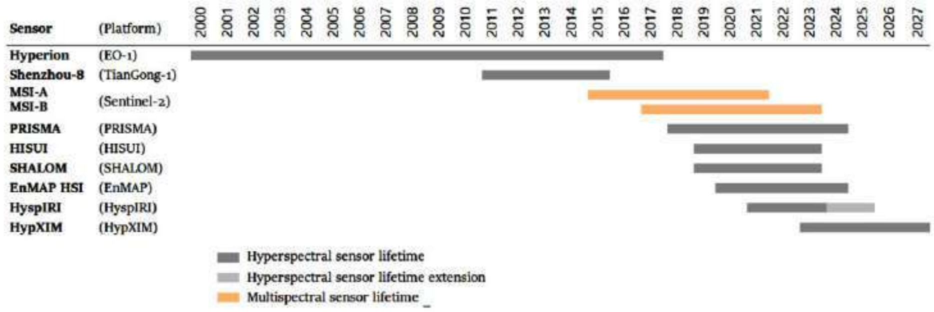

Figure 5.37 Hyperspectral remote sensing sensors and satellites (Transon et al., 2018)

5.16 Visual Interpretation Methods

Interpretation and analysis of remote sensing imagery involves the identification and/or measurement of various objects present on an image. The visual interpretation (or *manual analysis*) of satellite images includes recognition of objects and ascertaining their properties. The recognition of objects includes, such as roads, forest, agricultural fields, rivers, etc., which would depend on resolution of images. In manual interpretation, the objects in an image may also be recognized with previous knowledge and experience of the area, which play an important role in the interpretation process. The recognition and interpretation of objects is a repetitive process, where both rely on each other. Thematic maps can thus be prepared by manual image analysis which are taken to the field for making any correction as well as verification of interpretation accuracy.

The accuracy of recognition of objects and subsequently determination of their properties would depend on the knowledge and experience of an image interpreter. As human eye cannot interpret all spectral differences in imagery, looking at the familiar areas on the imagery is the best way of gaining experience in visual image interpretation. However, full exploitation of the data characteristics can't be done by visual interpretation of images. Visual interpretation methods require very simple devices, that's why it is most common method used, particularly in developing countries, where highly sophisticated equipment and software are not available. The equipment used for visual interpretation includes, magnifying lens, light table, magnifying project table, etc. It is fairly easy to use with quick start. Normally, a piece of tracing paper is kept ion the image and details/objects identified are traced out manually on the tracing sheet.

The visual interpretation utilizes the visual ability and human brain as well as image characteristics to derive information from remote sensing data. The elements of visual image interpretation are colour (or tone for black and white photos), texture, pattern, shape, size, shadow and location. Tone is considered as the primary element, texture, size and shape are considered as the secondary elements, while pattern and shadow as tertiary and site and locations as lower order elements of interpretation. These elements are explained below, while Table 5.7 gives a summary of these interpretation elements.

1. Tone

It refers to the relative brightness or colour of objects on photographs/images (Figure 5.38). Generally, tone is the most important element required to distinguish between different objects or features, as without tone nothing would be visible. It is the variation in tone that allows the shape, texture, and pattern of different objects to be distinguished from each other.