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Space

Missions, Applications and Exploration

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Overview

Earth observation is one of the areas in which space activity offers the broadest range of applications, thanks to the ability of satellites to acquire, in the course of repeat visits, overviews of broad areas which when juxtaposed cover the entire planet without the sort of constraints which go with political frontiers.

Earth observation satellite fall into three main families – meteorological satellites, medium-resolution remote-sensing satellites and high-resolution satellites, the latter restricted initially to military reconnaissance activity but today being used increasingly for civil applications.

Satellites belonging to the first of these families typically supply images covering very large areas but offering relatively poor resolution and relying on multiple passes. They are geostationary or placed at the upper end of the low circular orbits at altitudes of around 900 km–1800 km. In either case, they may be deployed in groups of satellite belonging to a single programme, as with the Russian Meteor-II craft or the American NOAA satellites.

Satellites in the second family generally operate from circular orbits at lower altitudes – between 600 km and 1000 km – and provide, at a lower revisit frequency, images with higher spatial resolution. Examples are the American Landsat, French SPOT and Indian IRS series.

Satellites in the third family commonly describe eccentric orbits, performing their observations close to the low-altitude perigee – which can be as low as about 160 km in the case of many Kosmos satellites; this makes for very fine ground resolution. A number of recent satellites, designed for a longer operational life, do however occupy circular orbits, at altitudes below 300 km in the case of those offering the highest resolution. Previously confined to defence duties, this family of satellites is now also being used to meet civil requirements. The launch in 1999 of the Ikonos 2 satellite, belonging to a private company, SpaceImaging, marked the emergence of a civil capability for metre-range resolution from circular orbits below 700 km, orbits not that distant from those occupied by certain military systems offering comparable resolution.

These three major families also differ from each other in terms of status. Meteorological satellites are operated by government bodies in the framework of programmes which may sometimes be international, such as the World Weather Watch. And while there is something of a trend towards commercialising some products, provision of a public service is still the guiding concern.

Remote-sensing satellites relying solely on optical technology and those carrying radar instrumentation, are used for cartography or for the study of continental and marine

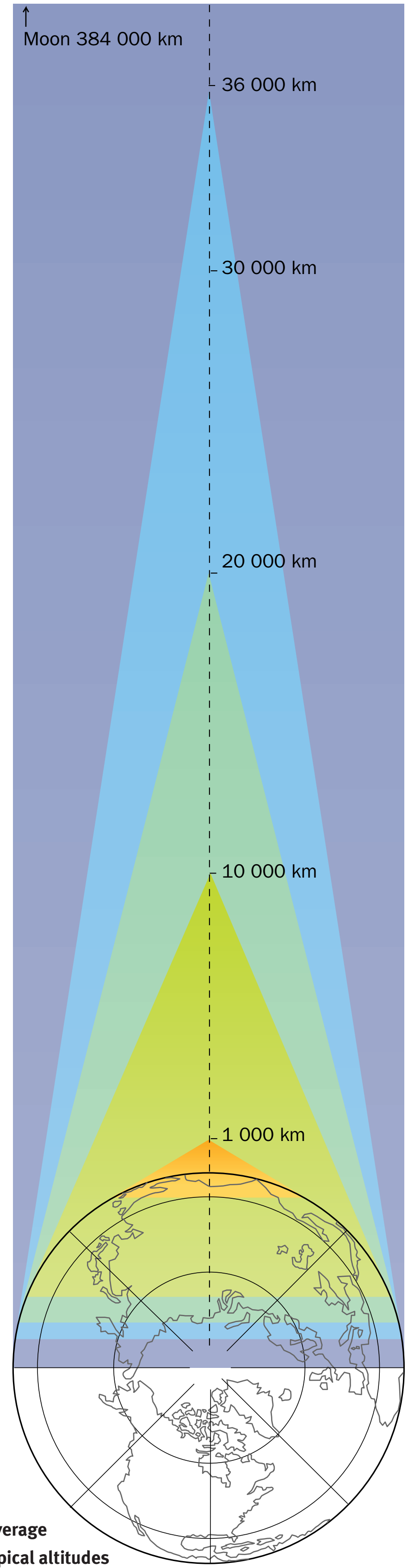


Figure 9.1. **Earth coverage from a number of typical altitudes**

resources. Exploitation of these systems, following initial funding by government agencies, is increasingly being handled by government-supported commercial outfits such as SPOT Image in France and Eosat in the United States. Since 1995 private firms have also been showing considerable interest in this area of activity.

High-resolution satellites are an established feature of military reconnaissance activity (see Chapter 12) but are still something of a rarity in civil Earth observation. This new category of civil programme relies on private funding and is governed at least in theory by industrial and commercial considerations.

In terms of how data are used, it is not always that easy to distinguish between the various families of satellite, especially where the mission addressed – environmental management or risk monitoring for example – is very wide-ranging. NOAA images are a case in point: though intended primarily for meteorology, considerable use is also made of them in the remote sensing of plant resources. Similarly, data collected by civil remote-sensing satellites such as SPOT have potential military uses and degraded data from Russian military satellites or again declassified images acquired by US military satellites may be used and commercialised for civil purposes. The emergence of metre-range resolution civil commercial satellites is confusing the picture still further but points to a growth in the range of potential users.

Altitudes and satellite coverage

The area viewed from satellites expands with altitude, eventually encompassing an entire hemisphere at infinite altitude. At lower altitudes, the variation in coverage is very marked: at 200 km, Apollo 9 could see 1.5% of the Earth's surface at a 151° angle, whereas NOAA 11 surveys more than 10% from its 1600 km vantage point. Conversely, at high altitudes very little variation occurs: at 20 000 km Navstar looks down on 38% of our planet's surface at an angle of 30°, while Meteosat, stationed at 36 000 km, improves that figure only slightly to 42% at an angle of 17° (fig. 9.1, 9.2 and 9.3).

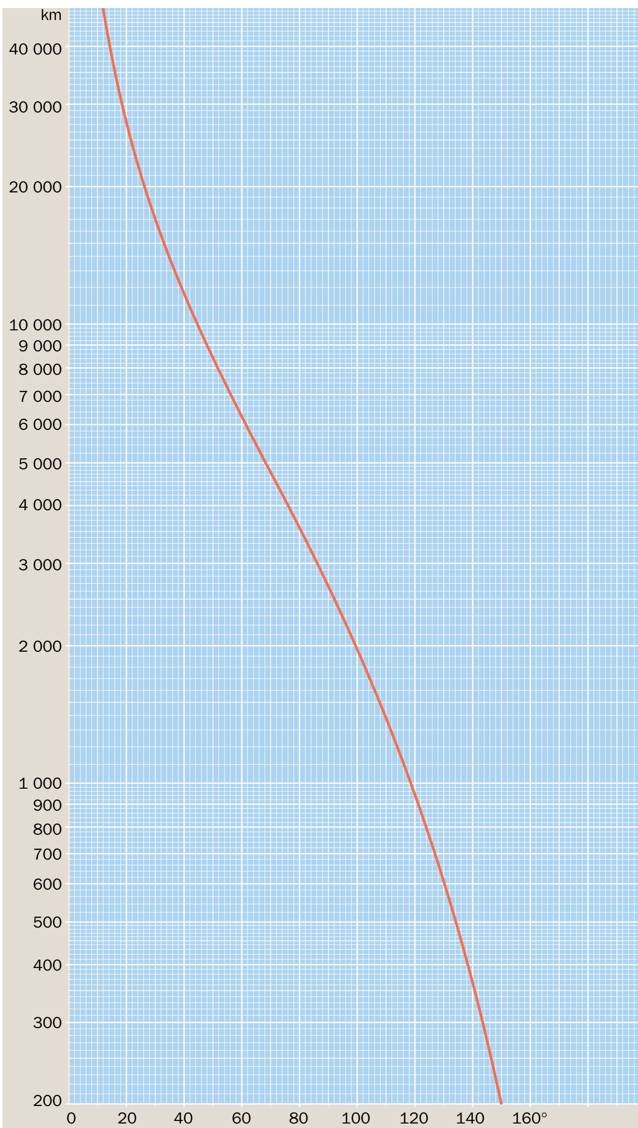


Figure 9.2. **Angle at which the Earth is viewed in relation to altitude**

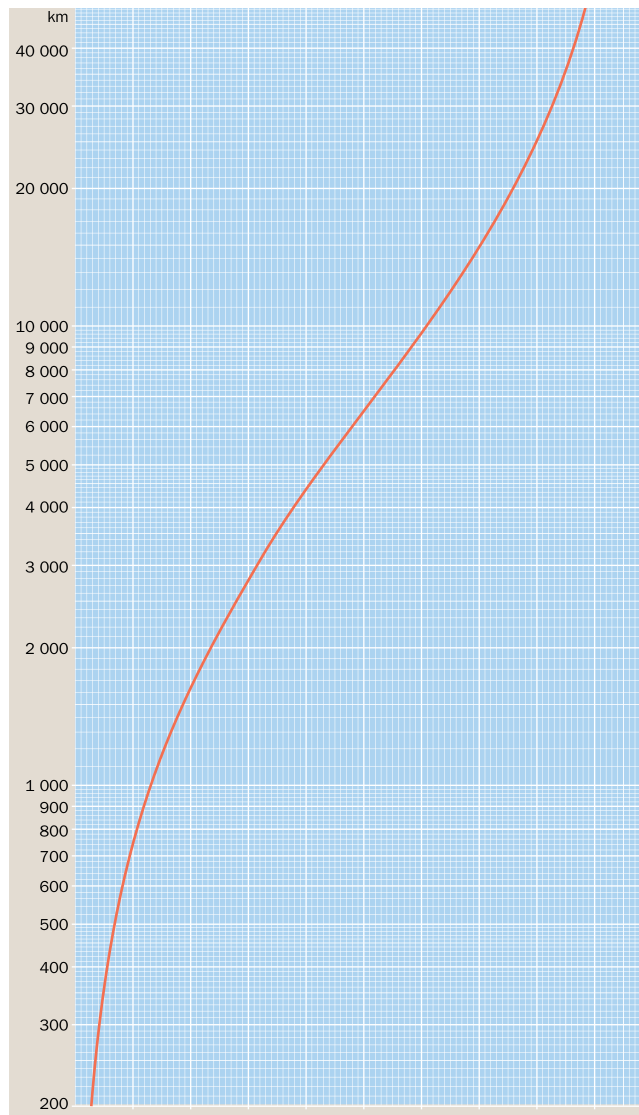


Figure 9.3. **Percentage of the Earth's surface that is visible in relation to altitude**

Sensors measure the electromagnetic radiation emanating from a geometrically defined field. The dimensions of the field are determined by the sensor's optics. The entire field may be explored in one take, with simultaneous acquisition of all points in the image, as with still or TV cameras. The field may also be scanned sequentially, complete images being built up from a juxtaposition of individual readings, as is the case with scanning systems.

The sensor's overall field of view corresponds to the size of the geographical area selected for observation. The *Instantaneous Field of View* (*IFOV*) is defined by the solid angle from which the electromagnetic radiation measured by the sensor at a given point in time emanates. While the sensor's overall field of view and the IFOV coincide in the case of still cameras and to a certain extent when CCDs are used, this does not apply in the case of scanners, whose overall field of view corresponds to the continuous movement of an instantaneous field.

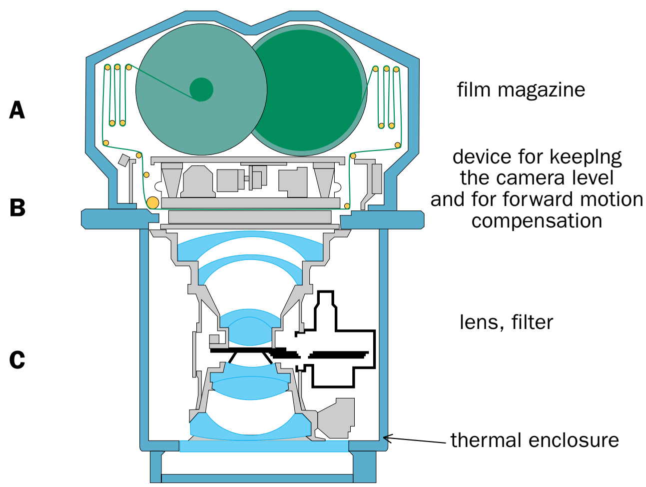


Figure 9.4. **Example of a spaceborne still camera: the Large Format Camera (LFC)**

The LFC is a very powerful multispectral imaging system used on the US Space Shuttle Challenger on its October 1984 mission. It consists of:

A – a magazine containing 1220 m of high-resolution film configured for 2400 images in a 460 mm along track x 230 mm across track format. These rather unusual dimensions support acquisition of images covering ground areas of 153 181 km^2 (553 km × 277 km) from an altitude of 370 km.

B – devices for keeping the camera perfectly level during exposure and for compensating forward motion.

C – a lens with a focal length of 305 mm and an angular aperture of 74°.

In addition, the Altitude Reference System (ARS), comprising two cameras with 152 mm focal lengths, records the star field at the point in time of each acquisition. Simultaneous collection of data concerning the satellite's altitude and position makes for highly precise mapping.

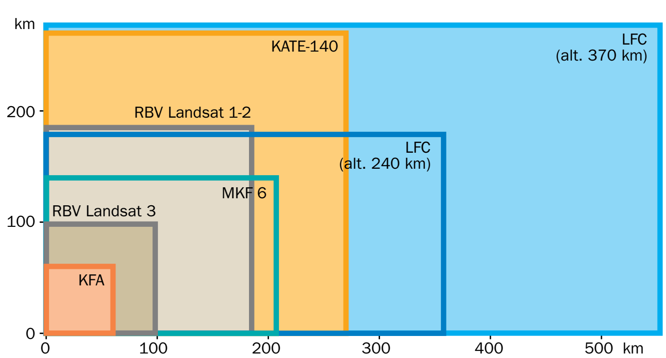


Figure 9.5. **Overall coverage area of some still and TV cameras**

Still cameras

Satellite-borne still cameras support instant acquisition of an image of the area of the Earth's surface over which the satellite is flying (fig. 9.4). The field of view on the ground is determined by the lens used and the altitude at which the satellite is flying. Photographs are generally centred on the nadir and the field dimensions are defined either by angular apertures independent of flight altitude or by altitude-dependent linear measurements on the ground (length of sides or of diagonal) (table 9.1 and fig. 9.5).

The quality of some images can be enhanced by a technique (known as forward motion compensation, or FMC) which counters the change in the satellite's position while the photograph is being taken.

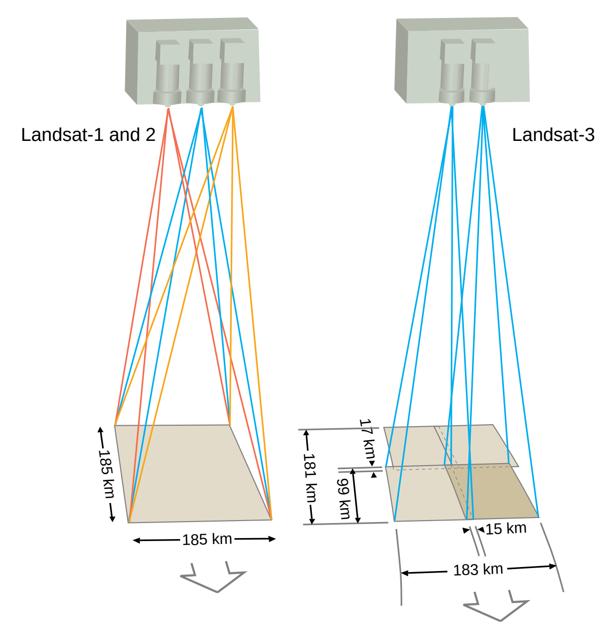


Figure 9.6. **The RBV systems on Landsat 1 and 2 and on Landsat 3**

camera	satellite	altitude (km)	number of lenses	focal length in mm	aperture	viewing angle	ground field in km	scale of the image	frame size in mm	exposure time (seconds)	forward motion compensation	resolution (metres)
Hasselblad	Gemini 4 to 7, 1965 Apollo 9 (S.065), 1969 Apollo 12, 1969	200	4	80	4-16	55°	70 x 70		57 x 57	1/125 - 1/250	—	125 70 70
Multiband Camera	Skylab (S.190 A), 1973	435	6	152	2.8-16	21,2°	163 x 163		57 x 57	1/500	+	99
Earth Terrain Camera (ETC)	Skylab (S.190 B),1973	435	1	460		14,2°	109 x 109		114 x 114	1/100 - 1/200	+	38
MKF-6	Soyuz 22, 1976 Salyut 7, 1982	250 275	6	125	4-13.5	41°	209 x 140	1/2 500 000	80 x 56		+	25 25
KATE-140	Soyouz 35, 1980 Salyut 7, 1982	250 275	1	140	6.8-16	85°	270 x 270	1/1 500 000	180 x 180	1/10 - 1/250	—	30 30
Metric Camera (MC)	STS 9 (Spacelab), 1983	250	1	305	5.6-11.	41°	180 x 180	1/820 000	230 x 230	1/250 - 1/500	—	30
Large Format Camera (LFC)	STS 41 G, 1984	370 240	1	305	8	74° x 41°	553 x 277 358 x 179	1/1 200 000	460 x 230	1/30 - 1/250	+	
ARS		240	2	152	2,8	stellar coverage			70 x 70	1/5	—	
KFA-1000	Resurs F	250	1	1 000		16,2°	75 x 75	1/250 000	300 x 300		—	5 (down to 2)
KVR-1000	Kometa, 1983	220		1 000	5	11,4°	37 x 165	1/220 000	758 x 40		+	0.75
TK-350	Kometa, 1983	220		350	5.6		200 x 300	1/630 000	284 x 189			10
KATE-200	Resurs F1, 1986	260		200			180 x 180	1/1 000 000	180 x 180			15
KFA-3000	Resurs F3, 1986	260		3 000			21 x 21	1/70 000	300 x 300			2
MK-4	Resurs F2, 1988	220		300			130 x 130	1/730 000	180 x 180			5
Return Beam Vidicon (RBV) Return Beam Vidicon (RBV)	Landsat 1-2, 1972 and 1975 Landsat 3, 1978	900 900	3 2	126 250		8° 4°	185 x 185 98 x 98			1/62 - 1/83 - 1/125		80 80

Table 9.1. **Technical characteristics of spaceborne still and TV cameras**

Some still cameras used on military reconnaissance satellites feature a very narrow field and hence a very long focal distance. A case in point is the KFA 3000 high-resolution camera equipping various Russian satellites which comprises a telescope with a focal length of 3 m.

Television cameras

Though very different from still cameras, TV cameras nevertheless also take the complete image immediately and their overall field of view coincides with the instantaneous field. When the shutter has closed the images are stored in a charge storage layer. The images are explored subsequently by means of scanning. The Return Beam Vidicon (RBV) systems on Landsat 1 to 3 are a good example of this (fig. 9.6).

Scanners and push-broom sensors

Scanners take measurements in the instantaneous field of view as it moves along the scanlines. The ground width of the IFOV, perpendicular to the scanning direction, widens as the distance between the sensor and the ground increases; in other words the field moves expands away from the satellite's nadir point and towards the limb. The lower the satellite altitude the greater the impact of this variation in strip width. Moreover, the ground length of the instantaneous field of view in the scanning plane increases with its skew from the viewing angle. It follows that with sensors which scan the Earth's surface from one limb to the other, the ground area encompassed by the instantaneous field of view varies considerably (fig. 9.7).

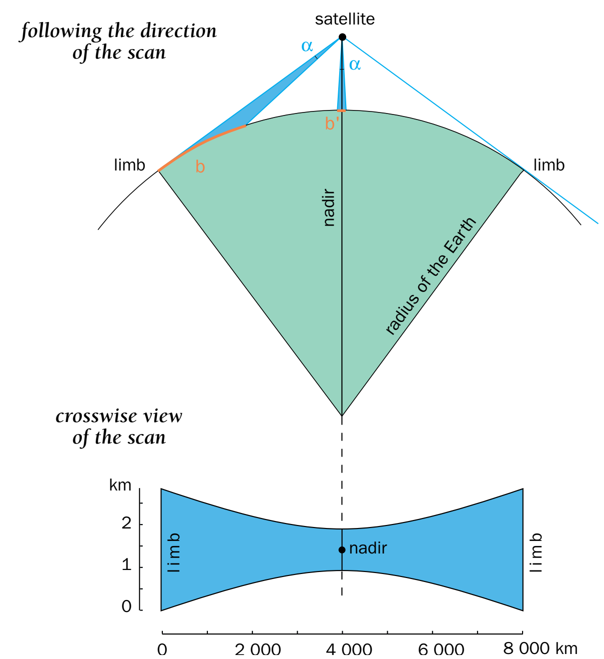


Figure 9.7. **Ground dimensions of the instantaneous field of view with limb-to-limb scanning.** The example shown here is the VHRR sensor on the NOAA 2 to 5 satellites.

Surfaces sensed by scanners are scanned in successive lines. The scanning process and scanlines result from a combination of the satellite's movements and those of the scanner itself.

Where geostationary satellites are concerned, the succession of scanlines is obtained by a mechanical device which orients the telescope. Each new line of images scanned by the

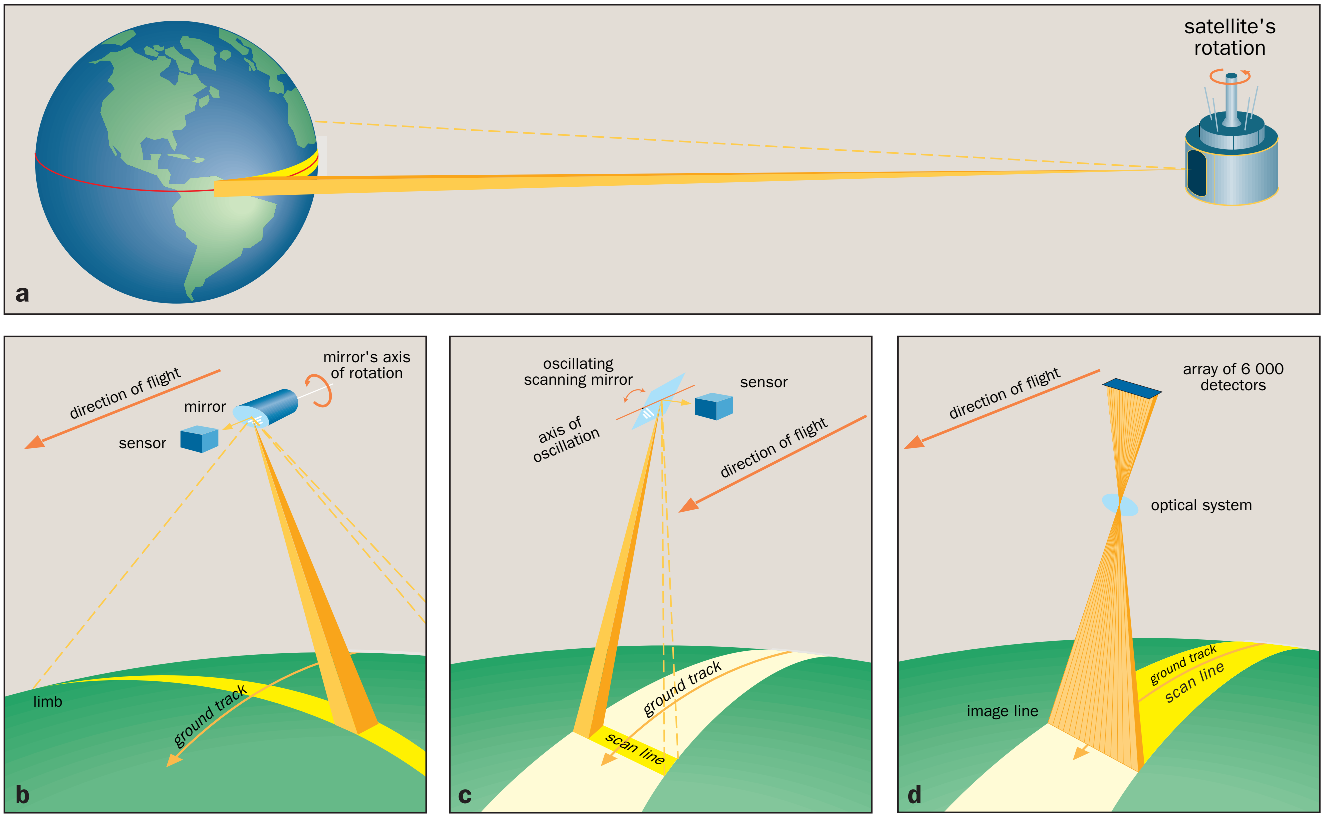


Figure 9.8. **The main scanning systems.**

a) Limb-to-limb scanning by satellite rotation. The example shown is the geostationary satellite Meteosat.
b) Scanning by mirror rotation.
c) Scanning by mirror oscillation.
d) Push-broom system. An array comprising a large number of detectors sweeps the ground in the direction of flight.

telescope is offset by a constant step from the line before. The Meteosat telescope thus moves through 18° in the course of 2500 passes in a north-south direction. Line scanning is effected by satellite rotation.

In the case of non-geostationary satellites, the general succession of scanlines is obtained by the motion of the satellite along its orbit. Scanlines may go from one terrestrial limb to the other or be restricted to much shorter distances corresponding to only part of our planet's apparent arcs.

Scanners performing limb-to-limb imaging explore a complete circle, of which the Earth's surface occupies only a small arc. In the case of geostationary satellites, this represents at most 17° of the total 360° sweep. Such scanners use various types of rotating system. In some cases – Meteosat being one example – a 360° scan is obtained by rotation of the satellite itself (fig. 9.8a). Another type of scanner uses a mirror revolving round an axis parallel to the satellite's velocity vector, a case in point being the Advanced Very High Resolution Radiometer (AVHRR) fitted to satellites NOAA 6 to 11 (fig. 9.8b). Some sensors do not sweep a complete circle, scanning only a limited arc in the visible part of the Earth. Scanning may be effected by oscillation of a mirror about an axis parallel to the satellite's velocity vector, as with the MSS and TM sensors carried by the Landsat series (fig. 9.8c). Finally, some mechanical systems perform conical scanning, the advantage of this approach being that a constant distance is maintained between the sensor and the ground throughout the scanned area: this is the case with the OCTS sensor which equipped ADEOS 1.

Detector cells arranged in linear array, with no mechanical scanning mechanism, can also be used to collect data along ground scanlines, using the platform's motion to sweep the ground in the direction of flight (push-broom concept). The HRV and HRVIR sensors on SPOT satellites, which measure energy using detectors configured in a Charge Coupled Device (CCD) array, are an example of this kind of arrangement (fig. 9.8d). CCD arrays of this kind can be replaced by Active Pixel Sensors (APS) which are intended to offer simplified sensing electronics through incorporation of many functions in the sensor itself.

The median line corresponding to the centre of the field of view scanlines is known as the instrument track. This coincides with the satellite ground track where viewing and scanning are centred on the nadir but is offset from it in the case of oblique viewing (fig. 9.9a). Some sensors have a capability of inclining their viewing axis either side of nadir. The High Resolution Visible (HRV) instrument on SPOT 1 to 3, for example, can adjust to 90 different inclinations in 0.6° steps within a total angle of 54° (fig. 9.9b).

Where oblique viewing angles are programmable, imaging at large distances from the satellite track becomes possible, which makes for considerable flexibility. By acquiring

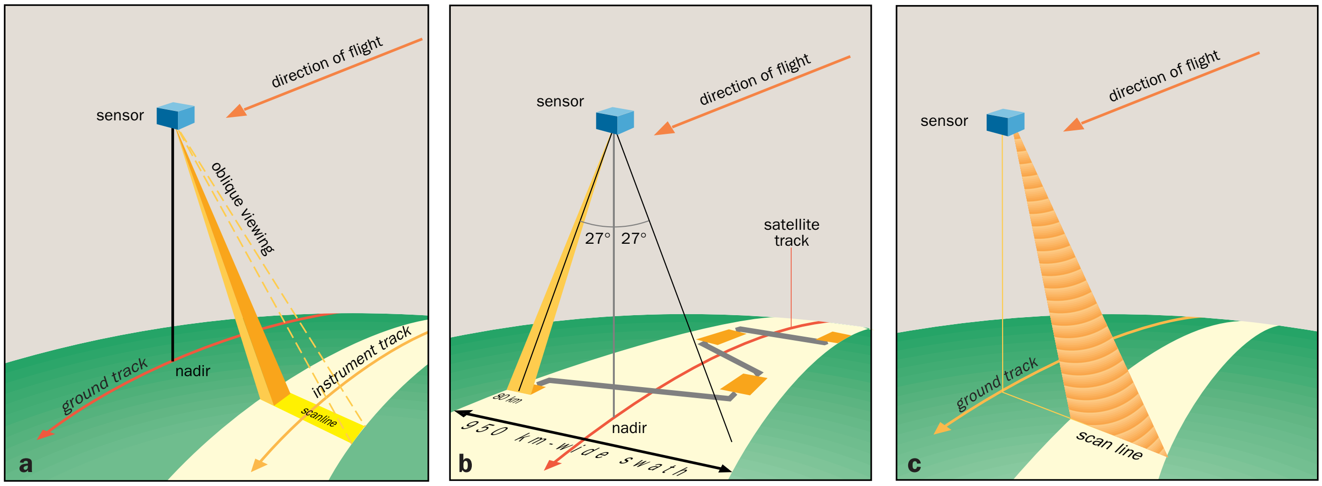


Figure 9.9. **Oblique viewing**

a) Instrument track and satellite track
b) SPOT: oblique viewing. The viewing angle may be remotely adjusted from the ground. The areas observed must be situated within a 950 km wide viewing corridor straddling the satellite track. Scene widths range from 60 km near nadir to 80 km with extreme sideways viewing.
c) Off-nadir swath of the Side Aperture Radar.

images of the same ground area from different viewpoints, the terrain can be mapped stereoscopically. This can be achieved through oblique viewing, as with SPOT 1 to 4, but it is also possible to build up stereoscopic images from series of observations taken from different viewpoints on the same orbit; this involves combining forward and nadir observations, as in the case of JERS 1.

The value most frequently used in defining the qualities of a remote-sensing instrument is the instantaneous field of view (IFOV). This is determined by the sensor's optics and is defined by a plane angle measured in radians and a solid angle measured in steradians. The instantaneous field of view is constrained by the radiometric sensitivity of the detector, which has to be exposed long enough to receive sufficient energy to operate effectively. The use of detector arrays, making it possible to obtain longer exposure times than with mechanical scanning systems, has done much to reduce the instantaneous field of view and this form of detection is now used on all fine-resolution sensors. The need for a minimum quantity of energy to ensure satisfactory observation quality also explains why higher spatial resolutions are incompatible with finer spectral resolutions. To take the example of the HRV on SPOT 1 to 3: panchromatic operation can be associated with 10 m resolution, whereas multispectral mode operation with its narrower spectral bands is consistent with 20 m resolution.

The lower the satellite's altitude and the nearer the angle formed by the viewing axis and the ground to 90°, the smaller the ground area intercepted by the solid angle. At the sub-satellite point, that area is taken to be a square, the length of whose sides can be seen from the graph in fig. 9.10.

Sensors which collect data in the thermal infrared band have lower resolving power than those operating in the visible or near infrared spectral regions. IFOV angles are generally wider in the thermal infrared than in either the visible or the near infrared.

Imaging radars

Sensors which measure naturally emitted radiation in the form of light or heat are passive remote-sensing instruments. Remote sensing is active, on the other hand, where the sensor itself emits radiation and then measures the radiation returned to the sensor, one example being radar instruments. Given the altitudes at which the satellites operate and the oblique sensing often used, enough energy must be emitted for the system to pick up the echo at considerable distances. Providing such quantities of energy on board is however a difficult matter, which explains why the use of space radar is lagging so far behind that of airborne radar.

Radar instruments have the advantage over optical sensors that they can operate round the clock – since they themselves emit the signal whose return values they then measure. And since they use microwaves, they can penetrate cloud cover with no effect on imagery.

Radars emit signals and receive the returning echoes, which are sent back by the ground in a variable length of time depending on the distance separating sensor and target. Target objects are located by measuring the varying distances between them and the sensor and not, as with other types of sensor, by the sensing angle. Synthetic Aperture Radars (SARs) use the frequency variation caused by the Doppler effect to produce high-resolution images.

Viewing is necessarily oblique and is generally restricted to one side of the satellite trajectory, either left or right (fig. 9.9c). In the case of Radarsat, viewing is normally to the right of the flight track but the look direction can be reoriented to left of the track by 180° rotation manoeuvres around the yaw axis (fig 9.11).

Radars can use vertical (V) or horizontal (H) polarisation for emission and reception. Four types of image can thus be obtained, two with parallel polarisation (HH and VV) and two with cross-polarisation (HV and VH). These various permutations were all operational together for the first time in

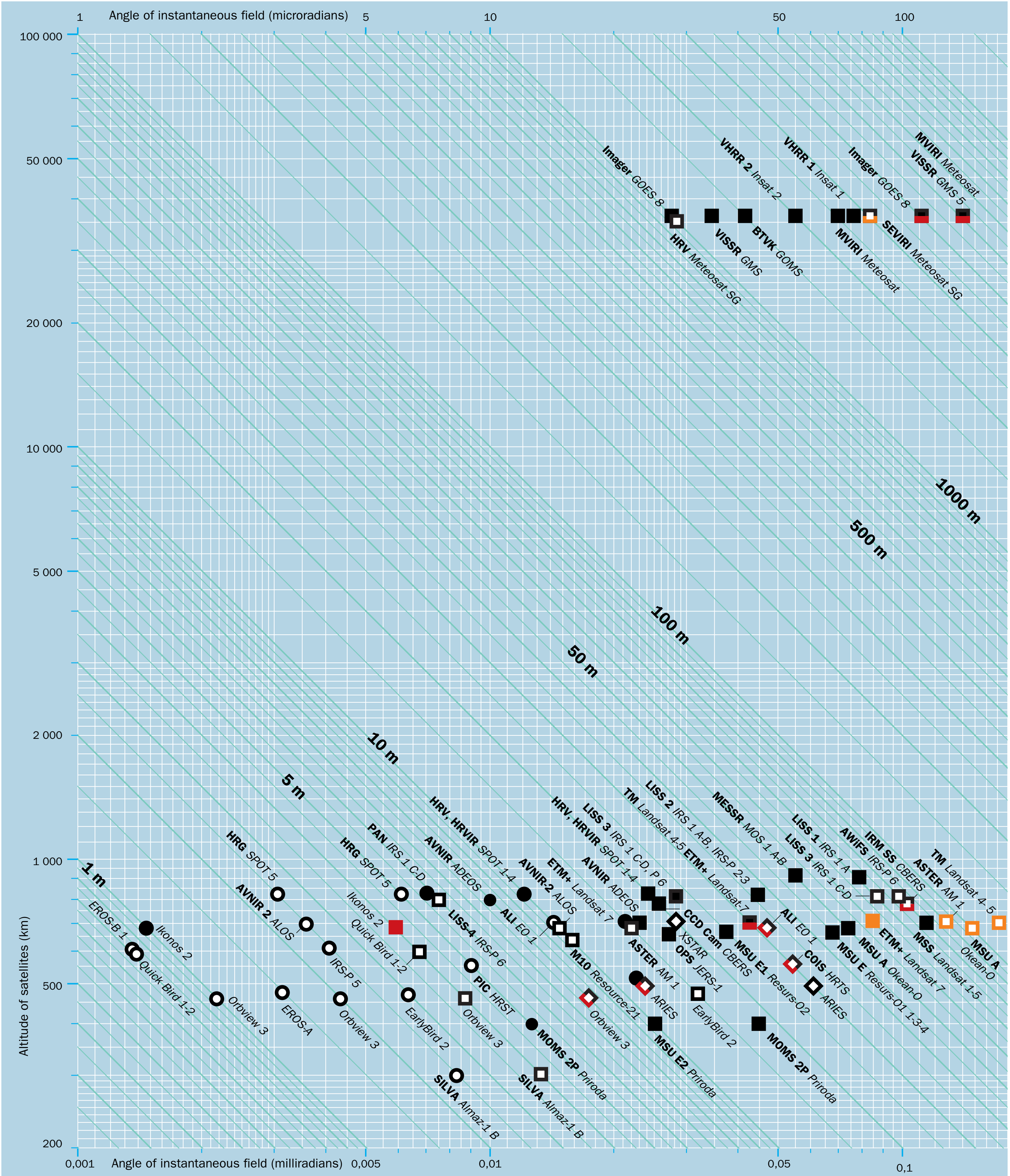
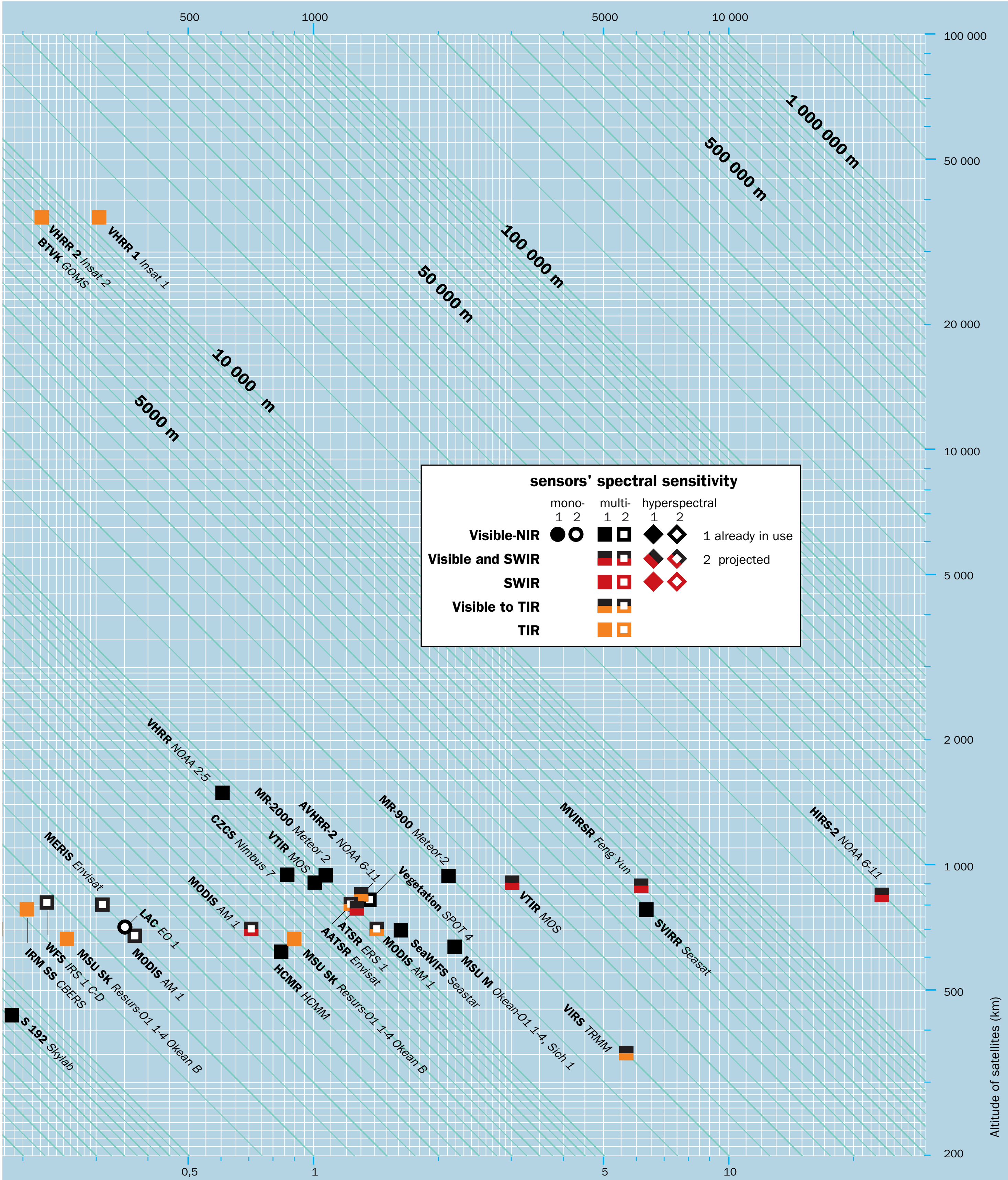


Figure 9.10. **Instantaneous fields of view.** Relationship between the satellite altitude (vertical scale), the angle of instantaneous field of view (horizontal scale) and the IFOV at the sub-satellite point (oblique scale).



500
1000
5000
10 000
100 000
50 000
20 000
10 000
5 000
2 000
1 000
500
200
0,5
1
5
10
Altitude of satellites (km)
1 000 000 m
500 000 m
100 000 m
50 000 m
10 000 m
5000 m
sensors' spectral sensitivity
mono-
multi-
hyperspectral
1 2
Visible-NIR
Visible and SWIR
SWIR
Visible to TIR
TIR
1 already in use
2 projected
VHRR 2 Insat 2
BTVK GOMS
VHRR 1 Insat 1
VHRR NOAA 2-5
MR-2000 Meteor 2
AVHRR-2 NOAA 6-11
MR-900 Meteor-2
MVIRSR Feng Yun
HIRS-2 NOAA 6-11
CZCS Nimbus 7
VTIR MOS
MERIS Envisat
Vegetation SPOT 4
VTIR MOS
SVIRR Seasat
LAC EO 1
MODIS AM 1
ATSR ERS 1
AATSR Envisat
MODIS AM 1
SeaWIFS Seastar
MSU M Okean-O1 1-4, Sich 1
VIRS TRMM
WFS IRS 1 C-D
IRM SS CBERS
MSU SK Resurs-O1 1-4 Okean B
MODIS AM 1
HCMR HCMM
MSU SK Resurs-O1 1-4 Okean B
S 192 Skylab

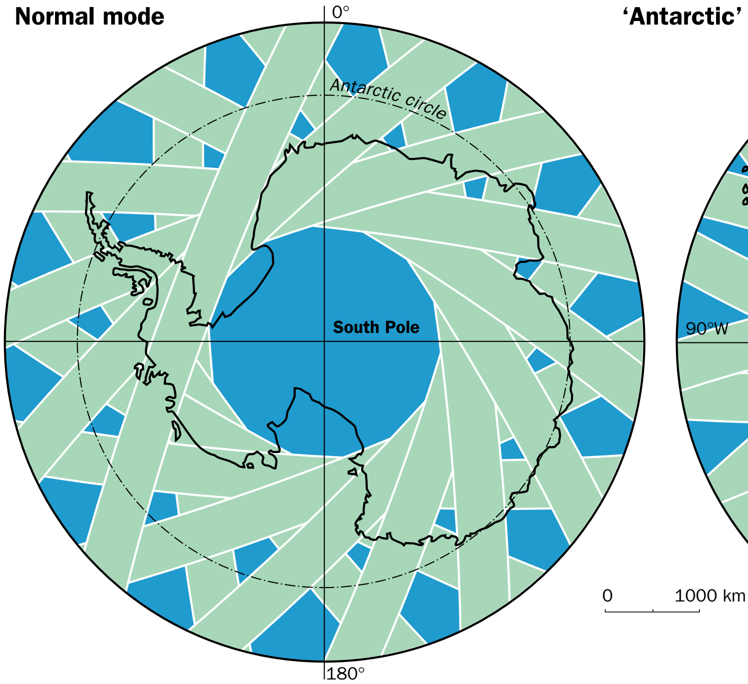


Figure 9.11. **Radarsat swaths over the Antarctic.** The strips represent the first day of synthetic aperture radar coverage with a 500 km swath. Viewing is to the right in normal operating mode and to the left in "Antarctic" mode.

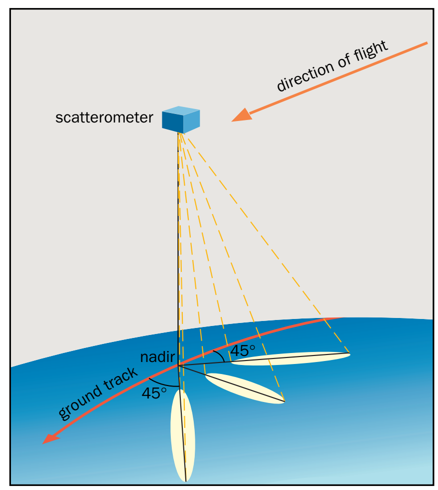


Figure 9.12. **Scatterometer viewing angles.** This is the arrangement on the AMI on ERS 1 and 2.

SIR C. By using a range of polarisations the radiometric quality of imagery can be improved without a resolution penalty.

Finally, it is also possible to use the phase difference between two radar echoes returned by the same terrain and received along two trajectories very close together, a technique known as interferometry. This technique, use of which is becoming increasingly widespread, offers a means of reconstituting terrain relief, in order in particular to elaborate digital elevation models. The critical limit - the distance beyond which the two radar beams become incoherent and interferometry can no longer be performed - increases as the wavelength used gets longer. The critical distance for SAR data collected on two trajectories by the ERS satellites operating in the C-band - something like 800 m – is shorter than in the case of Seasat operating in the L-band.

Non-imaging systems

Earth observation also makes use of sensors collecting data which do not build up to an image of the Earth in any literal sense. There are many different kinds of non-imaging sensor. They may take measurements relating to the entire visible part of the Earth – this is the case with some wide instantaneous field-of-view sensors on the Nimbus 7 Earth Radiation Budget (ERB) instrument – or they may concentrate on very limited areas of the Earth's surface, as in the case of the ERS 1 radar altimeter. Scatterometers are another form of non-imaging sensor with a very limited IFOV. They measure backscatter off the sea surface at different viewing angles, readings then used to calculate wind speed and direction (fig. 9.12). Scatterometers have been flown on Seasat, ERS 1 and 2 and Quikscat. Though not designed for imaging purposes, these sensors can be used to produce, by interpolation, cartographic images of the phenomena observed.

Spectral bands

All satellite remote-sensing systems designed to observe the Earth's surface use those regions of the electromagnetic spectrum in respect of which the atmosphere is transparent – hence the name "atmospheric windows" (fig. 9.13). Transmittance depends on many different factors, such as atmospheric composition (concentrations of water vapour, carbon dioxide, ozone etc.) or again aerosol content. It depends also on the density of the atmosphere through which incident energy and reflected radiation has to pass. This density is in turn affected by the illumination angle, the viewing angle and the altitude of the region being observed.

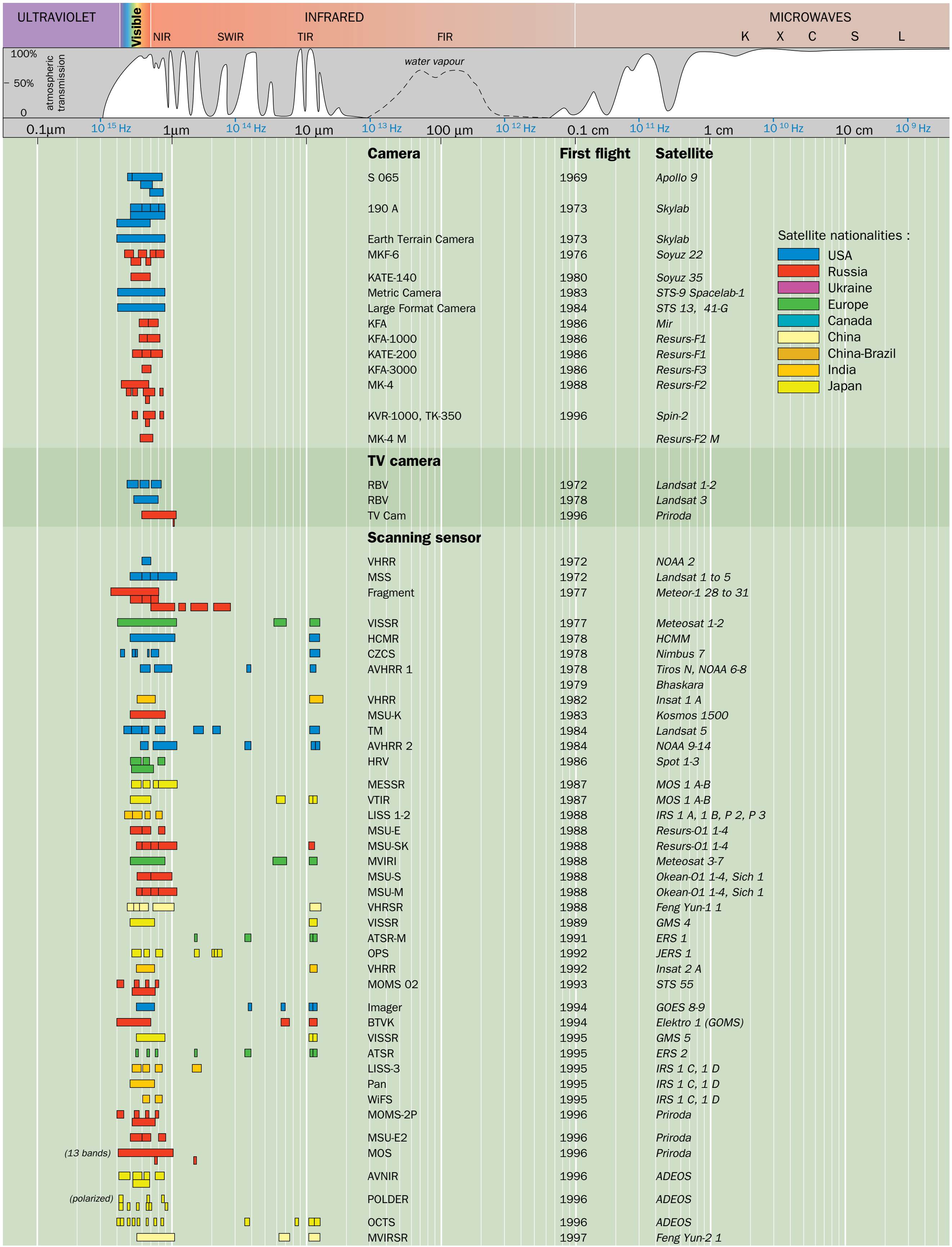


Figure 9.13. **The spectral bands used by the main imaging sensors.**

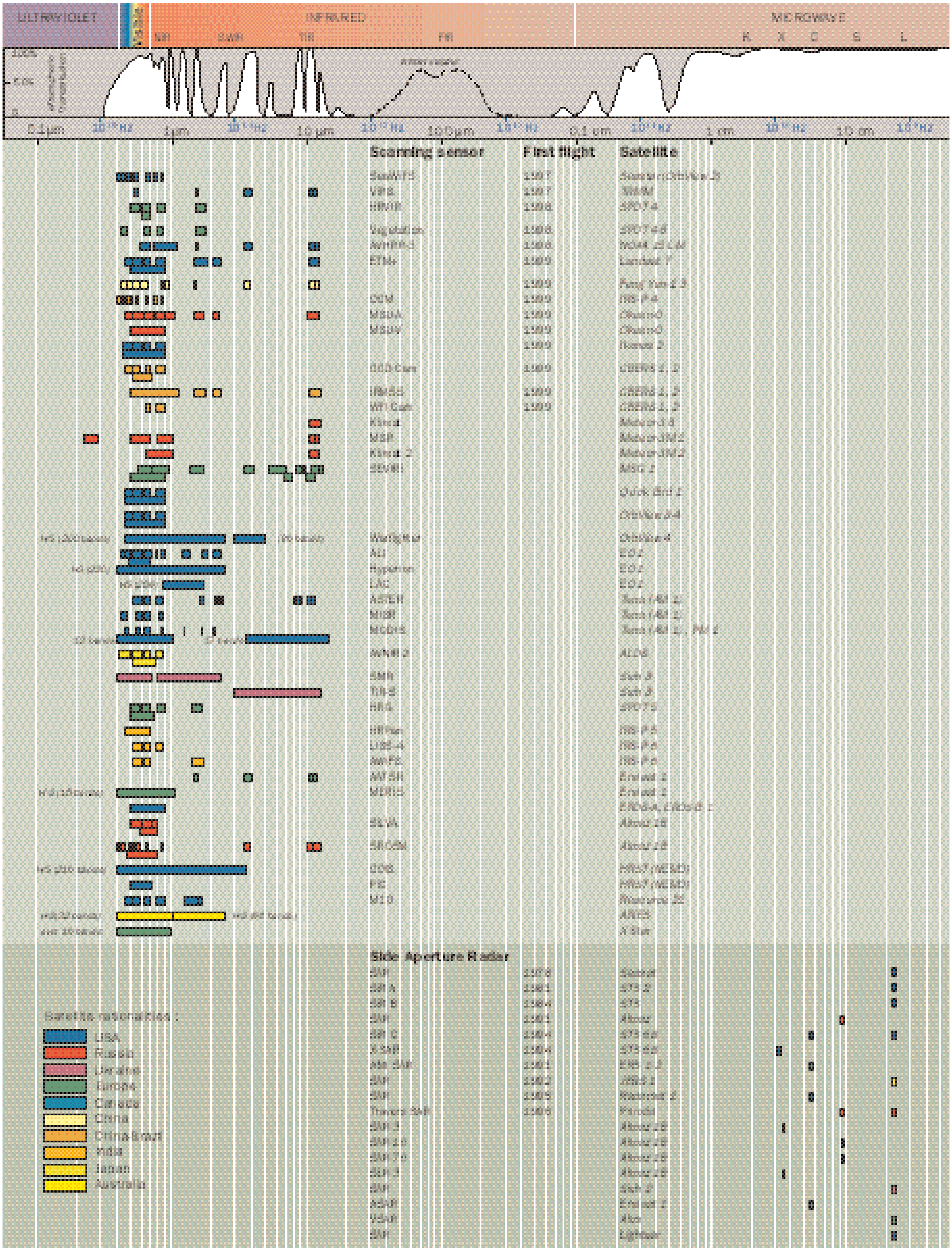


Figure 9.13. **The spectral bands used by the main imaging sensors.**

Sensors responding to the same spectral bands as the human eye have been very widely used for observation from space. Interpretation of images acquired at wavelengths in the visible (450 nm to 710 nm) relies on criteria with which we are familiar from our everyday experience. Vegetation has low reflectance in the visible, solar radiation being absorbed by chlorophyll in the blue and red wavebands. Maximum reflectance is obtained in the yellow-green band at about 550 nm. Generally speaking the reflectance of minerals, higher than that of vegetation, increases at longer wavelengths. Differences in mineralogical composition, in particle sizes and in water concentration do however produce considerable variation at the more detailed level.

Where liquid water is concerned, the important role played by specular reflection must be stressed. Here reflectance is reasonably strong only in the short wavelengths of the visible range, which explains why expanses of pure water are blue. Generally speaking, the reflectance of water depends primarily on the matter suspended or dissolved in it, although the nature of the bed may also be a factor. Gelbstoff, dissolved organic matter resulting primarily from the decomposition of terrestrial vegetation and carried by waterways fed by landwash, is characterised by very high absorptance in the blue. Chlorophyll-a exhibits two maximum absorptance peaks at around 430 nm and 680 nm. Minerals in suspension strongly absorb energy in the blue but show very weak absorptance between 500 nm and 600 nm.

The situation is very different where solid water is concerned. Snow is highly reflective in the visible with some decline in the near infrared. Ice has lower reflectance, on a diminishing scale from granular ice, through pure ice to slush.

Moving outside the visible spectrum, the near infrared (NIR) band, from 0.7 µm to 1.1µm – already regularly used in aerial photography – is highly valued for the weakness of the atmospheric scatter occurring in that range and for the sharply contrasting levels of reflectance it offers. Chlorophyll for example is strongly reflective in the NIR while water is strongly absorbent. And indeed on many satellites the responsivity of the sensors is limited to the visible and near infrared bands. These are also the spectral bands with the longest history of use on military photoreconnaissance satellites.

Beyond the NIR the terms used to refer to the different parts of the infrared vary according to specialists and languages. Short Wave Infrared (SWIR), from 1.4 µm to 2.5 µm, is referred to in the SPOT 4 context by the French acronym MIR, standing for *Moyen Infrarouge*. In this spectral region, absorption of radiation by water is particularly marked at wavelengths close to 1.45 µm, 1.95 µm and 2.5 µm, while vegetation shows reflectance maxima in the 1.65 µm and 2.2 µm bands. The first of these bands was selected for SPOT 4's HRVIR sensor and, on Landsat 4 and 5, for the TM sensor – which also featured a channel centred on the second band.

The Thermal Infrared (TIR) is another much used spectral range, by weather satellites in particular. The data concerned is used to determine surface temperatures of the oceans, landmasses and clouds.

In the TIR atmospheric window, water is strongly emissive; the emissivity of minerals, though weaker, varies considerably from one type to another. The sensor packages on many satellites combine measurements in this spectral range with readings in the visible, examples being the VHRR and later the AVHRR instruments on NOAA satellites. Sensors carried by military reconnaissance satellites also rely on this band, to acquire night images in particular, as has been the case with the American KH 7 series since 1966. The data readings, taken at repeat intervals of about 12 hours, provide information concerning surface inertia to daytime warming and night-time cooling. This repeat acquisition may be achieved locally by intersection of ascending and descending trajectories, as was the case with HCMM (fig. 3.20), or by combining data from two satellites with overflights 12 hours apart, the arrangement adopted for NOAA satellites.

Hitherto tested only on aeroplanes, hyperspectral sensors are now being looked at seriously as spaceborne apparatus. Their use will support very fine spectral resolution of signatures, significantly widening the range of remote-sensing techniques. Hyperspectral systems break the continuous spectrum of the incoming signal down into a large number of narrow bands. The Warfighter 1 instrument to be flown on Orbview 4 will for example analyse the spectral range between 0.45 µm and 5 µm into some 280 bands. The very fine spectral resolution offered by hyperspectral systems analysing not only the visible but also the NIR, SWIR and part of the TIR is opening up new perspectives, particularly for the study of seawater (chlorophyll), minerals and vegetation cover.

Other parts of the spectrum, such as microwave wavelengths, are being used increasingly widely. Satellite radar imagery was first used for civil purposes on the 1978 Seasat 1 mission, which featured a sidelooking L-band synthetic aperture radar. Radar sensing modes was also tested on the Space Shuttle in the course of three experiments, SIR A, SIR B and SIR C.

Many different bands are used, from the largest to the smallest (L, S, C, X). The largest offer greater penetration of the ground and vegetation while the shortest tell the user more about the roughness of surface minerals. The water content of the observed area greatly affects the penetrative power of radar waves. Microwave radiation penetrates dry ground far more deeply than ground which is waterlogged. It is thus possible using this technique to detect objects covered by dry sand in desert regions.

The number of spaceborne radars can be expected to grow rapidly, and these will operate at various incidence angles in several wavebands (the L, C and X bands under the EOS programme). They will deliver fresh insights into the surface roughness of continental landmasses and the nature of their subsurface and provide a basis for marine status mapping. Radar imaging is of course also of great interest to the military, a point borne out by the prominent roles played by Kosmos 1870 and the Lacrosse satellite.

Images of the Earth

The mass of images supplied by the various sensing systems described above form the satellite Earth observation archives, supporting meteorology and remote-sensing in the strictest sense but also military reconnaissance.

With the growing stockpile of such images comes the need for simple referencing principles. The principles adopted may be based on the themes treated in the images - clouds, water land – or on the geographical coordinates of the region surveyed, this being the method favoured for indexing data from the major satellite remote-sensing systems: Landsat with the World Reference System and SPOT with the SPOT Reference Grid (*Grille de Référence SPOT*, GRS). Within these overall structures, straightforward criteria are then required for classification to cope with the different acquisition modes and – a greater challenge still – the very many forms of image processing. These criteria are needed to assign images to categories for subsequent archiving but also for educational purposes.

Scalar levels

A simple approach to the classification of satellite images is based on the concept of scale – scale of field and resolution. Strictly speaking, the concept of scale is fully meaningful only when applied to images in the very literal pictorial sense. The photographic film used in the KVR 100 camera on Spin 2 (SPace INformation) or in the Metric and Large Format Cameras on Shuttle Spacelab missions records images for which there is a geometric relationship between ground distances and the distances on the original film. But in the case of a scanner sweeping the ground and collecting signals which define the luminescence of the instantaneous field of view on the ground, the concept of scale begins to blur, coming to mean the basic ground unit – the area represented by one picture element (pixel), the basic constituent of an image. An image consisting of a patchwork of pixels can be built up to the desired scale in the same way that a true photograph taken by the Metric Camera or MKF 6 can be enlarged or reduced at will.

While the criterion of scale is satisfactory for true photographs, a more helpful concept when referring to images obtained by scanning is that of the ground area – field or spot – corresponding to a pixel or the closely related idea of Ground Sample Distance (GSD), both of which are sometimes regarded by extension as units of resolution.

Working from the concepts of global field of view, instantaneous field of view and resolution, three main scalar levels can be defined (fig. 9.14):

A: planetary images: these cover an expanse of the planet from limb to limb and are acquired from a high altitude – generally from geostationary orbit some 36 000 km above the Earth. Images at this level have kilometre-range resolution. They are used in meteorology and global climate research (radiation budget etc.).

B: Images at regional level: these cover smaller expanses and are acquired from lower altitudes. Ground resolution is in the 100 m or 10 m range. Applications here are cartography and terrestrial resource surveying.

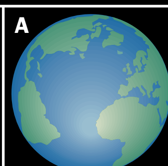
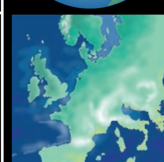
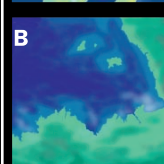
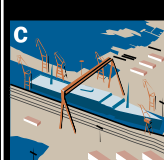
images			ground resolution	altitude (km)	examples of satellites	major users
limb to limb field	planetary	A 	10 - 2.5 km	36 000	Meteosat GOES Kosmos 1940	meteorology climatology oceanography
	regional		1 - 2 km	1500 to 800	Meteor NOAA 15	meteorology Earth resources studies
limited field		B 	120 - 25 m	900 to 700	MOS Landsat 1-5 JERS Almaz ERS	cartography Earth resources studies
			20 - 10 m	900 to 250	SPOT 1-4 Shuttle (metric camera)	cartography Earth resources studies
	local	C 	4 - 0.3 m	800 to 150	Yantar KH 11 Helios 1 A-B Ikonos 2	military observation arms control verification urban cartography

Figure 9.14. **Classification of satellite images by scalar level.**

C: Images at local level: these cover restricted areas and are acquired by vertical or oblique viewing, often from very low altitudes. Metre and decimeter range resolutions are obtained. Initially used for military reconnaissance purposes, these images are now finding civil applications at metre-level resolution.

Between these main levels there are many intermediate levels. Limb-to-limb images acquired by the AVHRR sensor on NOAA satellites are, for example, situated between levels **A** and **B**. Each pixel represents a ground area in excess of 1 km^2 and utilisation is a mix of meteorology and terrestrial resource surveying (location of local upwellings, study of Sahel vegetation etc.). Similarly, SPOT imagery and photos taken from the Mir space station are positioned somewhere between levels **B** and **C**.

Types of processing

Another system of classification is based on the nature of the image itself and the type of processing applied to it. This scheme rests on a distinction between primary and derived or secondary images. Images in the first category are those which have retained the geometry of acquisition and have undergone no specialised processing. They can be termed "primary images", although their primary status is difficult to define. The negative of a photographic film remains a primary image even after development. But can an image obtained by visualising an analog recording on film still be regarded as a primary image? When an image is digitised by sampling, is the output a primary or a secondary image?

Primary images acquired by satellite remote-sensing are used far less widely than the derived products, in sharp contrast to the situation in aerial photography interpretation. Secondary images, which exist in much larger quantities, can be classed according to various criteria. One of the most straightforward is whether only one or more than one primary image was used to produce the derived image. Images derived from a single image are described as monogenic and those resulting from a combination of images are called polygenic (fig. 9.15).

Monogenic secondary images are derived from a single image. They may be the product of enlargement, reduction, correcting geometric anamorphosis, change in projection or contrast adjustments. Contrast may be accentuated by extending the grey scale in such a way that the darkest grey in the entire image is shown as black and the lightest grey as white. This operation can also be performed in a small mobile window to heighten local contrasts in the image without regard to relative values in the image as a whole. Changes in the grey scale do not necessarily obey a monotonic function and may substitute for initially rising values, values which rise and fall alternately.

Other modifications may be governed by probability. Images may for example be created in which each grey tone occupies an equal surface area or relates to a gaussian distribution.

The original images may be simplified by reducing intensity levels or by sampling information elements and reducing the number of pixels. It is also possible by filtering to

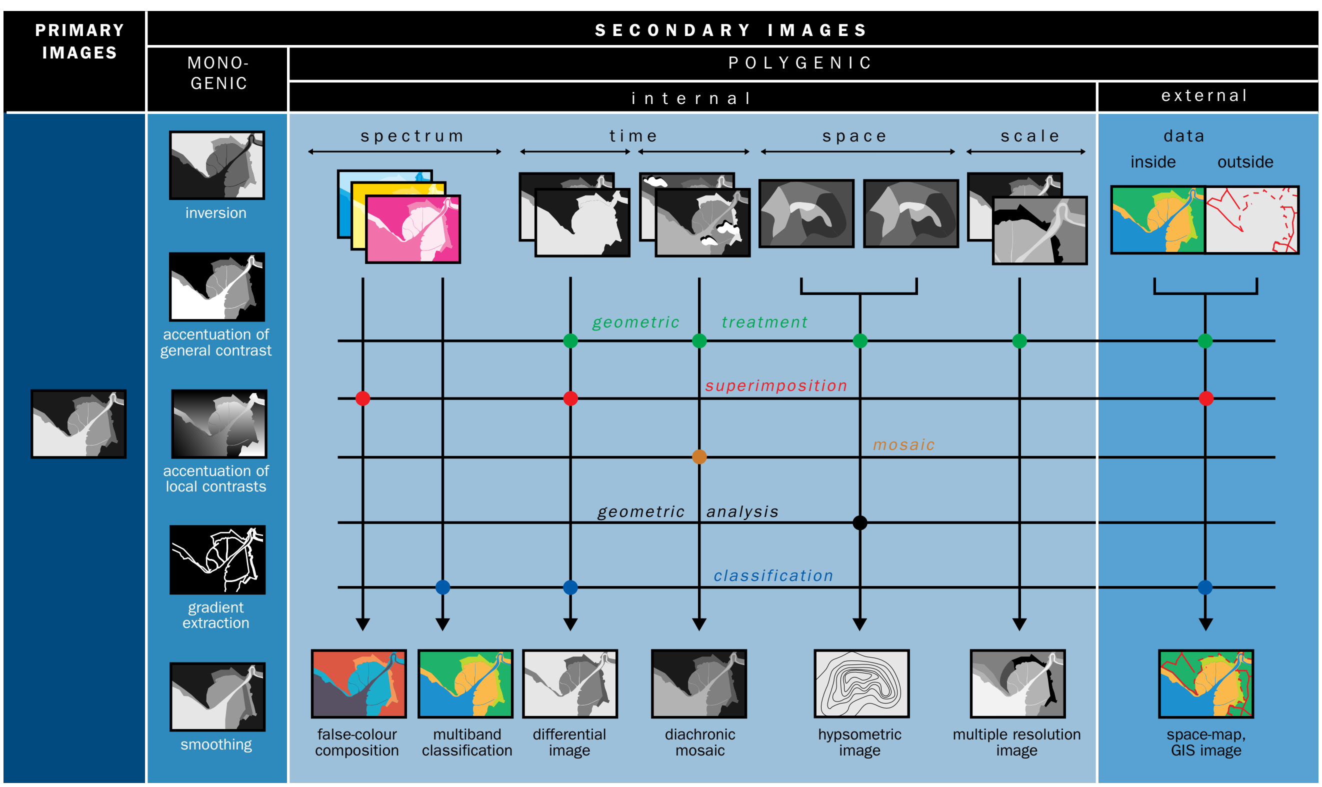


Figure 9.15. **Types of satellite remote-sensing image resulting from the most common forms of processing.**

replace the primary image with an image conveying the differences in value between adjacent pixels (a gradient image) or alternatively with a smoothed image in which each original pixel is replaced by the pixel most frequently encountered in a specified area.

Polygenic secondary images are composite products built up from several primary images in an internal process relying solely on remote-sensing data.

The most common type is the conventional false-colour composite in which each of three primary images acquired simultaneously in three spectral bands by a multiband sensor is translated by one of the sensitive layers of a colour film using the subtractive (cyan, magenta, yellow) colour process or by the colours of the TV screen using additive (green, blue, red) colour mixing. As computer displays have come into more widespread use, subtractive synthesis has given way to additive mixing of the primary colours. This is essentially a spectral technique for deriving images and spectral polygenic processing can form the basis for many other types of processing, such as classification by segmentation or by clustering around mobile points.

Diachronic processing – another form of polygenic treatment – involves combining images acquired at different dates. This may simply involve superimposing a positive image acquired at one date and a negative image acquired at another. Differences between the two images thus appear as areas of lighter or darker shading. Another approach is to use diachronic data to reference pixels so as to characterise families by their evolution. Images of this kind have been produced to define areas of coastal erosion and accretion in the time interval between two given successive satellite passes or again to monitor the evolution of vegetation frontiers or shrub die-back in zones subject to desertification. Derivation of images by diachronic composition has other applications too, one being to fill localised lacunae in particular images. Small isolated clouds may for example mask certain points on the surface of the Earth but there is every chance that the cloud positions will be different on images acquired on subsequent days: by taking the maximum values for thermographic images of the same locations several days running, it is generally easy enough to eliminate the offending clouds – which are colder than the ground. Similarly, it becomes possible to draw up notional maps of small regional units by combining the changing faces of landscapes over a year.

Directional polygenic treatment involves combining images of the same area acquired from different viewpoints. This is the only available means of reconstituting terrain contours from two images. A pair of SPOT images acquired at different angles in the course of two different orbital revolutions can thus be used to produce digital elevation models. Digital models of this kind, in conjunction with the colours deduced from the radiometric readings indicated by a multispectral image, can by computer calculation be used to derive and display a genuinely panoramic view for any given viewpoint. By computer processing it is thus possible to derive a new image corresponding to a viewpoint independent of the actual viewpoints of observation. What is really useful here is the directional aspect – the diachronic treatment which necessarily goes with it is more of a handicap than anything else as there is always the possibility of some change to objects between two image acquisitions. This problem can be overcome to some extent by an arrangement used on some satellites – on JERS 1 channels B3 and B4 for example - in which forward viewing is combined with nadir viewing in the same revolution; this limits to just a few fractions of a second the time-lag between two stereoscopic acquisitions. The POLDER system equipping the ADEOS series works in the same way, combining fractions of wide-angle images acquired from two viewpoints some distance apart.

Scalar polygenic processing involves combining images at varying scales. Combining an Ikonos multispectral image with a pixel area of 4 m × 4 m and a panchromatic image made up of 1 m × 1 m pixels amounts to double polygenic processing – both spectral and scalar – insofar as the combined data relate to different spectral bands and unequal surface areas.

External polygenic processing comes into play where data acquired otherwise than by satellite remote sensing are combined with satellite data. One impressive example of such treatment is the production of maps in which a satellite image is used as background, information of a topographic or toponymic nature being superimposed on the image. Geographical Information Systems (GIS) which choose to incorporate satellite data often generate considerable demand for polygenic images of this type. In some cases, administrative and statistical data are combined with classifications based on multispectral imagery. This particular technique, which calls for a firm grasp of the geometry of essentially heterogeneous data coupled with a sound understanding of the subject matter, is becoming an increasingly widespread feature of the civil and military exploitation of satellite data.

Images can therefore be differentiated by form of derivation – from one or more than one primary image – and, in the case of polygenic derivation, by the treatment applied to them, which may be spectral, diachronic, directional or scalar, and by whether non-satellite inputs are included in the process. These forms of differentiation determine the nature of the informational content. Images are distinguished too by the types of treatment applied to the source images in order to generate them.

The widening range of data sources and forms of processing is attributable in part to the growing number of satellites – which feed enormous collections of images – and in part to advances in computer-based image processing techniques. The biggest problem now facing users is that of deciding what images to choose and what treatment to apply to them for a given application.

Meteorology

Meteorology offers a range of practical applications which make a major contribution to human safety and the security of air and sea transport. Thanks to satellite data, the paths of tropical cyclones for example can now be predicted far more reliably. On the basis of such predictions, shipping is rerouted and preventive action is taken in the zones through which hurricanes pass. Meteorological information is also of considerable importance for the conduct of military operations and for the planning of photographic reconnaissance missions – hence the existence of dedicated military programmes such as the Defense Meteorological Satellite Program (DMSP).

There is a permanent demand for meteorological data from the media with their requirement for short-term forecasts for the general public. They are of interest too in agriculture as an input to forecasting of frost, rainfall and fog and to research into snowcover and the effects of drought.

Climatology is another area in which meteorological satellite data are of interest. While this discipline is less demanding than meteorology in terms of how quickly data must be supplied, it does require much longer time sequences.

The contribution which observation from space could make to meteorology was recognised at an early stage, prompting the launch of non-geostationary satellites in the first instance and, from 1966 onwards, geostationary satellites (fig. 9.16).

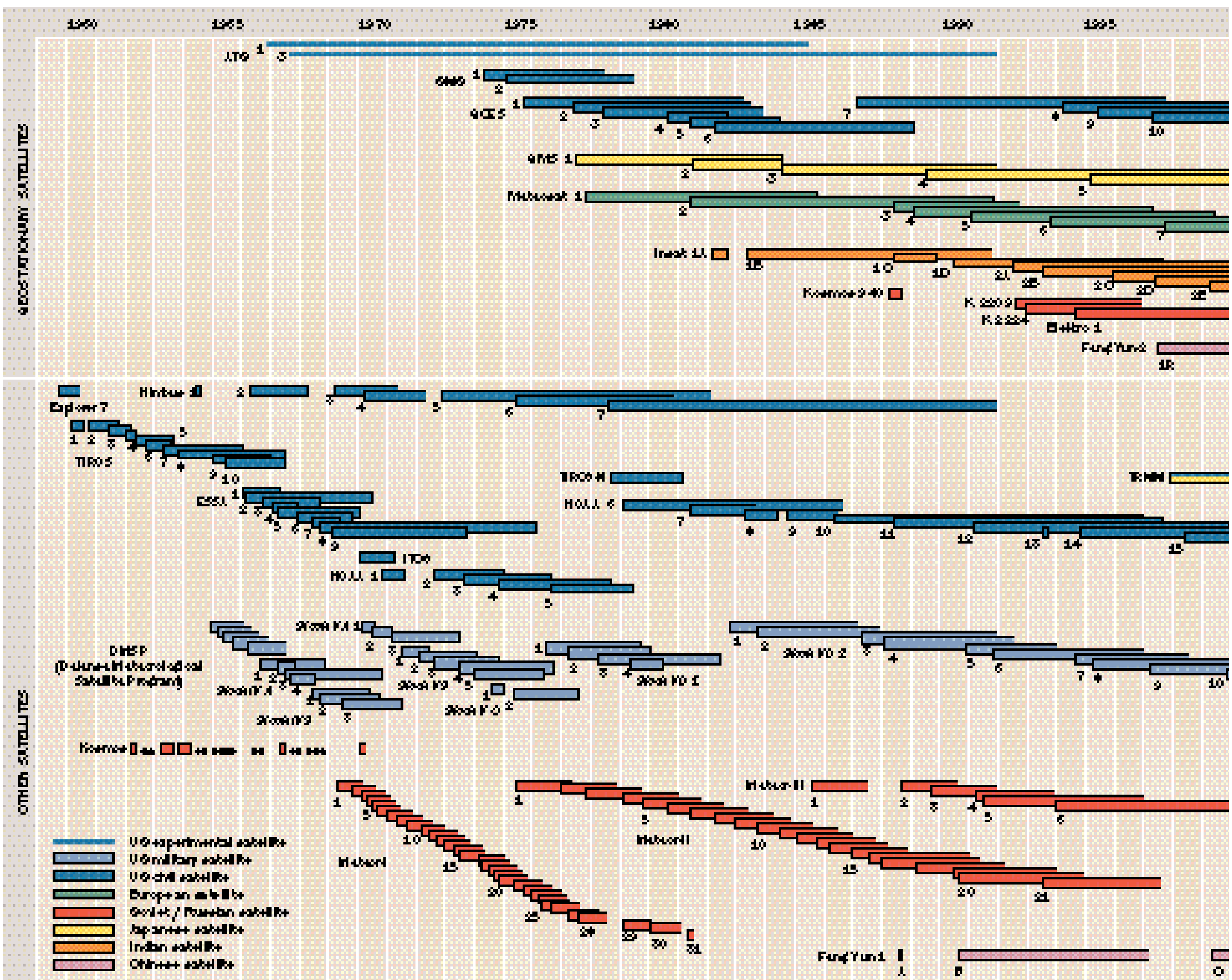


Figure 9.16. **Time chart of meteorological satellites.**