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New environmental remote sensing systems

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3.1 INTRODUCTION

Remote sensing can be defined as the acquisition of physical data of an object with a sensor that has no direct contact with the object itself. Photography of the Earth's surface dates back to the early 1800s, when in 1839 Louis Daguerre publicly reported results of images from photographic experiments. In 1858 the first aerial view from a balloon was produced and in 1910 Wilber Smith piloted the plane that acquired motion pictures of Centocelli in Italy. Image photography was collected on a routine basis during both world wars; during World War II non-visible parts of the electromagnetic (EM) spectrum were used for the first time and radar technology was introduced. In 1960s, the first meteorological satellite was launched, but actual image acquisition from space dates back to earlier times with various spy satellites. In 1972, with the launch of the earth observation land satellite Landsat 1 (renamed from ERTS-1), repetitive and systematic observations were acquired. Many dedicated earth observation missions followed Landsat 1 and in 1980 NASA started the development of high spectral resolution instruments (hyperspectral remote sensing) covering the visible and shortwave infrared portions of the EM spectrum, with narrow bands allowing spectra of pixels to be imaged (Goetz *et al.* 1985). Simultaneously in the field of active microwave remote sensing, research led to the development of multi-polarization radar systems and interferometric systems (Massonnet *et al.* 1994). The turn of the millennium marks the onset of a new era in remote sensing when many experimental sensors and system approaches will be mounted on satellites, thereby providing ready access to data on a global scale. Interferometric systems will provide global digital elevation models, while spaceborne hyperspectral systems will allow detailed spectrophysical measurements at almost any part of the earth's surface.

This chapter provides an overview of existing and planned satellite-based systems subdivided into the categories of high spatial resolution systems, high spectral resolution systems, high temporal resolution systems and radar systems (Figure 3.1). More technical details of some of these systems can be found in Kramer (1996). For readers requiring details of existing remote sensing systems as well as historical image archives, please refer to the references and internet links provided at the end of the chapter. The different sensor systems are catalogued within the internet links provided according to the order in which they are treated in the text. A brief discussion on the various application fields for the sensor types will follow the technical description of the instruments. The chapter provides a few classical references that serve as a starting point for further studies without attempting to be complete. In addition, cross references to other chapters in this book serve as a basis for a better understanding of the diversity of applications.

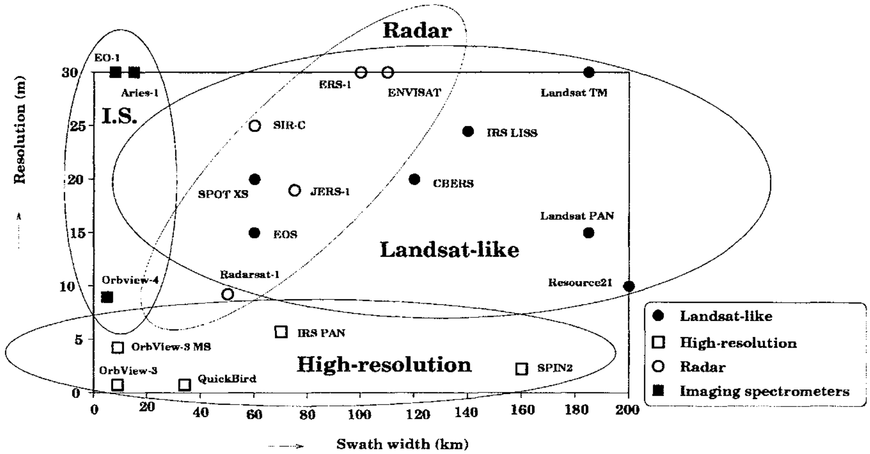

Figure 3.1: Classification of sensors.

3.2 HIGH SPATIAL RESOLUTION SENSORS

3.2.1 Historical overview

High spatial resolution sensors have a resolution of less than 5 m and were once the exclusive domain of spy satellites. In the 1960s, spy satellites existed that had a resolution better than 10 meters. Civil satellites had to wait until the very last days of the 20th century. The major breakthrough was one of policy rather than technology. The US Land Remote Sensing Act of 1992 concluded that a robust commercial satellite remote-sensing industry was important to the welfare of the USA and created a process for licensing private companies to develop, own, operate, and sell high-resolution data from Earth-observing satellites. Two years later four licences for one-meter systems were granted, and currently the first satellite, IKONOS, is in space. This innovation promises to set off an explosion in the amount and use of high resolution image data.

High-resolution imaging requires a change in instrument design to a pushbroom and large telescope, as well as a new spacecraft design. In contrast to the medium-resolution satellites, high-resolution systems have limited multispectral coverage, or even just panchromatic capabilities. They do have extreme pointing capabilities to increase their potential coverage. The pointing capability can also be used for last minute reprogramming of the satellite in case of cloud cover.

The private sector has shown an almost exclusive interest in high-resolution systems. Obviously, it is believed that these systems represent the space capability needed to create commercially valuable products. On the other hand, pure commercial remote sensing systems, with no government funding, implies a high risk, especially to data users. Most companies in the high-resolution business have a back-up satellite in store, in order to be able to launch a replacement satellite at short notice. But still, the loss of one satellite means a loss of millions of dollars, which may be considerable for a business just starting in this field. The characteristics of high-resolution satellites include a spatial resolution of less than 5 m, 1 to 4 spectral bands, a swath less than 100 km and a revisiting time of better than 3 days.

3.2.2 Overview sensors

An overview of high-resolution sensors to be discussed is given in Table 3.1.

Table 3.1: Typical high-resolution satellites.

Platform	Sensor	Spatial resolution	Multi-spectral	Swath width	Pointing capability	Revisit time
IRS-1C&D*	PAN	5.8 m	4 bands	70 km	±26°	5 days
Cosmos*	KVR-1000	~2 m	No	160 km	No	N/A
OrbView-3	PAN	1 m	4 bands	8 km	±45°	3 days
Ikonos 1	OSA	1 m	4 bands	11 km	±30°	1-3 days
QuickBird	QBP	1 m	4 bands	27 km	±30°	1-3 days
EROS A+	CCD	1.8 m	No	12.5 km		

3.2.3 IRS-1C and IRS-1D

Having been the seventh nation to successfully launch an orbiting remote sensing satellite in July 1980, India is pressing ahead with an impressive national programme aimed at developing launchers as well as nationally produced communications, meteorological and Earth resources satellites. The IRS-1C and 1D offer improved spatial and spectral resolution over the previous versions of the satellite, as well as on-board recording, stereo viewing capability and more frequent revisits. They carry three separate imaging sensors, the WiFS, the LISS, and the high-resolution panchromatic sensor.

The Wide Field Sensor (WiFS) provides regional imagery acquiring data with 800 km swaths at a coarse 188 m resolution in two spectral bands, visible (620-680 nm) and near infrared (770-860 nm), and is used for vegetation index mapping. The WiFS offers a rapid revisit time of 3 days.

The Linear Imaging Self-Scanning Sensor 3 (LISS-3) serves the needs of multispectral imagery clients, possibly the largest of all current data user groups. LISS-3 acquires four bands (520-590, 620-680, 770-860, and 1550-1750 nm) with

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* IRS-1, Pan and Cosmos do not meet the strict definition of 'high resolution imagery', but is considered to be an example of this genre.

a 23.7 m spatial resolution, which makes it an ideal complement to data from the aging Landsat 5 Thematic Mapper (TM) sensor.

The most interesting of the three sensors is the panchromatic sensor with a resolution of 5.8 m. With its 5.8 m resolution, the IRS-1C and IRS-1D can cover applications that require spatial detail and scene sizes between the 10 m SPOT satellites and the 1 m systems. The PAN sensor is steerable up to plus or minus 26 degrees and thus offers stereo capabilities and a possible frequent revisit of about 5 days, depending on the latitude. Working together, the IRS-1C and 1D will also cater to users who need a rapid revisiting rate. IRS-1C was launched on 28 December 1995, IRS-1D on 28 September 1997. Both sensors have a 817 km orbit, are sun-synchronous with a 10:30 equator crossing, and a 24-day repeat cycle.

India will initiate a high-resolution mapping programme with the launch of the IRS-P5, which has been dubbed Cartosat-1. It will acquire 2.5 m resolution panchromatic imagery. There seem to be plans to futher improve the planned Cartosat-2 satellite to achieve 1 m resolution.

3.2.4 KVR-1000

Data from the Russian KVR-1000 camera, flown on a Russian Cosmos satellite, is marketed under the name of SPIN-2 (Space Information – 2 m). It provides high-resolution photography of the USA in accordance with a Russian-American contract. Currently SPIN-2 offers some of the world's highest resolution, commercially available satellite imagery. SPIN-2 panchromatic imagery has a resolution of about 2 m. The data is single band with a spectral range between 510 and 760 nm. Individual scenes cover a large area of 40 km by 180 km. Typically, the satellite is launched and takes images for 45 days, before it runs out of fresh film; the last mission was in February-March 1998. The KVR-1000 is in a low-earth orbit and provides 40 x 160 km scenes with a resolution.

3.2.5 OrbView-3

OrbView-3 will produce 1 m resolution panchromatic and 4 m resolution multispectral imagery. OrbView-3 is in a 470 km sun-synchronous orbit with a 10:30 equator crossing. The spatial resolution is 1 m for a swath of 8 km and a 3 day revisit time. The panchromatic channel covers the spectral range from 450 nm to 900 nm. The four multispectral channels cover 450–520 nm, 520–600 nm, 625–695 nm, and 760–900 nm respectively. The design lifetime of the satellite is 5 years. In Europe, Spot Image will have the exclusive right to sell the imagery of OrbImage's planned OrbView-3 and OrbView-4 satellites. OrbView-3 and OrbView 4 are planned to be launched in 2001.

3.2.6 Ikonos

The Ikonos satellite system was initiated as the Commercial Remote Sensing System (CRSS). The satellite will routinely collect 1 m panchromatic and 4 m multispectral imagery. Mapping North America's largest 100 cities is an early priority. The sensor OSA (Optical Sensor Assembly) features a telescope with a 10 m focal length (folded optics design) and pushbroom detector technology. Simultaneous imaging in the panchromatic and multispectral modes is provided. A body pointing technique of the entire spacecraft permits a pointing capability of ±30° in any direction. Ikonos is in a 680 km, 98.2°, sun-synchronous orbit with a 14 days repeat cycle and a 1–3 day revisit time. The sensor has a panchromatic spectral band with 1 m resolution (0.45–0.90) and 4 multispectral bands (0.45–0.52, 0.52–0.60, 0.63–0.69, 0.76–0.90) with 4 m resolution. The swath is 11 km.

3.2.7 QuickBird

QuickBird is the next-generation satellite of the EarlyBird satellite. Unfortunately, EarlyBird was lost shortly after launch in December 1997. Its follow-up QuickBird (QuickBird-1 was launched on 20 November 2000, and also failed). The system has a planed panchromatic channel (0.45–0.90) with 1 m resolution at nadir and four multispectral channels (0.45–0.52, 0.53–0.59, 0.63–0.69, 0.77–0.90) with 4 m resolution.

3.2.8 Eros

Eros (12.5 km swath) is the result of a joint venture between the US and Israel. The Eros A+ satellite will have a resolution of about 1.8 m. The follow-up satellite Eros B will have a resolution of about 80 cm.

EROS satellites are light, low earth orbiting, high resolution satellites. There are two classes of EROS satellite, A and B. EROS A1 and A2 will weigh 240 kg at launch and orbit at an altitude of 480 km. They will each carry a camera with a focal plane of CCD (Charge Coupled Device) detectors with more than 7,000 pixels per line. The expected lifetime of EROS A satellites is at least 4 years. EROS B1-B6 will weigh under 350 kg at launch and orbit at an altitude of 600 km. They carry a camera with a CCD/TDI (Charge Coupled Device/Time Delay Integration) focal plane that enables imaging even under weak lighting conditions. The camera system provides 20,000 pixels per line and produces an image resolution of 0.82 m. The expected lifetime of EROS B satellites is at least 6 years.

EROS satellites will be placed in a polar orbit. Both satellites are sun-synchronous. The light, innovative design of the EROS satellites allows for a great degree of platform agility. Satellites can turn up to 45 degrees in any direction as they orbit, providing the power to take shots of many different areas during the same pass. The satellites' ability to point and shoot their cameras also allows for stereo imaging during the same orbit. The satellites will be launched using refurbished Russian ICBM rocket technology, now called Start-1. Satellites will be launched from 2000-2005; EROS-A1 was launched on 5 December 2000.

3.2.9 Applications and perspectives

Satellite images have traditionally been used for military surveillance, to search for oil and mineral deposits, infrastructure mapping, urban planning, forestry, agriculture and conservation research. Agricultural applications may benefit from the increased resolution. The health of agricultural crops can be monitored by analyzing images of near-infrared radiation. Known as 'precision agriculture', farmers are able to compare images one or two days apart and apply water, fertilizer or pesticides to specific areas of a field, based on coordinates from the satellite image, and a Global Positioning System (GPS). In forestry, individual trees could be identified and mapped over large areas (see Chapter 6 by Woodcock *et al.*). Geographic information systems (GIS) databases may be constructed using 1 m images, reducing reliance on out-of-date paper maps. Highly accurate elevation maps (or Digital Elevation Models – DEMs), may be also be developed from the images and added to the databases. Because they cover large areas, high-resolution satellite images could replace aerial photographs for certain types of detailed mapping; for example, gas pipeline routing, urban planning and real estate. This includes the use of high resolution imagery for three-dimensional drapes that can be used to visualize and simulate land-management activities.

3.3 HIGH SPECTRAL RESOLUTION SATELLITES

3.3.1 Historical overview

Imaging spectrometry satellites use a near-continuous radiance or reflectance to capture all spectral information over the spectral range of the sensor. Imaging spectrometers typically acquire images in a large number of channels (over 40), which are narrow (typically 10 to 20 nm in width) and contiguous (i.e., adjacent and not overlapping – see Figure 3.2). The resulting reflectance spectra, at a pixel scale, can be directly compared with similar spectra measured in the field, or laboratory. This capability promises to make possible entirely new applications and to improve the accuracy of current multispectral analysis techniques. The demand for imaging spectrometers has a long history in the geophysical field; aircraft-based experiments have shown that measurements of the continuous spectrum allow greatly improved mineral identification (Van der Meer and Bakker 1997). The first civilian airborne spectrometer data were collected in 1981 using a one-dimensional profile spectrometer developed by the Geophysical Environmental Research Company. These data comprised 576 channels covering the 4 to 2.5 μm wavelength range (Chiu and Collins 1978). The first imaging device was the Fluorescence Line Imager (FLI; also known as the Programmable Line Imager, PMI) developed by Canada's Department of Fisheries and Oceans in 1981. The Airborne Imaging Spectrometer (AIS), developed at the NASA Jet Propulsion Laboratory was operational from 1983 onward. This instrument acquired data in 128 spectral bands in the range of 1.2–2.4 μm. with a field-of-view of 3.7 degrees resulting in images of 32 pixels width (Vane and Goetz 1988). A later version of the instrument, AIS-2, covered the 0.8–2.4 μm region acquiring images 64 pixels wide (LaBaw 1987). In 1987 NASA began operating the Airborne Visible/Infrared Imaging

Spectrometer (AVIRIS; Vane *et al.* 1993). AVIRIS was developed as a facility that would routinely supply well-calibrated data for many different purposes. The AVIRIS scanner simultaneously collects images in 224 contiguous bands resulting in a complete reflectance spectrum for each 20 by 20 m. pixel in the 0.4 to 2.5 μm region with a sampling interval of 10 nm (Goetz *et al.* 1983; Vane and Goetz 1993). The field-of-view of the AVIRIS scanner is 30 degrees resulting in a ground field-of-view of 10.5km. Private companies now recognize the potential of imaging spectrometry and have built several sensors for specific applications. Examples are the GER imaging spectrometer (operational in 1986), and the ITRES CASI that became operational in 1989. Currently operational airborne instruments include the NASA instruments (AVIRIS, TIMS and MASTER), the DAIS instrument operated by the German remote sensing agency DLR, as well as private companies such as HyVISTA who operate the HyMAP scanner or the Probe series of instruments operated by Earth Search Sciences, Inc.

Imaging Spectroscopy is the acquisition of images where for each spatial resolution element in the image a spectrum of the energy arriving at the sensor is measured. These spectra are used to derive information based on the signature of the interaction of matter and energy expressed in the spectrum. This spectroscopic approach has been used in the laboratory and in astronomy for more than 100 years, but is a relatively new application when images are formed from aircraft or spacecraft.

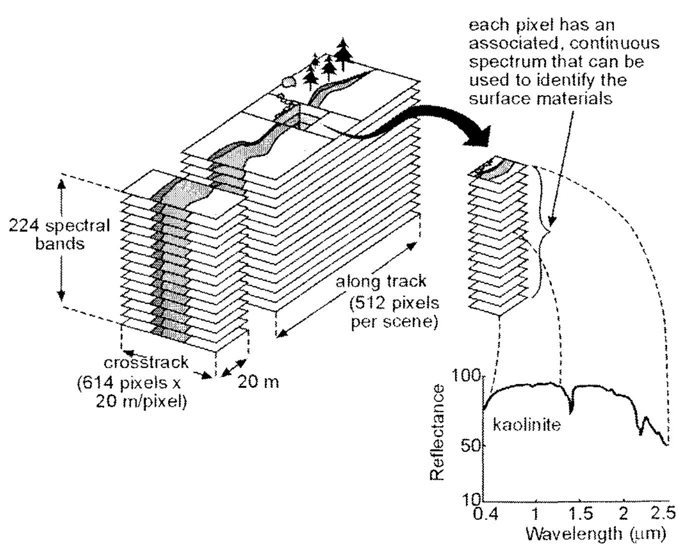

Figure 3.2: Concept of imaging spectroscopy.

3.3.2 Overview hyperspectral imaging sensors

An overview of imaging spectrometry sensors that are discussed here is given in Table 3.2.

Table 3.2: Some imaging spectrometry satellites.

Platform	Sensor	Spatial resolution	Spectral bands	Spectral range (μm)	Swath width	Revisit time
ENVISAT-1	MERIS	300 m	15			
EOS-AM1	ASTER	15-90 m	14	0.52–11.65	60 km	
Orbview 4		8 m	200	0.45–2.5	5 km	3 days
NMP/EO-1	Hyperion	30 m	220	0.4–2.5	7.5	
	LAC	250 m	256	0.9–1.6	185 km	
Aries-1		30 m	64	0.4–1.1	15 km	7 days
			64	2.0–2.5		

3.3.2.1 ENVISAT-1

The European Space Agency (ESA) is developing two spaceborne imaging spectrometers: The Medium Resolution Imaging Spectrometer (MERIS) and the High Resolution Imaging Spectrometer (HRIS); now renamed to PRISM, the Process Research by an Imaging Space Mission (Posselt *et al.* 1996). MERIS, currently planned as payload for the satellite Envisat-1 to be launched in 2002, is designed mainly for oceanographic application and covers the 0.39–1.04 μm wavelength region with 1.25 nm bands at a spatial resolution of 300 m or 1200 m. (Rast and Bézy 1995). PRISM, currently planned for Envisat-2 to be launched around the year 2003, will cover the 0.4–2.4 μm wavelength range with a 10 nm contiguous sampling interval at a 32 m ground resolution.

3.3.2.2 EOS-AM1

The EOS (Earth Observing System) is the centerpiece of NASA's Earth Science mission. The EOS AM-1 satellite, later renamed to Terra, is the main platform that was launched on 18 December 1999. It carries five remote sensing instruments (including MODIS and ASTER). EOS-AM1 orbits at 705 km, is sun-synchronous with a 10:30 equator crossing and a repeat cycle of 16 days. ASTER (the Advanced Spaceborne Thermal Emission and Reflectance Radiometer) has three bands in the visible and near-infrared spectral range with a 15 m spatial resolution, six bands in the short wave infrared with a 30 m spatial resolution, and five bands in the thermal infrared with a 90 m spatial resolution. The VNIR and SWIR bands have a spectral resolution in the order of 10 nm. Simultaneously, a single band in the near-infrared will be provided along track for stereo capability. The swath width of an image will be 60 km with 136 km crosstrack and a temporal resolution of less than 16 days. Also on the EOS-AM1, the Moderate resolution imaging spectroradiometer (MODIS) is planned as a land remote sensing instrument with high revisting time. MODIS is mainly designed for global change research (Justice *et al.*, 1998).

ASTER carries three telescopes: VNIR 0.56, 0.66, 0.81 μm; SWIR 1.65, 2.17, 2.21, 2.26, 2.33, 2.40 μm; TIR 8.3, 8.65, 9.10, 10.6, 11.30 μm with spatial resolutions of VNIR 15 m, SWIR 30 m, TIR 90 m.

3.3.2.3 OrbView 4

OrbView-4 will be the successor of the OrbView-3 high-resolution satellite. As with OrbView-3, OrbView-4's high-resolution camera will acquire 1 m resolution panchromatic and 4 m resolution multispectral imagery. In addition, OrbView-4 will acquire hyperspectral imagery. The sensor will cover the 450 to 2500 nm spectral range with 8 m nominal resolution and a 10 nm spectral resolution in 200 spectral bands. The data available to the public will be resampled to 24 m. The 8 m data will only be used for military purposes. OrbView-4 will be launched on 31 March 2001. The satellite will revisit each location on Earth in less than three days with an ability to turn from side-to-side up to 45 degrees from a polar orbital path.

3.3.2.4 EO-1

NASA's New Millennium Program Earth Observer 1 (NMP/EO-1; see Table 3.3) is an experimental satellite carrying three advanced instruments as a technology demonstration (EO-1 is now called Earth Observing-1). It carries the Advanced Land Imager (ALI), which will be used in conjunction with the ETM+ sensor (see Landsat 7 below for a comparison of the two sensors). Next to the multispectral instrument it carries two hyperspectral instruments, the Hyperion and the LEISA Atmospheric Corrector (LAC). The focus of the Hyperion instrument is to provide high-quality calibrated data that can support the evaluation of hyperspectral technology for spaceborne Earth observing missions. It provides hyperspectral imagery in the 0.4 to 2.5 μm region at continuous 10 nm intervals. Spatial resolution will be 30 m. The LAC is intended to correct mainly for water vapour variations in the atmosphere using the information in the 890 to 1600 nm region at 2 to 6 nm intervals. In addition to atmospheric monitoring, LAC will also image the Earth at a spatial resolution of 250 m. The imaging data will be cross-referenced to the Hyperion data where the footprints overlap. The EO-1 was successfully launched on 21 November 2000.

Table 3.3: Characteristics of EO-1.

	Hyperion LAC	
Spectral range	0.4–2.5 m	0.9–1.6 m
Spatial resolution	30 m	250 m
Swath width	7.5 km	185 km
Spectral resolution	10 nm	2–6 nm
Spectral coverage	continuous	continuous
Number of bands	220	256

3.3.2.5 Aries-1

Aries-1 is a purely Australian initiative to build a hyperspectral satellite, mainly targeted at geological applications for the (Australian) mining business. The ARIES-1 will be operated from a 500 km sun-synchronous orbit. The system will have a VNIR and SWIR hyperspectral, and PAN band setting with 128 bands in the 0.4 – 1.1 μm and 2.0 – 2.5 μm regions. The PAN band will have 10 m resolution, the hyperspectral bands will have 30 m resolution. The swath width is 15 km with a revisit time of 7 days.

3.3.3 Applications and perspectives

The objective of imaging spectrometry is to measure quantitatively the components of the Earth from calibrated spectra acquired as images for scientific research and applications. In other words, imaging spectrometry will measure physical quantities at the Earth's surface such as upwelling radiance, emissivity, temperature and reflectance. Based upon the molecular absorptions and constituent scattering characteristics expressed in the spectrum, the following objectives will be researched and solution found to:

- Detect and identify the surface and atmospheric constituents present
- Assess and measure the expressed constituent concentrations
- Assign proportions to constituents in mixed spatial elements
- Delineate spatial distribution of the constituents
- Monitor changes in constituents through periodic data acquisitions
- Simulate, calibrate and intercompare sensors.

Through measurement of the solar reflected spectrum, a wide range of scientific research and application is being pursed using signatures of energy, molecules and scatterers in the spectra measured by imaging spectrometers. Atmospheric science includes the use of hyperspectral sensors for the prediction of various constituents such as gases and water vapour. In ecology, some use has been made of the data for quantifying photosynthetic and non-photsynthetic constituents. In geology and soil science, the emphasis has been on mineral mapping to guide in mineral prospecting. Water quality studies have been the focus of coastal zone studies. Snow cover fraction and snow grain size can be derived from hyperspectral data. Review papers on geological applications can be found in van der Meer (1999). Cloutis (1996) provides a review of analytical techniques in imaging spectrometry while Van der Meer (2000) provides a general review of imaging spectrometry. Clevers (1999) provides a review of applications of imaging spectrometry in agriculture and vegetation sciences.

3.4 HIGH TEMPORAL RESOLUTION SATELLITES

3.4.1 Low spatial resolution satellite systems with high revisiting time

Typically, these satellites (Table 3.4) have a spatial resolution larger than 100 m. They trade reduced spatial and spectral resolution against high frequency visits. A global system of geo-stationary and polar orbiting satellites is used to observe global weather. Other satellites are used for oceanography, and for mapping phenomena on a continental or even global scale. Typical low-resolution satellite systems have a spatial resolution of 100 m or lower, few (3–7) spectral bands, large (>500 km) swath width and daily revisit capability.

Table 3.4: A selection of low-resolution satellites with high revisiting time.

Platform	Orbit	Sensor	Spatial resolution	Spectral bands	Swath width	Revisit time
Meteosat	GEO	VISSR	2.5 km	3	Earth Disc	30 min
NOAA	Polar	AVHRR	1	7	3000 km	Daily
Resurs-O1	Sun-sync	MSU-SK1	200–300 m	4	760 km	3–5 days
SeaStar	Sun-sync	SeaWiFS	1.1 km	8	2800 km	Daily

3.4.1.1 Meteosat

Meteosat 1 was the first European meteorological geo-stationary satellite. Meteosat 5 is currently the primary satellite, with Meteosat 6 as standby. Meteosat is controlled by Eumetsat, an international organization representing 17 European states. Meteosat Second Generation (MSG) will appear in the year 2000, together with the first polar orbiting Metop satellite. Meteosat is in a geo-stationary orbit at 0° longitude. The sensor has spectral bands at 0.5–0.9 μm (VIS), 5.7–7.1 μm (WV), and 10.5–12.5 μm (TIR) with spatial resolutions of 2.5 km VIS and WV and 5 km TIR. The revisit time is 30 minutes.

3.4.1.2 NOAA

The NOAA satellite program, designed primarily for meteorological applications, has evolved over several generations of satellites (TIROS, ESSA, TIROS-M, and TIROS-N, to NOAA-KLM series), starting with TIROS-1 through to the most recent NOAA-15. These satellites have provided different instruments for measuring the atmosphere's temperature and humidity profiles, the Earth's radiation budget, space environment, instruments for distress signal detection (search and rescue), instruments for relaying data from ground-based and airborne stations, and more.

For Earth observation the most interesting instrument is the Advanced Very High Resolution Radiometer (AVHRR) scanner. The AVHRR scans the Earth in five spectral bands: band 1 in the visible red around 0.6 μm, band 2 in the near infrared around 0.9 μm, band 3 in the mid-wave infrared around 3.7 μm, and band 4 and 5 in the thermal infrared around 11 and 12 μm respectively. This combination of bands makes the AVHRR suitable for a wide range of applications, from measurement of cloud cover, to sea surface temperature, vegetation, land and sea ice. The disadvantage of the AVHRR is its coarse resolution of about 1 km at nadir. But the major benefit of the AVHRR lies in its high temporal frequency of coverage.

The NOAA satellites are operated in a two-satellite system. Both satellites are in a sun-synchronous orbit, one satellite will always pass around noon and midnight, the other always passing in the morning and in the evening. The AVHRR sensors have an extreme field of view of 110°, and together they give a global coverage each day! Every spot on Earth is imaged at least twice each day, depending on latitude. It is *the* instrument for observation of phenomena on a global scale. Owing to its frequent revisit time, it is being used for many monitoring projects on a regional scale.

The imagery of the AVHRR is also known by other names. The HRPT (High Resolution Picture Transmission) is the digital real-time reception of the imagery by a ground station. There are over 500 HRPT receiving stations registered by the World Meteorological Organization (WMO) worldwide. The satellite can also be programmed to record a number of images. Such images, although having the same characteristics as HRPT, are called LAC (Local Area Coverage). Next to the 1 km resolution LAC, the satellite can resample the data on the fly to 4 km resolution GAC (Global Area Coverage). Finally, two bands of 4 km resolution imagery are transmitted by an analogue weather fax signal from the satellite, which can be received by relatively simple and low-cost equipment. This is called the APT (Automatic Picture Transmission). Two excellent sources of information on NOAA are Cracknell (1997) and D'Souza *et al.* (1996).

NOAA-14 (since 30 Dec 1994) and NOAA-15 (since 13 May 1998) are in a 850 km, 98.9°, sun-synchronous (afternoon or morning) orbit. The spatial resolution is 1 km at nadir, 6 km at limb of sensor. Spectral bands include band 1 at 580-680 nm, band 2 at 725-1100 nm, band 3 at 3.55-3.93 µm, band 4 at 10.3-11.3 µm and band 5 at 11.4-12.4 µm. The revisit time is 2-14 times per day, depending on latitude. NOAA-16 was launched on 21 September 2000.

3.4.1.3 Resurs-O1

Launched on 10 July 1998, the Resurs-O1#4 is the fourth operational remote sensing satellite in the Russian Resurs-O1 series. Maybe it is not altogether fair to list the Russian Resurs under the low-resolution category as it is actually equivalent to the US Landsat. But the satellite is best known for its relatively cheap large coverage images of the MSU-SK conical scanner. There are only two receiving stations located in Russia and in Sweden. The Swedish Space Corporation Satellitbild also processes and distributes the images. With a swath of 760 km and resolution of about 250 m Resurs fills the gap between the 1 km resolution NOAA images and the 30 m resolution Landsat images. Resurs-O1 is in a 835 km, 98.75°, sun-synchronous orbit. The sensor has spectral bands at 0.5–0.6 µm, 0.6–0.7 µm, 0.7–0.8 µm, 0.8–1.1 µm and 10.4–12.6 µm with a 30 m (MSU-E) and 200–300 m (MSU-SK) spatial resolution. The swath width is 760 km with a 3–5 day revisit time.

3.4.1.4 OrbView-2, a.k.a. SeaStar/SeaWiFS

Launched on 1 August 1997, SeaStar delivers multispectral ocean-colour data to NASA until 2002. This is the first time that the US Government has purchased global environmental data from a privately designed and operated remote sensing satellite. SeaStar carries the SeaWiFS Sea-viewing Wide Field Sensor, which is a next generation of the Nimbus 7's Coastal Zone Color Scanner (CZCS). SeaWiFS measures ocean surface-level productivity of phytoplankton and chlorophyll. However, SeaStar was originally designed for ocean colour but later changed to be able also to measure the higher radiances from land. Thus, it provides a more environmentally stable vegetation index than the one derived from NOAA's AVHRR, which is inaccurate under hazy atmospheric conditions because of its single visible and near infrared channels. Band 1 looks at gelbstoffe, bands 2 and 4 at chlorophyll, band 3 at pigment, band 5 at suspended sediments. Bands 6, 7 and 8 look at atmospheric aerosols, and are provided for atmospheric corrections.

Orbview-2 is in a 705 km, 98.2°, sun-synchronous, equator crossing (at noon) orbit. The spatial resolution of the data is 1.1 km, the swath width is 2800 km with a 1 day revisit time. Spectral bands of the system include: 402–422 nm, 433–453 nm, 480–500 nm, 500–520 nm, 545–565 nm, 660–680 nm, 745–785 nm, 845–885 nm.

3.4.2 Medium spatial resolution satellite systems with high revisiting time

These satellites (Table 3.5) all have medium area coverage, a medium spatial resolution, a moderate revisit capability, and multispectral bands characteristic of the current Landsat and Spot satellites. The scale of the images of these satellites makes them especially suited for land management and land-use planning for extended areas (regions, countries, continents). Most of these medium-resolution satellites are in a sun-synchronous orbit.

Characteristics of medium-resolution and satellites with high revisiting time include:

- Spatial resolution between 10 m and 100 m
- 3 to 7 spectral bands
- Swath between 50 km and 200 km
- Incidence angles
- Revisit 3 days and more.

Table 3.5: Some medium-resolution satellites.

Platform	Sensor	Spatial resolution	Spectral bands	Swath width	Pointing capability	Revisit time
Landsat 4&5	TM	30 m	7	185 km	No	16 days
Landsat 7	ETM+	15 m (PAN)	8	185 km	No	16 days
Spot 1-3	HRV	10 m (PAN)	3	60 km	±27°	4–6 days
Spot 4	HRVIR	10 m (PAN)	4	60 km	±27°	4–6 days
Resource21	M10	10 m (PAN)	6	205 km	±30°	3–4 days

3.4.2.1 Landsat

Earth observation is often associated with the Landsat satellites, having been in operation since 1972, while Landsat 5 has been in operation for 15 years! The Landsat satellites were developed in the 1960s. Landsats 1, 2 and 3 were enhanced versions of the Nimbus weather and research satellites, and originally known as the Earth Resources Technology Satellites (ERTS). The moment Landsat 1 became operational its images were regarded as sensational by early investigators. The quality of the images led to the information being put to immediate practical use. It became clear that they were directly relevant to the management of the world's food, energy and environment. The Landsat satellites have flown the following sensors:

- The Return Beam Vidicon (RBV) Camera
- Multi-spectral Scanner (MSS)
- Thematic Mapper (TM).

Landsat 4 was launched on 16 July 1982, and a failing power system on Landsat 4 prompted the launch of Landsat 5 two years later on 1 March 1984. The loss of Landsat 6 in October 1993 was a severe blow to the system. Both Landsat 4 and 5 suffer from degrading sub-systems and sensors and are expected to fail any moment. At present, Landsat 7 is in operation.

The characteristics of Landsats 4 and 5 include:

- Operational: Landsat 5 (since 1 March 1984!)
- Orbit: 705 km, 98.2°, sun-synchronous 09:45 AM local time equator crossing
- Repeat cycle: 16 days
- Sensor: Thematic Mapper (TM), electro-mechanical oscillating mirror scanner
- Spatial resolution TM: 30 m (band 6: 120 m)
- Spectral bands TM (μm): band 1 0.45–0.52; band 2 0.52–0.60; band 3 0.63–0.69; band 4 0.76–0.90; band 5 1.55–1.75;band 6 10.4–12.50; band 7 2.08–2.35
- Field of view (FOV): 15°, giving 185 km swath width.

Characteristics of Landsat 7 include:

- Operational: Landsat 7 Orbit: 705 km, 98.2°, sun-synchronous 10 AM local time equator crossing
- Repeat cycle: 16 days
- Sensor: Enhanced Thematic Mapper+ (ETM+), electro-mechanical oscillating mirror scanner; imagery can be collected in low- or high-gain modes; high gain doubles the sensitivity
- Spatial resolution: 30 m (PAN: 15 m, band 6: 60 m)
- Spectral bands (μm): band 1 0.45–0.52; band 2 0.52–0.60; band 3 0.63–0.69; band 4 0.76–0.90; band 5 1.55–1.75; band 6 10.4–12.50; band 7 2.08–2.35; band 8 (PAN) 0.50–0.90
- Field of view (FOV): 15°, 185 km
- Downlink: X-band, 2x150 Mbit/s, 300 Mbit/s playback
- Onboard recorder: 375 Gbit Solid State Recorder for about 100 ETM+ scenes.

3.4.2.2 SPOT 1/2/3 (Système Pour l'Observation de la Terre)

First named Système Probatoire d'Observation de la Terre (Test System for Earth Observation), but later renamed to Système Pour l'Observation de la Terre (System for Earth Observation), the Spot system has been in operation since 1986. The Spot satellites each carry two identical HRV (High-Resolution Visible) sensors, consisting of CCD (Charge-Coupled Device) linear arrays. Essentially, all the points of one line are imaged at the same time by the many detectors of the linear array. The Spot sensors can be tilted from the normal downward viewing mode by plus or minus 27 degrees, which offers the possibility to view objects from two different sides. These stereo images can be used to determine the height of objects, or even the height of the terrain. Spot 1 was already put in standby mode, but reactivated after Spot 3 failed on 14 November 1996. Spot 3 ran out of power when an incorrect series of commands was sent to the satellite, and could not be recovered. An important addition to Spot 4 is the VEGETATION instrument. With resolution of 1.15 km at nadir, and a swath width of 2,250 kilometers, the VEGETATION instrument will cover almost all of the globe's landmasses while orbiting the Earth 14 times a day. Characteristics of Spot 1/2/3 include:

- Orbit: 832 km, 98.7°, sun-synchronous 10:30 AM local time equator crossing
- Repeat cycle: 26 days
- Sensor: 2xHRV (High Resolution Visible), pushbroom linear CCD array
- Spatial resolution: MS mode 20 m, PAN 10 m
- Spectral bands MS (nm): band 1 500–590; band 2 610–680; band 3 790–890
- Panchromatic mode: 510–730 nm
- Swath width: 60 km
- Steerable: ±27° left and right from nadir
- Of-nadir Revisit time: 4–6 days.

Characteristics of Spot 4 include:

- Orbit: same as SPOT 1-2-3
- Sensors: 2xHRVIR (High-Resolution Visible and Infrared), pushbroom linear CCD array, VEGETATION
- Spatial resolution: MS mode 20 m, PAN 10 m, VEGETATION 1.15 km
- Spectral bands MS (nm): band 1 500–590; band 2 610–680; band 3 790–890; band 4 1.58–1.75 μm
- Panchromatic mode: 610–680 nm (same as MS band 2!)
- VEGETATION bands: band 1 0.43, bands 2/3/4 same as HRVIR
- VEGETATION swath: 2250 km.

3.4.2.3 Resource21

Resource21 is the name of a commercial remote sensing information services and services company based in the US. Resource21 will combine satellite and aircraft remote sensing to provide twice-weekly information products within hours of data collection, based on 10 m resolution multispectral. The complete system will consist of four satellites. All areas on Earth will be visited by one of the satellites every three or four days, resulting in a revisit twice a week. In other words, the constellation will give a global coverage every three or four days at 10 m resolution. The main application areas of Resource21 are agriculture ('precision farming'), and environment and natural resource monitoring.

Resource21 is at a 740 km, 98.6°, sun-synchronous, 10:30 crossing at ascending node orbit. The sensor has spectral bands (μm) at 0.45–0.52 blue, 0.53–0.59 green, 0.63–0.69 red, 0.76–0.90 NIR, 1.55–1.68 SWIR, and 1.23–1.53 cirrus clouds with a 10 m resolution in the VNIR, a 20 m resolution in the SWIR, and a 100 m+ resolution for the cirrus band. The swath width is 205 km with a 3–4 day revisit time. The status of the Resource21 programme is unclear. It has been on hold for some time because of budget considerations, but Boeing continues to work towards a realization of the programme.

3.5 RADAR

3.5.1 Historical overview

RADAR (Radio Detection And Ranging) remote sensing has been used operationally since the 1960s. The technique uses the microwave and radio part of the spectrum, with frequencies between 0.3 GHz and 300 GHz roughly corresponding to wavelengths between 1 mm and 1 m, with wavelengths between 0.5 and 50 cm being widely utilized. Table 3.6 summarizes the available wavelengths, their usage and the availability in terms of sensors.

Table 3.6: Radar bands used in Earth observation, with corresponding frequencies. Sources: Hoekman (1990) and van der Sanden (1997).

Band	Frequency (GHz)	Available in
Ka	35.5 – 35.6	Airborne sensors
K	24.05 – 24.25	Airborne sensors
Ku	17.2 – 17.3	Airborne sensors
Ku	13.4 – 14.0	Airborne sensors
X	9.50 – 9.80	Airborne sensors
X	8.55 – 8.65	Airborne sensors
C	5.25 – 5.35	Airborne sensors, ERS-1, -2, RADARSAT
S	3.1 – 3.3	ALMAZ
L	1.215 – 1.3	Airborne sensors, SEASAT, JERS-1 (out of use)
P	0.44 (central frequency)	Airborne sensors

The first airborne systems were called SLAR (Side Looking Airborne Radar), as the instrument looked at an area that was not directly under, but on one side of, an aircraft. These radar systems are also called RAR (Real Aperture Radar), as the real length of the antenna was used (Hussin *et al.* 1999).

Further technical developments made it possible to increase the antenna length virtually by using the Doppler effect. These systems are called SAR (Synthetic Aperture Radar). This new technique made it possible to increase the spatial resolution without increasing the antenna length (with the sensor flying at the same height) or to mount the sensor on a satellite without loosing too much of the spatial resolution. SAR systems also look at one side of the aircraft or the satellite, however, the term 'SLAR' is never used to describe these radar systems.

The latest development in radar technology is the so-called active phased array antenna, presently only operational in the airborne version in the PHARUS system (PHased ARray Universal SAR), but in future it may be also available in spaceborne systems (i.e., the ASAR instrument of the planned ENVISAT satellite). The advantage of this system is that it is relatively small and lightweight.

Most imaging radar systems use an antenna that generates a horizontal waveform, referred to as horizontal polarization. After backscattering from an object, a portion of the returned energy may still retain in the same polarization as that of the transmitted signal. However, some objects tend to depolarize (the vibration of the wave deviates from its original direction) a portion of the microwave energy. The portion of the signal that is depolarized is a function of surface roughness and structural orientation. The switching mechanism in the emitting and receiving system, alternating between two receiver or emitter channels, permits both the horizontal and the vertical signals to be emitted or echoes to be received and recorded. The notation HH is used to denote that the signal is horizontally emitted and the echo horizontally received, while HV indicates horizontal emission and vertical reception. In the same way the notations VV and VH are used. HH and VV represent like polarization, while HV and VH are called cross-polarization return. HV and VH tend to produce similar results, therefore they are not used simultaneously. The like, or cross-polarization is an important factor when considering the orientation of the ground objects or their geometric properties, e.g. a vertical stump of a tree returns more vertical than horizontally polarized signals.

Radar remote sensing is now used with interferometry. For example, the use of SAR as an interferometer, the so-called SAR interferometry (InSAR; Massonnet *et al.*, 1994), is technically difficult due to stringent requirements for stability of the satellite orbit. Interferometry coupled with satellite SAR offers the possibility to map the Earth's land and ice topography and to measure small displacements over large temporal and spatial scales with subcentimeter accuracy, independent of sun illumination and cloud coverage. Interferometric SAR makes use mainly of the phase measurements in two or more SAR images of the same scene, acquired at two different moments and at two slightly different locations. By interference of the two images, very small slant range of the same surface can be inferred. These slant range changes can be related to topography and/or surface deformations.

The most important drawback of radar images is that the reflections of radar signals are very complex functions of the physical and structural properties, as well as water content of the target objects. This means that the interpretation of radar images is completely different than the interpretation of optical images.

Characteristics of radar satellites include:

- Spatial resolution between 10 m to 100 m
- Single or multiple (up to 3) radar frequencies
- Single or multiple polarization modes (HH, VV, HV, VH)
- Wavelengths/frequencies (see Table 3.6).

3.5.2 Overview of sensors

3.5.2.1 ERS-1 and 2

The European Remote Sensing (ERS 1) satellite has three primary all-weather instruments providing systematic, repetitive global coverage of ocean, coastal zones and polar ice caps, monitoring wave height and wavelengths, wind speed and direction, precise altitude, ice parameters, sea surface temperature, cloud top temperature, cloud cover, and atmospheric water vapour content. ERS-1 was launched on 17 July 1991, it went out of service on 10 March 2000 due to a failure of the attitude control system. ERS-2 was launched on 21 April 1995.

The Active Microwave Instrument (AMI) can operate as a wind scatterometer or SAR. The Along-Track Scanning Radiometer & Microwave Sounder (ATSR-M) provides the most accurate sea surface temperature to date. The Radar Altimeter (RA) measures large-scale ocean and ice topography and wave heights. In addition to these instruments, the ERS 2 also carried a Global Ozone Monitoring Experiment (GOME) to determine ozone and trace gases in troposphere and stratosphere.

The ERS 2 satellite has provided continuity of data until the launch of Envisat 1. ERS 1 and 2 operated simultaneously from 15 August to May 1996, the first time that two identical civil SARs worked in tandem. The orbits were carefully phased to provide 1 day revisits, allowing the collection of interferometric SAR image pairs and improving temporal sampling. Although still working perfectly, a lack of funding required ERS 1 to be put on standby from May 1996.

ERS is a C-band radar system with a 100 km swath and a VV polarization. The orbital parameters include a 771x797 km, 98.55°, sun-synchronous orbit with a 168-day repeat cycle.

3.5.2.2 Radarsat

Radarsat was launched on 4 November 1995. The Boeing Company will launch Canada's Radarsat-2 Earth-observation satellite, synthetic aperture radar (SAR) system in 2003. Radarsat-2, follow-on to Radarsat-1, is a jointly funded programme between the Canadian Space Agency (CSA) and MacDonald Dettwiler. It is part of a public-private sector partnership and a further step towards commercialization of the spaceborne radar imaging business.

Designed, constructed, launched, and operated by the CSA, Radarsat is a commercial radar remote sensing satellite dedicated to operational applications. Its C-band SAR has seven different modes of 10 to 100 m resolution and 50 to 500 km swath widths combined with 25 beam positions ranging from 10 to 60 degrees incidence angles. Thus, a wide variety of products can be offered. The Radarsat system is designed to operate with no backlog, so that all imagery can be processed and distributed within 24 hours and be available to a customer within 3 days of acquisition.

3.5.2.3 Envisat

In 2002 the European Space Agency will launch Envisat-1, an advanced polar-orbiting Earth observation satellite, which will provide measurements of the atmosphere, ocean, land, and ice. Envisat-1, will be placed in a 800 km, 98.55°, orbit with a crossing at the equator at 10:00 and a 35 day repeat cycle, are a large satellite carrying a substantial number of sensors. The most important sensors for land applications are the Advanced Synthetic Aperture Radar (ASAR), the Medium Resolution Imaging Spectrometer (MERIS), and the Advanced Along-Track Scanning Radiometer (AATSR).

An ASAR, operating at C-band, ensures continuity with the image mode (SAR) and the wave mode of the ERS-1/2 AMI. It features enhanced capability in terms of coverage, range of incidence angles, polarization, and modes of operation. The ERS-1 and 2 could only be switched on for 10 minutes each orbit, while the ASAR can take up to 30 minutes of high resolution imagery each revolution.

In normal image mode the ASAR will generate high spatial resolution products (30 m) similar to the ERS SAR. It will image one of the seven swaths located over a range of incidence angles spanning from 15 to 45 degrees in HH or VV polarization. As well as cross-polarization modes (HV and VH). In addition to the 30 m resolution it offers wide swath modes, providing images of a wider strip (405 km) with medium resolution (150 m). The SAR system on Envisat, ASAR, is a C-band system with HH and VV, or HH/HV, or VV/VH modes of polarization. The spatial resolutions are 30 m or 150 m with a swath width of 56–100 km.

3.5.2.4 SIR-C/X-SAR

Together the Shuttle Imaging Radar C (SIR-C, built by JPL/NASA), and the X-band Synthetic Aperture Radar (X-SAR, jointly built by Germany and Italy) allow radar images to be collected at 3 different wavelengths (X, C, and L-band) and 4 different polarization modes (HH, VV, HV, and VH). The first mission was flown on board the Space Shuttle flight STS-59 in April 1994. The second mission was aboard STS-68 in September-October 1994. Roughly 20 per cent of the Earth was imaged at up to 10 m resolution. SIR-C and X-SAR have a spatial resolution of 25 m and use the X, C, and L-band frequencies with HH, VV, HV, VH, polarizations on SIR-C and VV for X-SAR. The swath width is 15–60 km (15–45 km X-SAR).

NASA has launched the Shuttle Radar Topography Mission (SRTM; launched on 11 February 2000) to map a digital elevation map with 16 m height accuracy at 30 m horizontal intervals. SRTM uses the SIR-C antenna working interferometrically with additional antenna on a 60 m long deployable mast. Approximately 80 per cent of the Earth's landmass (everything between 60° north and 56° south latitude) will be imaged in 1000 scenes.

3.5.2.5 JERS-1

JERS-1 is the Japanese Earth Resources Satellite, launched on 11 February 1992. In addition to the SAR system, it carries the OPS (Optical Sensor), which has 7 downward looking bands and one forward viewing band for stereo viewing and uses the L-band frequency with HH polarization. The spatial resolution is 18 m at a 75 km swadth width. The original design lifetime was 2 years, but JERS-1 operated until 1998, when a short-circuit in its solar panels immobilized it. The next Japanese radar system will be on the ALOS (Advanced Land Observing Satellite). ALOS will be launched in the summer of 2003.

An overview of spaceborne radar remote sensing sensors is given in Table 3.7.

Table 3.7: A selection of spaceborne radar remote sensing instruments.

Platform	Sensor	Spatial resolution	Frequency band	Polarization	Swath width	Incidence angle
ERS-1&2	AMI/SAR	30 m	C-band	VV	100 km	23° (up to 35°)
Radarsat-1	SAR	8–100 m	C-band	HH	50–500 km	10–60°
Envisat-1	ASAR	30 m	C-band	HH+VV, HH/HV, VV/VH	56–100 km	17–45°
		150 m			405 km	
Space Shuttle (2x in 1994)	SIR-C	25 m	C + L band	HH,VV,HV, VH	15–60 km	20–55°
	X-SAR		X-band	VV	15–45 km	
JERS-1	SAR	18 m	L-band	HH	75 km	35°

3.5.3 Applications and perspectives

Although some passive radar systems exist, using only the radiation emitted or reflected by the Earth, most radar sensors are active sensors that emit a signal and receive the portion of that signal that is scattered back to the sensor. Therefore, active radar sensors are independent of solar radiation and can operate both day and night. Because they utilize longer wavelengths, radar remote sensing is not obstructed by clouds or by rain. Heavy rainstorms may affect the radar image, especially if a small wavelength was used.

Radar provides information that is different from that obtained from optical and near infrared (NIR) remote sensing. Optical/NIR remote sensing for vegetation is based on differential scattering and absorption by the chlorophyll and leaf area, structural characteristics and chemical composition. In contrast, the radar return signal, or backscatter, is determined by the structure and roughness of the canopy, the spatial distribution of the parts of the plants as well as the moisture content of the plants, and the soil surface characteristics, such as roughness and moisture content. The longer radar wavelengths can penetrate tree canopies and topsoil. The use of SAR as an interferometer opens the possibility of accurate measuring of terrain height and height differences in time leading to estimates of surface deformation with applications in tectonics, volcanology, ice sheet mapping and so on.

3.6 OTHER SYSTEMS

3.6.1 Altimetry

Altimeters use the ranging capability of radar to measure the surface topographic profile, by simply emitting a pulse and measuring the time elapsed between emission and reception. The height h carries a linear relationship with the time lapse t: $h=ct/2$ (Elachi, 1987). Altimeters have been flown on a number of spacecraft, including Seasat, ERS 1&2, and TOPEX/Poseidon. Seasat produced the first images of the topography of the ocean floor, as a dip in the ocean floor causes a dip in the water surface due to reduced gravitational pull. The ocean surface can vary by up to 150 m. Knowing the mean water level of the oceans, minor variations around the mean level can be measured. TOPEX/Poseidon measures ocean temperature by these changes. There appears to be a direct relationship between temperature and water height. The sea surface temperature reflects the temperature in the top few centimeters of water. The sea surface measured by altimetry is related to the temperature at all depths, as well as other parameters, such as the water salinity and ocean currents. Note that, in general, the movement of currents has a bigger effect on sea level (± 1 m) than heating and/or winds (± 12 cm). All spaceborne radar altimeters have been wide-beam systems, limited in accuracy by their pulse duration. Such altimeters are useful for smooth surfaces (oceans), but are ineffective over continental terrain with relatively high relief. A fundamental problem in narrow-beam spaceborne radar altimetry is the physical constraint of antenna size. Again, large antennas are required for small radar footprints.

3.6.2 Scatterometers/spectrometers

Scatterometers are radar sensors that provide the backscattering cross section of the surface area illuminated by the sensor. They are particularly useful in measuring the ocean backscatter in order to derive the near-surface wind vector. The strength of the radar backscatter is proportional to the amplitude of the water surface capillary and small gravity waves (Bragg scattering), which in turn is related to the wind speed and direction near the surface (Elachi 1987).

3.6.3 Lidar

Lidar (LIght Detection And Ranging) refers to laser-based remote sensing. Lidar uses principles very much like the ones used in radar. The main difference is in wavelength; radar uses microwaves; lidar uses visible light. In fact, the term Lidar is a generic term used for a variety of sensors operated by different concepts. Going into detail in each of them would be beyond the scope this chapter.

The main applications of Lidar are measuring distance (height), movement, and chemical composition. By measuring the intensity, polarization, and spectral properties of the return signal as a function of time, one can obtain information on the properties of the atmosphere.

3.7 INTERNET SOURCES

The following provides an overview of internet sources of sensors listed in this chapter and includes sources of information for further reading.

3.7.1 High spatial resolution satellite systems

IRS: http://www.nrsa.org/
KVR: http://www.spin-2.com/
Orbital image (Orbview satellites): http://www.orbimage.com/
Quickbird/Early bird: http://www.digitalglobe.com/company/satellites.html
Ikonos: http://www.spaceimage.com/
EROS: http://www.westindianspace.com/
EROS: http://www.imagesatintl.com/

3.7.2 High spectral resolution satellite systems

ENVISAT: http://envisat.estec.esa.nl/instruments/
EOS-AM1/TERRA: http://terra.nasa.gov/
EOS-PM1/Aqua: http://aqua.gsfc.nasa.gov/
Orbview-4 Orbital image (Orbview satellites): http://www.orbimage.com/
NMP/EO-1: http://eo1.gsfc.nasa.gov/
ARIES: http://www.aries-sat.com.au/

3.7.3 High temporal resolution satellite systems

Meteosat: http://www.esoc.esa.de/external/mso/meteosat.html
NOAA (institute): http://www.noaa.gov/
NOAA (RS data): http://www.nesdis.noaa.gov/
NOAA-POES: http://poes.gsfc.nasa.gov/
Resurs: http://resurs.satellus.se/
Orbview-2 Orbital image (Orbview satellites): http://www.orbimage.com/
SeaWifs: http://seawifs.gsfc.nasa.gov/SEAWIFS.html
Landsat-7 (at USGS): http://landsat7.usgs.gov/
Landat-7 (at NASA): http://landsat.gsfc.nasa.gov/index.htm
Landsat program: http://geo.arc.nasa.gov/sge/landsat/landsat.html
SPOT: http://www.spotimage.fr/

3.7.4 RADAR satellite systems

ERS satellites: http://earth.esa.int/l2/2/ersnewhome
Radarsat: http://radarsat.space.gc.ca/
ENVISAT ASAR: http://envisat.estec.esa.nl/instruments/asar/index.html

SIR: http://southport.jpl.nasa.gov/
JERS (at NASDA): http://www.nasda.go.jp/
ALOS: http://www.eorc.nasda.go.jp/ALOS/
SRTM: http://www.jpl.nasa.gov/srtm/

3.7.5 General sources of information

3.7.5.1 General remote sensing sites

Good points for remote sensing data sources and other related information are:
http://www.itc.nl/~bakker/

3.7.5.2. Imaging spectroscopy

Spectroscopy: http://speclab.cr.usgs.gov/index.html:
Links: http://www.techexpo.com/WWW/opto-knowledge/IS_resources.html
Sensor list: http://www.geo.unizh.ch/~schaep/research/apex/is_list.html/

3.7.5.3 RADAR remote sensing

Glossary of terminology:
http://ceo1409.ceo.sai.jrc.it:8080/aladine/v1.2/tutorials/glossary/agrg.html
Principle of INSAR: http://www.sciam.com/0297issue/0297massonnet.html
Imaging radar: http://southport.jpl.nasa.gov/
Radar and radar interferometry:
http://southport.jpl.nasa.gov/scienceapps/dixon/report1.html

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