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CHAPTER 3. REMOTE-SENSING INSTRUMENTS

This chapter provides an overview of basic instrument concepts. It introduces the high-level technical features of representative types of Earth observation instruments.

3.1 INSTRUMENT BASIC CHARACTERISTICS

A large variety of instruments and sensing principles are used in Earth observation. The key instrument features introduced here are:

(a) Scanning, swath and observing cycle;

(b) Spectral range and resolution;

(c) Spatial resolution (IFOV, pixel, MTF);

(d) Radiometric resolution.

3.1.1 Scanning, swath and observing cycle

The most characteristic feature of an instrument is the way in which it scans the scene to acquire the necessary observations. That depends on the type of orbit (low Earth orbit or geostationary Earth orbit), on the platform attitude control (spinning, three-axis stabilized), and sometimes on the specific type of measurement being taken. Only the most common scanning techniques will be described in this chapter.

A driving requirement for scanning is whether the scene should be observed with continuity (imagery) or can be sampled (sounding). A similar scanning mode may be used in both cases. However, imagery requires continuous scene coverage, while sounding can accommodate sampling with gaps.

In low Earth orbit (LEO) spacecraft, a 2D Earth scene scanning can use satellite motion for an along-track dimension. A cross-track scan can then be provided by a rotating scan mirror (Figure 3.1). Rotation speed is synchronized with satellite motion so that the cross-track image lines come out contiguously.

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Figure 3.1. Typical scheme of a scanning radiometer in LEO

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In the case of geostationary Earth orbit (GEO), there is no satellite motion with respect to the Earth's surface. The two scanning dimensions must therefore be generated either by the instrument or by satellite rotation. In Figure 3.2, it is assumed that the satellite is spin-stabilized: the west–east scan is provided by the satellite rotation, while the north–south scan is obtained by a step motor. For a three-axis stabilized platform, the instrument must generate both west–east and north–south scans.

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Figure 3.2. Schematic scanning from a spin-stabilized GEO

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The advent of array detectors has led to additional scanning possibilities. With LEO, a linear array can be placed orthogonally to the satellite track, and can scan the scene without any mechanical movement (pushbroom scanning). Under another scheme, the linear array can be placed parallel to the track; cross-track mechanical scanning will then scan several lines in parallel (whiskbroom scanning). With GEO, whiskbroom scanning is now the rule. For instance, SEVIRI on Meteosat Second Generation scans three lines in parallel for the infrared (IR) channels, and nine lines for the high-resolution visible spectrum (VIS) channel.

A very convenient scanning mechanism for polarization-sensitive measurements is conical scanning (Figure 3.3). In this geometry, the incidence angle is constant. Therefore the effect of polarization does not change along the scan line (an arc). By contrast, the incidence angle for cross-track scanning changes along the scan line, when moving from the nadir to the image edge. This invariance of the polarization effect across the image is very important for microwave (MW) measurement in window channels, where radiation reflected from elements such as the sea surface is strongly polarized. The measurement of the differential polarization constitutes important information that would be very difficult to use if the incidence angle changed across the scene. Another interesting feature of conical scanning is that the resolution remains constant across the whole image.

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Figure 3.3. Geometry of conical scanning

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A disadvantage of conical scanning is that, with the selected incidence angle, the field of view does not normally reach the horizon. For example, the swath from an 800 km orbital height is ~1 600 km for a typical zenith angle of 53°, which is optimal for enhancing differential polarization information in MW. By contrast, the swath for a cross-track scanning instrument is close to 3 000 km, assuming a ± 70° zenith angle range, as shown in ~~Part III~~Volume IV, Chapter 2, Table 2.1.

The swath is an important feature of an instrument in LEO since it determines the observing cycle. ~~Part III~~Volume IV, Chapter 2, Table 2.2 outlines that, for a Sun-synchronous orbit at 800 km, one instrument with a swath of at least 2 800 km provides one global coverage per day for measurements operated in daytime only (~~e.g.~~for example, short-wave (SW) sensors), or two global coverages per day for measurements operated day and night (~~e.g.~~for example, IR or MW sensors). MW conical scanning instruments generally provide one global coverage per day.

Estimating the observing cycle

The order of magnitude of the observing cycle (Δt, in days) for a given swath can be estimated by a simple calculation. Considering the Equator's length (~40 000 km), the number of orbits per day

(~14.2) and assuming that there is no significant overlap between adjacent swaths at the Equator, the calculation is as follows:

(a) For day and night sensors (IR or MW) operating on both ascending and descending passes: Δt = 1 400/swath (~~e.g.~~for example, for a MW conical scanner with 1 400 km swath: Δt = 1 day);

(b) For daytime only sensors (SW) operating on only one pass per orbital period: Δt = 2 800/swath (~~e.g.~~for example, for VIS land observation with 180 km swath: Δt = 16 days).

The concept of swath is not applicable for instruments with no cross-track scanning, such as altimeters or cloud radars. Where that is the case, the cross-track sampling interval Δx at the Equator replaces "swath" in the relationship above. It is also useful to estimate the global average of this sampling interval. The interval is given by a slightly different relationship because of shorter orbit spacing at higher latitudes:

(a) At an average cross-track sampling interval Δx, the typical time needed for global coverage is:

   (i) Δt = 900/Δx for day and night sensors (~~e.g.~~for example, the Environmental Satellite (Envisat) Radar Altimeter – 2 (RA-2): Δx = 26 km, Δt = 35 days);

   (ii) Δt = 1 800/Δx for daytime only (~~e.g.~~for example, the National Oceanic and Atmospheric Administration (NOAA) Solar Backscatter Ultraviolet (SBUV) instrument: Δx = 170 km, Δt = 11 days).

(b) Reciprocally, in a time interval Δt (~~e.g.~~for example, the orbit repeat cycle or a main sub-cycle) the average cross-track sampling interval obtained is:

(i) Δx = 900/Δt for day and night sensors (~~e.g.~~for example, the Joint Altimetry Satellite Oceanography Network (JASON) altimeter: Δt = 10 days, Δx = 90 km);

(ii) Δx = 1 800/Δt for daytime only (~~e.g.~~for example, NOAA SBUV: Δt = 5 days, Δx = 360 km).

Limb sounders are generally considered as non-scanning instruments in the cross-track direction. Assuming a cross-track sampling interval Δx = 300 km which is equal to the horizontal resolution of the measurements, the relationships above yield, taking MIPAS (which flew on the ENVISAT satellite) as an example, the following observing ~~cycles~~cycle:

~~(a)~~ - $\Delta t \approx$ 3 days for day and night sensors (~~e.g.~~for example, MIPAS on Envisat~~: 3 days = 1 orbit sub-cycle~~);

~~(b) $\Delta t \approx$ 6 days for daytime sensors (e.g. SCIAMACHY-limb on Envisat: 6 days = 2 orbit sub-cycles).~~

For instruments providing sparse but well-distributed observations, the coverage cycle or the average sampling can be estimated by comparing the number of events and their resolution with the Earth's surface to be covered. In the example of radio occultation using GPS and GLONASS, each satellite is able to provide about 1 000 observations per day, with a typical measurement resolution of 300 km for a total Earth's surface of 510 million km^2. Therefore:

(a) Time required with one satellite providing 1 000 observations/day: Δt = 510 000 000/300/300/1 000 = 5.7 days;

(b) Number of satellites required for an observing cycle Δt: N = 5.7/Δt (~~e.g.~~for example, for Δt = 0.5 days, the number of satellites is close to 12).

Sun-, moon- or star-occultation instruments are an extreme case. Sun or moon occultation provides very few measurements per day, and only at the high altitudes of the day/night terminator in the case of the Sun, or at somewhat lower latitudes for the moon. Star occultation may provide several tens of measurements per day (~~e.g.~~for example, 40 for the Envisat Global Ozone Monitoring by Occultation of Stars (GOMOS)), evenly distributed by latitude.

3.1.2 Spectral range: radiometers and spectrometers

Another major characteristic feature of an instrument is the spectral range over which it operates. As discussed in ~~Part III~~Volume IV, Chapter 2, 2.2, the spectral range determines which of the body's properties can be observed including reflectance, temperature and dielectric properties. Within the spectral range, there may be window regions and absorption bands, which mainly address condensed or gaseous bodies, respectively.

A spectral range may be more or less narrow, depending on the effects to be enhanced, or on the disrupting factors that need to be eliminated. The sub-divisions of a band or a window covered by an instrument are called channels. The number of channels depends on the number of pieces of independent information which have to be extracted from one band. If a limited number of well-separated channels are sufficient for the purpose, the instrument may only include those channels, and it is called a radiometer. If the information content rapidly changes with the frequency along the spectral range to the extent that channels must be contiguous, the instrument is called a spectrometer.

The technique adopted for channel separation, or for spectrometer subrange separation, is a major characteristic of the instrument. There are essentially two possible ways to physically separate two channels towards individual detectors (or detector arrays) and associated filter systems. First, the beam could be focused on a field stop and split into two bands by a dichroic mirror. The advantage is that co-registration is ensured, as the two channels look at the same field of view (which could comprise an array of instantaneous fields of view (IFOVs)). However, if the two wavelengths are too close to each other (~~e.g.~~ for example, a split window), a dichroic mirror cannot separate them sharply enough. The second solution is to let the full beam produce the image in the focal plane and set detectors (or detector arrays) with different filters (thus identifying different channels) in different parts of the focal plane (in-field separation). It is a much simpler solution, but as each channel looks at a different IFOV, co-registration problems can occur. Combined solutions are possible: Figure 3.4 illustrates the solution implemented in the Meteosat Second Generation SEVIRI to separate the eight IR channels. Each channel is viewed by three detectors. Current detector arrays are much larger than they have been in the past, which makes in-field separation more convenient.

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Figure 3.4. Channel separation scheme in SEVIRI on Meteosat Second Generation

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Spectrometers provide continuous spectral sampling within the spectral range or in a number of spectral subranges. (These subranges are sometimes called channels and should not be confused with the channels of a radiometer). There are several types of spectrometer, the simplest of which is the prism. Others include grating spectrometers and interferometers; the most common interferometers are the Michelson and the Fabry-Pérot. Figure 3.5 shows the scheme of a Michelson interferometer.

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Figure 3.5. Scheme of a Michelson interferometer emphasizing the two input and output ports

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The spectral resolution of a spectrometer is an important feature. The resolution of a Michelson interferometer is determined by the maximum length of the optical path difference (OPD) between the rays reflected by the fixed and moving mirrors. Referring to the unapodized resolution, the formula is:

$$\cancel{\Delta\nu = 1/\mathrm{OPD}_{\max}} \quad \Delta\nu = 1/\mathrm{OPD}_{\max} \tag{3.1}$$

For example, in IASI, an instrument mounted on the Meteorological Operational (Metop) satellite, the excursion of the moving mirror is ± 2 cm. Therefore, OPD_{max} = 4 cm and $\Delta\nu$ = 0.25 cm^{-1}. If fine analysis of the spectrum is needed (for instance, to detect trace gas lines), apodization that implies a factor ~2 is required. The apodized resolution is therefore $\Delta\nu$ = 0.5 cm^{-1}.

For a grating spectrometer, the resolution is determined by the number of grooves, N, and the chosen order of diffraction, m. The resolving power $\lambda/\Delta\lambda$ is given by:

$$\cancel{\lambda/\Delta\lambda = m \cdot N} \quad \lambda/\Delta\lambda = m \cdot N \tag{3.2}$$

For a Michelson interferometer, the spectral resolution is constant with a variable wavelength. For a grating spectrometer, however, it is the resolving power that is constant, and the spectral resolution that changes with wavelength. If a grating spectrometer is to cover a wide spectral range, that range should be subdivided into subranges that use different orders of diffraction, m. Resolving power may thus change based on subrange.

For a radiometer, the number of channels and their bandwidths play an equivalent role to spectral resolution for a spectrometer.

3.1.3 Spatial resolution (instantaneous field of view, pixel, and the modulation transfer function)

Colloquially, spatial resolution means the association of different features.

The IFOV is probably the closest to what is commonly meant by resolution. In optical instruments (i.e. SW and IR instruments), it is determined by the beamwidth of the optics and the size of the detector. In MW it is determined by the size of the antenna.

In optical systems, the size of the IFOV is designed primarily on the basis of energy considerations (see ~~section~~ 3.1.4). The IFOV may be determined by the shape of the detector; and although that may be square, the contour of an IFOV is not unduly sharp. In fact, the image of a point is a diffraction figure called point spread function (Figure 3.6). The IFOV is the convolution of the point spread function and the spatial response of the detector.

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Figure 3.6. Shape of the point spread function

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The energy entering the detector is also determined by the integration time between successive signal readings. During image scanning, the position of the line of sight will change by an amount called sampling distance. When plotted in a rasterized 2D pattern, a pixel (picture element) appears as a series of rectangular elements. In the x-direction, they correspond to the sampling distance and in the y-direction, to the satellite motion during the time distance from one line to the next (or the step motion in the north–south direction from GEO). The pixel is often confused with the resolution. That is because users can directly perceive the size of the picture element, whereas the IFOV is an engineering parameter that the user cannot see. Nevertheless, it is wrong to think that resolution can be improved by reducing the integration time, since the integration time must be suitable to ensure an appropriate radiometric accuracy (see ~~section~~ 3.1.4).

There is a balance between the size of the IFOV and the size of the pixel. When using a "perfect" imager, sampling is performed so that the sampling distance is equal to the IFOV size. That means that the IFOVs are continuous and contiguous across the image. Otherwise the image may be oversampled (pixel < IFOV, i.e. there is overlap between successive IFOVs) or undersampled (pixel > IFOV, i.e. there are gaps between successive IFOVs). Oversampling is useful to reduce aliasing effects (undue enhancement of high spatial frequencies because of reflection from the border). Undersampling may be necessary when more energy must be collected in order to ensure the required radiometric accuracy. Examples of relationships between IFOV and pixel are:

(a) AVHRR – IFOV: 1.1 km; pixel: 1.1 km along-track, 0.80 km along-scan (oversampled);

(b) SEVIRI – IFOV: 4.8 km; pixel: 3.0 km across-scan and along-scan (oversampled).

The modulation transfer function (MTF) is closely linked to the concept of IFOV and pixel. It is even more directly linked to the size "L" of an instrument's primary optics. The MTF represents the capability of the instrument to correctly manage the response to amplitude variation at the scene. It is the ratio between the observed amplitude, and the true signal amplitude from the scene, figured as sinusoidal. The observed amplitude is damped due to factors such as the diffraction from the optical aperture, the “window” introduced by the detector and smearing from integrating electronics. The effect of integrating the radiation over the (squared) detector introduces a contribution to the MTF:

$$\cancel{\mathrm{MTF}_{\mathrm{window}}(f) = \mathrm{sinc}(\pi \cdot \mathrm{IFOV} \cdot f), \text{ with } f = 1/(2\,\Delta x)\left(\mathrm{km}^{-1}\right) \text{ and } \mathrm{sinc}\, y = \frac{\sin y}{y}}$$

$$\mathrm{MTF}_{\mathrm{window}}(f) = \mathrm{sinc}(\pi \cdot \mathrm{IFOV} \cdot f), \text{ with } f = 1/(2\,\Delta x)\left(\mathrm{km}^{-1}\right) \text{ and } \mathrm{sinc}\, y = \frac{\sin y}{y} \qquad (3.3)$$

This shows that, for Δx = IFOV, MTF = sinc ($\pi/2$) = $2/\pi$. Therefore, even for a “perfect” imager, MTF is lower than unity. The value $2/\pi \approx 0.64$ corresponds to the area of a half sinusoid inscribed in a square. The concept of MTF must be seen as closely associated with radiometric accuracy: it specifies at which spatial wavelength two features are actually resolved if their radiation differs by just the detectable minimum. Two features whose radiation differs by substantially more than the detectable minimum can be resolved, even if they are substantially smaller. However, if they are as small as IFOV/2, then MTF = 0, and they can in no way be resolved (f = 1/IFOV is called the cut-off frequency).

It is interesting to note how $\mathrm{MTF}_{\mathrm{window}}$ changes at different spatial wavelengths measured in terms of IFOV (where spatial wavelength is 2 Δx). Table 3.1 can be derived from equation 3.3:

Table 3.1. Variation of the $\mathrm{MTF}_{\mathrm{window}}$ function of the ratio Δx / IFOV

TABLE: Table horizontal lines

Δx/IFOV	1/2	2/3	1	2	3	4	5	6
$\mathrm{MTF}_{\mathrm{window}}$	0	0.30	0.64	0.90	0.95	0.97	0.98	0.99

This shows that features as small as two thirds of the IFOV can be resolved, but only if their radiances differ by more than three times the detectable minimum. It also shows that features twice as large as the IFOV can be resolved if their radiance difference exceeds the minimum by 10%.

The other major contribution to the MTF is diffraction. The relation is:

$$\cancel{\mathrm{MTF}_{\mathrm{diffraction}} = \frac{2}{\pi}\left[\cos^{-1}\left(\frac{f}{f_d}\right) - \frac{f}{f_d}\sqrt{1-\left(\frac{f}{f_d}\right)^2}\right]}$$

$$\mathrm{MTF}_{\mathrm{diffraction}} = \frac{2}{\pi}\left[\cos^{-1}\left(\frac{f}{f_d}\right) - \frac{f}{f_d}\sqrt{1-\left(\frac{f}{f_d}\right)^2}\right] \quad (3.4)$$

where $f = 1/(2\,\vartheta\,H)$ (with H = satellite height); ϑ = angular resolution (i.e. IFOV/H); $f_d = L/(\lambda\,H)$; L = aperture of the primary optics; and thus $f/f_d = \lambda/(2\,\vartheta\,L)$.

Diffraction is dominant when the wavelength λ is relatively large (as with microwaves), when the optics aperture is relatively small, or when the satellite altitude is relatively large (as with GEO). The value $\mathrm{MTF}_{\mathrm{diffraction}} = 0.5$ occurs for $f/f_d = 0.404$, that is:

$$\cancel{\vartheta = 1.24\frac{\lambda}{L}} \quad \vartheta = 1.24\frac{\lambda}{L} \quad (3.5)$$

which is the classical law of diffraction.

In summary, what is commonly meant by the term "resolution" involves at least three parameters. Although they should be considered in context, each one is more closely associated with a different perception:

(a) IFOV: not visible to the user; controls the radiometric budget of the image;

(b) Pixel: provides direct perception of the degree of detail in the image;

(c) MTF: by monitoring the amplitude restitution, provides the perception of contrast.

3.1.4 Radiometric resolution

Although scarcely visible to the user, radiometric resolution is a defining element of instrument design. Scanning mechanisms, spectral resolution, spatial resolution, integration time and optics apertures are all designed to fulfil radiometric resolution requirements. Radiometric resolution is the minimum radiance difference necessary to distinguish two objects in two adjacent IFOVs. The observed difference is a combination of the true radiance difference between two bodies (signal) and the difference observed even when the contents of the IFOVs are identical (noise). The signal-to-noise ratio (SNR) is one way of expressing radiometric resolution.

Noise is a function of several factors, as set out in the radiometric performance formula:

$$\cancel{\mathrm{NESR} = \frac{2\,F}{D^{*}\cdot\Delta\nu\cdot\tau\cdot\sqrt{\pi\cdot t\cdot\Delta\Omega}}} \quad \mathrm{NESR} = \frac{2\,F}{D^{*}\cdot\Delta\nu\cdot\tau\cdot\sqrt{\pi\cdot t\cdot\Delta\Omega}}$$

(3.6)

where:
NESR = noise equivalent spectral radiance (unit: W m^{-2} sr^{-1} [cm^{-1}]$^{-1}$, i.e. per unit of wave number);
$F = f/L$, F-number (f = system focal length, L = telescope aperture);
D^{*} = detectivity (strongly depending on ν);
$\Delta\nu$ = spectral resolution (expressed in terms of wave number $\nu = 1/\lambda$);
τ = instrument transmissivity;
t = integration time;
$\Delta\Omega$ = system throughput, given by the product of ($\pi\cdot L^2/4$) by (IFOV$^2/H^2$); where:
$\pi\cdot L^2/4$ = areal aperture of the telescope;
H = satellite altitude;

$IFOV^2/H^2$ = solid angle subtended by the IFOV.

In general, when defining $I(\nu)$ = spectral radiance at instrument input (unit: W m^{-2} sr^{-1} [cm^{-1}]$^{-1}$), this leads to:

$$\cancel{\mathrm{SNR} = I(\nu)/\mathrm{NESR}} \; \mathrm{SNR} = I(\nu)/\mathrm{NESR} \qquad (3.7)$$

For SW, the input radiance is the solar spectral radiance corrected for the incidence angle and reflected according to body reflectivity (or albedo, if the body can be approximated as a Lambertian diffuser). Equations 3.6 and 3.7 lead to:

$$\cancel{\frac{\mathrm{SNR}}{\mathrm{IFOV}\sqrt{\Delta\nu \cdot t}} \propto L \quad \text{(at a specific input radiance } I(\nu) \text{ or albedo } \rho)}$$

$$\frac{\mathrm{SNR}}{\mathrm{IFOV}\sqrt{\Delta\nu \cdot t}} \propto L \quad \text{(at a specific input radiance } I(\nu) \text{ or albedo } \rho) \tag{3.8}$$

That relationship explicitly links user-oriented parameters such as SNR, spectral resolution $\Delta\nu$, IFOV and integration time t to the size of the primary optics L.

In the case of narrowband IR channels, radiometric resolution is usually quoted as:

$$\cancel{\mathrm{NE}\Delta\mathrm{T} = \frac{\mathrm{NESR}}{dB/dT}} \quad \mathrm{NE}\Delta\mathrm{T} = \frac{\mathrm{NESR}}{dB/dT} \tag{3.9}$$

where B = Planck function, and NEΔT = noise equivalent differential temperature at a specific temperature T.

With NEΔT, the performance formula 3.6 can be rewritten as follows:

$$\cancel{\mathrm{NE}\Delta\mathrm{T} \cdot \Delta\nu \cdot \mathrm{IFOV} \cdot \sqrt{t} = \frac{4H}{\pi \cdot dB/dT} \cdot \frac{F}{L \cdot D^* \cdot \tau}}$$

$$\mathrm{NE}\Delta\mathrm{T} \cdot \Delta\nu \cdot \mathrm{IFOV} \cdot \sqrt{t} = \frac{4H}{\pi \cdot dB/dT} \cdot \frac{F}{L \cdot D^* \cdot \tau} \tag{3.10}$$

The left-hand side of formula 3.10 shows user-oriented parameters (radiometric, spectral, horizontal and time resolutions), while the right-hand side shows instrument sizing parameters (F-number, optics aperture, detectivity and transmissivity). This formula is not valid in all circumstances, but is instructive for a rough analysis in many instances. Cases where the formula is not valid mainly occur when the detector itself constitutes the dominant noise source, or when the detector response time is not short enough in comparison with the available integration time. This is normally the case in the far infrared (FIR) range. But it may also be the case with shorter wavelengths if, for instance, microbolometers or thermal detectors are used in order to operate at room temperature. In other words, D^*, which obviously depends on ν, may be heavily dependent on the available integration time.

In the case of broadband channels, the concept of NESR, as expressed in equation 3.6, must be redefined in terms of integrated noise over the full spectral range of each channel. In that case, it is also possible to obtain a relationship similar to formula 3.10:

$$\cancel{\mathrm{NE}\Delta\mathrm{R} \cdot \mathrm{IFOV} \cdot \sqrt{t} \propto \frac{1}{L}} \quad \mathrm{NE}\Delta\mathrm{R} \cdot \mathrm{IFOV} \cdot \sqrt{t} \propto \frac{1}{L} \tag{3.11}$$

where NEΔR = noise equivalent differential radiance (unit: W m^{-2} sr^{-1}).

The situation is different in the microwave range for two reasons. First, the need to limit the antenna size means that diffraction law establishes a link between the IFOV and the optics aperture L:

$$\cancel{\mathrm{IFOV} = \frac{1.24 \cdot H \cdot c}{L \cdot \nu^*}} \quad \mathrm{IFOV} = \frac{1.24 \cdot H \cdot c}{L \cdot \nu^*} \tag{3.12}$$

where ν^* = frequency = c/λ; and c = speed of light.

Thus, there is less latitude for trade-off parameters. Second, the detection mechanism is based on comparing the scene temperature with the "system temperature", which increases with the bandwidth. The final outcome is that the equivalent of equations 3.8, 3.10 and 3.11 in the MW range is:

$$\cancel{\mathrm{NE}\Delta\mathrm{T}\cdot\sqrt{\Delta\nu * t} = T_{\mathrm{sys}}}\ \underline{\mathrm{NE}\Delta\mathrm{T}\cdot\sqrt{\Delta\nu * \cdot t} = T_{\mathrm{sys}}} \qquad (3.13)$$

where T_{sys} = system temperature.

The system temperature depends on many technological factors, and increases sharply as frequency increases. On the one hand, equation 3.13 shows that, in the case of MW, radiometric resolution can only marginally be improved by increasing bandwidth and integration time, since the benefit only grows with the square root. On the other hand, because of the diffraction-limited regime, the usual way to increase SNR by increasing optics aperture is not applicable. That is because, if the antenna diameter is increased, the IFOV is reduced commensurately (see equation 3.12).

This short review highlights the direct impact of user and mission requirements on instrument sizing. In addition, it shows how important it is to formulate requirements in a way that leaves room for optimization, without necessarily compromising the overall required performance. For instance with reference to equation 3.10, it is possible to draw a number of conclusions.

(a) For a given set of instrument parameters (L, F, τ and $D*$), some user-driven parameters (NEΔT, $\Delta\nu$, IFOV and t) can be enhanced at the expense of others. In certain cases, this can be done at the software level during data processing on the ground. However, if all user requirements become more demanding and no compromises are made, a larger instrument will be necessary.

(b) The effect of NEΔT, $\Delta\nu$ and IFOV on instrument size is linear in relation to the optics diameter L. The effect of t (the integration time, driven by the requirement to cover a given area in a given time) is damped by the square root. Therefore, requirements for increased coverage and/or more frequent observation have a lesser impact than requirements for improved spatial, spectral and radiometric resolution.

(c) Increasing the optics aperture L has a significant impact on instrument size. Since it is very difficult to implement optical systems with F-number = f/L < 1, an increase in L implies an increased focal length, and therefore a volumetric growth of overall instrument optics. For example, a reduction in the IFOV from three to two kilometres would double the instrument mass.

3.2 INSTRUMENT CLASSIFICATION

In this section, Earth observation instruments are classified according to their main technical features. The following instrument types are considered:

(a) Moderate-resolution optical imager

(b) High-resolution optical imager

(c) Cross-nadir scanning short-wave sounder

(d) Cross-nadir scanning infrared sounder

(e) Microwave-imaging radiometer or microwave-sounding radiometer

(f) Limb sounder

(g) Global navigation satellite system radio-occultation sounder

(h) Broadband radiometer

(i) Solar irradiance monitor

(j) Lightning imager

(k) Cloud radar and precipitation radar

(l) Radar scatterometer

(m) Radar altimeter

(n) Imaging radar (synthetic aperture radar)

(o) Space lidar

(p) Gravity sensor

(q) Solar activity, solar wind or deep space monitor

(r) Space environment monitor

(s) Magnetosphere or ionosphere sounder

Most instrument types are subdivided into more detailed categories. Examples are provided to illustrate how instrumental features can be suited to particular applications. A comprehensive list of satellite Earth observation instruments, with their detailed descriptions, is available through the WMO online database of space-based capabilities, available from the WMO Space Programme website.

3.2.1 Moderate-resolution optical imager

This instrument has the following main characteristics:

(a) Operates in the VIS, near infrared (NIR), short-wave infrared (SWIR), medium-wave infrared (MWIR) and thermal infrared (TIR) bands (i.e. from 0.4 to 15 μm);

(b) Discrete channels, from a few to several tens, separated by dichroics, filters or spectrometers, with bandwidths from ~10 nm to ~1 μm;

(c) Imaging capability: continuous and contiguous sampling, with spatial resolution in the order of one kilometre, covering a swath of several hundred to a few thousand kilometres;

(d) Scanning: generally cross-track, but sometimes multiangle, and sometimes under several polarizations;

(e) Applicable in both LEO and GEO.

Depending on the spectral bands, number and bandwidth of channels, and radiometric resolution, the application fields may include:

(a) Multi-purpose VIS/IR imagery for cloud analysis, aerosol load, sea-surface temperature, sea-ice cover, land-surface radiative parameters, vegetation indexes, fires, and snow cover. The extent of the spectral range is a critical instrument feature;

(b) Ocean-colour imagery, aerosol observation and vegetation classification. The number of channels with narrow bandwidth in VIS and NIR is a critical instrument feature;

(c) Imagery with special viewing geometry, for the best observation of aerosol and cirrus, accurate sea-surface temperature, land-surface radiative parameters including bidirectional reflectance distribution function. The critical instrument features are the number of viewing angles and, when available, polarizations.

Tables 3.2–3.6 describe three examples of multi-purpose VIS/IR imagers (AVHRR/3 in LEO, MODIS in LEO and SEVIRI in GEO), one example of an ocean-colour imager (MERIS) and one example of an imager with special viewing geometry (POLDER). MODIS is an experimental sensor and plays a particular role as a wide scope multi-purpose VIS/IR imager. It is largely used to help define the specifications of follow-on operational instruments. The main uses of its various groups of channels are highlighted in Table 3.3.

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Table 3.2. Example of multi-purpose VIS/IR imager operating in LEO: AVHRR/3 on NOAA and Metop

TABLE: Table horizontal lines

AVHRR/3	*Advanced Very High Resolution Radiometer 3*
Satellites	NOAA-15, NOAA-16, NOAA-17, NOAA-18, NOAA-19, Metop-A, Metop-B, Metop-C
Mission	Multi-purpose VIS/IR imagery for cloud analysis, aerosol load, sea-surface temperature, sea-ice cover, land-surface radiative parameters, normalized difference vegetation index, fires, snow cover, etc.
Main features	6 channels (channel 1.6 and 3.7 are alternative), balanced VIS, NIR, SWIR, MWIR and TIR
Scanning technique	Cross-track: 2 048 pixels of 800 m SSP (sub-satellite point) with a swath of 2 900 km Along-track: six 1.1 km lines a second
Coverage/cycle	Global coverage twice a day (LW (long-wave) channels) or once a day (SW channels)
Resolution (SSP)	1.1 km IFOV
Resources	Mass: 33 kg Power: 27 W Data rate: 621.3 kbps

Central wavelength	*Spectral interval*	*NEΔT or SNR at specified input spectral radiance*
0.630 μm	0.58–0.68 μm	9 at 0.5 % albedo
0.862 μm	0.725–1.00 μm	9 at 0.5 % albedo
1.61 μm	1.58–1.64 μm	20 at 0.5 % albedo
3.74 μm	3.55–3.93 μm	0.12 K at 300 K
10.80 μm	10.3–11.3 μm	0.12 K at 300 K
12.00 μm	11.5–12.5 μm	0.12 K at 300 K

Table 3.3. Example of multi-purpose VIS/IR imager operating in LEO: MODIS on EOS-Terra and EOS-Aqua

TABLE: Table horizontal lines

MODIS	*Moderate-resolution Imaging Spectroradiometer*
Satellites	EOS-Terra and EOS-Aqua
Mission	Multi-purpose VIS/IR imagery for cloud analysis, aerosol properties, sea- and land-surface temperature, sea-ice cover, ocean colour, land-surface radiative parameters, vegetation indexes, fires, snow cover, total ozone, cloud motion winds in polar regions, etc.
Main features	36-channel VIS, NIR, SWIR, MWIR and TIR spectroradiometer
Scanning technique	Whiskbroom: a 19.7 km-wide strip of along-track is cross-track scanned every 2.956 s. The strip includes 16 parallel lines sampled by 2 048 pixels of 1 000 m SSP, or 32 parallel lines sampled by 4 096 pixels of 500 m SSP, or 64 parallel lines sampled by 8 192 pixels of 250 m SSP, with a swath of 2 330 km.
Coverage/cycle	Global coverage nearly twice a day (LW channels) or once a day (SW channels)
Resolution (SSP)	IFOV: 250 m (two channels), 500 m (5 channels), 1 000 m (29 channels)
Resources	Mass: 229 kg Power: 225 W Data rate: 11 Mbps (daytime); 6.2 Mbps (average)

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TABLE: Table horizontal lines

Central wavelength	*Spectral interval*	*NE∆T or SNR at specified input spectral radiance*	*IFOV at SSP*	*Primary use*
0.645 μm	0.62–0.67 μm	128 at 21.8 W m^{-2} sr^{-1} μm^{-1}	250 m	Land/Cloud/
0.858 μm	0.841–0.876 μm	201 at 24.7 W m^{-2} sr^{-1} μm^{-1}	250 m	Aerosol boundaries
0.469 μm	0.459–0.479 μm	243 at 35.3 W m^{-2} sr^{-1} μm^{-1}	500 m	Land/Cloud/
0.555 μm	0.545–0.565 μm	228 at 29.0 W m^{-2} sr^{-1} μm^{-1}	500 m	Aerosol properties
1.240 μm	1.230–1.250 μm	74 at 5.4 W m^{-2} sr^{-1} μm^{-1}	500 m	
1.640 μm	1.628–1.652 μm	275 at 7.3 W m^{-2} sr^{-1} μm^{-1}	500 m	
2.130 μm	2.105–2.155 μm	110 at 1.0 W m^{-2} sr^{-1} μm^{-1}	500 m	
0.418 μm	0.405–0.420 μm	880 at 44.9 W m^{-2} sr^{-1} μm^{-1}	1 000 m	Ocean colour,
0.443 μm	0.438–0.448 μm	838 at 41.9 W m^{-2} sr^{-1} μm^{-1}	1 000 m	Phytoplankton,
0.488 μm	0.483–0.493 μm	802 at 32.1 W m^{-2} sr^{-1} μm^{-1}	1 000 m	Biogeochemistry
0.531 μm	0.526–0.536 μm	754 at 27.9 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
0.551 μm	0.546–0.556 μm	750 at 21.0 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
0.667 μm	0.662–0.672 μm	910 at 9.5 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
0.678 μm	0.673–0.683 μm	1 087 at 8.7 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
0.748 μm	0.743–0.753 μm	586 at 10.2 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
0.870 μm	0.862–0.877 μm	516 at 6.2 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
0.905 μm	0.890–0.920 μm	167 at 10.0 W m^{-2} sr^{-1} μm^{-1}	1 000 m	Atmospheric
0.936 μm	0.931–0.941 μm	57 at 3.6 W m^{-2} sr^{-1} μm^{-1}	1 000 m	water vapour
0.940 μm	0.915–0.965 μm	250 at 15.0 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
3.75 μm	3.660–3.840 μm	0.05 K at 0.45 W m^{-2} sr^{-1} μm^{-1}	1 000 m	Surface/Cloud
3.96 μm	3.929–3.989 μm	2.00 K at 2.38 W m^{-2} sr^{-1} μm^{-1}	1 000 m	temperature
3.96 μm	3.929–3.989 μm	0.07 K at 0.67 W m^{-2} sr^{-1} μm^{-1}	1 000 m	

4.06 μm	4.020–4.080 μm	0.07 K at 0.79 W m^{-2} sr^{-1} μm^{-1}	1 000 m	
4.47 μm 4.55 μm	4.433–4.498 μm 4.482–4.549 μm	0.25 K at 0.17 W m^{-2} sr^{-1} μm^{-1} 0.25 K at 0.59 W m^{-2} sr^{-1} μm^{-1}	1 000 m 1 000 m	Atmospheric temperature
1.375 μm 6.77 μm 7.33 μm	1.360–1.390 μm 6.535–6.895 μm 7.175–7.475 μm	150 at 6.0 W m^{-2} sr^{-1} μm^{-1} 0.25 K at 1.16 W m^{-2} sr^{-1} μm^{-1} 0.25 K at 2.18 W m^{-2} sr^{-1} μm^{-1}	1 000 m 1 000 m 1 000 m	Cirrus clouds, Water vapour
8.55 μm	8.400–8.700 μm	0.25 K at 9.58 W m^{-2} sr^{-1} μm^{-1}	1 000 m	Cloud properties
9.73 μm	9.580–9.880 μm	0.25 K at 3.69 W m^{-2} sr^{-1} μm^{-1}	1 000 m	Ozone
11.01 μm 12.03 μm	10.780–11.280 μm 11.770–12.270 μm	0.05 K at 9.55 W m^{-2} sr^{-1} μm^{-1} 0.05 K at 8.94 W m^{-2} sr^{-1} μm^{-1}	1 000 m 1 000 m	Surface/Cloud temperature
13.34 μm 13.64 μm 13.94 μm 14.24 μm	13.185–13.485 μm 13.485–13.785 μm 13.785–14.085 μm 14.085–14.385 μm	0.25 K at 4.52 W m^{-2} sr^{-1} μm^{-1} 0.25 K at 3.76 W m^{-2} sr^{-1} μm^{-1} 0.25 K at 3.11 W m^{-2} sr^{-1} μm^{-1} 0.35 K at 2.08 W m^{-2} sr^{-1} μm^{-1}	1 000 m 1 000 m 1 000 m 1 000 m	Cloud-top temperature

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Table 3.4. Example of multi-purpose VIS/IR imager operating in GEO: SEVIRI on Meteosat Second Generation

TABLE: Table horizontal lines

SEVIRI	*Spinning Enhanced Visible Infrared Imager*
Satellites	Meteosat-8, Meteosat-9, Meteosat-10, Meteosat-11
Mission	Multi-purpose VIS/IR imagery for cloud analysis, aerosol load, sea-surface temperature, land-surface radiative parameters, normalized difference vegetation index, fires, snow cover, wind from cloud motion tracking, etc.
Main features	12 channels, balanced VIS, NIR, SWIR, MWIR and TIR
Scanning technique	Mechanical Spinning satellite E–W continuous S–N stepping
Coverage/cycle	Full disk every 15 min Limited areas in correspondingly shorter time intervals
Resolution (SSP)	4.8 km IFOV, 3 km sampling for 11 narrow channels 1.6 km IFOV, 1 km sampling for 1 broad VIS channel
Resources	Mass: 260 kg Power: 150 W Data rate: 3.26 Mbps

Central wavelength	*Spectral interval (99% encircled energy)*	*SNR or NEΔT at specified input radiance*
Not applicable (broad bandwidth channel)	0.6–0.9 μm	4.3 at 1 % albedo

0.635 μm	0.56–0.71 μm	10.1 at 1 % albedo
0.81 μm	0.74–0.88 μm	7.28 at 1 % albedo
1.64 μm	1.50–1.78 μm	3 at 1 % albedo
3.92 μm	3.48–4.36 μm	0.35 K at 300 K
6.25 μm	5.35–7.15 μm	0.75 K at 250 K
7.35 μm	6.85–7.85 μm	0.75 K at 250 K
8.70 μm	8.30–9.10 μm	0.28 K at 300 K
9.66 μm	9.38–9.94 μm	1.50 K at 255 K
10.8 μm	9.80–11.8 μm	0.25 K at 300 K
12.0 μm	11.0–13.0 μm	0.37 K at 300 K
13.4 μm	12.4–14.4 μm	1.80 K at 270 K

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Table 3.5. Example of ocean-colour imager operating in LEO: MERIS on Envisat

TABLE: Table horizontal lines

MERIS	*Medium Resolution Imaging Spectrometer*
Satellite	Envisat
Mission	Ocean-colour imagery, aerosol properties, vegetation indexes, etc.
Main features	15 very narrow-bandwidth VIS and NIR channels
Scanning technique	Pushbroom 3 700 pixel/line (split into 5 parallel optical systems) Total swath: 1 150 km
Coverage/cycle	Global coverage in 3 days in daylight
Resolution (SSP)	Basic IFOV 300 m Reduced resolution for global data recording: 1 200 m
Resources	Mass: 200 kg Power: 175 W Data rate: 24 Mbps

Central wavelength	*Bandwidth*	*SNR at specified input spectral radiance*
412.5 nm	10 nm	1 871 at 47.9 W m^{-2} sr^{-1} μm^{-1}
442.5 nm	10 nm	1 650 at 41.9 W m^{-2} sr^{-1} μm^{-1}
490 nm	10 nm	1 418 at 31.2 W m^{-2} sr^{-1} μm^{-1}
510 nm	10 nm	1 222 at 23.7 W m^{-2} sr^{-1} μm^{-1}
560 nm	10 nm	1 156 at 18.5 W m^{-2} sr^{-1} μm^{-1}
620 nm	10 nm	863 at 12.0 W m^{-2} sr^{-1} μm^{-1}

665 nm	10 nm	708 at 9.2 W m^{-2} sr^{-1} μm^{-1}
681.25 nm	7.5 nm	589 at 8.3 W m^{-2} sr^{-1} μm^{-1}
708.75 nm	10 nm	631 at 6.9 W m^{-2} sr^{-1} μm^{-1}
753.75 nm	7.5 nm	486 at 5.6 W m^{-2} sr^{-1} μm^{-1}
760.625 nm	3.75 nm	205 at 3.4 W m^{-2} sr^{-1} μm^{-1}
778.75 nm	15 nm	628 at 4.9 W m^{-2} sr^{-1} μm^{-1}
865 nm	20 nm	457at 3.2 W m^{-2} sr^{-1} μm^{-1}
885 nm	10 nm	271 at 3.1 W m^{-2} sr^{-1} μm^{-1}
900 nm	10 nm	211 at 2.4 W m^{-2} sr^{-1} μm^{-1}

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Table 3.6. Example of imager with special viewing geometry: POLDER on PARASOL

TABLE: Table horizontal lines

POLDER	*Polarization and Directionality of the Earth's Reflectances*
Satellite	Polarisation et anisotropie des réflectances au sommet de l'atmosphère, couplées avec un satellite d'observation emportant un lidar (PARASOL)
Mission	Imagery with special viewing geometry, for best observation of aerosol and cirrus, land–surface radiative parameters including bidirectional reflectance distribution function, etc.
Main features	Bidirectional viewing Multipolarization 9 narrow-bandwidth VIS and NIR channels
Scanning technique	242 x 274 charge-coupled device (CCD) arrays Swath: 2 400 km Each Earth's spot viewed from more directions as satellite moves
Coverage/cycle	Near-global coverage every day in daylight
Resolution (SSP)	6.5 km IFOV
Resources	Mass: 32 kg Power: 50 W Data rate: 883 kbps

Central wavelength	*Bandwidth*	*No. of polarizations*	*SNR at specified input spectral radiance*
443.5 nm	13.4 nm	–	200 at 61.9 W m^{-2} sr^{-1} μm^{-1}
490.9 nm	16.3 nm	3	200 at 63.2 W m^{-2} sr^{-1} μm^{-1}
563.8 nm	15.4 nm	–	200 at 58.1 W m^{-2} sr^{-1} μm^{-1}
669.9 nm	15.1 nm	–	200 at 48.7 W m^{-2} sr^{-1} μm^{-1}
762.9 nm	10.9 nm	3	200 at 38.9 W m^{-2} sr^{-1} μm^{-1}

762.7 nm	38.1 nm	–	200 at 38.9 W m^{-2} sr^{-1} μm^{-1}
863.7 nm	33.7 nm	–	200 at 30.8 W m^{-2} sr^{-1} μm^{-1}
907.1 nm	21.1 nm	3	200 at 27.5 W m^{-2} sr^{-1} μm^{-1}
1 019.6 nm	17.1 nm	–	200 at 22.6 W m^{-2} sr^{-1} μm^{-1}

3.2.2 High-resolution optical imager

This instrument has the following main characteristics:

(a) Spatial resolution in the range of less than one metre to several tens of metres;

(b) Wavelengths in the VIS, NIR and SWIR bands (0.4 to 3 μm) with possible extension to MWIR and TIR;

(c) Variable number of channels and bandwidths:

(i) Single channel (panchromatic) with around 400 nm bandwidth (~~e.g.~~for example, 500–900 nm);

(ii) 3–10 multispectral channels with around 100 nm bandwidth;

(iii) Continuous spectral range (hyperspectral); typically has 100 channels with around 10 nm bandwidth;

(d) Imaging capability: continuous and contiguous sampling, covering a swath ranging from a few tens of kilometres to approximately 100 km, often addressable within a field of regard of several hundreds of kilometres;

(e) Applicable in LEO. GEO is not excluded but not yet in use.

High-resolution optical imagers may perform a number of missions, depending on the spectral bands, the number and bandwidth of channels, and steerable pointing capability. Those missions include:

(a) Panchromatic imagers: surveillance, recognition, stereoscopy for digital elevation model, etc. Critical instrument features are the resolution and the steerable pointing capability;

(b) Multispectral imagers: land observation for land use, land cover, ground water, vegetation classification, disaster monitoring, etc. Critical instrument features are the number of channels and the spectral coverage;

(c) Hyperspectral imagers: land observation, especially for vegetation process study, carbon cycle, etc. Critical instrument features are the spectral resolution and the spectral coverage.

Tables 3.7–3.9 describe an example of a panchromatic imager (WV60), a multispectral imager (ETM+) and a hyperspectral imager (Hyperion).

Table 3.7. Example of panchromatic high-resolution imager: WV60 on WorldView-1

TABLE: Table horizontal lines

WV60	*World View 60 camera*
Satellite	WorldView – 1

Mission	Surveillance, recognition, stereoscopy for digital elevation model, etc.
Main features	Panchromatic Resolution: 0.5 m Steering capability 60 cm telescope aperture
Scanning technique	Pushbroom 35 000 detector array Swath: 17.6 km, addressable by tilting the satellite in a variety of operating modes Stereo capability both along-track and cross-orbits
Coverage/cycle	Global coverage in 6 months in daylight Global coverage in a few days (down to 3) by strategic pointing
Resolution (SSP)	0.50 m
Resources	Mass: 380 kg Power: 250 W Data rate: 800 Mbps

Table 3.8. Example of multispectral high-resolution imager: ETM+ on Landsat-7

TABLE: Table horizontal lines

ETM+	*Enhanced Thematic Mapper +*
Satellite	Landsat-7
Mission	Land observation for land use, land cover, ground water, vegetation classification, disaster monitoring, etc.
Main features	8 channels: 1 panchromatic, 6 VIS, NIR and SWIR, 1 TIR Resolution: 15 m, 30 m and 60 m
Scanning technique	Whiskbroom 6 000 pixel/line (narrowband) 12 000 pixel/line (panchromatic) 3 000 pixel/line (TIR) Swath: 185 km
Coverage/cycle	Global coverage in 16 days in daylight
Resolution (SSP)	30 m (6 narrowband channels), 15 m (panchromatic), 60 m (TIR)
Resources	Mass: 441 kg Power: 590 W Data rate: 150 Mbps

Central wavelength	*Spectral interval*	*SNR at specified input spectral radiance or NEΔT*	
		Low signal	*High signal*
Panchromatic	0.50–0.90 μm	14 at 22.9 W m^{-2} sr^{-1} μm^{-1}	80 at 156.3 W m^{-2} sr^{-1} μm^{-1}
0.48 μm	0.45–0.52 μm	36 at 40 W m^{-2} sr^{-1} μm^{-1}	130 at 190 W m^{-2} sr^{-1} μm^{-1}
0.56 μm	0.53–0.61 μm	37 at 30 W m^{-2} sr^{-1} μm^{-1}	167 at 193.7 W m^{-2} sr^{-1} μm^{-1}
0.66 μm	0.63–0.69 μm	24 at 21.7 W m^{-2} sr^{-1} μm^{-1}	127 at 149.6 W m^{-2} sr^{-1} μm^{-1}
0.83 μm	0.78–0.90 μm	33 at 13.6 W m^{-2} sr^{-1} μm^{-1}	226 at 149.6 W m^{-2} sr^{-1} μm^{-1}

1.65 μm	1.55–1.75 μm	34 at 4.0 W m^{-2} sr^{-1} μm^{-1}	176 at 31.5 W m^{-2} sr^{-1} μm^{-1}
2.20 μm	2.09–2.35 μm	27 at 1.7 W m^{-2} sr^{-1} μm^{-1}	130 at 11.1 W m^{-2} sr^{-1} μm^{-1}
11.45 μm	10.4–12.5 μm	0.2 K at 300 K	0.2 K at 320 K

Table 3.9. Example of hyperspectral high-resolution imager: Hyperion on NMP EO-1

TABLE: Table horizontal lines

Hyperion	
Satellite	New Millennium Program Earth Observing – 1 (NMP EO-1)
Mission	Land observation, especially for vegetation process study, carbon cycle, etc.
Main features	VIS/NIR/SWIR grating spectrometer with 220 channels (hyperspectral) in two groups, covering the ranges 0.4–1.0 μm and 0.9–2.5 μm respectively Channel bandwidth: 10 nm Resolution: 30 m
Scanning technique	Pushbroom 250 pixel/line Swath: 7.5 km
Coverage/cycle	Global coverage in one year in daylight
Resolution (SSP)	30 m
Resources	Mass: 49 kg Power: 51 W Data rate: 105 Mbps

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3.2.3 Cross-nadir ~~scanning~~ short-wave sounder

~~This spectrometer~~ An example is TROPOMI (TROPOspheric Monitoring Instrument) on the Sentinel-5 Precursor Satellite which has the following main characteristics:

(a) ~~Operates~~The nadir viewing shortwave spectrometer of TROPOMI operates in the ultraviolet (UV), VIS, NIR and SWIR bands (~~0.2~~see table below), the polarization sensitivity of TROPOMI is reduced to ~~3 μm);~~less than 0.5 % with a polarization scrambler;

~~(b) Spectral resolution ranging from a fraction of a nanometre to a few nanometres;~~

(b) Typical spectral resolutions of short-wave sounders are fractions of a nanometre (see Table 3.10);

(c) Spatial resolution is in the order of 10 km - for TROPOMI it is 7 km x 7 km;

(d) Horizontal sampling is not necessarily continuous and contiguous~~;~~

~~(e) Scanning~~. However for TROPOMI it is contiguous thus providing imaging capability;

(e) The scanning capabilities can be from nadir-only pointing to a swath of a few thousand kilometres. In the case of TROPOMI it has a swath of 2 600 km;

(f) Applicable both in LEO and GEO.

~~Depending on spectral bands and resolution,~~Generally speaking cross-nadir ~~scanning~~ SW sounders may be used in atmospheric chemistry for monitoring a number of species~~, mostly~~. Which species are detectable is determined by the spectral bands ~~used~~and necessitates sufficient spectral resolution. Good spatial resolution benefits sounding because it increases the number of clear-sky views. Contiguous sampling is a priori less critical however it has the great advantage of enabling imaging capabilities. Species that can be retrieved, depending on spectral coverage, include:

(a) UV only: ozone profile;

(b) UV and VIS: ozone profile and total column or gross profile of a small number of other species, such as BrO, NO_2, OClO, SO_2 and aerosol;

(c) UV, VIS and NIR: ozone profile and total column or gross profile of several other species, such as BrO, ClO, H_2O, HCHO, NO, NO_2, NO_3, O_2, O_4, OClO, SO_2 and aerosol;

(d) UV, VIS, NIR and SWIR: ozone profile and total column or gross profile of many other species, such as BrO, CH_4, ClO, CO, CO_2, H_2O, HCHO, N_2O, NO, NO_2, NO_3, O_2, O_4, OClO, SO_2 and aerosol;

(e) NIR and SWIR, possibly complemented by MWIR and TIR: total column or gross profile of selected species, such as CH_4, CO, CO_2, H_2O and O_2.

Tables 3.10 and 3.11 describe one example with ~~full~~in LEO its spectral coverage (~~SCIAMACHY-nadir in LEO~~TROPOMI) and another with ~~reduced~~its spectral coverage ~~(UVN~~ in GEO (UVN on Meteosat Third Generation).

Table 3.10. Example of cross-nadir ~~scanning~~ SW sounder in LEO: ~~SCIAMACHY-nadir~~TROPOMI instrument on ~~Envisat~~Sentinel-5 Precursor (S-5 P)

TABLE: Table horizontal lines

Spectral and Radiometric Performance Parameters for the TROPOMI Instrument

~~SCIAMACHY-nadir~~TROPOMI	*~~Scanning Imaging Absorption Spectrometer for Atmospheric Cartography – nadir scanning unit~~The TROPOspheric Monitoring Instrument is a UV/VIS/NIR/SWIR non-scanning nadir viewing imaging spectrometer with a swath of about 2 600 km and high spatial resolution (7 km x 7 km at nadir). TROPOMI flies in loose formation with with the SUOMI-NPP meteorological satellite 13:30h equator crossing time.*
Satellite	~~Envisat~~Sentinel- 5 Precursor (S5-P)
Mission	Atmospheric chemistry ~~Tracked species: BrO, CH_4, ClO,~~ Mandatory products: O_3, SO_2, HCHO, NO_2, CO, ~~CO_2~~CH_4, cloud fraction/pressure/optical depth, aerosol index and layer height Optional products: surface UV, aerosol optical depth, H_2O, ~~HCHO, N_2O, NO, NO_2, NO_3, O_2, O_3, O_4,~~ CHOCHO, BrO, OClO, ~~SO_2 and aerosol~~HDO/ H_2O ratio.

Main features	Spectral range: UV/VIS/NIR/SWIR Imaging capability~~:~~ with 8 bands; grating spectrometer ~~covering eight bands, 8 192 channels, with 7~~ with polarization ~~channels~~scrambler
Scanning technique	~~Mechanical, cross-track~~ ~~IFOV: 25 km along-track x 0.6 km across-track at the SSP~~ ~~Time integration is performed across track to achieve the required SNR~~ ~~Swath: 960 km; one scan line in 4.5 seconds~~ ~~The cross-nadir mode alternates with the limb mode and the solar/lunar occultation mode~~Push-broom scanner Swath: 2600 km; one scan line in 1 second
Coverage/cycle	Cross-track mode~~:~~ providing global coverage every ~~3 days~~day in daylight~~, if used full time~~
Resolution~~ (SSP)~~	~~Typical resolution is 30~~ 7 km ~~along-track~~ x ~~60~~ 7 km ~~across-track~~ at the SSP
Resources	Mass: ~~198~~200 kg Power: ~~122~~170 W Data rate: ~~400 kbps~~140 GBits per orbit

Spectral ~~range~~Range	*Spectral resolution*	*~~SNR at specified input spectral radiance~~Spectral Sampling*	*Required signal-to-noise*	*Radiometric accuracy (%)*
~~214–334~~ 270 - 300 nm	0.~~24~~48 nm	0.071 nm	100 – 800 [1,2]	~~200 at 0.5 W m^{-2} sr^{-1} μm^{-1}~~
300 – 320 nm	0.49 nm	0.073 nm	90 – 700 [1]	1.9 [5]
320 – 405 nm	0.54 nm	0.22 nm	800 – 1000 [1]	1.6 [5]
405 – 495 nm	0.54 nm	0.22 nm	800 – 1000 [1]	1.6 [5]
675 – 725 nm	0.38 nm	0.14 nm	100 – 500 [1,3]	1.6 [5]
725 – 775 nm	0.38 nm	0.14 nm	100 – 500 [1,3]	1.6 [5]
2305 – 2345 nm	0.25 nm	0.10 nm	100 – 120 [4]	1.6 [5]
2345 – 2385 nm				1.5 [5]

	0.25 nm	0.10 nm	100 -120 [4]	
				1.5 [5]
~~300–412 nm~~	~~1 024~~	~~0.26 nm~~	~~2 300 at 58 W m^{-2} sr^{-1} μm^{-1}~~	
~~383–628 nm~~	~~1 024~~	~~0.44 nm~~	~~2 600 at 90 W m^{-2} sr^{-1} μm^{-1}~~	
~~595–812 nm~~	~~1 024~~	~~0.48 nm~~	~~2 800 at 61 W m^{-2} sr^{-1} μm^{-1}~~	
~~773–1 063 nm~~	~~1 024~~	~~0.54 nm~~	~~1 900 at 40 W m^{-2} sr^{-1} μm^{-1}~~	
~~971–1 773 nm~~	~~1 024~~	~~1.48 nm~~	~~1 500 at 25 W m^{-2} sr^{-1} μm^{-1}~~	
~~1 934–2 044 nm~~	~~1 024~~	~~0.22 nm~~	~~100 at 3.4 W m^{-2} sr^{-1} μm^{-1}~~	
~~2 259–2 386 nm~~	~~1 024~~	~~0.26 nm~~	~~320 at 2.2 W m^{-2} sr^{-1} μm^{-1}~~	
~~310–2 380 nm~~	~~7~~	~~67–137 nm~~	~~Not applicable~~	

Note on spectral channels of TROPOMI:

[1]: The minimum SNR is specified for a reference scene with a surface albedo of 2 % and the sun in zenith.

[2]: The SNR for band 1 is specified for a ground pixel size of 21 x 28 km^2.

[3]: The SNR for band 6 is specified for a ground pixel size of 7 x 7 km^2.

[4]: The minimum SNR is specified for a reference scene with a surface albedo of 5 % and solar zenith angle of 70°.

[5]: Values refer to absolute radiometric accuracy of the measured Earth spectral reflectance.

SOURCE: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-5p-tropomi/samplings-resolutions/spectral-radiometric

Table 3.11. Example of cross-nadir scanning SW sounder in GEO: UVN on Meteosat Third Generation (MTG)

TABLE: Table horizontal lines

UVN	*Ultraviolet, Visible and Near-infrared sounder* *Also known as Sentinel 4*
Satellites	MTG-S1 MTG-S2
Mission	Atmospheric chemistry Tracked species: BrO, ClO, H_2O, HCHO, NO, NO_2, NO_3, O_2, O_3, O_4, OClO, SO_2 and aerosol
Main features	Spectral range: UV/VIS/NIR Imaging capability: grating spectrometer covering 3 bands, 1 470 channels
Scanning technique	Mechanical 3-axis stabilized satellite E–W continuous S–N stepping
Coverage/cycle	European area (lat. 30°N–65°N, long. 15°W–50°E) in 60 minutes (30 minutes is also possible)
Resolution	Defined at 45°N 0°: < 8 km in both N–S and E–W directions
Resources	Mass: 150 kg Power: 100 W Data rate: 25 Mbps

Spectral ranges	*No. of channels*	*Spectral resolution*	*SNR at specified input spectral radiance*
305–400 nm	570	0.5 nm	200–1 400 at 40–120 W m^{-2} sr^{-1} μm^{-1}
400–500 nm	600	0.5 nm	1 400 at 140 W m^{-2} sr^{-1} μm^{-1}
755–775 nm	300	0.2 nm	1 200 at 60 W m^{-2} sr^{-1} μm^{-1}

3.2.4 Cross-nadir scanning infrared sounder

These radiometers or spectrometers have the following main characteristics:

(a) Wavelengths in the MWIR and TIR bands (3–15 μm) with a possible extension to FIR (up to 50 μm) and auxiliary channels in the VIS/NIR bands;

(b) Spectral resolution in the order of 0.1 cm^{-1} (very high resolution), 0.5 cm^{-1} (hyperspectral) or 10 cm^{-1} (radiometer);

(c) Spatial resolution in the order of 10 km;

(d) Horizontal sampling not necessarily continuous or contiguous;

(e) Scanning capability can be from nadir-only pointing to a swath of a few thousand kilometres;

(f) Applicable both in LEO and GEO.

Depending on their spectral bands and resolution, cross-nadir scanning IR sounders may be used for atmospheric temperature and humidity profiling, and/or in atmospheric chemistry for a number of species:

(a) Radiometers provide coarse-vertical-resolution temperature and humidity profiles;

(b) Spectrometers provide high-vertical-resolution temperature and humidity profiles, coarse ozone profiles, total column and gross profile of a small number of other species, such as CH_4, CO, CO_2, HNO_3, NO_2, SO_2 and aerosol;

(c) Very high-resolution spectrometers that are specifically for atmospheric chemistry provide profiles or total columns of C_2H_2, C_2H_6, CFC-11, CFC-12, CH_4, $ClONO_2$, CO, CO_2, COS, H_2O, HNO_3, N_2O, N_2O_5, NO, NO_2, O_3, PAN, SF_6, SO_2 and aerosol.

Tables 3.12–3.14 set out three examples: a radiometer in GEO (Sounder on Geostationary Operational Environmental Satellite (GOES)); a hyperspectral sounder in LEO (IASI on Metop) and a very high-resolution spectrometer in LEO (TES-nadir on EOS-Aura).

Table 3.12. Example of radiometric cross-nadir scanning infrared sounder in GEO: Sounder on GOES

TABLE: Table horizontal lines

GOES Sounder	
Satellites	GOES-8, GOES-9, GOES-10, GOES-11, GOES-12, GOES-13, GOES-14, GOES-15
Mission	Coarse-vertical-resolution temperature and humidity profiles
Main features	Radiometer: 18 narrow-bandwidth channels in MWIR/TIR + 1 VIS
Scanning technique	Mechanical Biaxial 3-axis stabilized satellite Step-and-dwell
Coverage/cycle	Full disk in 8 h 3 000 x 3 000 km^2 in 42 minutes 1 000 x 1 000 km^2 in 5 minutes
Resolution (SSP)	8.0 km
Resources	Mass: 152 kg Power: 93 W Data rate: 40 kbps

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TABLE: Table horizontal lines

Wavelength	*Wave number*	*Bandwidth*	*SNR or NEΔT at specified input*
14.71 μm	680 cm^{-1}	13 cm^{-1}	1.24 K at 290 K
14.37 μm	696 cm^{-1}	13 cm^{-1}	0.79 K at 290 K
14.06 μm	711 cm^{-1}	13 cm^{-1}	0.68 K at 290 K
13.64 μm	733 cm^{-1}	16 cm^{-1}	0.55 K at 290 K
13.37 μm	748 cm^{-1}	16 cm^{-1}	0.49 K at 290 K
12.66 μm	790 cm^{-1}	30 cm^{-1}	0.23 K at 290 K
12.02 μm	832 cm^{-1}	50 cm^{-1}	0.14 K at 290 K

11.03 μm	907 cm^{-1}	50 cm^{-1}	0.10 K at 290 K
9.71 μm	1 030 cm^{-1}	25 cm^{-1}	0.12 K at 290 K
7.43 μm	1 345 cm^{-1}	55 cm^{-1}	0.06 K at 290 K
7.02 μm	1 425 cm^{-1}	80 cm^{-1}	0.06 K at 290 K
6.51 μm	1 535 cm^{-1}	60 cm^{-1}	0.15 K at 290 K
4.57 μm	2 188 cm^{-1}	23 cm^{-1}	0.20 K at 290 K
4.52 μm	2 210 cm^{-1}	23 cm^{-1}	0.17 K at 290 K
4.45 μm	2 248 cm^{-1}	23 cm^{-1}	0.20 K at 290 K
4.13 μm	2 420 cm^{-1}	40 cm^{-1}	0.14 K at 290 K
3.98 μm	2 513 cm^{-1}	40 cm^{-1}	0.22 K at 290 K
3.74 μm	2 671 cm^{-1}	100 cm^{-1}	0.14 K at 290 K
0.70 μm	Not applicable	0.05 μm	1 000 at 100% albedo

Table 3.13. Example of hyperspectral cross-nadir scanning infrared sounder in LEO: IASI on Metop

TABLE: Table horizontal lines

IASI	*Infrared Atmospheric Sounding Interferometer*
Satellites	Metop-A, Metop-B, Metop-C
Mission	High vertical-resolution temperature and humidity profile Coarse ozone profile Total column or gross profile of a number of other species, such as CH_4, CO, CO_2, HNO_3, NO_2, SO_2 and aerosol
Main features	Spectrometer: spectral resolution 0.25 cm^{-1} (unapodized) MWIR/TIR spectral range Interferometer with 8 461 channels and a one-channel embedded TIR imager
Scanning technique	Cross-track: 30 steps of 48 km SSP Swath: 2 130 km Along-track: one 48 km line every 8 seconds
Coverage/cycle	Near-global coverage twice a day
Resolution (SSP)	4 x 12 km IFOV close to the centre of a 48 x 48 km^2 cell (average sampling distance: 24 km)
Resources	Mass: 236 kg Power: 210 W Data rate: 1.5 Mbps (after onboard processing)

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TABLE: Table horizontal lines

Spectral range (μm)	*Spectral range (cm^{-1})*	*Spectral resolution (unapodized)*	*NEΔT at specified scene temperature*

8.26–15.50 μm	645–1210 cm^{-1}	0.25 cm^{-1}	0.2–0.3 K at 280 K
5.00–8.26 μm	1 210–2 000 cm^{-1}	0.25 cm^{-1}	0.2–0.5 K at 280 K
3.62–5.00 μm	2 000–2 760 cm^{-1}	0.25 cm^{-1}	0.5–2.0 K at 280 K
10.3–12.5 μm	Not applicable	Not applicable	0.8 K at 280 K

Table 3.14. Example of very high-resolution cross-nadir scanning infrared sounder in LEO: TES-nadir on EOS-Aura

TABLE: Table horizontal lines

TES-nadir	*Tropospheric Emission Spectrometer – nadir scanning unit*
Satellite	EOS-Aura
Mission	Atmospheric chemistry: profiles or total columns of C_2H_2, C_2H_6, CFC-11, CFC-12, CH_4, $ClONO_2$, CO, CO_2, COS, H_2O, HNO_3, N_2O, N_2O_5, NO, NO_2, O_3, PAN, SF_6, SO_2 and aerosol
Main features	Spectrometer Spectral resolution: 0.059 cm^{-1} (unapodized) MWIR/TIR spectral range Imaging interferometer: four bands; 40 540 channels
Scanning technique	Cross-track mode: array of 16 detectors with a 0.53 km^2 x 0.53 km^2 nadir footprint moving in 10 steps to cover a 5.3 km^2 x 8.5 km^2 field of view that can be pointed everywhere within a 45°-aperture cone or an 885 km swath. The cross-nadir mode is alternative to the limb mode.
Coverage/cycle	Cross-track mode: if used full time with strategic pointing, global coverage could be obtained for cells of ~80 km wide in 16 days (the orbital repeat cycle)
Resolution (SSP)	0.53 km sampling
Resources	Mass: 385 kg Power: 334 W Data rate: 4.5 Mbps

Spectral range (μm)	*Spectral range (cm^{-1})*	*Spectral resolution (unapodized)*	*NEΔT at specified scene temperature*
11.11–15.38 μm	650–900 cm^{-1}	0.059 cm^{-1}	< 1 K at 280 K
8.70–12.20 μm	820–1 150 cm^{-1}	0.059 cm^{-1}	< 1 K at 280 K
5.13–9.09 μm	1 100–1 950 cm^{-1}	0.059 cm^{-1}	< 1 K at 280 K
3.28–5.26 μm	1 900–3 050 cm^{-1}	0.059 cm^{-1}	< 2 K at 280 K

3.2.5 Microwave radiometers

These radiometers have the following main characteristics:

(a) Frequencies from 1 to 3 000 GHz (wavelengths from 0.1 mm to 30 cm);

(b) Channel bandwidths from a few MHz to several GHz;

(c) Spatial resolution from a few kilometres to approximately 100 kilometres, determined by antenna size and frequency;

(d) Horizontal sampling not necessarily continuous or contiguous;

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Figure 3.7. Sketch view of SMOS with MIRAS (left) and the satélite de aplicaciones científicas – D (SAC-D) with Aquarius (right). The Aquarius real aperture antenna measures 2.5 m in diameter. The MIRAS synthetic aperture antenna is inscribed in a circle that measures 4 m in diameter.

(e) Scanning: cross-track (swath in the order of 2 000 km), conical (swath in the order of 1 500 km, possibly providing single or dual polarization) or nadir-only;

(f) Applicable in LEO.

Depending on their frequency, spatial resolution, and scanning mode, MW radiometers may perform a number of missions:

(a) Multi-purpose MW imagery for precipitation, cloud liquid water and ice, precipitable water, sea-surface temperature, sea-surface wind speed (and direction if multipolarization is used), sea-ice cover, surface soil moisture, snow status, water equivalent, etc. Critical instrument features are: the extension of the spectral range, from 19 GHz as a minimum (possibly 10 GHz, or ideally 6–7 GHz) to at least 90 GHz; and conical scanning to make use of differential polarization under conditions of a constant incidence angle;

(b) Nearly-all-weather temperature and humidity sounding, which is also relevant for precipitation. Critical instrument features are the channels in absorption bands: O_2 for temperature (main frequency: 57 GHz) and H_2O for humidity (main frequency: 183 GHz);

(c) Sea-surface salinity and volumetric soil moisture. One critical instrument feature is the low frequency in the L band (main frequency: 1.4 GHz); this implies the use of very large antennas (see Figure 3.7);

(d) Atmospheric correction in support of altimetry missions. Critical instrument features are the frequency of the water-vapour 23 GHz band and its nearby windows; and the nadir viewing, co-centred with an altimeter.

Tables 3.15–3.18 describe a multi-purpose radiometer (AMSR-E), a temperature and humidity sounder (ATMS), a low-frequency radiometer (MIRAS) and a nadir-viewing radiometer (AMR).

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Table 3.15. Example of multi-purpose MW imager: AMSR-E on EOS-Aqua

TABLE: Table horizontal lines

AMSR-E	*Advanced Microwave Scanning Radiometer for Earth Observation System (EOS)*
Satellite	EOS-Aqua
Mission	Multi-purpose MW imagery for precipitation, cloud liquid water and ice, precipitable water, sea-surface temperature, sea-surface wind speed, sea-ice cover, surface soil moisture, snow status, water equivalent, etc.
Main features	Spectral range: 6.9–89 GHz 6 frequencies, 12 channels, mostly windows Conical scanning

Scanning technique	Conical: 55° zenith angle Swath: 1 450 km Scan rate: 40 scan/min = 10 km/scan
Coverage/cycle	Global coverage once a day
Resolution (SSP)	Changes with frequency Consistent with an antenna diameter of 1.6 m
Resources	Mass: 314 kg Power: 350 W Data rate: 87.4 kbps

Central frequency (GHz)	*Bandwidth (MHz)*	*Polarizations*	*NEΔT*	*IFOV*	*Pixel*
6.925	350	Vertical (V), Horizontal (H)	0.3 K	43 x 75 km	10 x 10 km
10.65	100	V, H	0.6 K	29 x 51 km	10 x 10 km
18.7	200	V, H	0.6 K	16 x 27 km	10 x 10 km
23.8	400	V, H	0.6 K	14 x 21 km	10 x 10 km
36.5	1 000	V, H	0.6 K	9 x 14 km	10 x 10 km
89.0	3 000	V, H	1.1 K	4 x 6 km	5 x 5 km

Table 3.16. Example of MW temperature/humidity sounder: ATMS on Suomi National Polar-orbiting Partnership (NPP) and Joint Polar Satellite System (JPSS)

TABLE: Table horizontal lines

ATMS	*Advanced Technology Microwave Sounder*
Satellites	Suomi-NPP, JPSS-1 and JPSS-2
Mission	Nearly-all-weather temperature and humidity sounding; also relevant for precipitation
Main features	Spectral range: 23–183 GHz 22 channels, including the 57 and 183 GHz bands Cross-track scanning
Scanning technique	Cross-track: 96 steps of 16 km SSP Swath: 2 200 km Along-track: one 16 km line every 8/3 seconds
Coverage/cycle	Near-global coverage twice a day
Resolution (SSP)	16 km for channels at 165–183 GHz 32 km for channels at 50–90 GHz 75 km for channels at 23–32 GHz
Resources	Mass: 75.4 kg Power: 93 W Data rate: 20 kbps

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TABLE: Table horizontal lines

Central frequency (GHz)	*Bandwidth (MHz)*	*Quasi-polarization*	*NEΔT*

23.800	270	Quasi-vertical (QV)	0.90 K
31.400	180	QV	0.90 K
50.300	180	Quasi-horizontal (QH)	1.20 K
51.760	400	QH	0.75 K
52.800	400	QH	0.75 K
53.596 ± 0.115	170	QH	0.75 K
54.400	400	QH	0.75 K
54.940	400	QH	0.75 K
55.500	330	QH	0.75 K
f0 = 57.290344	330	QH	0.75 K
f0 ± 0.217	78	QH	1.20 K
f0 ± 0.3222 ± 0.048	36	QH	1.20 K
f0 ± 0.3222 ± 0.022	16	QH	1.50 K
f0 ± 0.3222 ± 0.010	8	QH	2.40 K
f0 ± 0.3222 ± 0.0045	3	QH	3.60 K
89.5	5 000	QV	0.50 K
165.5	3 000	QH	0.60 K
183.31 ± 7.0	2 000	QH	0.80 K
183.31 ± 4.5	2 000	QH	0.80 K
183.31 ± 3.0	1 000	QH	0.80 K
183.31 ± 1.8	1 000	QH	0.80 K
183.31 ± 1.0	500	QH	0.90 K

Table 3.17. Example of L-band MW radiometer: MIRAS on SMOS

TABLE: Table horizontal lines

MIRAS	*Microwave Imaging Radiometer using Aperture Synthesis*
Satellite	Soil Moisture and Ocean Salinity (SMOS)
Mission	Sea-surface salinity, volumetric soil moisture
Main features	Very large synthetic aperture antenna Single L-band frequency (1.413 GHz) Several polarimetric modes
Scanning technique	Pushbroom: correlation interferometry is implemented among receiver arrays deployed on the three arms of a Y-shaped antenna Swath: 1 000 km
Coverage/cycle	Global coverage in 3 days (soil moisture) Depending on the desired accuracy for salinity measurements, average figures measured over a number of weeks may be needed

Resolution (SSP)	50 km basic; may be degraded, depending on the desired accuracy for salinity measurements
Resources	Mass: 355 kg Power: 511 W Data rate: 89 kbps

Table 3.18. Example of non-scanning MW radiometer designed to support altimetry: AMR on JASON

TABLE: Table horizontal lines

AMR	*Advanced Microwave Radiometer*
Satellites	JASON-2, JASON-3
Mission	Atmospheric correction in support of the altimeters of JASON-1 and JASON-2
Main features	3 frequencies: 18.7 GHz, 23.8 GHz and 34 GHz
Scanning technique	Nadir-only viewing, associated with the Poseidon-3 and Poseidon-3B radar altimeters
Coverage/cycle	Global coverage in 1 month for 30 km average spacing, or in 10 days for 100 km average spacing
Resolution (SSP)	25 km
Resources	Mass: 27 kg Power: 31 W Data rate: 100 bps

3.2.6 Limb sounders

This family of instruments has the following main characteristics:

(a) Scanning of the Earth's limb: this determines vertical resolution (in the range 1–3 km), the observed atmospheric layer (in the range 10–80 km), and spatial resolution (about 300 km along-view);

(b) Spectrometers using the UV/VIS/NIR/SWIR (200–3 000 nm) bands, the MWIR/TIR (3–16 μm) bands, or the high-frequency range of MW (100–3 000 GHz);

(c) Spatial resolution, from a few tens of kilometres to a few hundreds of kilometres in the transverse direction;

(d) Horizontal sampling, limited to one or a few azimuth directions;

(e) Applicable only in LEO.

Limb sounders can observe the high troposphere, stratosphere and mesosphere with high vertical resolution, and are mainly used for atmospheric chemistry. Depending on their spectral bands, limb sounders may track different species:

(a) SW spectrometers for a number of species, depending on the part of the spectrum covered; for the full range (UV/VIS/NIR/SWIR), the main species are: BrO, CH_4, ClO, CO, CO_2, H_2O, HCHO, N_2O, NO, NO_2, NO_3, O_2, O_3, O_4, OClO, SO_2 and aerosol;

(b) IR spectrometers for a number of species, depending on the part of the spectrum covered; for the full range (MWIR/TIR), the main species are: C_2H_2, C_2H_6, CFCs (CCl_4, CF_4, F11, F12, F22), CH_4, $ClONO_2$, CO, COF_2, H_2O, HNO_3, HNO_4, HOCl, N_2O, N_2O_5, NO, NO_2, O_3, OCS, SF_6 and aerosol;

(c) MW spectrometers for a number of species, depending on the part of the spectrum covered; for the range 100–3 000 GHz, the main species are: BrO, ClO, CO, H_2O, HCl, HCN, HNO_3, HO_2, HOCl, N_2O, O_3, OH and SO_2;

(d) Occultation sounders, tracking the Sun, the moon or the stars, for a number of species, depending on the part of the spectrum covered; for the full range (UV/VIS/NIR/SWIR) the main species are: H_2O, NO_2, NO_3, O_3, OClO and aerosol.

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Table~~s~~ 3.19~~–3.22~~ shows example of limb sounder~~s~~ that uses SW ~~(SCIAMACHY-limb), IR (MIPAS), MW (MLS) and~~in occultation ~~in SW~~ (SAGE-III on ISS).

~~**Table 3.19. Example of limb sounder using SW: SCIAMACHY-limb on Envisat**~~

~~**TABLE: Table horizontal lines**~~

~~*SCIAMACHY-limb*~~	~~*Scanning Imaging Absorption Spectrometer for Atmospheric Cartography – limb scanning unit*~~
~~Satellite~~	~~Envisat~~
~~Mission~~	~~Chemistry of the high atmosphere.~~ ~~Tracked species: BrO, CH_4, ClO, CO, CO_2, H_2O, HCHO, N_2O, NO, NO_2, NO_3, O_2, O_3, O_4, OClO, SO_2 and aerosol~~
~~Main features~~	~~UV/VIS/NIR/SWIR grating spectrometer~~ ~~Eight bands~~ ~~8 192 channels, with 7 polarization channels~~
~~Scanning technique~~	~~Limb scanning of ± 500 km horizontal sector~~ ~~Solar and lunar occultation: the instrument is self-calibrating in this mode (principle of differential optical absorption spectroscopy)~~ ~~The limb mode, solar/lunar occultation mode and cross-nadir mode are alternatives to each other.~~
~~Coverage/cycle~~	~~If used full time, the limb mode would provide global coverage every 3 days in daylight.~~ ~~Not applicable for solar and lunar occultation~~
~~Resolution (SSP)~~	~~Vertical: 3 km, in the altitude range 10–100 km~~ ~~Horizontal: effective resolution: ~ 300 km (limb geometry)~~ ~~Solar and lunar occultation: vertical 1 km, in the altitude range 10–100 km; horizontal ~ 300 km~~
~~Resources~~	~~Mass: 198 kg~~ ~~Power: 122 W~~ ~~Data rate: 400 kbps~~

~~*Spectral range*~~	~~*No. of channels*~~	~~*Spectral resolution*~~	~~*SNR at specified input spectral radiance*~~
~~214–334 nm~~	~~1 024~~	~~0.24 nm~~	~~500 at 1.5 W m^{-2} sr^{-1} μm^{-1}~~
~~300–412 nm~~	~~1 024~~	~~0.26 nm~~	~~4 000 at 130 W m^{-2} sr^{-1} μm^{-1}~~
~~383–628 nm~~	~~1 024~~	~~0.44 nm~~	~~4 500 at 170 W m^{-2} sr^{-1} μm^{-1}~~

~~595–812 nm~~	~~1 024~~	~~0.48 nm~~	~~3 000 at 49 W m^{-2} sr^{-1} μm^{-1}~~
~~773–1 063 nm~~	~~1 024~~	~~0.54 nm~~	~~2 500 at 24 W m^{-2} sr^{-1} μm^{-1}~~
~~971–1 773 nm~~	~~1 024~~	~~1.48 nm~~	~~1 000 at 8.2 W m^{-2} sr^{-1} μm^{-1}~~
~~1 934–2 044 nm~~	~~1 024~~	~~0.22 nm~~	~~10 at 0.2 W m^{-2} sr^{-1} μm^{-1}~~
~~2 259–2 386 nm~~	~~1 024~~	~~0.26 nm~~	~~7 at 0.1 W m^{-2} sr^{-1} μm^{-1}~~
~~310–2 380 nm~~	~~7~~	~~67–137 nm~~	~~Not applicable~~

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~~Table 3.20. Example of limb sounder using IR: MIPAS on Envisat~~

~~**TABLE: Table horizontal lines**~~

~~*MIPAS*~~	~~*Michelson Interferometer for Passive Atmospheric Sounding*~~
~~Satellite~~	~~Envisat~~
~~Mission~~	~~Chemistry of the high atmosphere~~ ~~Tracked species: C_2H_2, C_2H_6, CFCs (CCl_4, CF_4, F11, F12, F22), CH_4, $ClONO_2$, CO, COF_2, H_2O, HNO_3, HNO_4, HOCl, N_2O, N_2O_5, NO, NO_2, O_3, OCS, SF_6 and aerosol~~
~~Main features~~	~~IR spectrometer: Michelson interferometer~~ ~~Range 685–2 410 cm^{-1} (4.15–14.6 μm)~~ ~~Spectral resolution 0.035 cm^{-1} (unapodized)~~ ~~60 000 channels/spectrum~~ ~~NESR: 50 nW cm^{-2} sr^{-1} cm at 685 cm^{-1}, 4.2 nW cm^{-2} sr^{-1} cm at 2 410 cm^{-1}~~
~~Scanning technique~~	~~Limb scanning, forward and side~~ ~~75 seconds for one vertical scan; 80 scans per orbit; 1 145 profiles per day~~
~~Coverage/cycle~~	~~Global coverage every 3 days for one measurement in every 300 km^2 x 300 km^2 cell~~
~~Resolution (SSP)~~	~~Vertical: 3 km, in the altitude range 5–150 km~~ ~~Horizontal effective resolution: ~300 km (limb geometry)~~
~~Resources~~	~~Mass: 320 kg~~ ~~Power: 210 W~~ ~~Data rate: 8 Mbps~~

~~Table 3.21. Example of limb sounder using MW: MLS on EOS-Aura~~

~~**TABLE: Table horizontal lines**~~

~~*MLS*~~	~~*Microwave Limb Sounder*~~
~~Satellite~~	~~EOS-Aura~~
~~Mission~~	~~Chemistry of the high atmosphere~~ ~~Tracked species: BrO, ClO, CO, H_2O, HCl, HCN, HNO_3, HO_2, HOCl, N_2O, O_3, OH and SO_2~~

~~Main features~~	~~MW spectrometer: 5-band, 36 sub-bands, 1 000 channels, Millimetre-submillimetre heterodyne radiometer at frequencies of 118 GHz (9 bands), 190 GHz (6 bands), 240 GHz (7 bands), 640 GHz (9 bands) and 2 500 GHz (5 bands)~~
~~Scanning technique~~	~~Limb scanning~~
~~Coverage/cycle~~	~~Global coverage every 3 days for 300 km wide cells~~
~~Resolution (SSP)~~	~~Vertical: 1.5 km, in the altitude range 5–120 km~~ ~~Horizontal effective resolution: ~300 km (limb geometry)~~
~~Resources~~	~~Mass: 490 kg~~ ~~Power: 550 W~~ ~~Data rate: 100 kbps~~

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Table 3.~~22~~19. Example of limb sounder using SW in occultation: SAGE-III on ISS

TABLE: Table horizontal lines

SAGE-III ISS	*Stratospheric Aerosol and Gas Experiment – III for the ISS*
Satellite	International Space Station (ISS)
Mission	Atmospheric chemistry in the stratosphere Tracked species: H_2O, NO_2, NO_3, O_3, OClO and aerosol
Main features	UV/VIS/NIR/SWIR (290–1 550 nm) 9-band solar and lunar occultation grating spectrometer
Scanning technique	Sun and moon tracking during occultation phase, 1 km step from ~10 km to ~85 km
Coverage/cycle	A few tens of events per day, limited to latitudes below ~52° (orbital inclination of the ISS)
Resolution (SSP)	300 km (horizontal), 1–2 km (vertical)
Resources	Mass: 76 kg Power: 80 W Data rate: 115 kbps

3.2.7 Global navigation satellite system radio-occultation sounders

ELEMENT 14: Floating object (Bottom)
ELEMENT 15: Picture inline fix size
Element Image: 8_III_3-8_en.eps
END ELEMENT

Figure 3.8. The overall system for radio occultation

END ELEMENT

These instruments have the following main characteristics:

(a) Global navigation satellite system (GNSS) receivers using at least two L-band frequencies around 1 180 GHz, 1 250 GHz and 1 580 GHz;

(b) Earth's limb observation, from surface to satellite altitude during the occultation phase of satellites from the GNSS constellations (such as GPS, GLONASS, Galileo and Compass/Beidou);

(c) Directional antennas: aft-looking (for setting GNSS), forward-looking (for rising GNSS), and toroidal (for navigation);

(d) Effective spatial resolution at around 300 km along the direction from the LEO satellite to the occulting GNSS satellite; a few tens of kilometres in the transverse direction;

(e) Horizontal sampling limited by the daily number of occultation events: from 250 to 1 500 events by satellite, depending on the number of GNSS systems received, and on the aft-looking/forward-looking tracking capability;

(f) Supported by a complex system of ground stations (see Figure 3.8);

(g) Applicable in LEO only.

Depending on their detailed features, GNSS radio-occultation sounders can provide different types of information:

(a) The signal-sampling time interval determines the vertical resolution of temperature, humidity and density profiles;

(b) Measurement sensitivity to the low atmospheric layers is determined by the size of the occultation antennas and the time-sampling technique;

(c) The number of frequencies that are used affects the accuracy of two ionospheric measurements: total electron content and electron density profile;

(d) The number of occultation events per day depends on the number of GNSS constellations used (GPS, GLONASS, Galileo, Beidou), the number of receiving channels for simultaneous tracking of further GNSS satellites, and the antenna accommodation feature: only aft-looking, only forward-looking, or both.

Table 3.2~~3~~0 sets out the main features of an example of a radio-occultation sounder (GRAS).

Table 3.2~~3~~0. Example of radio-occultation sounder: GRAS on Metop

TABLE: Table horizontal lines

GRAS	*GNSS Receiver for Atmospheric Sounding*
Satellites	Metop-A, Metop-B, Metop-C
Mission	High-vertical-resolution temperature, humidity and density profiles
Main features	Measuring the phase delay due to refraction during occultation between a navigation satellite and the LEO satellite GNSS constellation: GPS Frequencies: L1 = 1 575.42 MHz and L2 = 1 227.6 MHz 8 receiving channels: 4 for occultation, 8 for navigation
Scanning technique	Limb scanning from 80 km to close-to-surface by time sampling Azimuth: 90° sectors fore and aft

Coverage/cycle	1 constellation tracked About 650 soundings/day Average spacing 880 km Global coverage (300 km spacing) in 8.5 days
Resolution (SSP)	About 300 km horizontal, 0.5 km vertical
Resources	Mass: 30 kg Power: 30 W Data rate: 27 kbps

3.2.8 Broadband radiometers

These instruments have the following main characteristics:

(a) Wavelengths in the bands of total radiation emerging from the Earth and the atmosphere (0.2–300 μm) as well as from the fraction represented by reflected solar radiation (0.2–4.0 μm);

(b) One broadband channel, integrating over each of the two bands, and optional narrow-bandwidth channels in VIS and/or TIR to collect information on clouds within the IFOV;

(c) Cross-track scanning with continuous and contiguous sampling, to cover a swath of a few thousand kilometres with a spatial resolution of the order of 10 km;

(d) Applicable in LEO and GEO; observation from the L1 Lagrange libration point also is possible.

Broadband radiometers are designed to measure the Earth radiation budget – upward LW and SW irradiance at the top of the atmosphere (TOA). Accuracy depends on their detailed features:

(a) The greatest possible extension of the SW end of the spectrum into the UV range, and of the LW end of the spectrum into the FIR range, with a maximally flat response inside those ranges;

(b) Built-in multiviewing capability to convert radiance into irradiance;

(c) Supportive narrowband channels to collect information on clouds within the IFOV.

Tables 3.24 and 3.25 set out an example of a broadband radiometer in LEO (CERES) and one in GEO (GERB).

Table 3.2~~4~~1. Example of broadband radiometer in LEO: CERES on TRMM, EOS-Terra/Aqua, Suomi-NPP and JPSS

TABLE: Table horizontal lines	
CERES	*Clouds and the Earth's Radiant Energy System*
Satellites	TRMM, EOS-Terra, EOS-Aqua, Suomi-NPP, JPSS-1
Mission	Earth radiation budget: upward LW and SW irradiance at TOA
Main features	Two broadband channels and one narrowband channel Either: two units, one for cross-track scanning, one for biaxial scanning for irradiance computation Or: one unit operating in alternative modes
Scanning technique	Cross-track: 80 steps of 20 km SSP Swath: 3 000 km; along-track: one 20 km line every 3 seconds

	Biaxial scanning by rotating azimuth while cross-nadir scanning
Coverage/cycle	Global coverage twice a day (IR and total radiance) or once a day (SW)
Resolution (SSP)	20 km
Resources	Double unit configuration: Mass: 114 kg Power: 100 W Data rate: 21 kbps

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TABLE: Table horizontal lines

Channel	*Spectral interval*	*Noise equivalent radiance*	*Absolute accuracy*	*SNR*
SW	0.3–5.0 μm	0.3 W m^{-2} sr^{-1}	0.8 W m^{-2} sr^{-1}	225
Total radiance	0.3–100 μm	0.3 W m^{-2} sr^{-1}	0.6 W m^{-2} sr^{-1}	750
Narrowband	8–12 μm	0.3 W m^{-2} sr^{-1}	0.3 W m^{-2} sr^{-1}	750

Table 3.2~~5~~2. Example of broadband radiometer in GEO: GERB on Meteosat Second Generation

TABLE: Table horizontal lines

GERB	*Geostationary Earth Radiation Budget*
Satellites	Meteosat-8, Meteosat-9, Meteosat-10, Meteosat-11
Mission	Earth radiation budget: upward LW and SW irradiance at TOA
Main features	Two broadband channels
Scanning technique	N–S direction: pushbroom by a linear array of 256 detectors E–W provided by the spinning satellite Integration over 5 minutes to comply with SNR requirements and over 15 minutes to synchronize with SEVIRI
Coverage/cycle	Full disk every 15 minutes
Resolution (SSP)	42 km
Resources	Mass: 25 kg Power: 35 W Data rate: 50.6 kbps

Channel	*Spectral interval*	*Noise equivalent radiance*	*Absolute accuracy*	*SNR*
SW	0.32–4.0 μm	0.8 W m^{-2} sr^{-1}	2.4 W m^{-2} sr^{-1}	1 250
Total radiance	0.32–100 μm	0.15 W m^{-2} sr^{-1}	0.4 W m^{-2} sr^{-1}	400

3.2.9 Solar irradiance monitors

These instruments have the following main characteristics:

(a) Wavelengths in the solar radiation range 0.15–50 μm;

(b) Integration over the full range (total solar irradiance) and/or spectroscopy in the 0.15–3.00 μm range;

(c) Total solar irradiance is measured by absolute techniques, such as active cavity radiometers pointing at the Sun;

(d) Applicable both in LEO and in GEO.

Solar irradiance monitors complement broadband radiometers in order to measure the Earth radiation budget. They also contribute to solar activity monitoring for the purpose of space weather observation. Detailed features that affect their performance are:

(a) Extending their sensitivity to within the solar radiation range;

(b) Their capability to provide spectral information in context in the UV/VIS/NIR/SWIR ranges.

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Table 3.2~~6~~3 sets out the main features of an example of a solar irradiance monitor in LEO (TSIS).

Table 3.2~~6~~3. Example of solar irradiance monitor in LEO: TSIS on JPSS – Free Flyer (FF)

TABLE: Table horizontal lines

TSIS	*Total and Spectral Solar Irradiance Sensor*
Satellite	JPSS-FF (to be confirmed)
Mission	Solar irradiance monitoring (total and spectrally resolved)
Main features	Assemblage of: Four active cavity radiometers for total irradiance (total irradiance monitor: range of 0.2–10 μm), Prism spectrometer for spectral irradiance (spectral irradiance monitor: range of 0.2–2.0 μm; spectral resolution: 0.25–33 nm)
Scanning technique	Sun pointing during orbital movement; data sampled every two minutes
Coverage/cycle	100 minutes: one measurement after integration on all data taken during the diurnal orbit arc
Resolution (SSP)	Not applicable (Sun pointing)
Resources	Total irradiance monitor: Mass 7.9 kg; power 14 W; data rate 0.53 kbps Spectral irradiance monitor: Mass 22 kg; power 25.3 W; data rate 4.84 kbps

3.2.10 Lightning imagers

These instruments have the following main characteristics:

(a) Detector matrix (CCD): continuous Earth observation in a very narrow O_2 band at 777.4 nm;

(b) Measurement of flash rate and intensity in the IFOV;

(c) Spatial resolution of 5–10 km;

(d) Continuous and contiguous horizontal sampling; swath of several hundred kilometres from LEO, and full disk from GEO;

(e) Applicable in LEO and GEO.

Lightning imagery is useful as a proxy for convective precipitation and turbulence, in order to monitor the Earth's electric field, and as a proxy for NO_x generation. Different sampling is applicable from LEO and GEO:

(a) From LEO, the measurement is available for the interval during satellite motion in which one Earth's spot is visible within the field of view of the CCD matrix (about 90 seconds);

(b) From GEO, monitoring is continuous.

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Tables 3.2~~7~~4 and 3.2~~8~~5 set out an example of a lightning imager in LEO (LIS) and one in GEO (GLM).

Table 3.2~~7~~4. Example of lightning imager in LEO: LIS on TRMM

TABLE: Table horizontal lines

LIS	*Lightning Imaging Sensor*
Satellite	Tropical Rainfall Measuring Mission (TRMM)
Mission	Proxy for convective precipitation and turbulence Proxy for NO_x generation Study of the Earth electric field
Main features	CCD camera operating at 777.4 nm (O_2) to count flashes and measure their intensity
Scanning technique	Pushbroom: matrix array of 128 x 128 detectors; swath of 600 km Each Earth location is observed continuously (every 2 milliseconds) for about 90 seconds
Coverage/cycle	Intertropical coverage: several sequences of passes at ~100 min intervals; longer gaps as latitude increases; more regular coverage at 15°N and 15°S
Resolution (SSP)	4 km
Resources	Mass: 21 kg Power: 33 W Data rate: 6 kbps

Table 3.2~~8~~5. Example of lightning imager in GEO: GLM on GOES

TABLE: Table horizontal lines

GLM	*Geostationary Lightning Mapper*
Satellites	GOES-R, GOES-S, GOES-T, GOES-U
Mission	Proxy for convective precipitation and turbulence Proxy for NO_x generation

	Study of the Earth electric field
Main features	CCD camera operating at 777.4 nm (O_2) to count flashes and measure their intensity
Scanning technique	Pushbroom: matrix array of 1 372 x 1 300 detectors; time resolution of 2 milliseconds
Coverage/cycle	Large fraction of the disk is continuously observed
Resolution (SSP)	8 km
Resources	Mass: 35 kg Power: 110 W Data rate: 77 Mbps

3.2.11 Cloud radar and precipitation radar

These instruments have the following main characteristics:

(a) Operating frequencies in K_u (~14 GHz), K_a (~35 GHz) or W (~94 GHz) bands;

(b) Pulse repetition rate that results in a vertical resolution of a few hundred metres;

(c) Spatial resolution of 2–5 km;

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(d) Continuous and contiguous horizontal sampling; swath from nadir-only to several hundreds of kilometres;

(e) Only applicable in LEO.

The operating frequency determines possible applications:

(a) K_u band is suitable for heavy rain (liquid, with droplets that may exceed 1 cm). Non-precipitating clouds (droplets of less than 0.1 mm) are totally transparent, and light precipitation can hardly be detected. At these relatively low frequencies, electronic switching, which is necessary to avoid mechanical movements of large antennas, is relatively easy. Relatively wide swaths (several hundreds of kilometres) can therefore be implemented.

(b) K_a band is suitable for light rain (from stratiform clouds) and snowfall. Electronic switching is still possible, and swaths of a few hundreds of kilometres can be implemented.

(c) W band is suitable for non-precipitating clouds (droplets of less than 0.1 mm). Several studies have also reported that this can be applied to the observation of precipitating cloud systems, specifically on the edges of precipitation or in cases of no precipitation, including the eye of tropical cyclones.

Tables 3.2~~9~~6 and 3.~~30~~27 set out an example of a dual-frequency (K_u and K_a) precipitation radar (DPR) and an example of a W-band cloud radar (CPR on CloudSat).

Table 3.2~~9~~6. Example of precipitation radar: DPR on GPM Core Observatory

TABLE: Table horizontal lines

DPR	*Dual-frequency Precipitation Radar*

Satellite	Global Precipitation Measurement (GPM) Core Observatory
Mission	Vertical profile of heavy rain (liquid), light rain and snowfall
Main features	Dual-frequency imaging radar Frequencies: 13.6 GHz and 35.55 GHz Sensitivity: 0.5 mm/h at 13.6 GHz; 0.2 mm/h at 35.55 GHz
Scanning technique	Electronic scanning Planar array of 148 elements Swath: 245 km at 13.6 GHz; 125 km at 35.55 GHz
Coverage/cycle	Nearly global in 5 days High latitudes (> 65°) not covered
Resolution (SSP)	Horizontal: 5 km Vertical: 250 m (blind to the lowest ~150 m)
Resources	Mass: 780 kg Power: 710 W Data rate: 190 kbps

Table 3.~~30~~27. Example of cloud radar: CPR on CloudSat

TABLE: Table horizontal lines

CPR	*Cloud Profiling Radar*
Satellite	CloudSat
Mission	Vertical profile of non-precipitating cloud water (liquid and ice)
Main features	Frequency: 94.05 GHz Sensitivity: 30 dBZ
Scanning technique	None. Along-track sampling at 2 km intervals
Coverage/cycle	Global coverage in 1 month for 30 km average spacing, or in 10 days for 100 km average spacing
Resolution (SSP)	Horizontal: 1.4 km (cross-track) x 3.5 km (along-track) Vertical: 500 m
Resources	Mass: 230 kg Power: 270 W Data rate: 15 kbps

3.2.12 Radar scatterometers

These instruments have the following main characteristics:

(a) Operating frequencies in C (~5 GHz) or K_u (~14 GHz) bands;

(b) Very accurate calibration in order to measure backscatter coefficients (σ^0) from sea capillary waves;

(c) Spatial resolution: 10–50 km;

(d) Continuous and contiguous horizontal sampling; swath of approximately 1 000 km;

(e) Only applicable in LEO.

There are two concepts, mainly differing by the scanning principle (see Figure 3.9):

(a) Electronic scanning: side-looking, generally uses C band and provides three azimuth views for differential σ^0. It is more accurate for low-intensity sea-surface wind and for soil moisture.

(b) Conical scanning: generally uses K_u band, with two beams and two polarizations. It provides four azimuth views for differential σ^0.

ELEMENT 16: Floating object (Automatic)
ELEMENT 17: Picture inline fix size
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Figure 3.9. Two concepts for multiviewing scatterometers. Left: six antennas for three $\sigma = s$ under azimuth angles, 45°, 90° and 135° respectively, on both the left and right side of the sub-satellite track (ASCAT on Metop). Right: conical scanning of an antenna with two beams and two polarizations, for $\sigma = s$ under four azimuth angles for areas in the inner circle (SeaWinds on QuikSCAT). The ASCAT concept leaves an uncovered strip of ~700 km around the sub-satellite track. In the SeaWinds concept, there appears to be no gap, but accuracy is poor in the inner part of the swath around the sub-satellite track.

END ELEMENT

Tables 3.~~31~~28 and 3.~~32~~29 describe radar scatterometers using pushbroom scanning (ASCAT) and conical scanning (SeaWinds).

Table 3.~~31~~28. Example of pushbroom radar scatterometer: ASCAT on Metop

TABLE: Table horizontal lines

ASCAT	*Advanced Scatterometer*
Satellites	Metop-A, Metop-B, Metop-C
Mission	Sea-surface wind vector; large-scale soil moisture
Main features	C band (5.255 GHz) Left and right side-looking 3 antennas on each side
Scanning technique	Two 550 km swaths, separated by a 700 km along-track gap 3 looks each pixel (45°, 90° and 135° azimuth)
Coverage/cycle	Global coverage in 1.5 days
Resolution (SSP)	Best quality: 50 km Standard quality: 25 km Basic sampling: 12.5 km
Resources	Mass: 260 kg Power: 215 W Data rate: 42 kbps

Table 3.~~32~~29. Example of conical-scanning radar scatterometer: SeaWinds on QuikSCAT

TABLE: Table horizontal lines

SeaWinds	
Satellite	Quick Scatterometer (QuikSCAT) mission

Mission	Sea-surface wind vector
Main features	K_u band (13.4 GHz) Conical scanning 2 beams 2 polarizations
Scanning technique	Conical scanning: 2 beams to provide four views of each spot from different angles Swath: 1 800 km
Coverage/cycle	Global coverage every day
Resolution (SSP)	Best quality: 50 km Standard quality: 25 km Basic sampling: 12.5 km
Resources	Mass: 200 kg Power: 220 W Data rate: 40 kbps

3.2.13 Radar altimeters

These instruments have the following main characteristics:

(a) Operating frequencies in K_u band (~14 GHz), with auxiliary C band (~5 GHz), or K_a band (~35 GHz);

(b) Very accurate ranging measurement between the satellite and the Earth's surface;

(c) Spatial resolution in the range of 20 km;

(d) Exclusively nadir-pointing;

(e) Only applicable in LEO.

Radar altimeters generally operate in K_u band, using C band for correction of the signal rotation induced by the ionosphere. They are linked to a nadir-pointing MW radiometer for water vapour correction. Their accurate ranging is used for ocean topography: the echo spread provides information on significant wave height, while the echo intensity provides information on wind speed.

Depending on the detailed features of the instrument and of the satellite orbit, altimeters may be optimized for different applications:

(a) Relatively high, non-Sun-synchronous orbit (~~e.g.~~for example, 1 336 km), where inclination provides high stability to the orbit (~~e.g.~~for example, 66°); especially suited to solid Earth (geoid) and ocean circulation;

(b) SAR-like processing of the return echoes to synthesize higher spatial resolution along the sub-satellite track (see Figure 3.10);

(c) Parallel antennas to implement wide-swath altimetry by interferometry; particularly useful for land use including on inland waters, such as lakes;

(d) Dual frequency (C and K_u bands), which provides information on the total electron content between a satellite and the Earth's surface.

ELEMENT 18: Floating object (Top)
ELEMENT 19: Picture inline fix size

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Figure 3.10. Enhancing along-track altimeter resolution by SAR-like signal processing

END ELEMENT

Table 3.3~~3~~0 sets out the main features of a radar altimeter with data of geodetic quality (Poseidon-3).

Table 3.3~~3~~0. Example of radar altimeter: Poseidon-3 on JASON-2

TABLE: Table horizontal lines

Poseidon-3	*Solid-state radar altimeter – 3*
Satellite	JASON-2
Mission	Ocean topography, the geoid, significant wave height, wind speed, total electron content
Main features	2 frequencies: 5.3 GHz; 13.58 GHz
Scanning technique	Nadir-only viewing Sampling at 30 km intervals along track
Coverage/cycle	Global coverage in 1 month for 30 km average spacing, or in 10 days for 100 km average spacing
Resolution (SSP)	30 km IFOV
Resources	Mass: 70 kg Power: 78 W Data rate: 22.5 kbps

3.2.14 Imaging radar (synthetic aperture radar)

This wide range of instruments has the following main characteristics:

(a) Operating frequencies in P (~0.4 GHz), L (~1.3 GHz), S (~2.7 GHz), C (~5.3 GHz), X (~9.6 GHz), or K_u (~17.2 GHz) bands. The L, C and X bands are most commonly used;

(b) Several combinations of polarizations in transmission and reception: HH, VV, VV/HH, HH/HV and VV/VH;

(c) There is a trade-off between spatial resolution and swath: a 1–30 m resolution is associated with a swath of 30–100 km; but a 100–1 000 m resolution is associated with a swath of 300–500 km;

(d) Side looking, generally on one side, maintaining high resolution within a field of regard of several hundreds of kilometres;

(e) Applicable in LEO only.

Figure 3.11 illustrates the operating modes of one C-band SAR (ASAR).

The operating frequency is a critical feature, optimized for the purposes for which a synthetic aperture radar (SAR) is designed:

(a) P band is most suited to biomass monitoring and hydrological mapping;

(b) L band is best suited to wave observation and volumetric soil moisture;

(c) S band is best suited to volumetric soil moisture;

(d) C band covers a wide range of applications: sea ice, wave parameters by spectral analysis of image segments, surface soil moisture, snow parameters, glaciers, ground water, etc. However, each individual parameter can be optimally observed at other frequencies;

(e) X band provides the best spatial resolution, and is therefore best suited to surveillance;

(f) K_a band is specifically suited to snow, which is transparent at lower frequencies;

(g) Interferometry of the signals from one SAR at different times or two SARs flying in tandem enables the measurement of the digital elevation model and the detection of contour changes (such as coastlines and lakes) and elevation (~~e.g.~~ for example, volcano top surface).

ELEMENT 20: Picture inline fix size
Element Image: 8_III_3-11_en.eps
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Figure 3.11. Operating modes of ASAR on Envisat. In the global monitoring and wide swath modes, the swath is 405 km and is linked to either a 1 000 m or 150 m resolution. In the image and alternating polarization modes, a 100 km swath with a 30 m resolution can be pointed to one of seven positions within a field of regard of 485 km. In the wave mode, vignettes of 5 km x 5 km with 30 m resolution are sampled at every 100 km along track.

Table 3.3~~4~~1 records the main features of a C-band SAR (ASAR).

Table 3.3~~4~~1. Example of C-band SAR: ASAR on Envisat

TABLE: Table horizontal lines

ASAR	*Advanced Synthetic Aperture Radar*
Satellite	Envisat
Mission	Sea ice, wave parameters by spectral analysis of image segments, surface soil moisture, snow parameters, glaciers, ground water, etc.
Main features	C-band SAR Frequency: 5.331 GHz Multipolarization and variable pointing/resolution
Scanning technique	Side-looking; 15°–45° off-nadir Swath: 100–405 km, depending on operation mode (see lower part of table)
Coverage/cycle	Global coverage in 5 day in global monitoring mode (if used for 70% of the time) Longer periods (up to 3 months) for other operation modes
Resolution (SSP)	30 m to 1 km, depending on operation mode (see lower part of the table)
Resources	Mass: 832 kg Power: 1 400 W Data rate: 100 Mbps

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TABLE: Table horizontal lines

Operation mode	*Resolution*	*Swath*	*Field of regard*	*Polarization*
Stripmap	30 m	100 km	485 km	HH or VV
ScanSAR alternating pol	30 m	100 km	485 km	VV/HH, HH/HV, VV/VH
ScanSAR wide swath	150 m	405 km	405 km	HH or VV
ScanSAR wide swath	150 m	405 km	405 km	HH or VV
ScanSAR global monitoring	1 km	405 km	405 km	HH or VV
Wave	30 m	5 x 5 km^2 imagettes sampled at 100 km intervals		HH or VV

3.2.15 Lidar-based instruments

This group of instruments has the following main characteristics:

(a) Operating wavelengths in the UV (~~e.g.~~for example, 355 nm), VIS (~~e.g.~~for example, 532 nm), NIR (~~e.g.~~for example, 1 064 nm), or SWIR (~~e.g.~~for example, 1 600 nm) bands;

(b) Possible dual wavelength, two receivers (for Mie and Rayleigh scattering); polarimetry;

(c) Horizontal resolution within a 100 m range, often degraded by up to 50 km in order to collect enough de-correlated samples;

(d) Vertical resolution within a 100 m range (approximately 10 cm for lidar altimeters);

(e) Non-scanning: either nadir-viewing or oblique.

A space lidar is a voluminous instrument that needs to be optimized for specific applications:

(a) Doppler lidars generally operate in UV, for both Mie and Rayleigh scattering, in order to track aerosol and air molecules; oblique view is used to measure radial wind in clear air and aerosol;

(b) Backscatter lidars operate at one (on UV) or two (VIS and NIR) wavelengths, often with more polarizations; nadir view is used for obtaining aerosol profiles, cloud-top height and atmospheric discontinuities, such as the height of the top of the planetary boundary layer and of the tropopause;

(c) Lidar altimeters usually operate at two wavelengths (VIS and NIR); nadir view is used, as is very high-vertical resolution (for sea-ice elevation) and horizontal resolution (for ice boundaries);

(d) Differential absorption lidar operate at one wavelength centred on the absorption peak of one trace gas, in UV, VIS, NIR or SWIR, and nearby windows; nadir view is used for high-vertical-resolution observation of, for example, O_3, H_2O and CO_2.

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Tables 3.3~~5~~2–3.3~~8~~5 give details of a Doppler lidar (ALADIN), a backscatter lidar (CALIOP), a lidar altimeter (GLAS) and a differential absorption lidar (CO_2 lidar).

Table 3.3~~5~~2. Example of Doppler lidar: ALADIN on ADM-Aeolus

TABLE: Table horizontal lines

ALADIN	*Atmospheric Laser Doppler Instrument*
Satellite	Atmospheric Dynamics Mission (ADM) – Aeolus
Mission	Wind profile in clear air, aerosol profile, cloud-top height
Main features	Single-wavelength (355 nm), side-looking; 35° off-nadir High spectral resolution laser for distinguishing aerosol types
Scanning technique	No scanning Pulse echoes averaged over a 50 km field of view Field of view sampled at 200 km intervals
Coverage/cycle	Global coverage in 1 month for 30 km average spacing, or in 10 days for 100 km average spacing
Resolution (SSP)	Horizontal: 50 km field of view sampled at 200 km intervals Vertical: from 250 m in the planetary boundary layer to 2 km at ~20 km
Resources	Mass: 500 kg Power: 840 W Data rate: 11 kbps

Table 3.3~~6~~3. Example of backscatter lidar: CALIOP on CALIPSO

TABLE: Table horizontal lines

CALIOP	*Cloud–Aerosol Lidar with Orthogonal Polarization*
Satellite	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)
Mission	Aerosol profile, cloud-top height and atmospheric discontinuities (height of the top of the planetary boundary layer and of the tropopause)
Main features	Two wavelengths (532 and 1 064 nm) Measurements at two orthogonal polarizations
Scanning technique	Nadir-only viewing Sampling at 330 m intervals along track Near-continuous profiling
Coverage/cycle	Global coverage in 1 month for 30 km average spacing, or in 10 days for 100 km average spacing
Resolution (SSP)	Horizontal: 70 m IFOV sampled at 333 m intervals along track Vertical: 30 m
Resources	Mass: 156 kg Power: 124 W Data rate: 332 kbps

Table 3.3~~7~~4. Example of lidar altimeter: GLAS on ICESat

TABLE: Table horizontal lines

GLAS	*Geoscience Laser Altimeter System*
Satellite	Ice, Cloud and Land Elevation Satellite (ICESat)
Mission	Polar ice sheet thickness and topography, cloud-top height, aerosol
Main features	Dual-wavelength lidar (532 and 1 064 nm)
Scanning technique	Nadir-only viewing Sampling at 170 m intervals along track Near-continuous profiling
Coverage/cycle	Global coverage in 183 days (orbit repeat cycle) Leaves cross-track 2.5 km gaps at 80° latitude (15 km at the Equator)
Resolution (SSP)	Horizontal: 66 m IFOV sampled at 170 m intervals along track Vertical: 10 cm surface, 200 m cloud top
Resources	Mass: 298 kg Power: 300 W Data rate: 450 bps

Table 3.3~~8~~5. Example of differential absorption lidar: CO_2 lidar on ASCENDS

TABLE: Table horizontal lines

CO_2 lidar	
Satellite	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)
Mission	Monitoring CO_2 with unprecedented accuracy by using lidar
Main features	Wavelength: 1.572 μm for CO_2 Option for O_2 at 1 260 or 765 nm also considered
Scanning technique	Nadir-only viewing
Coverage/cycle	Global coverage in one month for 30 km average spacing, or in 10 days for 100 km average spacing
Resolution (SSP)	Horizontal: 125 m Vertical: total column
Resources	Mass: 420 kg Power: 920 W Data rate: 1.9 Mbps

3.2.16 Gradiometers / accelerometers

Knowledge of the gravity field is crucial for modelling the solid Earth. Several space techniques address this subject.

(a) The long-wave components of the gravity field are measured through radar or lidar altimetry, or through precise orbitography (~~e.g.~~for example, with laser ranging, radio positioning, GNSS, star tracking).

(b) Short-wave components (anomalies and perturbations of the gravity field) are observed at satellite altitude by accelerometers or gradiometers, in association with satellite-to-satellite ranging systems. An accelerometer measures the variation of the gravity field along the satellite trajectory. A gradiometer comprises a network of accelerometers, which measures the gravity-gradient tensor. Satellite-to-satellite ranging systems are transmitter-receiver systems, usually in K band (24 GHz) and K_a band (32 GHz). They are designed to accurately measure the distance and its variations between satellites flying in coordinated orbits. The same measurements are possible through the simultaneous reception of signals from tens of GNSS satellites: that determines positioning changes highly accurately.

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Part title in running head: PART III. SPACE-BASED OBSERVATIONS

Tables 3.3~~9~~6 and 3.~~40~~37 describe a gradiometer/accelerometer (EGG) and a satellite-to-satellite ranging system (HAIRS).

Table 3.3~~9~~6. Example of accelerometer/gradiometer: EGG on GOCE

TABLE: Table horizontal lines

EGG	*Three-axis Electrostatic Gravity Gradiometer*
Satellite	Gravity Field and Steady-state Ocean Circulation Explorer (GOCE)
Mission	Solid Earth Observation of the Earth’s gravity field along the orbit
Main features	Three pairs of 3-axis accelerometers, specially assembled to measure the gravity-gradient tensor Accuracy: 10^{-12} m s^{-2} Resolution: 2 10^{-12} m s^{-2} $Hz^{-1/2}$

Table 3.~~40~~37. Example of satellite-to-satellite ranging system: HAIRS on Gravity Recovery and Climate Experiment (GRACE)

TABLE: Table horizontal lines

HAIRS	*High Accuracy Inter-satellite Ranging System*
Satellites	GRACE (2 satellites flying in tandem, 220 km apart)
Mission	Solid Earth Observation of the Earth’s gravity field along the orbit
Main features	Dual-frequency ranging, in K band (24 GHz) and K_a band (32 GHz) Accuracy: 10 μm

3.2.17 Solar activity monitors

Solar activity is monitored either by remote-sensing or in situ in the solar wind, from deep space and Earth’s orbit. Several measurement approaches are possible:

(a) Electromagnetic radiation: measured by radiometers, spectrometers and polarimeters for γ-rays (less than 0.001 nm), X-ray (0.001–10 nm), extreme UV (10–120 nm), UV (120–380 nm), VIS (380–780 nm) and longer wavelengths including radio waves (more than 1 m);

(b) Energetic particles (electrons, protons, α-particles, ions, cosmic rays, neutrons): the energy range is generally broken down into high-, medium- and low-energy; the boundaries of the ranges depend on the type of charged particle; measurements can be integrated over the full energy range, or over partial ranges; spectroscopy within a range may also be performed;

(c) Magnetic and electric fields, directly measured in the solar wind, and inferred in the photosphere; those fields are inferred from measurements in the solar wind or from spectroscopy of VIS solar images using the Zeeman effect, Doppler analysis or multipolarization;

(d) Measurements can be performed by: integrating over the full solar disk; imaging the solar disk; or imaging the corona only by occulting the disk (a coronagraph);

(e) A specific observation is that of solar irradiance, either total or spectrally resolved (see ~~section~~ 3.2.9).

An example of an instrument package for solar activity monitoring from the L1 Lagrange libration point, SOHO, is described in Table 3.~~41~~38.

3.2.18 Space environment monitors

Space environment monitoring at platform level provides information used for monitoring and making predictions about overall space weather conditions, as well as for platform safety. The instrumentation generally includes:

(a) Charged particle detectors, designed for specific ranges of energy, either integrated or spectrally resolved;

(b) Magnetometers and electrometers.

An example of an instrument package for in situ space environment monitoring, GGAK-M, is described in Table 3.~~42~~39.

3.2.19 Magnetometers and electric field sensors

Magnetic and electric fields in the magnetosphere can be measured in situ as the satellite moves along its orbit. If the orbit is highly eccentric, it crosses the magnetosphere at different altitudes, thus providing 3D profiles. Gradients of the fields are better observed when more satellites are flown together in coordinated orbits. Usual instruments are:

(a) Either scalar or vector magnetometers;

(b) Electron fluxometers (used to compute the electric field).

An example of an instrument package, Cluster, for 3D observation of the magnetosphere, which uses four satellites, is described in Table 3.4~~3~~0.

Table 3.~~41~~38. Example of solar activity monitoring package: SOHO instrumentation

TABLE: Table horizontal lines

SOHO instrumentation	
Satellite	Solar and Heliospheric Observatory (SOHO)
Mission	Sun monitoring from the L1 Lagrange point
Main features	Solar atmosphere remote-sensing instrument package: Solar UV Measurement of Emitted Radiation (SUMER) Coronal Diagnostic Spectrometer (CDS) Extreme UV Imaging Telescope (EIT) UV Coronagraph and Spectrometer (UVCS) Large Angle and Spectrometric Coronagraph (LASCO) Solar Wind Anisotropies (SWAN)

	Solar wind “in situ particle” instrument package: Charge, Element and Isotope Analysis System (CELIAS) Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) Energetic and Relativistic Nuclei and Electron Experiment (ERNE) Helio-seismology instrument package (study of the Sun's interior): Global Oscillations at Low Frequencies (GOLF) Variability of Solar Irradiance and Gravity Oscillations (VIRGO) Michelson Doppler Imager (MDI)
Scanning technique	Sun pointing
Coverage/cycle	Continuous from the L1 Lagrange point
Resources (of the satellite)	Mass: 1 850 kg Power: 1.5 kW Data rate: 200 kbps

Table 3.~~42~~39. Example of space environment monitoring package: GGAK-M on Meteor-M

TABLE: Table horizontal lines

GGAK-M	*Geophysical Monitoring System Complex*
Satellites	Meteor-M N1, Meteor-M N2, Meteor-M N2-1, Meteor-M N2-2
Mission	Space environment monitoring at platform level
Main features	Spectrometer for Geoactive Measurements (MSGI-MKA) package: Electron fluxes in the energy range 0.1–15 keV (high-sensitivity channel) Ion (proton) fluxes in the energy range 0.1–15 keV (high-sensitivity channel) Electron fluxes in the energy range 0.1–15 keV (low-sensitivity channel) Monitoring of integral electron fluxes with a threshold energy of 40 keV Radiation Monitoring System (KGI-4C) package: Total proton flux threshold energy of: 5, 15, 25, 30 and 40 MeV Total electron flux threshold energy of: 0.17, 0.7, 1.7, 2.0 and 3.2 MeV Proton fluxes with threshold energies of: 25 and 90 MeV
Resources	Mass: 17 kg Power: 13.6 W Data rate: 16 kbps

Table 3.4~~3~~0. Example of magnetosphere monitoring package: Cluster instrumentation

TABLE: Table horizontal lines

Cluster instrumentation	
Satellites	Cluster A, B, C and D (four satellites flying together in coordinated orbits)
Mission	Monitoring of the 3D magnetosphere
Main features	Package of the following instruments: Fluxgate Magnetometer (FGM) Spatio-temporal Analysis of Field Fluctuations (STAFF) Electric Fields and Waves (EFW) Waves of High Frequency and Sounder for Probing of Density by Relaxation (WHISPER) Wide Band Data (WBD) Digital Wave Processor (DWP) Electron Drift Instrument (EDI) Cluster Ion Spectrometry (CIS) experiment Plasma Electron and Current Analyzer (PEACE)

	Research with Adaptive Particle Imaging Detectors (RAPID) Active Spacecraft Potential Control (ASPOC)
Scanning technique	4 satellites travelling across the magnetosphere in highly elliptical orbits
Coverage/cycle	Continuous; in situ along the orbit
Resources (of one satellite)	Mass: 1 200 kg Power: 224 W Data rate: 16.9 kbps