RECOMMENDATION ITU-R RS.1804*

Technical and operational characteristics of Earth exploration-satellite service (EESS) systems operating above 3 000 GHz

(Question ITU-R 235/7)

(2007)

Scope

Instruments have been operating on EESS systems at frequencies above 3 000 GHz for many years. The instruments are comprised of both active and passive devices, are deployed on geostationary orbit (GSO) and non-GSO systems, and utilize narrow-spectral lines as well as widebands. This recommendation summarizes the instruments, spacecraft, spectrum of interest and type of data collected using spectrum above 3 000 GHz.

The ITU Radiocommunication Assembly,

considering

a) that observations at frequencies above 3 000 GHz provide data critical to the study of the characteristics of the Earth and its natural phenomena, including data relating to the state of the environment;

b) that the technology for Earth exploration-satellite service (EESS) sensors operating above 3 000 GHz is continuously evolving to provide better accuracy and resolution of measurement data;

c) that the spectrum above 3 000 GHz is used for active and passive sensor systems as well as for many telecommunication applications;

d) that, as these systems are rapidly expanding and increasing in number, the likelihood of harmful interference between sensors in the EESS and other services operating above 3 000 GHz may increase;

e) that the Earth-to-space laser radiation used by some optical ground stations to conduct precise satellite and lunar ranging and to measure atmospheric parameters represents a possible source of interference to, and may potentially damage, sensitive satellite passive sensors;

f) that while there are significant differences between the technologies used in this part of the spectrum compared with lower frequencies (e.g. counting photons versus integrating power over time), there are also many similarities;

g) that protective measures and sharing considerations have to be considered to ensure that EESS sensors can continue to operate at frequencies above 3 000 GHz without harmful interference,

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* This Recommendation should be brought to the attention of Radiocommunication Study Groups 1, 3, 4, 8 and 9.

recommends

1 that operators of EESS systems operating above 3 000 GHz should take into account the possibility of interference from transmitters of the science services (including those of EESS) in their selection of mission requirements and choices of sensor design;

2 that studies of interference to and from EESS systems operating above 3 000 GHz should take into account the technical and operational parameters provided in Annex 1.

Annex 1

1 Introduction

Instruments have been operating on EESS systems at frequencies above 3 000 GHz for many years. These instruments operate in several modes and provide a variety of types of data. The instruments are comprised of both active and passive devices, are deployed on GSO and non-GSO systems, and utilize narrow-spectral lines as well as widebands. The information contained in the following sections summarizes the instruments, spacecraft, spectrum of interest and type of data collected using spectrum above 3 000 GHz.

2 Instruments

The instruments to be described are categorized as the following: imagers, radiometers/ spectrometers, or LIDAR altimeters. Imagers are instruments whose prime objective is to present two-dimensional representations of physical phenomena such as clouds or the Earth's surface. Radiometers/spectrometers are instruments which measure electromagnetic radiative flux. LIDAR altimeters are instruments which measure the height from the spacecraft to the surface directly underneath via pulses of light emissions.

2.1 Imaging technical characteristics

One of the earliest uses of the spectrum above 3 000 GHz for EESS applications is imaging the Earth's surface and cloud cover. More recently imaging systems have been used to gather data on the distribution and frequency of lightning. The three types of imaging systems described below are representative of the general capabilities of EESS systems performing imaging at frequencies above 3 000 GHz. A fourth system described below optically senses weather phenomena.

2.1.1 Multispectral cloud imaging

Systems A1 through A3 operate as a single instrument which collects imagery at 14 different wavelengths ranging from 0.5 to 12 µm. It is used for long-term cloud monitoring at spatial resolutions of 15 to 90 m depending on the wavelength measured. The instrument is divided into three separate systems each with its own telescope monitoring a different set of wavelengths. The systems' bands are:

– Visible/near infrared (VNIR) 0.50 to 0.90 µm (600 to 333 THz[1]).

– Short-wave infrared (SWIR) 1.6 to 2.43 µm (187.5 to 123 THz).

– Thermal infrared (TIR) 8 to 12 µm (37.5 to 25 THz).

With its high-spatial resolution, broad spectral coverage, and stereo imaging capability, this instrument provides essential measurements of cloud amount, type, spatial distribution, morphology, and radiative properties. While many cloud imagery instruments measure similar parameter sets, the ability to observe with this high-spatial resolution provides data that can be directly related to detailed physical properties. Furthermore, in areas where no cloud cover is present, this instrument provides long-term monitoring of local and regional changes to the Earth's surface which either lead to, or are in response to, global climatic changes (e.g. land use, deforestation, desertification, lake and playa water-level changes and other changes in vegetation communities, glacial movement and volcanic processes). A summary of the technical parameters of this instrument is provided in Table 1.

TABLE 1

Technical parameters of multispectral cloud imaging systems

System	A1	A2	A3
Field of view (degrees)	6.09	4.9	4.9
Instantaneous field of view (µrad)	21.5	42.6	128
Wavelengths measured (µm)	0.52-0.60 0.63-0.69 0.76-0.86	1.60-1.70 2.145-2.185 2.185-2.225 2.235-2.285 2.295-2.365 2.360-2.430	8.125-8.475 8.475-8.825 8.925-9.275 10.25-10.95 10.95-11.65
Spatial resolution (m)	15	30	90
Data rate (Mbit/s)	62	23	4.2
Cross-track pointing (degrees)	±24	±8.55	±8.55
Cross-track pointing (km)	±318	±116	±116
Swath width (km)	60	60	60
Detector type	Silicon (Si)	Platinum Silicide-Silicon (PtSi-Si)	Mercury Cadmium Telluride (HgCdTe)
Quantization (bits)	8	8	12

[1] 1 THz = 1 000 GHz.

2.1.2 Multispectral imaging of the Earth's surface

Systems B1 through B5 operate together as a single instrument to collect imagery at seven narrow wavelengths ranging from 0.45 to 12.5 µm and one panchromatic range from 0.5 to 0.9 µm. It is used to characterize and monitor change in land-cover and land-surface processes. The high-spatial resolutions (15 to 60 m depending on wavelength range) and seasonal global coverage of this instrument will allow assessment of both the rates of land-cover change and the local processes responsible for those changes. Deforestation, ecosystem fragmentation, agricultural productivity, glacier dynamics, coastal hazards, and volcano monitoring are representative science targets for this instrument.

The instrument conducts its measurements through a single aperture in four bands:

– Visible (VIS) 0.45 to 0.69 µm (667 to 435 THz).

– Near infrared (NIR) 0.76 to 0.90 µm (395 to 333 THz).

– SWIR 1.55 to 2.35 µm (194 to 128 THz).

– TIR 10.42 to 12.5 µm (28.8 to 24 THz).

System B6 is a visible and near-infrared radiometer for observing land and coastal zones. It is used to provide land coverage maps and land-use classification maps for monitoring regional environment. The instrument has a cross-track pointing capability for disaster monitoring.

System B7 is a panchromatic radiometer with 2.5 m spatial resolution. In order to obtain terrain data including elevation, this instrument has three optical systems for forward, nadir, and backward views. The instrument provides precise geographical information suitable to create 1/25 000 scale global maps.

A summary of the technical parameters of these systems is provided in Table 2.

TABLE 2

Technical parameters of multispectral imaging of the Earth's surface

System	B1	B2	B3	B4	B5	B6	B7
Instantaneous field of view (µrad)	42.5	42.5	42.5 × 39.4	42.5 × 85.0	21.25 × 18.5	14.28	3.57
Wavelengths measured (µm)	0.45-0.52 0.52-0.60 0.63-0.69	0.76-0.90	1.55-1.75 2.08-2.35	10.42-12.50	0.50-0.90	0.45-0.50 0.52-0.60 0.61-0.69 0.76-0.89	0.52-0.77
Spatial resolution (m)	30	30	30	60	15	10	2.5
Data rate	Data merged into 150 Mbit/s data stream					160 Mbit/s (after data compression: 120 Mbit/s)	320 Mbit/s × 3 telescopes = 960 Mbit/s (after data compression: 240 Mbit/s, 120 Mbit/s)
Swath width	185 km (±7.5°). Each image frame represents a 170 km increment along the satellite track					70 km	Up to 70 km
Detectors per band	16	16	16	8	32	7 000	40 000

2.1.3 Hyperspectral imaging

This instrument works in a similar manner as multispectral imagers; however, hyperspectral analysis utilizes contiguous spectral channels, allowing the use of derivatives and sophisticated analysis techniques. A much larger number of bands allows more complex systems to be addressed without the under-sampling inherent in multispectral systems. Hyperspectral imaging has wide ranging applications in mining, geology, forestry, agriculture, and environmental management.

The System C hyperspectral imager utilizes 220 bands over a spectral range, 0.4 to 2.5 µm (from 750 to 120 THz). Detailed classification of land assets through System C will enable more accurate remote mineral exploration, better predictions of crop yield, and assessments, and better containment mapping.

A summary of the technical parameters of this system is provided in Table 3.

TABLE 3

Technical parameters of a hyperspectral imaging system

System	C
Instantaneous field of view (µrad)	43
Wavelengths measured (µm)	0.4 to 2.5 (contiguous across 220 bands)
Spatial resolution (m)	30
Data rate	250-500 MB over 8-12 second collection periods
Image size (km^2)	7.6 × 100
Detectors per band	1 (220 individual detectors)

2.1.4 Lightning sensing

System D investigates the global incidence of lightning, its correlation with convective rainfall, and its relationship with the global electric circuit. This instrument consists of a staring imager that is optimized to locate and detect lightning with storm-scale resolution (from 4 to 7 km) over a large region (600 × 600 km) of the Earth’s surface. The system can monitor individual storms in its field of view for 80 s, long enough to estimate the lightning flash rate. A combination of four methods is used to extract lightning data from the surrounding image. These methods require the ability to separate spatial, temporal and spectral details from consecutive image frames in order to identify lightning signatures from other emissions. Temporal filtering is required to confirm the duration of the emission is approximately that of a lightning flash (typically ~400 µs). Spectral filtering is required to confirm the presence of energy at the strong OI(1) emission multiplet in the lightning spectrum 0.7774 µm (385.9 THz). Spatial filtering is then required to identify the location of the lightning flash.

A summary of the technical parameters of this system is provided in Table 4.

TABLE 4

Technical parameters of a lightning sensing system

System	D
Field of view (degrees)	80 × 80
Instantaneous field of view (degrees)	0.7
Wavelengths measured (μm)	0.7774
Spatial resolution (km)	~5
Data rate (kbit/s)	6
Image size (km)	600 × 600
Detector	128 × 128 CCD

2.2 Radiometry and spectrometry

Radiometry and spectrometry are unique measurement techniques which may be performed individually or in combination to monitor atmospheric chemical composition (including pollutants), meteorological profiles, cloud structure, and land surface characteristics. These systems may operate over frequencies ranging from ultraviolet (i.e. wavelengths < 0.4 μm) to thermal infrared (i.e. wavelengths > 10.0 μm). These instruments may operate in push-broom, scanning, or fixed pointing modes with targets on the Earth's surface as well as the limb.

Radiometric measurements usually occur over less than 50 different bands without strict filtering. In contrast, spectrometry measurements may simultaneously collect data on thousands of narrow bands. Valuable information can be drawn from both measurement techniques not only by examining data in individual bands but also by evaluating differential data derived from data in multiple bands.

System E1 is a space-borne instrument designed specifically to measure global climate change indicators. System E1, with spectral coverage from 3.7 to 15.4 μm (from 81 to 19.5 THz), can very accurately measure the amounts of atmospheric water vapour and greenhouse gases and can produce precise 3-D maps of the water vapour and trace greenhouse gas distribution throughout the atmosphere.

System E2 plays a vital role in the development of validated, global, interactive Earth system models able to predict global change by measuring parameters such as land, cloud, and aerosol boundaries and temperatures, ocean biogeochemistry, and cloud-top height. This instrument provides high radiometric sensitivity (12 bit) in 36 spectral bands ranging in wavelength from 0.4 μm to 14.4 μm (from 750 to 20.8 THz).

System E3 provides global, long-term measurements of key components of the Earth's atmosphere, the most important being the vertical distribution of aerosols, ozone, and water vapour in the upper troposphere through the stratosphere. This instrument is a grating spectrometer that measures ultraviolet/visible energy using an 800 element CCD linear array to provide continuous spectral coverage between 0.29 and 1.03 μm (from 1 034 to 291 THz). Additional aerosol information is provided by a discrete photodiode at 1.55 μm (193.5 THz).

This configuration enables the instrument to make multiple measurements of absorption features of target gaseous species and multi-wavelength measurements of broadband extinction by aerosols.

System E4 is an optical sensor that observes the reflected solar radiation from the Earth's surface, including land, oceans and clouds and/or infrared radiation with a multichannel system for measuring the biological content, such as chlorophyll, organic substance, and vegetation index as well as temperature, snow and ice, and cloud distribution. These data are used for understanding climate change and the global circulation of carbon.

System E5 is a spectrometer that observes the atmospheric limb absorption spectrum from the upper troposphere to the stratosphere using sunlight as a light source (solar occultation technique). The spectrometer covers the 3-13 µm (100 to 23.1 THz) and 0.753 to 0.784 µm (398 to 383 THz) spectral regions. It was developed to monitor the high-latitude stratospheric ozone. The objectives of the system are to monitor and study changes in the stratosphere triggered by the presence of chlorofluorocarbons (CFC) and to evaluate the effectiveness of world-wide emission controls of CFC. System E5 is intended to observe only the high latitude (57-73º N, 64-90º S) regions because of the geometrical relation of the solar occultation events with the sun synchronous orbit. From these spectral observations, System E5 can measure the vertical profiles of species related to ozone depletion phenomena, including ozone (O_3), nitrogen dioxide (NO_2), nitric acid (HNO_3), aerosols, water vapour (H_2O), CFC-11, CFC-12, methane (CH_4), nitrous oxide (N_2O), chlorine nitrate ($ClONO_2$), and temperature and pressure.

System E6 is a Fourier transform spectrometer with high optical throughput and spectral resolution. The instrument is designed to detect the solar SWIR spectrum reflected on the Earth's surface as well as the TIR spectrum radiated from the ground and the atmosphere. An interferogram of the incoming radiation is obtained by the instrument. This interferogram is then processed with the fast Fourier transformation (FFT) algorithm into spectra which includes the absorption spectra of greenhouse gases. By applying a processing algorithm to remove cloud and aerosol contamination from the transformed spectra, the column density of the gases can be calculated.

System E7 is a combined optical/microwave meteorological imaging/sounding system for remote sensing of ocean and land surface, as well as measuring global atmospheric temperature and water vapour profiles.

The microwave radiometer associated with System E7 is based on the technology of combining in space and time multifrequency and polarization measurements. It operates at frequencies located both in the transparent windows of atmosphere 6.9, 10.6, 18.7, 23.8, 31, 36.5, 91 GHz and in the absorbing lines of oxygen 52-57 GHz and water vapour 183.31 GHz. In addition, this instrument includes some complementary non-typical operating frequencies for oceanographic research at the 42 and 48 GHz bands. The instrument will provide measurements of atmosphere temperature profile to approximately 42 km and water vapour profile to 6 km.

By combining optical and microwave observations in the same instrument, some mutually beneficial advantages for determining geophysical parameters are obtained. Atmospheric temperature profiles and atmospheric humidity profiles, sea surface temperatures and near-surface wind speeds, ocean color, and biological processes in the upper ocean layer will all be observed concurrently, enabling ocean currents to be visualized and upwelling areas to be better observed. The ocean-atmosphere interaction can be studied as well. Uncertainties that often exist when multispectral and multifrequency observations are taken from different instruments looking through different parts of the atmosphere at different angles and different times are removed through the System E7's capabilities.

A summary of the technical parameters of these representative spectro-radiometric instruments is provided in Table 5.

TABLE 5

Technical parameters of radiometry and spectrometry systems

System	E1	E2	E3
Measurements	High-spectral resolution infrared sounder	Imaging spectro-radiometer	Solar and lunar occultation
Data	Vertical temperature and water vapour profiles, cloud characteristics and distributions	Surface temperature, vegetation/land-surface cover, cloud masks, fires	Vertical profiles of OClO, NO_2, NO_3, O_3 and H_2O, in the meso-, strato-, tropospheres
Spectral region (µm)	0.4-15.4 (2 378 channels) 6.3, 9.6, 11 for specific profiles	0.4-3.0 (21 channels) 3.0-14.5 (15 channels)	0.29-1.55 (9 channels)
FOV (degrees)	±49.5° (cross-track)	±55°	±185° azimuth 13-31° elevation
Instantaneous field of view	13.5 km at nadir	250 m (2 channels), 500 m (5 channels), 1 000 m (29 channels)	< 0.5 km at/20 km tangent height
Scan rate	22.5 rpm (1 revolution/2.667 s) 2.0 s/Earth scan; 0.667 s/calibration	20.3 rpm	Points at limb
Data rate (Mbit/s)	1.44	6.2 (average), 10.5 (day), 3.2 (night)	0.115 for 8 min; 3 times/day
Accuracy	Irradiance: 3%	Absolute irradiance: 5% < 3 µm; 1% > 3 µm	5-15% depending on chemical measured

TABLE 5 (*continued*)

Technical parameters of radiometry and spectrometry systems

System	E4	E5	E6
Measurements	Imaging spectro-radiometer	Solar occultation	Fourier transform spectrometer
Data	Chlorophyll, dissolved organic matter, surface temperature, vegetation distribution, snow, ice	Vertical profile of O_3, HNO_3, NO_2, N_2O CH_4, H_2O, $ClONO_2$, temperature and pressure	Greenhouse gas concentration measurement of O_2, CO_2, CH_4, H_2O
Spectral region (µm)	0.375-0.88 (23 channels) 1.040-2.32 (6 channels) 3.55-12.5 (7 channels)	3.0-5.7 (Ch. 1) 6.21-11.76 (Ch. 2) 12.78-12.85 (Ch. 3) 0.753-0.784 (Ch. 4)	0.75-0.78 (Band 1) 1.56-1.72 (Band 2) 1.92-2.08 (Band 3) 5.5-14.3 (Band 4)
FOV (degrees)	±45	0.017	±35 (cross track) ±20 (along track)
Instantaneous field of view	250 m (6 channels) 1000 m (30 channels)	1.0 km × 13.0 km (Ch. 1, 2) 1.0 km × 21.7 km (Ch. 3) 1.0 km × 2.0 km (Ch. 4)	10 km
Scan rate	16.7 rpm	N/A	0.25, 0.5, 1 (interferograms)/s
Data rate (Mbit/s)	1 km ch: 4 Mbit/s max 250 m ch: 60 Mbit/s max	54 kbit/s	8 Mbit/s
Accuracy	below 3 µm Relative irradiance 5% Absolute irradiance 10% above 3 µm Thermal 0.6 K	3% (O_3), 5% (others)	1% (CO_2), 2%(CH_4) (Column density)

TABLE 5 (*end*)

Technical parameters of radiometry and spectrometry systems

System	E7
Measurements	Optical/microwave meteorological imaging/sounding system
Data	Remote sensing of atmospheric temperature profile (to 42 km) and atmospheric humidity profile (to 6 km), sea surface temperature and near-surface wind speed, precipitation, ocean colour and processes of the active ocean layer, ice and snow monitoring
Spectral region (µm)	0.37-0.45 0.45-0.51 0.58-0.68 0.68-0.78 3.55-3.93
FOV (degrees)	120° per sweep (2 000 km wide swath), 19 km in length
Instantaneous FOV (km)	1.1 × 1.1
Scan rate	20.8 rpm (1/2.88 s)
Sampling (data) rate	665.4 kbit/s, 30.7 Mbit/s
Accuracy	1.1 km spatial resolution, 10^{-4} temporal stability

2.3 Altimetry – active

Altimetry is performed from space using nadir viewing light detection and ranging (LIDAR) systems operating at around 1.064 µm (283 THz) and 0.532 µm (566 THz). System F1 is a 283 THz system used to measure ice-sheet topography and its associated temporal changes, cloud, and atmospheric properties, and along-track topography over land and water. For ice-sheet applications, the laser altimeter may measure height from the spacecraft to the ice sheet to a precision of better than 10 cm with a 66 m surface spot size. The height measurement coupled with knowledge of the orbit position provides the determination of surface topography. Characteristics of the return pulse are used to determine surface roughness. Changes in ice-sheet thickness of a few tens of cm occurring on a subdecadal time-scale provide information about ice-sheet mass balance and can support prediction analyses of cryospheric response to future climatic changes. The ice-sheet mass balance and contribution to sea-level change may also be monitored. The accuracy of height determinations over land may be assessed using ground slope and roughness. The surface echoes may be digitized over a total dynamic range of 30 m over the oceans and 80 m elsewhere.

System F2 measures along-track cloud and aerosol height distributions at 566 THz with a vertical resolution of 75 to 200 m. The horizontal resolution can vary from 150 m for dense clouds to 50 km for aerosol structure and planetary boundary layer height. Unambiguous measurements of cloud height and the vertical structure of thin clouds will support studies on the influence of clouds for radiation balance and climate feedbacks. Polar clouds and haze can be detected and sampled with much greater sensitivity, vertical resolution, and accuracy than can be achieved by passive sensors. Planetary boundary layer height may be directly and accurately measured for input into surface flux and air-sea and air-land interaction models. Direct measurements of aerosol vertical profiles will contribute to understanding of aerosol-climate effects and aerosol transport.

A summary of the technical parameters of space-based LIDAR altimeter systems is provided in Table 6.

TABLE 6

Technical parameters of altimetry systems

System	F1	F2
Wavelength (μm)	0.532	1.064
Transmitted energy (mJ)	36	74
Pulse repetition rate (Hz)	40	
Beam divergence (μrad)	110	
LIDAR transmitter aperture (cm)	15	
Footprint at nadir (m)	66	
Receiving telescope aperture (m)	1	
Receiver field of view (μrad)	150	475
Detector quantum efficiency	0.6	0.3
Data rate (kbit/s)	~450	
Pointing accuracy (arcsec)	1.5	
Ranging accuracy (m)	75	0.15

There are many currently planned Earth science missions that will use orbital lasers. Most of these are planned with lasers at other than 0.532 μm and 1.064 μm wavelengths. An example is an active CO_2 measurement mission, which has laser channels operating at 1.570 μm, 0.770 μm and probably 0.532 μm. Other missions are targeting, for example, ozone at wavelengths less than 0.400 μm and water vapour, likely in the 0.930 μm band.

3 Spacecraft

Though no formal procedure exists to record EESS systems utilizing spectrum above 3 000 GHz, these instruments may be present on about half of all EESS spacecraft. About one to three new EESS systems utilizing spectrum above 3 000 GHz are anticipated to be launched each year for the foreseeable future, with additional instruments being temporarily deployed on space shuttles and the international space station. The majority of EESS systems utilize non-geostationary orbits, with a significant portion of these systems in sun-synchronous orbits.

4 System sensitivity and natural emissions

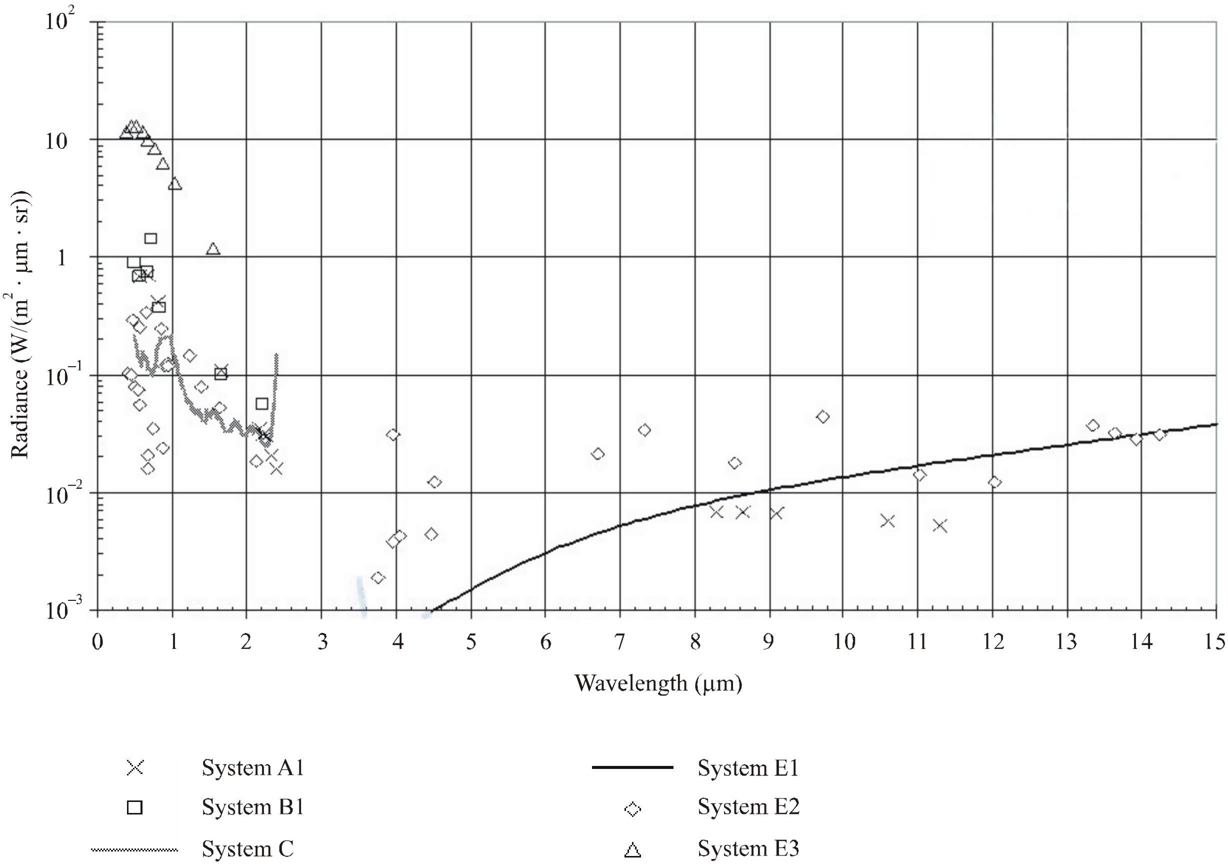
EESS systems collect information relating to the characteristics of the Earth and its natural phenomena, including data relating to the state of the environment. Each EESS system has unique technical characteristics and mission requirements that directly influence instrument sensitivity. Sensitivity requirements will also vary with solar illumination, measurement subject, and even instrument age.

4.1 Sensitivity of detectors

The sensitivity of an EESS detector operating at frequencies above 3 000 GHz varies by detector type. Examples of the minimum sensitivity for six EESS systems operating above 3 000 GHz are provided in Fig. 1.

FIGURE 1

Minimum detectable radiance of several EESS systems operating above 3 000 GHz



Note – Points are placed at spectral lines used for observations. As System C performs observations across more than 200 bands and System E1 performs observations over more than 2 300 bands, detector sensitivities are represented by a single line.

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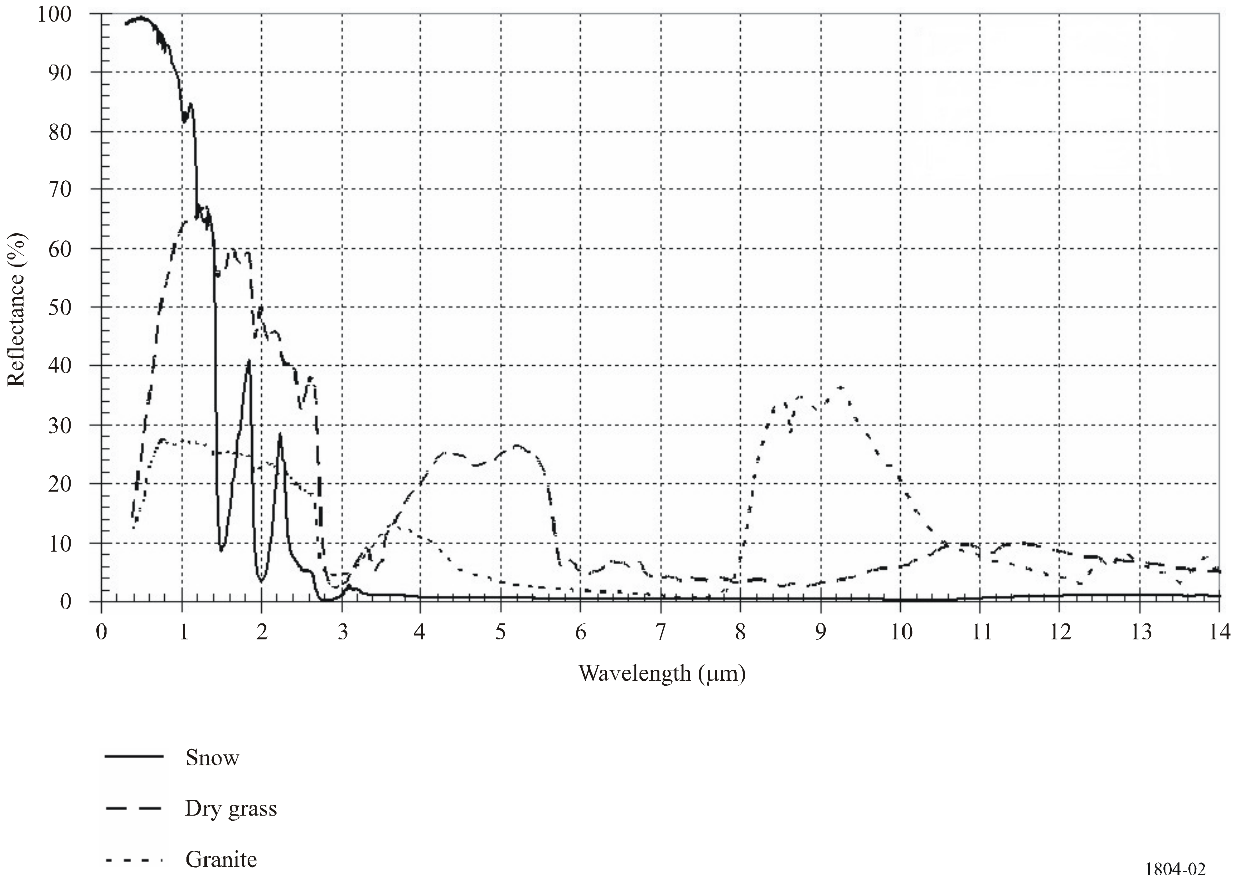
4.2 Effective temperature of the Earth

The effective temperature of the Earth varies with the emissivity of the subject in the sensor's field of view as well as the reflectance of the subject at the wavelengths which illuminate it. EESS sensors operating at frequencies above ~420 THz (< 0.7 µm) usually perform measurements based on reflectivity. EESS sensors operating below ~420 THz, particularly below 100 THz usually perform measurements based on emissivity.

EESS systems operating above 3 000 GHz are able to distinguish between materials observed on the ground using reflectance signatures viewed over spectral ranges of several hundred THz (several µm). An example of these reflectance signatures is provided in Fig. 2.

FIGURE 2

Reflectance signatures of different materials



EESS sensors operating above 3 000 GHz which measure emissivity generally assume the subject emits radiation like a blackbody though with an average emissivity less than 1.0. The theoretical concept of a blackbody assumes a surface which absorbs all radiation incident upon it and has the maximum possible radiative emission for its given temperature. The emissivity of a subject is governed by three functions: Wien's displacement law, Stefan-Boltzmann's law, and the Planck function.

Wien's displacement law states that the wavelength of maximum spectral radiant emittance, λ_M, is inversely proportional to the temperature of the object.

$$\lambda_M = \frac{A}{T} \qquad \mu\text{m} \tag{1}$$

where:

- A: Wien's constant (2 897 K·μm)
- T: temperature (K).

The Stefan-Boltzmann Law states that total power emitted per unit of surface area of blackbody, S, is proportional to the fourth power of its temperature.

$$S = \sigma_B T^4 \qquad \text{W/m}^2 \tag{2a}$$

where:

- σ_B: Stefan-Boltzmann constant (5.671×10^{-8} W/(m^{2}K^4))

However, as natural materials are not perfect blackbody radiators, the effective brightness temperature is proportional to the average emissivity of the substance, ε, thereby making the power emitted:

$$S = \sigma_B \varepsilon T^4 \qquad \text{W/m}^2 \qquad (2b)$$

where:

ε: average emissivity ($0 \leq \varepsilon \leq 1$)

The Planck function is used to compute the radiance emitted from objects that radiate like a perfect blackbody.

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{k_B T \lambda}} - 1\right)} \qquad \text{W/(m}^2\cdot\mu\text{m}\cdot\text{sr)} \qquad (3)$$

where:

h: Planck constant (6.63×10^{-34} J·s)

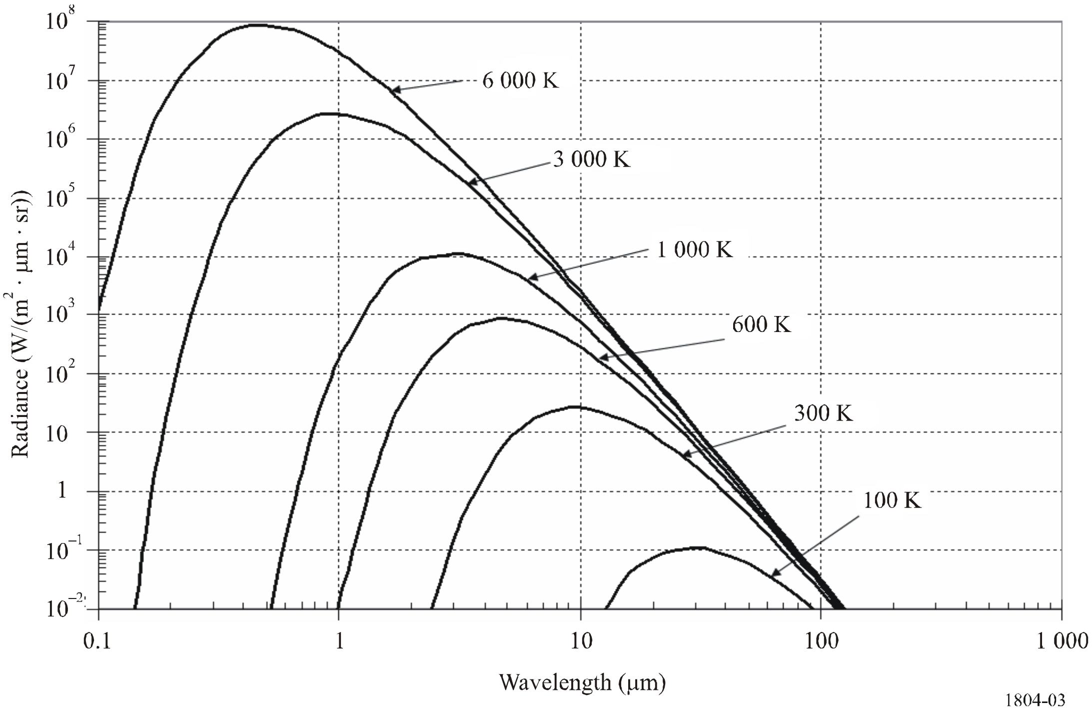
c: speed of light (3×10^{8} m/s)

k_B: Boltzmann's constant (1.38×10^{-23} J/K).

These principles result in the relationships shown in Fig. 3 showing the theoretical radiance, W/(m^2·µm·sr), for several brightness temperatures (K).

FIGURE 3

Radiance of a perfect blackbody at several temperatures



5 Summary

Spectrum above 3 000 GHz has been used in a variety of active and passive EESS applications for many years. Such uses are anticipated to continue, if not increase, in the future. The technical and operational characteristics of these systems, as presented in § 2 to 4, should be taken into account in future studies. For additional reference, the URLs for the official web pages of several missions used as the bases for the systems defined in § 2 are provided in Appendix 1 to this Annex.

Appendix 1
to Annex 1

Official websites for various EESS sensors operating above 3 000 GHz

Advanced Along Track Scanning Radiometer (AATSR):

http://envisat.esa.int

Atmospheric Infrared Sounder (AIRS):
http://airs.jpl.nasa.gov/

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER):
http://asterweb.jpl.nasa.gov/

Advanced Very High Resolution Radiometer (AVHRR):
http://www.esa.int/esaLP/LSmetop.html

Advanced Visible and Near Infrared Radiometer type-2 (AVNIR-2):
http://www.eorc.jaxa.jp/ALOS/about/avnir2.htm

Enhanced Thematic Mapper Plus (ETM+):
http://landsat.gsfc.nasa.gov/about/etm+.html

Geoscience Laser Altimeter System (GLAS):
http://glas.gsfc.nasa.gov/

Geostationary Earth Radiation Budget (GERB):
http://www.esa.int/specials/msg

Global Imager (GLI):
http://suzaku.eorc.jaxa.jp/GLI/ov/sensor.html

Global Ozone Monitoring Experiment (GOME-2):
http://www.esa.int/esaLP/LSmetop.html

Greenhouse gases Observing Sensor (GOS):
http://www.jaxa.jp/missions/projects/sat/eos/gosat/index_e.html

High Resolution Infrared Sounder (HIRS):
http://www.esa.int/esaLP/LSmetop.html

Hyperion:
http://eo1.usgs.gov/hyperion.php

Improved Limb Atmospheric Spectrometer-II (ILAS-II):
http://www-ilas2.nies.go.jp/en/project/ilas2outline.html

Infrared Atmospheric Sounding Interferometer (IASI)
http://www.esa.int/esaLP/LSmetop.html

Lightning Imaging Sensor (LIS):
http://trmm.gsfc.nasa.gov/overview_dir/lis.html

Medium Resolution Imaging Spectrometer (MERIS):
http://envisat.esa.int

Michelson Interferometer for Passive Atmospheric Sounding (MIPAS):
http://envisat.esa.int

Moderate Resolution Imaging Spectroradiometer (MODIS):
http://modis.gsfc.nasa.gov/

Microwave Radiometer (MTVZA-OK):
http://kargonet.narod.ru/rab2/mtvza.htm (Russian only)

Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM):
http://www.eorc.jaxa.jp/ALOS/about/prism.htm

SCIAMACHI:
http://envisat.esa.int

Space Environment Monitor (SEM):
http://www.esa.int/esaLP/LSmetop.html

Spinning Enhanced Visible and Infrared Imager (SEVIRI):
http://www.esa.int/specials/msg

Stratospheric Aerosol and Gas Experiment (SAGE III):
http://www-sage3.larc.nasa.gov/instrument/

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