

# The Remote Sensing Data Book

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*For Christine*

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# Preface

## What is remote sensing?

Remote sensing is, rather broadly speaking, the obtaining of information about an object without actually coming into contact with it. A more restricted definition includes the stipulations that the object is located on or near the Earth's surface, that the observations are made from above the object, and that the information is carried by electromagnetic radiation, some measurable property of which is affected by the object being sensed. This narrower definition excludes such techniques as sonar, geomagnetic and seismic sounding, as well as medical imaging, but includes a wide and fairly coherent set of techniques, often known by the alternative name of *Earth Observation*, that form the subject of this book.

Remote sensing can be viewed as an extension of aerial photography, and thus dated to (probably) 1858, when Tournachon made the first aerial photograph from a balloon at a height of about 80 metres. In the century and a half since then, three principal developments can be identified: the possibility of using aircraft (from the early years of the twentieth century) and spacecraft (from the 1960s) as platforms to carry sensors; the development of sensors exploiting a much wider range of the electromagnetic spectrum than is responded to by photographic film; and the computer revolution, which can again probably be dated to the 1960s and which still appears to be in full swing.

Remote sensing has seen dramatic growth over the last few decades. In part, this can be attributed to the technical developments just outlined, but it is clear that remotely sensed data (in the sense in which I have defined them) must also have some tangible advantages to justify the expense of acquiring and analysing them. These advantages derive from a number of characteristics of remote sensing. Probably the most important of these is the fact that data can be gathered from a large area of the Earth's surface (or a large volume of the atmosphere) in a short space of time, allowing a virtually instantaneous 'snapshot' to be obtained. For example, the Landsat Thematic Mapper, a spaceborne instrument, can acquire data from an area 185 km square in about half a minute. When this aspect is combined with the fact that airborne and spaceborne systems can obtain information from locations that would be difficult (slow, expensive, dangerous, politically awkward) to measure *in situ*, the potential power of remote sensing becomes

apparent. Further advantages derive from the fact that most remote sensing systems now generate calibrated digital data which can be manipulated in a computer.

Remote sensing finds a very wide range of applications including, famously, military reconnaissance. The great majority of the non-military applications, with which this book deals, can be loosely categorised as 'environmental', and we can distinguish a range of environmental properties that can be sensed. In the atmosphere, these include temperature, humidity, precipitation, and the spatial distribution of clouds, winds, aerosols and minor constituents, especially ozone. The Earth's radiation budget can also be measured. Over land surfaces, topography, temperature, albedo, vegetation type and distribution, rock type, soil moisture and land use can all be measured. Over ocean surfaces, colour (which is often related to biological productivity), temperature, topography (from which surface currents can be inferred), wind velocity and wave spectra can be measured. Finally one should mention the cryosphere, where the distribution and condition of snow, sea ice, icebergs and glaciers and ice sheets can be monitored.

This wide range of measurable physical properties generates a correspondingly wide range of applications. Again it is not practicable to present an exhaustive list, but the major non-military applications can perhaps be categorised as follows:

**Atmosphere**

- weather forecasting
- stratospheric chemistry
- global climate research

**Land surface**

- cartography
- land-use surveying
- agriculture and forestry mapping and monitoring
- geological and geomorphological mapping
- geodetic mapping and observation of tectonic motion
- hydrological assessment and forecasting
- resource mapping
- hazard and disaster assessment

**Oceans**

- coastal zone management
- wave forecasting
- measurement of sea-floor topography and determination of the oceanic geoid
- location of fishing areas
- monitoring surface pollution

**Cryosphere**

- snow monitoring and runoff prediction
- sea ice and icebergs
- glaciers and ice sheets

## **Aim and scope of this book**

This book was conceived with several aims in mind. For the comparative newcomer, it attempts to provide brief definitions of terms and concepts commonly encountered in remote sensing. For the more experienced practitioner, the book collects reference data that are often scattered rather widely throughout the existing literature, and it also aims to provide an insight into the wide range of applications of remote sensing so that specialists in one area can obtain helpful insights from others.

The book is organised alphabetically, as a dictionary, in order to facilitate the location of information from unfamiliar areas. Extensive cross-referencing should ensure that the required entry can be found even if the user is unsure of the best starting point. The entries cover the following main areas: definitions and surveys of the principal types of remote sensing system; definitions of the concepts defining the operation and performance of remote sensing systems; propagation and scattering of electromagnetic radiation; characterisation of the Earth's atmosphere; the orbital dynamics of satellites; brief notes on the principal space agencies; remote-sensing satellites; spaceborne remote sensing instruments; concepts and techniques of image processing of remotely sensed data. Brief notes on a number of important applications of remote sensing are also included.

The book addresses itself to remote sensing of the Earth's surface and atmosphere from space. Airborne systems are excluded, although reference is made to them where appropriate. Similarly, the majority of short-duration Space Shuttle missions are not described. Observation programmes directed primarily towards astronomy or the exploration of the solar-terrestrial environment are also excluded, as are specifically military applications.

A comment is appropriate with regard to the information provided on space agencies. The last few years have seen an increasing trend towards spaceborne missions operated jointly by national (or international) space agencies and by commercial companies, and it seems likely that this trend will continue. The book therefore includes some information on relevant commercial operators; naturally, such inclusion constitutes neither an advertisement for nor an endorsement of the company in question.

While the editor and contributors have made every effort to ensure that the book is as up-to-date as it can be, consistent with publishing timetables, some 'dating' of the material is inevitable as a result of the rapid evolution of national and international Remote Sensing programmes. The book attempts to address this fact by including information on the major satellite programmes and missions planned for the next ten years or so. Some of this information is necessarily provisional, and in order to help the user of this book to keep track of changes in mission profiles, relevant World Wide Web (Internet) addresses (URLs, or uniform resource locators) have been included wherever they have been thought helpful. There are also a number of useful WWW pages providing general information on remote sensing, particularly NASA's 'Space Hotlist', CEOS's 'Yellow Pages' and the Centre for Earth Observation's pages. At the



time of writing, the URLs of these sites are

<http://www.hq.nasa.gov/osf/hotlist/>

<http://www.smithsys.co.uk/yp/intro.htm>

<http://ewse.ceo.org/>

These and other URLs listed in the book may change over time, as may their content and relevance. The wide range of WWW search engines should enable the user to locate relevant sites in future.

This book necessarily represents a synthesis of data and information from many sources. As such, it does not readily lend itself to the provision of specific references to books and to articles published in scientific journals. A short bibliography has been provided to enable the interested reader to pursue any of the topics discussed in the book in greater depth.

## **A note about abbreviations and acronyms**

Remote sensing is a discipline that tends to generate large numbers of abbreviations and acronyms, especially in the naming of the various instruments carried by remote-sensing satellites. In general, definitions will be found under the appropriate abbreviation (for example, *ATSR*), although the definition will also be cross-referenced from the full name (*along-track scanning radiometer*). The editor believes that this policy places the definition under the more commonly used term; it also avoids the difficulty caused by the fact that, while the abbreviated name of an instrument is generally fixed, the ‘expansion’ of the abbreviation is not unknown to vary.

## **Errors, omissions and suggestions**

The editor accepts complete responsibility for the content and structure of the book. He would welcome suggestions for improvements.

Gareth Rees  
Cambridge



**AATSR** (Advanced Along-Track Scanning Radiometer) U.K. optical/near infrared/thermal infrared mechanically scanned imaging radiometer, planned for inclusion on *Envisat*. Wavebands: 0.65, 0.85, 1.27, 1.6, 3.7, 11.0, 12.0  $\mu\text{m}$ . Spatial resolution: 0.5 km (wavelengths up to 1.6  $\mu\text{m}$ ), 1.0 km (wavelengths 1.6  $\mu\text{m}$  and above). Swath width: 500 km.

Like the *ATSR*, the AATSR will use a conical scanning technique which provides data from both nadir and  $52^\circ$  forward of nadir. This allows correction of the thermal infrared data for atmospheric emission and absorption effects.

URL: <http://envisat.estec.esa.nl/instruments/aatsr/index.html>

**Ablation** See *glaciers*.

**Absorption coefficient** Term describing the rate at which energy is lost from electromagnetic radiation as it propagates through an absorbing medium. If the intensity (*radiance* etc.) of the radiation propagating in the  $x$ -direction is  $I$ , the absorption coefficient  $\gamma_a$  is defined by

$$\gamma_a = -\frac{dI}{I dx}$$

and has dimensions of  $(\text{length})^{-1}$ . For constant  $\gamma_a$ , the solution of this equation is

$$I = I_0 \exp(-\gamma_a x),$$

or equivalently

$$\ln(I) = \ln(I_0) - \gamma_a x,$$

where  $I_0$  is a constant. (See *Lambert–Bouguer law*.) Absorption coefficients are sometimes also expressed in *decibel* per unit length.

See also *radiative transfer equation*, *refractive index*.

**AC** Russian broad-band UV/optical/infrared radiometer for Earth radiation budget measurements, carried on *Meteor-1* satellites. Waveband: 0.3–30  $\mu\text{m}$ . Spatial resolution: 50 km. Swath width: 2500 km.

**Accumulation** See *glaciers*.

**Accuracy, classification** See *error matrix*.

**Across-track direction** See *range direction*.

**Active Microwave Instrument** See *AMI*.

**Active system** A remote sensing system that emits radiation and analyses the returned component, such as a *lidar*, an imaging *radar*, a *radar altimeter* or a *scatterometer*. Compare *passive system*.

**ADEOS** (Advanced Earth Observing Satellite) Japanese satellite, operated by *NASDA*, launched in August 1996 with a nominal lifetime of 3 years. The satellite's solar power system failed irrecoverably in June 1997. **Objectives:** Global land, ocean, and atmospheric observations. **Orbit:** Circular *Sun-synchronous LEO* at 797 km altitude. Period 101 minutes; inclination 98.6°; equator crossing time 10:30 (descending node). *Exactly-repeating orbit* (585 orbits in 41 days). **Principal instruments:** *AVNIR*, *ILAS*, *IMG*, *NSCAT*, *OCTS*, *POLDER*, *TOMS*. The satellite also has a laser retroreflector array (RIS) for laser ranging from ground stations and for atmospheric absorption measurements.

ADEOS was also known as Midori.

URL: <http://www.eorc.nasda.go.jp/ADEOS/>

**ADEOS II** (Advanced Earth Observing Satellite) Japanese satellite, operated by *NASDA*, scheduled for launch in February 1999 with a nominal mission of 5 years. **Objectives:** Part of IEOS (International Earth Observation System – see *EOS*) for global change studies through WCRP, GEWEX, CLIVER, IGBP, GCOS, and integrated into the *EOS* programme. **Orbit:** Circular *Sun-synchronous LEO* at 797 km altitude. Period 101 minutes; inclination 98.6°; equator crossing time 10:30 (descending node). **Principal instruments:** *AMSR*, *GLI*, *ILAS-II*, *POLDER-2*, *SeaWinds*. The satellite will also carry a data collection package. ADEOS-II was formerly known as **JPOP** (Japanese Polar Platform).

URL: <http://titan.eorc.nasda.go.jp/test/GLI/adeos2.html>

**Adjacency effect** Contribution to the *radiance* (optical or near infrared) of a *pixel* by atmospherically scattered radiation originating in nearby pixels. The adjacency effect is mainly due to scattering by atmospheric *haze*, and has a horizontal scale of the order of 1 km.

**Advanced Along-Track Scanning Radiometer** See *AATSR*.

**Advanced Earth Observing Satellite** See *ADEOS*, *ADEOS II*.

**Advanced Land Observing Satellite** See *ALOS*.

**Advanced Microwave Scanning Radiometer** See *AMSR*.

**Advanced Microwave Sounding Unit** See *AMSU/MHS*, *AMSU-B*.

**Advanced Millimetre-wave Atmospheric Sounder** See *AMAS*.

**Advanced optical and Near Infrared Radiometer** See *AVNIR*.

**Advanced SAR** See *ASAR*.

**Advanced Spaceborne Thermal Emission and Reflection Radiometer** See *ASTER*.

**Advanced Synthetic Aperture Radar** See *ASAR*.

**Advanced TIROS-N** See *NOAA-6* to *NOAA-8*.

**Advanced Very High Resolution Radiometer** See *AVHRR*.

**Advanced Vidicon Camera Subsystem** See *AVCS*.

**Advanced Wind Scatterometer** See *ASCAT*.

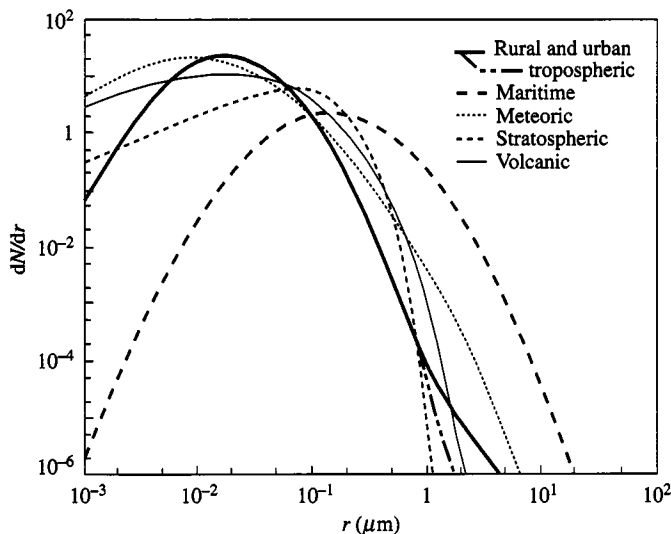
**AEM-1** See *HCMM*.

**AEM-2** (Applications Explorer Mission 2) U.S. satellite, operated by *NASA*, launched in February 1979 and terminated in November 1981. Objectives: Monitoring of stratospheric gases and aerosols. Orbit: Nominally circular *LEO* at 550 km altitude. Inclination 55°; period 97 minutes. Principal instruments: *SAGE-I*.

**Aerosol** A suspension of very small (typically 1 nm to 10  $\mu\text{m}$ ) solid particles (e.g. dust, sulphates) or liquid droplets in air, mostly found in the atmospheric *boundary layer*. Aerosols are climatically important as a result of the attenuation of solar radiation and their role in *cloud* formation. Some aerosols are also chemically active (see *chemistry, atmospheric*). Scattering and absorption of optical and near infrared radiation by aerosols is the major source of uncertainty in *atmospheric correction*. Concentrations of aerosols are difficult to measure, especially in the *troposphere* and over land, where the high surface reflectance masks the radiation scattered by the aerosol.

Aerosols of different origin have markedly different size distributions and refractive indices, and hence different absorption and scattering properties. The figure summarises the size distributions of rural, urban, tropospheric, maritime, meteoric, stratospheric and volcanic aerosols. The horizontal axis shows the particle size in  $\mu\text{m}$ ; the vertical axis the value of  $dN/dr$  where  $N$  is the concentration of particles of size  $r$ . All the graphs have been normalised to a total concentration of 1.

Over a limited range of wavelength, both the scattering and absorption coefficients of an aerosol can be described approximately by the *Ångström*



relation

$$\gamma = \gamma_0(\lambda/\lambda_0)^{-\nu},$$

where  $\lambda$  is the wavelength and  $\gamma$  has the value  $\gamma_0$  at some reference wavelength  $\lambda_0$ .  $\nu$  is the Ångström exponent. The table below summarises the approximate values of  $\gamma_0$  (in  $\text{km}^{-1}$ ) and  $\nu$  for the optical/near infrared region, corresponding to a total attenuation coefficient of  $1 \text{ km}^{-1}$  and taking  $\lambda_0 = 0.55 \mu\text{m}$ .

Aerosol	Total		Scattering		Absorption	
	$\gamma_0$	$\nu$	$\gamma_0$	$\nu$	$\gamma_0$	$\nu$
rural	1.0	1.3	0.95	1.3	0.05	0.5
urban	1.0	1.2	0.77	1.3	0.23	0.8
tropospheric	1.0	1.8	0.97	1.8	0.03	0.8
maritime	1.0	0.2	0.99	0.2	0.01	-0.1
meteoric	1.0	0.4	0.995	0.4	0.005	-2
stratospheric	1.0	2.1	1.0	2.1	$10^{-7}$	-6
volcanic	1.0	1.2	0.94	1.2	0.06	1.2

The attenuation coefficient at sea level typically ranges between 0.05 and  $0.5 \text{ km}^{-1}$ ; at the tropopause it typically ranges between 0.001 and  $0.003 \text{ km}^{-1}$ .

Measurement of the vertical profile of aerosol scattering coefficient can be made by optical/near infrared limb sounding (e.g. *GOMOS*, *HiRDLS*, *ILAS*, *POAM-2*, *SAGE III*, *SAM-II*), backscatter lidar (e.g. *Alissa*, *GLAS*) or nadir ultraviolet/optical/infrared spectrometry (e.g. *MISR*, *MODIS-N*, *MOS*, *POLDER*).

**Agenzia Spaziale Italiana** The Italian space agency. See *CEOS*.

**AIRS** (Atmospheric Infrared Sounder) U.S. optical/infrared grating spectrometer, planned for inclusion on *EOS-PM* satellites. Wavebands: 2300 bands between 3.74 and 15.4  $\mu\text{m}$  (spectral resolution 3 nm to 13 nm), 6 bands between 0.4 and 1.7  $\mu\text{m}$ . Spatial resolution: 13.5 km horizontal (at nadir), 1 km vertical. Swath width: 1650 km (scans to  $\pm 49^\circ$  from nadir).

AIRS will provide atmospheric temperature profiles by measuring thermal emission.

URL: <http://www-airs.jpl.nasa.gov/>

**Albedo** The fraction of incident radiation that is reflected by a surface. See *bidirectional reflectance distribution function*.

**Albedo, planetary** The fraction of incident solar radiation that is reflected back into space by a planet. The Earth's planetary albedo (approximately 30%) is a fundamental factor in determining its energy budget and hence climate (see *Earth radiation budget*). It can be measured by calibrated optical/near infrared radiometry from *LEO* or from *geostationary* orbit. See *bidirectional reflectance distribution function*.

**Algorithm** A mathematical process connecting a remote sensing measurement to the surface or atmospheric property of interest.

**Aliasing** A periodic phenomenon of frequency  $f_1$ , sampled at a frequency  $f_0$ , will appear to vary with a frequency  $f_a$  given by

$$f_a = f_1 - f_0 \left[ \frac{f_1}{f_0} + \frac{1}{2} \right],$$

where  $[x]$  is the least-integer function. This phenomenon is called aliasing, and  $f_a$  is the aliased frequency. See also *Nyquist frequency*.

**Alisa** (l'Atmosphere par Lidar sur Saliout) French backscatter *lidar*, for measurement of cloud and aerosol structure, carried on *Mir-1*. Wavelength: 532 nm (Nd-YAG laser). Spatial resolution: 300 m (horizontal), 150 m (vertical). Pulse repetition frequency: 8 Hz.

**Almaz-1** Russian satellite, launched in March 1991, lifetime 1.5 years. Objectives: Global land, ocean, atmosphere observations. Orbit: Nominally circular *LEO* at 270–380 km altitude. Period 92 minutes; inclination  $73^\circ$ . Principal instruments: *SAR*, *UHF radiometer*. 'Almaz' is the Russian word for 'diamond'.

**Almaz-1B** Russian satellite, scheduled for launch in 1998 with a nominal lifetime of 3 years. Objectives: Global land, ocean, atmosphere observations. Orbit: Circular *LEO* at 400 km altitude. Period 90 minutes; inclination  $73^\circ$ . Principal instruments: *Balkan-2*, *MSU-E*, *MSU-SK*, *OEA*, *SAR-3/SLR-3*, *SAR-10*, *SAR-70*, *SROM*.

**Along-track direction** The direction on the Earth's surface parallel to the motion of a *side-looking radar* or *synthetic aperture radar*, also called the azimuth direction.

**Along-Track Scanning Radiometer** See *ATSR*.

**ALOS** (Advanced Land Observing Satellite) Japanese satellite planned for launch in 2002. Objectives: Cartography, environmental monitoring, hazard monitoring. Orbit: Circular *Sun-synchronous LEO*. Equator crossing time 10:30 descending. Principal instruments: *AVNIR-2*, *VSAR*.

The ALOS mission was formerly called HIROS.

URL: <http://www.goin.nasda.go.jp/GOIN/NASDA/act/alos.html>

**ALT** U.S. dual-frequency nadir-viewing radar altimeter, carried on *Topex-Poseidon*. Frequencies:  $K_u$  band (13.6 GHz) and C band (5.3 GHz). Pulse length (uncompressed): 102  $\mu$ s; (compressed): 3.1 ns. Range precision: 2.4 cm. Beam-limited footprint: 26 km (13.6 GHz); 65 km (5.3 GHz). Pulse-limited footprint: 2.2 km. Dual frequency operation allows for correction of ionospheric delays.

URL: [http://www-aviso.cls.cnes.fr/English/TOPEX\\_POSEIDON/More\\_On\\_Payload.html](http://www-aviso.cls.cnes.fr/English/TOPEX_POSEIDON/More_On_Payload.html)

**Altimetry Microwave Radiometer** See *AMR*.

**Altitude, orbital** See *height, orbital*.

**AMAS** (Advanced Millimetre-wave Atmospheric Sounder) European passive microwave atmospheric limb sounder, operating in the frequency range 298–626 GHz (wavelengths 0.5–1.0 mm), planned for inclusion on *Meteor-3M* satellite. Frequencies: 298, 301, 302, 325, 346, 500, 501, 626 GHz. Spatial resolution: vertical: 1 km (troposphere); 3 km (stratosphere); 5–10 km (mesosphere). Horizontal: 300 km. Height range: 5–100 km.

AMAS is designed to measure temperature and pressure profiles, ozone, water vapour,  $N_2O$  and other chemical constituents of the middle and upper atmosphere.

**AMI** (Active Microwave Instrument) European *synthetic aperture radar*/microwave scatterometer carried on *ERS-1* and *-2* satellites. Frequency: C band (5.3 GHz). Polarisation: VV. Incidence angle: 23° at mid-swath. Spatial resolution: 30 m (wave and image modes), 50 km with data on a 25 km grid (scatterometer mode). Swath width: 5 km  $\times$  5 km (wave mode), 100 km (image mode), 500 km (scatterometer mode). Radiometric resolution: 2.5 dB in image mode, 0.3 dB in scatterometer mode.

In scatterometer mode, the AMI generates beams in directions 45°, 90°, 135° (zero is along-track, 90° to the right). The near edge of the swath is 150 km to the right of the sub-satellite track; the far edge is 650 km from it. Wind velocity

vectors over oceans can be retrieved with an accuracy of  $\pm 2$  m/s,  $\pm 20^\circ$ , in the range 4 to 24 m/s.

The duty cycle for image mode is approximately 12% (i.e. 12 minutes of data can be stored per orbit). For wave and scatterometer modes the duty cycle is 100%.

URL: <http://earth1.esrin.esa.it/f/eo2.402/ERS1.3>

**Among-class covariance** See *canonical components*.

**AMR** (Altimetry Microwave Radiometer) U.S. nadir-viewing *passive microwave radiometer*, planned for inclusion on *TPFO*. Frequencies: 18.2, 23.8, 34.0 GHz. Spatial resolution: 29 km, 23 km, 16 km respectively.

The AMR will be used to provide propagation delay estimates for correction of data from the *DFA*. It is based on the design of the *TMR*.

**AMSR** (Advanced Microwave Scanning Radiometer) Japanese conically scanned *passive microwave radiometer*, planned for inclusion on *ADEOS II*. Frequencies: 6.9, 10.65, 18.7, 23.8, 36.5, 50.3, 52.8, 89 GHz. Polarisation: H and V. Spatial resolution: 50 km at 6.9 GHz to 5 km at 89 GHz. Swath width: 1600 km. Sensitivity: 0.3–1 K. Absolute accuracy: 1–2 K.

**AMSU/MHS** (Advanced Microwave Sounding Unit/Microwave Humidity Sounder). U.S.–European mechanically scanned *passive microwave radiometer* for profiling atmospheric temperature and water vapour, planned for inclusion on *EOS-PM*, *Metop* and future *NOAA* satellites. Channels 1 and 2 are the

Channel	Frequency (GHz)	Bandwidth (MHz)
1	23.80	280
2	31.40	180
3	50.30	180
4	52.80	400
5	53.60 $\pm$ 0.12	170
6	54.40	400
7	54.94	400
8	55.50	330
9	57.29	330
10	57.29 $\pm$ 0.22	78
11	57.29 $\pm$ 0.32	36
12	57.29 $\pm$ 0.32	16
13	57.29 $\pm$ 0.32	8
14	57.29 $\pm$ 0.32	3
15	89.00	6000
16	89.00	2800
17	157.0	2800
18	183.31 $\pm$ 1	500
19	183.31 $\pm$ 3	1000
20	183.31 $\pm$ 7	2200



AMSU-A2 instrument, channels 3–15 the AMSU-A1, and channels 16–20 the MHS unit.

Spatial resolution: 40 km at nadir (AMSU); 15 km at nadir (MHS). Swath width: 1650 km. Height range: 0–70 km. Temperature resolution: 0.25–1.2 K (AMSU-A), 1.0 K (MHS).

AMSU uses channels 3–14 for temperature profiling, using the oxygen absorption band between 50 and 60 GHz. The other AMSU channels provide corrections for surface temperature and atmospheric water and water vapour. MHS, which is similar to *AMSU-B*, provides water vapour profiles, and will also give qualitative estimates of precipitation rates.

**AMSU-B** (Advanced Microwave Sounding Unit-B) U.K. mechanically scanned passive microwave radiometer for atmospheric water vapour profiling, planned for inclusion on future *NOAA* satellites.

Channel	Frequency (GHz)	Bandwidth (GHz)
1	89.00	6
2	150.0	4
3	183.31 ± 1	1
4	183.31 ± 3	2
5	183.31 ± 7	4

Spatial resolution: 16 km at nadir. Swath width: 2200 km. Height range: 0–42 km. Temperature resolution: 1.0–1.2 K.

AMSU-B is very similar to MHS (see *AMSU-A/MHS*).

**Ångström relation** The assumption that the *optical thickness*  $\tau$  of an atmospheric *aerosol* varies with wavelength  $\lambda$  according to

$$\tau \propto \lambda^{-\nu},$$

where  $\nu$  is the Ångström exponent. In the absence of any other information, it is often assumed that  $\nu = 0$ .

**Angular frequency** see *frequency*.

**Antenna** A transducer that couples a guided electromagnetic wave on a transmission line to an unguided wave in the medium surrounding the antenna, and vice versa. Antennas are used by both passive microwave radiometers (see *passive microwave radiometry*) and *radar* systems. The directional pattern of an antenna, specified by its *power pattern*, consists of a main beam surrounded by a number of sidelobes, with the effective width of the beam  $\beta$  (radians) in a given plane being approximately equal to  $\lambda/D$ , where  $\lambda$  is the wavelength and  $D$  is the width of the antenna in that plane (see *beamwidth*). The antenna may consist of a single element, such as a parabolic dish, a horn, or a microstrip radiating patch, or it may consist of an array of such elements. A synthetic

aperture may be formed by combining the signals received by a real antenna as it travels in space and then processing them together as if they had been received by a long array of individual elements, thereby attaining high angular resolution in the plane containing the synthetic array. This is the basis of *synthetic aperture radar*.

**Antenna temperature** The antenna temperature represents the power received by an *antenna* and transferred to the receiver. For a lossless antenna with a *power pattern* consisting of only a single main beam with no sidelobes, the antenna temperature  $T_A$  is equal to the *brightness temperature*  $T_b$  incident upon the antenna through its main beam, where  $T_b$  represents the power radiated by the scene observed by the antenna. A real antenna, however, is characterised by a radiation efficiency  $\eta$  and a main-beam efficiency  $\eta_m$ , where  $\eta$  accounts for ohmic losses in the antenna structure and  $\eta_m$  accounts for the fraction of the total antenna power pattern contained in its main beam. In that case,  $T_A$  is related to  $T_b$  through

$$T_A = \eta\eta_m T_b + \eta(1 - \eta_m)T_{SL} + (1 - \eta)T_0,$$

where  $T_{SL}$  is the average brightness temperature of radiation incident upon the antenna along directions other than through its main beam and  $T_0$  is the physical temperature of the antenna. It is possible to achieve values of  $\eta$  as high as 0.99. It is also possible to design the antenna such that its side-lobe levels are very low, thus achieving values of  $\eta_m$  in the range 0.90 to 0.98, but this is accomplished at the expense of widening the main beam by as much as a factor of two, compared with the narrowest beam attainable for an antenna of a given size, with a corresponding loss in angular resolution.

**Apogee** The furthest point of a satellite's *orbit* from the Earth's centre.

**Applications Explorer Mission** See *AEM-2*, *HCMM*.

**APT** (Automatic Picture Transmission)

1. See *AVHRR*.
2. U.S. visible-wavelength *vidicon* imaging system with direct transmission of image data, carried on even-numbered *ESSA* satellites, *Nimbus-1*, *TIROS-8* and *NOAA-1*. Waveband: 0.45–0.65  $\mu\text{m}$ . Spatial resolution: 4 km at nadir. Swath width: 1200–1600 km (3100 km from *ESSA*).

**Archaeological site detection** The mastery of nature by man results in a transformation of the landscape through agriculture and construction. In arid parts of the world it is often easy to see the remains left by human activity which survive for long periods above the ground. But in heavily occupied and farmed regions most surface traces have been obliterated. Traces remaining in the ground just below the surface are usually studied through excavation, a tool of last resort, since it destroys the evidence. Techniques for non-destructive investigation have been developed to protect sites by leaving them undisturbed.

The methods derive from geological geophysical prospecting and low altitude aerial survey. Buried remains are detected and mapped by measuring or recording differences in water content, magnetic, thermal and mechanical properties, and displaying these with modern processing methods as two- or three-dimensional coloured images. Low level oblique aerial photographs have been used since the 1920s and are still the most economical approach. Electrical, magnetic, electromagnetic, *radar* and sensitive remote temperature measurements add techniques for use under widely varying geological, climatic and man-made conditions. Buried structures are recognised by skilled archaeologists via their characteristic shapes in properly processed images made from such data.

## Argon

1. A minor constituent of the Earth's *atmosphere*.
2. Series of U.S. military reconnaissance satellites, operating between February 1961 and August 1964. The satellites carried panchromatic cameras (Keyhole) with a resolution of 140 m. The data are now declassified.

URL: <http://edcwww.cr.usgs.gov/dclass/dclass.html>

**Argos** French/U.S. data collection system, carried on *TIROS-N*, *NOAA-6* onwards. Argos-equipped spacecraft carry a Data Collection and Location System (DCLS or DCS) package capable of receiving transmissions (402 MHz) from registered data-collection platforms (on ships, buoys, aircraft etc.). These transmissions are downlinked to ground stations for processing (position determination and data formatting). Positions can be determined to  $\pm 300$  m ( $\pm 30$  m on some days).

**ASAR** (Advanced SAR) European *synthetic aperture radar* planned for inclusion on *Envisat*. Frequency: C band (5.3 GHz). Polarisation: VV and HH. Incidence angle:  $15^\circ$  to  $45^\circ$  at mid swath (image, wave and alternating polarisation modes). Spatial resolution: 30 m (image, wave and alternating polarisation modes), 100 m (wide swath mode), 1000 m (global monitoring mode). Swath width:  $5 \text{ km} \times 5 \text{ km}$  images (wave mode), 56–120 km with 7 sub-swaths (image and alternating polarisation modes), 400 km with 5 sub-swaths (wide swath and global monitoring modes). Radiometric resolution: 1.3 to 1.7 dB.

All modes can operate at either HH or VV polarisation. The 'alternating polarisation' mode interleaves observations in each polarisation state.

URL: <http://envisat.estec.esa.nl/instruments/asar/index.html>

**ASCAT** (Advanced Wind Scatterometer) European microwave wind *scatterometer* planned for inclusion on *Metop*. Frequency: C band (5.3 GHz). Polarisation: VV. Beam angles: [ $0^\circ = \text{forward}$ ,  $90^\circ = \text{right}$ ]  $\pm 45^\circ$ ,  $\pm 90^\circ$ ,  $\pm 135^\circ$ . Spatial resolution: 50 km (data provided on 25 km grid). Swath width: two 500 km swaths (left and right sides). Near edges 150 km from sub-satellite track; far edges 650 km. Accuracy:  $\pm 2 \text{ m/s}$ ,  $\pm 20^\circ$  for ocean surface wind vectors.

ASCAT is derived from the *AMI* scatterometer.

**Ascending node** The point in a satellite's *orbit* at which it crosses the Earth's equatorial plane from the southern to the northern hemisphere.

**ASI** (Agenzia Spaziale Italiana) See *CEOS*.

**ASTER** (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Japanese optical/near infrared/thermal infrared multispectral imaging radiometer, to be carried on *EOS AM-1* satellite. Wavebands and spatial resolution:

Band	Waveband ( $\mu\text{m}$ )	Spatial resolution (m)
1	0.52–0.60	15
2	0.63–0.69	15
3N*	0.76–0.86	15
3B*	0.76–0.86	15
4	1.60–1.70	30
5	2.15–2.19	30
6	2.19–2.23	30
7	2.24–2.29	30
8	2.30–2.37	30
9	2.36–2.43	30
10	8.13–8.48	90
11	8.48–8.83	90
12	8.93–9.28	90
13	10.25–10.95	90
14	10.95–11.65	90

\*Band 3 views both towards nadir and backwards, to give stereoscopic viewing.

Swath width: 60 km, steerable to  $\pm 100$  km across-track from sub-satellite track ( $\pm 300$  km for optical/near infrared bands).

ASTER was formerly known as **ITIR** (Intermediate Thermal Infrared Radiometer).

URL: <http://asterweb.jpl.nasa.gov/asterhome/>

**ATMOS** U.S. limb-sounding infrared spectrometer, for molecular profiling of the atmosphere, carried on *Spacelab-3*. Waveband: 2.2 to 16  $\mu\text{m}$  (Fourier transform spectrometer).

## Atmosphere

1. A unit of pressure, equal to 101.325 kPa.
2. The gaseous envelope surrounding the Earth. The main constituents of the atmosphere are nitrogen, oxygen, water vapour, argon and carbon dioxide, though other gases present at low concentrations can also have a significant effect on the *Earth radiation budget*. The composition and physical properties of the atmosphere vary considerably with height, and also with geographical position (especially with latitude, but also with proximity to land or sea, or

to industrial or rural areas). The table below shows the mean composition of the atmosphere at sea level, in terms of the fraction by volume, and the mean column-integrated quantity of gases, expressed in moles per square metre.

Gas	Volume fraction	Column integral (moles per m <sup>2</sup> )
N <sub>2</sub>	0.7808	$2.784 \times 10^5$
O <sub>2</sub>	0.2095	$7.468 \times 10^4$
H <sub>2</sub> O	$10^{-3}$ – $2.8 \times 10^{-2}$	$3.6 \times 10^2$ – $9.8 \times 10^3$
Ar	$9.34 \times 10^{-3}$	$3.32 \times 10^3$
CO <sub>2</sub>	$3.5 \times 10^{-4}$	$1.3 \times 10^2$
Ne	$1.8 \times 10^{-5}$	6.5
He	$5.2 \times 10^{-6}$	1.9
CH <sub>4</sub>	$1.8 \times 10^{-6}$	0.62
Kr	$1.1 \times 10^{-6}$	0.41
CO	$6 \times 10^{-8}$ – $10^{-6}$	0.02–0.4
SO <sub>2</sub>	$10^{-6}$	0.4
H <sub>2</sub>	$5 \times 10^{-7}$	0.2
O <sub>3</sub>	$10^{-8}$ – $10^{-6}$	0.11
N <sub>2</sub> O	$2.7 \times 10^{-7}$	0.09
Xe	$9 \times 10^{-8}$	0.03
NO <sub>2</sub>	$5 \times 10^{-10}$ – $2 \times 10^{-8}$	$2 \times 10^{-4}$ – $9 \times 10^{-3}$

The atmosphere is conventionally divided into a number of layers on the basis of its vertical temperature structure. The **troposphere**, in which the temperature usually decreases with height, extends from sea level to a height of about 10 km. This is the most turbulent layer, in which most meteorological phenomena occur. The lowest region of the troposphere, the *boundary layer*, is approximately 1 km deep. Above the troposphere is the **stratosphere**, in which the temperature increases with height (as a result of increasing absorption of solar ultraviolet radiation by ozone), extending up to about 50 km. The molecular concentration of ozone increases with height in the stratosphere, reaching a maximum at about 50 km. Between about 50 km and 85 km is the **mesosphere**, in which the temperature decreases with height, and above this is the **thermosphere**, in which it increases. Figure A summarises the variations of temperature, pressure and density between sea level and the lower part of the thermosphere, although it is representative only since the heights of the layer boundaries vary considerably with latitude.

Absorption of electromagnetic radiation by the atmosphere limits the range of wavelengths or frequencies at which remote sensing of the Earth's surface can be performed. Conversely, observations made at the wavelength of an absorption line give the possibility of *atmospheric sounding* of temperature, pressure and molecular composition of the atmosphere. Figures B and C summarise the typical atmospheric attenuation spectrum for a one-way vertical path through the atmosphere, although these values are again dependent on latitude and on the concentrations of different molecular species.

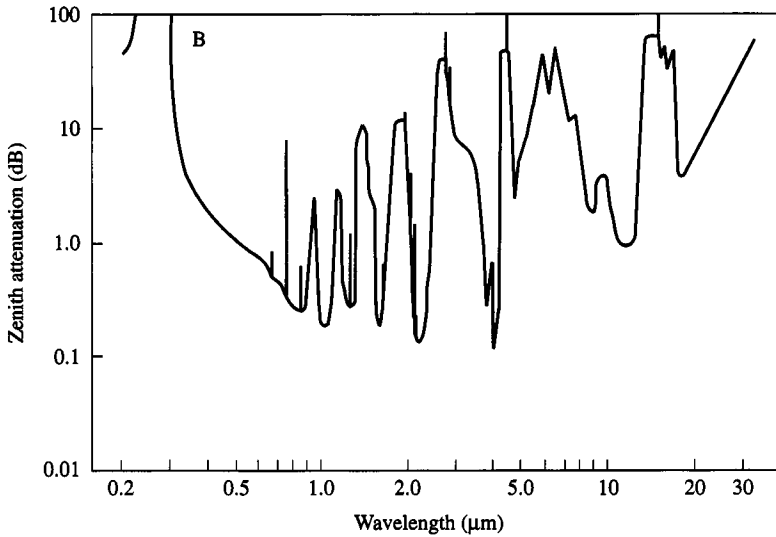
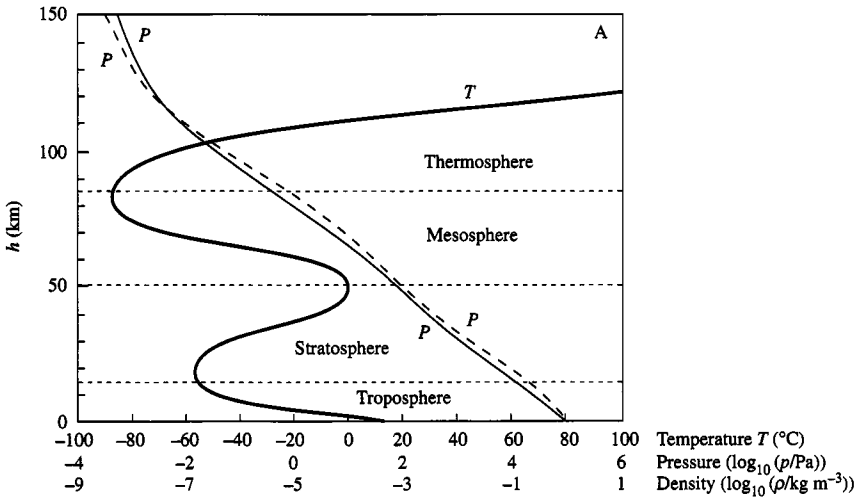


Figure B shows schematically the zenith attenuation plotted against wavelength in the ultraviolet, optical and infrared parts of the electromagnetic spectrum. The main peaks are as follows ( $\mu\text{m}$ ):

$\text{CH}_4$ :	1.66	2.1	2.3	2.4	3.3			
$\text{CO}_2$ :	1.95	2.0	2.1	2.7	2.8	3.3	4.3	15
$\text{H}_2\text{O}$ :	0.72	0.82	0.93	1.12	1.37	1.85	2.6	5.9 6.5
$\text{N}_2\text{O}$ :	3.8	7.8						
$\text{O}_3$ :	0.26	0.60	4.7	9.7				
$\text{O}_2$ :	0.69	0.76	1.25					