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Passive microwave space missions

The rapid introduction of microwave sensing methods and means into airspace observations in the last 10–15 years was a consequence, as we have shown above, of the significantly new (in relation to optical and infrared bands) physical information content of microwave sensing in studying terrestrial objects (the surface and the atmosphere). The development and evolution of instruments and research missions of microwave sensing has occurred, certainly, in a quite inhomogeneous and irregular manner. Nevertheless, at the present time none of potential large-scale satellite missions on earth investigation fails to employ passive and active radiophysical instruments in some configuration. The present chapter analyses some historical elements of the development of microwave missions (including the issues of instrument development), the state of the art and some prospects for the future.

14.1 ELEMENTS OF MICROWAVE RADIOMETRY HISTORY

The study and understanding of microwave patterns of the terrestrial surface–atmosphere system has cardinally changed both the configuration of existing satellite systems designed for sensing the Earth, and the character and informative saturation of the whole remote sensing area. However, microwave radiometry was initially born in the entrails of radio-astronomy as some kind of an auxiliary direction invoked to satisfy the needs of ground-based radio-astronomy, which had passed through stages of build-up and vigorous development in the 1940s and 1950s of the past century. This required, first of all, eliminating the influence of a disperse component (and, then, also of a gaseous component) of atmosphere radiation in the microwave band on high-precision radio-astronomical measurements carried out from the earth's surface. Some special techniques of performing radio-astronomical experiments (such as the diagram modulation method) (Esepkina *et al.*, 1973) have been directed to solving this problem. For these reasons the earliest microwave investigations were entirely based on an instrumental foundation and on the methodological basis of radio-astronomy.

The first microwave investigations of radio-emission of the atmosphere at the wavelength of 1.5 cm were carried out by Professor Dicke in 1946 by means of the modulation method of measuring the noise signal proposed by himself. This technique, as well as the method of designing the instruments, underwent efficient development and improvement by radio-astronomers in quite various bands of the electromagnetic spectrum (Troitskii, 1951, 1954).

However, the further development and exploration of the short-centimetre and millimetre wavelength bands has put on the agenda the problems of the detailed spectral study of the characteristics of radiowave propagation in the atmosphere and in plasma-like media and of thermal radiation of geophysical media in these bands (Zhevakin and Naumov, 1967; Basharinov *et al.*, 1968). Both the instrumental base of radio-astronomy, and the measurement techniques began to undergo serious reconstruction. This was associated, first of all, with the brevity of the time for observing an object under study (a small accumulation time) and with the prominent polarization properties of geophysical objects. The problem also arose of manufacturing the small-sized instruments and antenna systems that have to be installed on moving platforms and flight vehicles. The existing stationary radio-astronomical instruments and the techniques of stationary (ground-based) measurements would obviously not have satisfied the necessary requirements. It may seem surprising, but historically the first extra-vehicular operation of microwave instruments was the launching of the Mariner-2 spacecraft in 1962 (Table 14.1), designed to study the structure and physicochemical content of the cloudy layers of Venus. It was, in fact, searching for water vapour by means of a two-frequency technique, which subsequently became a fully standard and conventional method in the system of space sounders of the terrestrial atmosphere (see Chapter 12 and below). The natural (as we know now) negative scientific result of this mission has been, nevertheless, an important step in the planetary research; and it confirmed the scientific significance of microwave sensing in onboard implementation.

A difficult stage of the establishment of microwave sensing as an independent discipline began in the middle of the 1960s: a series of air-based radiometric instruments was produced for meteorological investigations and military–technological applications (see the review by Khodyrev *et al.*, 1972). An important step at this stage was the development, for the first time in the USSR, of multifrequency onboard radiothermal instruments and their installation on the 'Cosmos-243' satellite that was launched in 1968 (Table 14.1). The significance of this space-based experiment can hardly be exaggerated. In essence, the principal possibility was demonstrated of receiving physical and geophysical information from outer space by means of radiothermal systems. In addition, some serious scientific results were obtained concerning the relation between the global integrated content of water vapour and liquid-drop water in the atmosphere, as well as some other results (see Chapter 12). This space-based experiment was repeated in 1970 on the 'Cosmos-384' satellite. However, these experiments have also revealed some limitations of the measurement methodology used – namely, a purely track mode of measurements employing nadir-viewing antennas. Under such an observation mode it was impossible to obtain a spatial map of the distribution of the radiation field of geophysical objects and to find their polarization characteristics.

An important step in this direction was the development and launching of panoramic scanning radiothermal instruments ESMR on the Nimbus-5 satellite in 1972. Its characteristics were as follows: the frequency, 19.35 GHz; the swath-width of scan, 3000 km; and the instantaneous spatial resolution, 29 km. The scanning was performed in the cross-track mode by means of an electronically scanned phase array. The second item of instrumentation was the first version of the radiothermal probe (Table 14.1), which included three channels in the 5-mm line of oxygen and two channels for sensing according to the two-frequency technique (Chapter 12). This set has operated in the track mode. At this stage, in essence, there took place the formation and separation of microwave observation systems into three types: track-type systems, systems of panoramic (or scanner) type (the imagers), and measurement systems (or atmospheric sounders). This tendency has strengthened subsequently. However, each of these channels, in its turn, has continued operating in the mode of mono-configuration type, that is, one frequency/one polarization/one angle. Apart from using the centimetre band, in 1973 an attempt was undertaken to build an onboard radiometre of decimetre band (at the wavelength of 21 cm) with an angular resolution of 15°, and to operate this system onboard the Skylab spacecraft. Radiothermal instruments of centimetre band with a parabolic-type antenna system, having a considerable aperture (the diametre of 117 cm) and mechanical scanning, were installed on the same station.

The next step in microwave sensing was the inclusion of polarization measurements on the Meteor satellite (1974) in a track mode, and panoramic-type ESMR instruments (37 GHz) of have operated on the Nimbus-6 satellite in the two-polarization mode. The SCAMS sounder has also already operated in the scanner mode. It is important to note that in the microwave ESMR system the phase array was used for the last time as a scanning antenna system. The reason for this was, first of all, the high electromagnetic losses in the beam control system and, accordingly, the great noise contribution to the measured signal. Besides, the specialists had some doubts concerning the chosen cross-track type of scanning. This is associated with the fact that the elements of the surface under investigation are considered in a single frame at various angles, and, since the earth's surface and the sea surface have prominent polarization properties in the microwave band, a serious uncertainty arises in interpreting the microwave images. This problem was solved by developing and introducing a new type of scanning, namely, conical-type scanning, where all elements of the surface under investigation are observed at a strictly fixed viewing angle. Then the multifrequency (five frequencies), two-polarization (vertical and horizontal) panoramic SMMR instruments set was developed and launched in 1978 on two spacecraft simultaneously – Nimbus-7 and Seasat (Njoku *et al.*, 1980). Whereas the Seasat spacecraft has operated for three months only, Nimbus-7 has successfully functioned for nine years (up to 1988). According to the radiothermal SMMR system data, a set of interesting results was obtained on studying the state of the World Ocean surface, on the state of snow and glacial

Table 14.1. History of microwave radiometry in space.

Year of launch	Spacecraft	Instrument acronym	Frequencies (GHz)	Sensitivity (response time, s)	Swath width of scan (km)	Antenna type	Angle and spatial resolution	Principal parameters measured or inferred
1962	Mariner-2 (Venus fly by)	—	15.8 22.2	2 (1 s)	Planetary	Mechanically scanned parabola; diameter 50 cm	1300 km	Limb darkening; temperature; H_2O vapour
1968 1970	Cosmos-243 Cosmos-384	—	3.5 8.7 22.2 37	0.7 (1 s) 0.7 (1 s) 2.0 (1 s) 2.0 (1 s)	Nadir viewing	Parabolic horn Lens-loaded horn	8.6° 3.5° 3.5° 3.5° (15–50 km)	H_2O vapour and liquid; sea ice concentration; sea temperature
1972	Nimbus-5	ESMR	19.35	1.5 (0.05 s)	3000	Electronically scanned phase array; ±50° scan	1.4° (29 km)	Rain and H_2O vapour maps; firn and ice concentration and classification
		NEMS	22.35 31.40 53.65 54.90 58.80	0.3 (2 s) 0.4 (2 s) 1.2 (2 s) 0.6 (2 s) 0.7 (2 s)	Nadir viewing	Five lens-loaded horns	185 km	Temperature profile; H_2O vapour and liquid; firn and ice classification and snow cover
1973	Skylab	S-193	13.9		180	Mechanically scanned parabola; diametre 117 cm	2.8° (16 km)	Soil moisture
		S-194	1.41	0.5 (1 s)	Nadir viewing	Phase array	15° (115 km)	Soil moisture
1974	Meteor	—	37		Dual polarization 35° from nadir		40 × 60 km	H_2O precipitation and vapour

1975	Nimbus-6	ESMR	37	1.0 (1 s)	1300	Dial polarization electronically scanned array	0.7 × 0.95° (20 × 43 km)	Same as Nimbus-5 ESMR
		SCAMS	22.2 31.6 52.8 53.8 55.4		2700	Three rotating hyperbolic mirrors	150 km	Same as Nimbus-5 NEMS
1978 1979	TirosN, NOAA-5 NOAA-6	MSU	50.3 53.7 55.0 57.9		2300	Dual rotating mirrors	110 km	Temperature profile maps
1978 (1988)	Nimbus-7	SMMR	6.6 10.69 18.0 21.0 37.0	0.7 (0.1 s) 0.8 (0.06 s) 0.9 (0.06 s) 1.0 (0.06 s) 1.4 (0.06 s)	800 Incidence angle 50.3°	Conical scan single oscillating mirror; dial polarization; diameter 0.79 m	95 × 148 km 70 × 109 km 43 × 68 km 36 × 56 km 18 × 27 km	Same as ESMR; sea state (wind speed), sea temperature, snow cover; soil moisture
1978	Seasat	SMMR	6.6 10.7 18.0 21.0 37.0	0.9 (0.1 s) 0.9 (0.06 s) 1.2 (0.06 s) 1.5 (0.06 s) 1.5 (0.03 s)	600 Incidence angle 48.8°	Conical scan single oscillating mirror; dial polarization; diameter 0.79 m	4.2° 2.6° 1.6° 1.4° 0.8°	Same as SMMR Nimbus-7
1979	Salyut-6	KRT-10	2.5 (12 cm) 0.42 (72 cm)			Single parabolic mirror; diameter 10 m		Thermal maps of soil and sea surface

covers, on humidity conditions among others. Doubtless, the successful operation of the radiothermal SMMR instruments has marked by itself the termination of the primary stage (1968–1978) and the beginning of the contemporary stage of microwave space-based sensing in the centimetre and millimetre bands.

However, attempts to advance into the decimetre (and even into the metre) band with acceptable spatial resolution are continuing. So, the deployable KRT-10 space radiotelescope with an antenna mirror diametre of 10 m was successfully launched and operated at wavelengths of 72 and 12 cm on the Russian ‘Salyut-6’ manned space station in 1979 (Danilov *et al.*, 1979). This achievement gave, at the end of the 1970s, Russian and Western specialists a reason to hope for a rapid realization of ambitious projects on building giant radio-antennas with a mirror diametre of 100 m to 10 km (!) (Bujakos *et al.*, 1978; Card *et al.*, 1978; Blume *et al.*, 1978). These instruments should be designed for radio astronomy and microwave radio sensing applications. These hopes could not be realized, however. And only in the most recent times have similar projects became the subject of active discussion in the literature (Wilson *et al.*, 2000); and the ‘Radioastron’ project (Kardashiov, 2000) is at the stage of industrial implementation now.

14.2 ONGOING MISSIONS AND TENDENCIES OF THEIR DEVELOPMENT

Below we shall briefly outline a series of ongoing space missions studying and monitoring geophysical and meteorological systems of the earth. A key element of each mission is the inclusion of passive microwave instruments as a major integral part of the space observational system.

14.2.1 DMSP mission

The Defense Meteorological Satellite Program (DMSP) is a Department of Defense (DoD) program (Asrar and Dokken, 1993). The DMSP program was developed in an effort to study oceanographic, and solar–terrestrial physics environments. DMSP satellites are in a near-polar orbiting, Sun-synchronous orbit at an altitude of approximately 830 km above the earth. Each satellite crosses any point on the earth twice a day and has an orbital period of about 101 minutes thus providing complete global coverage of clouds every six hours. Earth DMSP satellite monitors the atmospheric, oceanographic and solar–geophysical environment of the earth. Visible and infrared sensors collect images of global cloud distribution across a 3,000 km swath during both daytime and night-time conditions. The coverage of the microwave imagery and sounders are one-half the visible and infrared sensors coverage; thus they cover the polar regions above 60° on a twice-daily basis but the equatorial region on a daily basis. The space environmental sensors record along track plasma densities, velocities, composition and drifts. Visible and infrared imagery from DMSP Operational Linescan System (OLS) instruments are used to monitor the global distribution of clouds and resolution, global coverage, and high resolution, regional coverage, imagery recorded along a 3,000 km scan, satellite ephemeris and solar and lunar data. IR pixel values vary from 190 to 310 kelvins in 256 equally spaced steps. Onboard calibration is performed during each scan. Visible pixels are currently relative values ranging from 0 to 63 rather than absolute values in watts per square metre. Instrumental gain levels are adjusted to maintain constant cloud reference values under varying conditions of solar and lunar illumination. Telescope pixel values are replaced by photomultiplier tube (PMT) values at night. A telescope pixel is 0.55 km at high resolution and 2.7 km at low resolution. Low-resolution values are the mean of the appropriate 25 high-resolution values. A PMT pixel is 2.7 km at nadir. In addition to cloud images, ground-based sources, such as fires, and upper atmospheric sources, like the Northern Lights, night-time imagery records the aurora, city lights, manmade and natural fires and natural gas flaring. The TC images are the most prominent examples of the efficiency of the optical and IR OLS system.

The main element of the DMSP observing system is passive microwave instrumetation. The Special Sensor Microwave/Imager (SSM/I) aboard the Defense Meteorological Satellite Program (DMSP) spacecraft is a seven-channel, four-frequency, linearly polarized, passive microwave radiometric system which measures atmospheric, ocean and terrain microwave brightness temperatures at 19.35, 22.235, 37.0 and 85.5 GHz (Table 14.2). The data are used to obtain synoptic maps of critical atmospheric, oceanographic and selected land parameters on a global scale. SSM/I data are used to derive geophysical parameters; notably,

Table 14.2. SSM/I characteristics (DMSP mission).

Observation frequency (GHz)	19.35	22.235	37.0	85.5
Polarization (V/H)	V, H	V	V, H	V, H
Sensitivity (K)	0.5	0.7	0.4	0.8
Bandwidth (MHz)	250	250	1000	1500
Antenna beam width (degrees)	1.87	1.65	1.1	0.45
Spatial resolution along and across scan (km)	69 × 43	60 × 40	37 × 29	15 × 13
Scan period (s)	1.9			
Antenna offset angle (degrees)	51.2			
Earth-inclination angle (degrees)	53			
Swath width (km)	1400			
Mass (kg)	48.5			
Power (W)	45			

ocean surface wind speed, area covered by ice, age of ice, ice edge, precipitation over land, cloud liquid water, integrated water vapour, precipitation over water, soil moisture, land surface temperature, and snow cover.

The Special Sensor Microwave/Temperature (SSM/T-2) sensor is a five-channel, total power microwave radiometre, three channels situated symmetrically about the 183.31 GHz water vapour resonance line and window channels. This instrument was flown on all DMSP Block 5D-2 satellites starting with F11 launched in 1991. SSM/T-2 is designed to provide global monitoring of the concentration of water vapour in the atmosphere under all sky conditions by taking advantage of the reduced sensitivity of the microwave region to cloud attenuation.

This exciting and developing technology appears to be the logical synergistic consolidation of the imager and sounder type of instrument as SSMIS instruments onboard the DMSP F16 satellite and instruments being developed – the Conical Scanning Microwave/Sounder (CMIS) (Flaming, 2000).

14.2.2 TRMM

The Tropical Rainfall Measuring Mission (TRMM) (Simpson *et al.*, 1988; Kummerow *et al.*, 1998, 2000) is a joint space mission between Japan and the United States, with the cooperation of several other nations (TRMM Office, 1990). As originally planned, TRMM is a synergistic complement of three instruments – active and passive microwave and optics sensors. A key feature is the first rain radar to be flown in space. The other instruments are a multichannel, dual polarized, passive microwave radiometre and a high-resolution visible/infrared radiometre.

TRMM can be regarded as a 'flying rain gauge' because the improved measurement capability of the microwave instruments can be used to calibrate techniques based on infrared brightness temperatures. The calibrations are likely to be different in different climate regimes. After calibration, the improved IR techniques can be applied to fill in between TRMM swathes using geosynchronous data, and to upgrade many of the past rain estimations which used the proxy variable approach. A basic TRMM data product will be mean monthly rainfalls over areas 50 by 50 km for climate studies. The orbit has been selected to optimize the effectiveness of the instruments. The low 350-km altitude obtains good resolution for the instruments (the 19-GHz channel of the passive microwave instrument will have a resolution of about 10 km). The orbit inclination of 350° ensures overflights at different local times every day, covering the entire 24 hours in a month, permitting documentation of the diurnal variability of tropical rain. More extensive discussion of the TRMM motivation, design and scientific results are provided in the Report of the Science Steering Group (Simpson, 1988), and in annual publications of the TRMM Office (TRMM Office, 1994) and in publications (Simpson *et al.*, 2000).

The Precipitation Radar (PR) onboard TRMM is the first spaceborne rain radar. Major objectives of PR are: (1) to provide three-dimensional rainfall structure, (2) to achive quantitative rainfall measurement over land as well as the

Table 14.3. TMI characteristics (TRMM).

Observation frequency	10.7, 19.4, 21.3, 37 and 85.5 GHz
Polarization	vertical/horizontal (21.3 GHz channel: horizontal only)
Horizontal resolution	6–50 km
Swath width	about 760 km
Scan mode	conical scan (49 degrees)
Data rate	8.8 kbps
Weight	65 kg
Power consumption	50 W

ocean; and (3) to improve the accuracy of TMI measurements by providing rain structure information.

The TRMM Microwave Imager (TMI) is a multi-channel/dual-polarized microwave radiometre which provides data related to rainfall rates over the ocean (Table 14.3). The TMI data together with PR data is the primary data set of precipitation measurements.

The Visible Infrared Scanner (VIRS) is a passive cross-track scanning radiometre which measures scene radiance in five spectral bands operating in the visible through the infrared spectral regions. The VIRS data provide information about convective cloud fields (cloud type, convective conditions).

The Cloud and the Earth's Radiant Energy System (CERES) is a passive broadband scanning radiometre which has three spectral bands in the visible through the infrared spectral regions and measures the earth's radiation budget and atmospheric radiation from the top of the atmosphere to the surface of the earth.

The Light Imaging Sensor (LIS) is an optical telescope and filter imaging system which will acquire and investigate the distribution and variability of both intracloud and cloud-to-ground lightning over the earth. The LIS data will also be used with PR, TMI and VIRS data to investigate the correlation of the global incidence of electrical activity with rainfall and other storm properties (including tropical cyclones).

14.2.3 Aqua mission

Earth Observing System PM1 (Aqua) was developed by NASA to investigate the mechanism of the earth's environment systems, such as atmosphere, cloud, snow ice, water and vegetation. The development and operation of Aqua are conducted as an international project. Aqua satellite was launched into orbit on May 4 2002. Orbit

Table 14.4. AMSR-E characteristics (Aqua mission).

Frequency (GHz)	6.9	10.7	18.7	23.8	36.5	89.0
Bandwidth (MHz)	350	100	200	400	1000	3000
Sensitivity (K)	0.3	0.6	0.6	0.6	0.6	1.1
IFOV (km)	75 × 43	48 × 27	27 × 16	31 × 18	17 × 8	6 × 4
Sample spacing (km)	10	10	10	10	10	5
Integration time (ms)	2.6	2.6	2.6	2.6	2.6	1.3
Beam efficiency (%)	95.3	95.0	96.3	96.4	95.3	96.0
Antenna diametre (m)	1.6					
Scan period (s)	1.5					
Antenna offset angle (degrees)	47.4					
Earth-inclination angle (degrees)	54.8					
Orbit type	Sun-synch., 98.2° incl., 705 km alt., 1:30 pm equator crossing					
Swath width (km)	1445					

parameters are the following: Sun-synchronous orbit at an altitude of 705 km; inclination is 98.2°; and period is 100 minutes.

Aqua carries five sensors: Advanced Microwave Scanning Radiometre (AMSR-E) developed by NASDA; atmospheric microwave sounder Humidity Sounder for Brazil (HSB) developed by INPE, Brazil, as well as NASA's Atmospheric Infrared Sounder (AIRS); Advanced Microwave Sounding Unit (AMSU); Clouds and the Earth's Radiant Energy System (CERES); and Moderate Resolution Imaging Spectroradiometre (MODIS).

AMSR-E instruments (Table 14.4) were modified for Aqua from the design used for AMSR, which was onboard ADEOS-2 at a later time. AMSR-E and AMSR are microwave sensors capable of accurately acquiring weak radiation from land surface and atmosphere with its wide frequency bands and obtaining the necessary data for the study of earth hydrologic circulation. Microwave sensors, unlike optical sensors, can continuously observe night and day, regardless of weather. Allocating AMSR on a morning orbit and AMSR-E on an afternoon orbit allows observation of everyday changes of the earth's environment, and it is expected to contribute to the study of the earth's environmental system (Shibata, 2000; Njoku *et al.*, 2000a; Koike *et al.*, 2000).

The EOS Aqua AMSR will measure geophysical parameters supporting several global change science and monitoring efforts. Of particular importance to its success is an external calibration design, which has proved suitable in other satellite microwave instrumentation for long-term monitoring of subtle changes in temperature and other variables.

The science objectives of AMSR-E are the following:

- Precipitation: Precipitation has extremely important roles, through provision of water to the biosphere and as an air-conditioning agent that removes excess heat from the surface (through evapouration) and makes earth habitable. The AMSR will measure rain rates over both land and ocean. Over the ocean, the AMSR microwave frequencies can probe through smaller cloud particles to measure the microwave emission from the larger raindrops. The AMSR will provide sensitivity to oceanic rain rates as high as 50 mm/hour. Over land, the AMSR can measure the scattering effects of large ice particles which later melt to form raindrops. These measurements, though less direct as a measure of rainfall intensity, are converted to a rain rate with the help of cloud models.
- Sea surface temperature: Over the ocean, AMSR will provide sea surface temperatures (SST) through most types of cloud cover, supplementing infrared-based measurements of SST that are restricted to cloud-free areas. SST fluctuations are known to have a profound impact on weather patterns across the globe, and the AMSR's all-weather capability could provide a significant improvement in our ability to monitor SSTs and the processes controlling them.
- Total integrated water vapour: The total integrated water vapour of the atmosphere will be measured over the ocean, which is important for the understanding of how water is cycled through the atmosphere. Since water vapour is the Earth's primary greenhouse gas, and it contributes the most to future projections of global warming, it is critical to understand how it varies naturally in the earth's system.
- Wind speed: Ocean surface roughness is also measured by AMSR, which will be converted into a near-surface wind speed. These winds are one important component of how much water is evapourated from the surface of the ocean. The winds help to maintain the water vapour content of the atmosphere while precipitation continually removes it.
- Cloud liquid water: AMSR cloud water estimates over the ocean will help studies of whether clouds, and their ability to reflect sunlight, increase or decrease under various conditions. This could be an important feedback mechanism that either enhances or mitigates global warming, depending on whether clouds increase or decrease with warming.
- Sea ice: Monitoring of sea ice parameters, such as ice type and extent, is necessary to understand how this frozen blanket over the ocean acts to change climate through its ability to insulate the water against heat loss to the frigid atmosphere above it, and through its ability to reflect sunlight that would otherwise warm the ocean.
- Snow cover: In much the same way as the AMSR can see large ice particles in the upper reaches of rain systems, it also measures the scattering effects of snow cover. These measurements are empirically related to snow cover depth and

water content based upon field measurements. Like sea ice, snow cover has a large influence on how much sunlight is reflected from the earth. It also acts as a blanket, keeping heat from escaping from the underlying soil, and allowing deep cold air masses to develop during the winter. It further provides an important storage mechanism for water during the winter months, which then affects how much surface wetness is available for vegetation and crops in the spring. AMSR monitoring of snow cover will allow studies and monitoring of how snow cover variations interplay with other climate fluctuations.

- Soil moisture: Wet soil can be identified in the AMSR observations if not too much vegetation is present. The AMSR will provide the most useful satellite data yet for determination of how well low-frequency (6.9 GHz) microwave observations can be used to monitor surface wetness. Surface wetness is important for maintaining crop and vegetation health, and its monitoring on a global basis will allow drought-prone areas to be monitored for signs of drought.

The Advanced Microwave Sounding Unit (AMSU-A) is a 15-channel microwave sounder designed primarily to obtain temperature profiles in the upper atmosphere (especially the stratosphere) and to provide a cloud-filtering capability for tropospheric temperature observations. The first AMSU was launched in May 1998 on board the National Oceanic and Atmospheric Administration's (NOAA's) NOAA-15 satellite. The EOS AMSU-A will be part of a closely coupled triplet of instruments that include the AIRS and HSB. A passive multichannel microwave radiometer obtained 15-channel microwave sounder with a frequency range of 15–90 GHz provides atmospheric temperature measurements from the surface up to 40 km. AMSU instrument characteristics are the following: instrument instantaneous field of view is 3.3°; linear scan field of view is ±49.5°; swath width is 1650 km; spatial resolution at nadir is 40 km. The AMSU instrument measures air temperatures at five levels in the atmosphere.

14.2.4 ADEOS-II mission

Advanced Earth Observing Satellite-II (ADEOS-II), also known as Midori-2, is a Japanese (NASDA) remote sensing spacecraft launched December 14 2002 ($H = 805\,\mathrm{km}$, $\theta = 98,69^\circ$, $T = 100.99\,\mathrm{min}$). The 3.7-tonne (with fuel), 5-kW spacecraft carries five instruments to monitor global climate trends (Kondratyev and Tanaka, 1997; Shibata, 2000). One, the Advanced Microwave Scanning Radiometre (AMSR) monitors water vapour, precipitation, sea surface temperature, wind and ice by means of the microwave emission emanating from the earth's surface and atmosphere (see above). It is a radiometre that operates in eight frequency bands covering 6.9 to 69 GHz and monitors the horizontal and vertical polarizations separately. With a dish of 2-m aperture, the spatial resolution is 5 km in the 89 GHz band degrading to 60 km at 6.9 GHz (Table 14.5) (Shibata, 2000). The Global Imager (GLI) is an optical sensor to observe solar radiation reflected from the earth's surface and to map vegetation, clouds, etc. The data are acquired in 23 visible/

Table 14.5. AMSR Characteristics (ADEOS-II mission).

Frequency (GHz)	6.9	10.65	18.7	23.8	36.5	89.0	50.3	52.8
Spatial resolution (km)	50		25		15	5	10	
Bandwidth (MHz)	350	100	200	400	1000	3000	200	400
Polarization	horizontal and vertical						vertical	
Incident angle (degrees)	about 55							
Cross polarization (dB)	under -20							
Swath width (km)	1600							
Dynamic range(K)	2.7–340							
Absolute accuracy (K)	1 (1σ)							
ΔT (K)	0.3–1.0 (1σ)						2 (1σ)	
Quantization (bit)	12	10						

near-infrared and 13 far-infrared channels. Scanning is accomplished by a rotating mirror covering 12 km along track and 1600 km a cross track at a resolution of 1.0 km. SeaWinds is a scatterometre that provides wind speed and direction by observing the microwave backscattering from ocean surfaces. With its 1.0-m dish, it scans the surface along conical surfaces at 18 rpm. It provides speed at an accuracy of 2 m/s, wind direction at an accuracy of 20°, both with a spatial resolution of 5 km. ILAS-2 (Improved Limb Atmospheric Spectrometre 2) maps the vertical distribution of O_3, NO_2, HNO_3, H_2O, CFC-11, CFC-12, CH_4, N_2O and $ClONO_2$, as well as the distribution of temperature and pressure, all in the stratosphere. It observes the absorption spectrum in the earth's atmospheric limb in the 3–13 µm wavelength band, and in the 753–784 nm band of the occulting Sun. The altitude resolution is 100 m. POLDER (POLarization and Directionality of Earth's Reflectances) measures the polarization, and spectral characteristics of the solar light reflected by aerosols, clouds, oceans and land surfaces. Eight narrowband wavelengths (443, 490, 564, 670, 763, 765, 865 and 910 nm) are covered by the instrument which facilitates identification of the physical and optical properties of the aerosols and their role in radiation budget.

NASDA will use Global Change Observation Mission (GCOM) to contribute process study and prediction of global change phenomena and preservation of global environments for 15 years with ADEOS-II (Sobue *et al.*, 2000; Shimoda, 2000). There are three main goals of GCOM: (1) understanding the material energy cycle, and documenting and predicting global warming, (2) understanding atmosphere–ocean interaction, radiative forcing and documenting and predicting medium-to long-term climate changes, and (3) understanding ozone and the GHG circulation mechanism, and documenting and predicting ozone layer and atmospheric composition variabilities. The GCOM will consist of the GCOM-A satellite series, the GCOM-B satellite series and ground infrastructures. The GCOM-AI satellites will measure the ozone layer and greenhouse gases while the GCOM-BI satellites will observe the material and energy cycles. The main GCOM-BI instrument will be AMSR Follow On.

14.3 FUTURE PASSIVE MICROWAVE SPACE MISSIONS

In this section we shall briefly outline a series of potential space missions on studying and monitoring geophysical and meteorological systems of the earth. Each of them is at a completely different preparation stage – from a flight model ready for launching up to the engineering design stage. Each of these missions is directed at the solution of various geophysical and hydrometeorological problems; but, here, a key element of each mission is the inclusion of passive microwave instruments as a major integral part of a space observational system.

14.3.1 MTVZA-OK mission

The present mission is the combined optical–microwave imager/sounder MTVZA-OK (Russia) of spacecraft 'Sich-1M' (Russia/Ukraine), which will be launched in 2003 on Sun-synchronous orbit at an altitude of 650 km (Cherny and Chernyavsky, 2001).

MTVZA-OK will be used as the meteorological imaging/sounding system for the remote sensing of the ocean and the land surface, as well as for measuring global atmospheric temperature and water vapour profiles. The instrument is the next version of the microwave imager/sounder MTVZA deployed on spacecraft 'Meteor-3M' (Cherny and Raizer, 1998).

MTVZA-OK combines both optical and microwave systems deployed on a single scanning platform. Field of view (FOV) is common for optical and microwave imaging and sounding channels. MTVZA-OK microwave performance characteristics are given in Table 14.6. The microwave radiometre MTVZA-OK is based on the technology of combining in space and time multifrequency and polarization measurements. MTVZA-OK operating frequencies are located both in the transparent windows of atmosphere, 6.9, 10.6, 18.7, 23.8, 31, 36.5, 42, 48, 89 GHz, and in absorbing lines of oxygen 52–57 GHz and water vapour 183.31 GHz. In addition, the MTVZA-OK includes some complementary non-typical operating frequencies especially for oceanographic research. The instrument will provide measurements of atmosphere temperature profile to approximately 42 km and water vapour profile to 6 km.

All microwave radiometre channels are switched to single feed-horn antenna. The antenna system consists of an offset parabolic reflector of dimension 60 cm, illuminated by broadband feed-horn antenna. To retain the invariant viewing

Table 14.6. MTVZA-OK microwave frequency channel characteristics.

Channel no.	Centre frequency (GHz)	No. of pass-bands	Band-width (MHz)	Effective FOV (km × km)	Imagery pixel (km × km)	Sensitivity (K/pixel)	Approximate peak sensitivity altitude (km)
1	6.9	1	350	112 × 260	24 × 24	0.3	—
2	10.6	1	100	76 × 177	24 × 24	0.5	—
3	18.7	1	200	45 × 104	24 × 24	0.4	—
4	23.8	1	400	36 × 86	24 × 24	0.3	—
5	31	1	1000	30 × 69	24 × 24	0.3	—
6	36.5	1	1000	26 × 60	24 × 24	0.3	—
7	42	1	1000	22 × 53	24 × 24	0.4	—
8	48	1	1000	21 × 47	24 × 24	0.4	—
9	52.28	1	400	18 × 43	36 × 36	0.4	2
10	52.85	1	400	18 × 43	36 × 36	0.4	4
11	53.33	1	400	18 × 43	36 × 36	0.4	6
12	54.40	1	400	18 × 43	36 × 36	0.4	10
13	55.45	1	400	18 × 43	36 × 36	0.4	14
14	57.290344 ± 0.3222	4	50	18 × 43	48 × 48	0.4	20
15	57.290344 ± 0.3222	4	20	18 × 43	48 × 48	0.7	25
16	57.290344 ± 0.3222	4	10	18 × 43	48 × 48	0.9	29
17	57.290344 ± 0.3222	4	5	18 × 43	48 × 48	1.3	35
18	57.290344 ± 0.3222	4	3	18 × 43	48 × 48	1.7	42
19	89	1	4000	12 × 28	12 × 12	0.6	surface
20	183.31 ± 7.0	2	1500	7 × 16	24 × 24	0.5	1.5
21	183.31 ± 3.0	2	1000	7 × 16	24 × 24	0.6	2.9
22	183.31 ± 1.0	2	500	7 × 16	24 × 24	0.8	5.3

Channels 1–8, and 19 operate on both vertical and horizontal polarization, while other remaining channels operate on vertical polarization only.

angle and polarization in the scanning sector, the reflector and feed-horn antenna are mounted on a scanning platform containing the radiometres, digital data subsystem, power and signal transfer assembly, which rotates continuously about an axis parallel to the local spacecraft vertical.

The MTVZA-OK scanning platform rotates continuously about an axis parallel to the local spacecraft vertical with a period of 1.8 s during which the subsatellite point travels 12 km. The scan direction is from the right to the left when looking in the forward direction of the spacecraft, with an active scanning sector of 120°, resulting in a swath width of 2000 km. The viewing angle is 55.4° and the incidence angle with respect to the earth's surface is 65°. The sampling rate is 12×12 km for all microwave channels.

Russian specialists hope (Cherny and Chernyavsky, 2001; Grankov *et al.*, 2000) that MTVZA-OK will provide some very interesting and powerful capabilities for complementary studies of the ocean–atmosphere system. By combining optical and microwave observations in the same instrument, some mutually beneficial advantages for determining geophysical parameters are obtained. Both atmospheric temperature profile and atmospheric humidity profile, sea surface temperature and near-surface wind speed, ocean colour and processes of the active ocean layer will be observed concurrently, enabling flow visualization and upwelling area to be better observed as well as estimates of the ocean–atmosphere interaction.

14.3.2 CLOUDS mission

The cloud and radiation monitoring satellite (CLOUDS) is a project co-funded by the EC, conducted by 12 European partners (7 scientific institutes and 5 industrial companies), also cooperating with NOAA/ETL (Bruzzi, 1995; Bizzari and Spera, 2000; Bizzari *et al.*, 2000). It is the mission study of a monitoring satellite to perform measurements necessary to describe cloud–radiation interaction in operational models for climate and long-term weather prediction (Arkin and Xie, 1994; Asrar and Dokken, 1993; Houze, 1993; IPCC, 2001). Complementary to missions for process study, CLOUDS addresses the monitoring aspect. Therefore it has to comply with requirements of sufficiently frequent observing cycle, and operational sustainability. This prevents using active systems (radar and lidar) and leads to considering passive radiometry only, but exploiting as much as possible of the electromagnetic spectrum, with more polarizations and more viewing geometries. The objective of the CLOUDS project was to study the mission of a new satellite to provide accurate, comprehensive, consistent and frequent information on cloud structures and on the associated radiative parameters. The information would be used by meteorological services and research centres to improve weather forecasting and climate modelling.

CLOUDS is proposed as a monitoring mission. Its strategic objective is to extend the overall European service of climate monitoring from space, beyond what is achievable by the instrumentation at present foreseen for MSG and METOP/EPS, whose mission definition has been driven by nowcasting and short–medium-term weather prediction.

User requirements were established, specifying a list of geophysical parameters to be measured in the areas of:

- the 'classical' cloud parameters, mostly referring to the top surface, with emphasis on ice/liquid discrimination and size;

- the cloud interior, specifically water phase (ice or liquid) and whether drop-size is likely to produce precipitation;
- the outgoing radiation from the top of atmosphere to space;
- the main parameter impacting with both clouds and radiation in the 3-D atmosphere, i.e. aerosols;
- the primary source of clouds, i.e. water vapour, also primary factor of radiative processes in the 3-D atmosphere;
- the indicator of final removal of water from the atmosphere, i.e. precipitation.

The mission requirements established for CLOUDS were strongly conditioned by the monitoring objective, which implies compliance with long-term sustainability requirements, and the requirement for an observing cycle consistent with routine use.

The key aspect of the CLOUDS mission is the exploitation of the widest range of the electromagnetic field to collect as many ‘signatures’ as possible of the different parameters to be measured. The spectral range utilized spans from 340 nm to 4.3 cm, i.e. over five orders of magnitude. Six instruments are described, operating, respectively, in narrow channels of the UV/VIS/NIR/SWIR, the TIR/FIR, the sub-millimetre waves and the MW, in broadband channels from UV to FIR, and in a relatively large-band channel of VIS/NIR. Several channels have three or four polarizations, all take images fore and aft (conical scanning), one has multi-angle-viewing capability. The overall system size is estimated as 900 kg mass, 1600 W power, 1.1 Mbps data rate for real-time S-band transmission, and 30 Mbps data rate for global data recovery in X-band.

An important instrument requirement to note is that all channels in CLOUDS must have consistent scanning mechanism, so as to ensure compatible viewing geometry and make possible accurate co-registration, for a true multi-spectral approach, as necessary when dealing with fractal fields. Since most channels require differential polarization, conical scanning is most suitable.

The CLOUDS mission is implemented by six instruments:

- the CLOUDS Integrated Optical Payload (CIOP), composed of four instruments:
  —the Clouds and Aerosol Short-wave Imaging Radiometre (CASIR);
  —the CLOUDS Infra Red Imaging Radiometre (CIRIR);
  —the Broad-band Earth Radiation Imaging Radiometre (BERIR);
  —the Multi-Angle VIS Imaging Radiometre (MAVIR);
- the MW/sub-millimetre instruments:
  —the Cloud Ice and Water-vapour Sub-mm Imaging Radiometre (CIWSIR);
  —the Cloud Liquid-water And Precipitation Microwave Imaging Radiometre (CLAPMIR).

The two instruments covering the MW/sub-millimetre range perform conical scanning with the same speed of 1 scan per 2 s. The viewing geometry is the same as for the optical payload (45° off-nadir observing the scene under the zenith angle 53.2°, with two arcs of over ±45° fore and aft for a swath of nearly 1400 km).

The CIWSIR instrument includes channels in the sub-millimetre and very-high frequency MW range. Their main purposes are:

- to observe cloud ice with higher penetration in the cloud interior as compared with what is possible in the shortwave and in IR;
- to discriminate water phase in the cloud interior;
- to infer convective penetration in the troposphere through differential water vapour optical depth.

CIWSIR is a 6-frequency, 13-channel microwave radiometre—7 channels in the millimetre- (water vapour) and 6 channels in the sub-millimetre-range (ice clouds).

To be synergistic with the optical package and with CLAPMIR, the same viewing geometry is adopted. The main instrument features of CIWSIR, and its expected performances compared with requirements, are reported in Table 14.7.

The CLAPMIR instrument includes microwave channels in window and absorption bands. The main purposes are:

- to observe cloud liquid water, precipitating and non-precipitating, with inference of drop size;
- to discriminate water phase in the cloud interior and total-column water vapour;
- to infer a gross vertical profile of liquid/precipitating water cores as linked to air temperature.

Additional observations, outside the CLOUDS objectives, are: earth surface parameters such as sea-surface wind, sea-surface temperature, sea-ice cover and type, ice/snow cover and melting conditions, and soil moisture.

The CLAPMIR instrument will consist of an offset parabolic reflector of 1.6×1.4 m dimensions, illuminated by a cluster of feeds. The reflector and feed horn antennas are mounted on a ‘drum’ which contains the receivers, a digital data unit, mechanical balancing subsystem and power supply. The entire drum assembly is rotated about the axis of the instrument by a coaxially mounted bearing and brushless DC motor. The polarimetric channels are designed to provide the third Stokes parameter by means of adding analogue correlators. To be synergistic with the optical package and with CIWSIR, the same viewing geometry is adopted. The main instrument features of CLAPMIR, and its expected performances compared with requirements, are reported in Table 14.8.

14.3.3 MEGHA-TROPIQUES mission

Supported by the French and Indian scientific communities, the MEGHA-TROPIQUES mission aims at studying the water cycle and energy exchanges in the tropical belt (Desbois, 1995, 1999; Aguttes *et al.*, 2000; Eymard, 1999; Narayanan, 1999). It will be jointly developed by the Indian Space Research Organization (ISRO) and the French Space Agency (CNES). The small satellite (<600 kg) could be launched as early as 2005 by an Indian launcher in a low inclination (22°) orbit. Longwave and shortwave outgoing fluxes from the top of

Table 14.7. Instrument features and expected performances of CIWSIR (CLOUDS mission).

IFOV	0.35° corresponding to ellipse of 13×7.8 km, equivalent to 10 km circular
Scanning	Conical, $\alpha = 45°$, $\zeta = 53.2°$, fore- and aft-views by $>\pm 45°$ in azimuth, swath ~1400 km
Sampling	1 scan/2 s, 1 feed/channel, readings at 1.25 ms intervals
Antenna	$L = 40$ cm for channels 150 to 220 GHz, $L = 16$ cm for channels 463 to 874 GHz
Detection	Subharmonic Schottky-mixers for millimetre-channels, fundamentally pumped mixers for sub-millimetre channels
Resources	Mass: 79 kg, volume (cylindrical): diameter = 110 cm, $h = 43$ cm; power: 110 W; data rate 83.2 kbps

Channel centre (GHz)	Bandwidth (GHz)	Polarization	ΔT (required) (K)	ΔT (estimated) (K)
874.38 ± 6.0	3.0	two	1.0 @ 240	2.0 @ 240
682.95 ± 6.0	3.0	two	1.0 @ 240	1.2 @ 240
462.64 ± 3.0	2.0	two	1.0 @ 240	0.9 @ 240
220.50 ± 3.0	2.0	two	1.0 @ 240	0.9 @ 240
183.31 ± 1.0	1.0	one	1.0 @ 240	1.2 @ 240
183.31 ± 3.0	2.0	one	1.0 @ 260	0.9 @ 260
183.31 ± 7.0	4.0	one	1.0 @ 280	0.6 @ 280
150	4.0	two	1.0 @ 300	0.6 @ 300

the atmosphere will be derived from the ScaRaB radiometre, already developed in France (Desbois, 1999). Measurement of the atmospheric water vapour vertical distribution will be given by SAPHIR, a new microwave sounder around strong water line 183 GHz and MADRAS, the main and biggest instrument, will scrutinize cloud and precipitation properties. It is a conical scanning radiometre with six channels (10, 18, 23, 36, 89, and 157 GHz) and a resolution ranging from 60 km (10 GHz) to 6 km (157 GHz).

The main objective of the MEGHA-TROPIQUES mission is to study the convective systems that influence the tropical weather and climate. The tropical region is the domain of monsoons, squall lines and tropical cyclones. It is also characterized by large intra-seasonal, inter-seasonal and inter-annual variations, which may lead to catastrophic events such as droughts or floods. Any change in the energy and

Table 14.8. Instrument features and expected performances of CLAPMIR (CLOUDS mission).

IFOV	At 89 GHz: 0.175° corresponding to ellipse of 6.5×3.9 km, equivalent to 5 km circular. Bands 118 and 55 GHz: 0.35° corresponding to ellipse of 13×7.8 km, equivalent to 10 km circular. At other channels: changing with frequency according to the diffraction limits
Scanning	Conical, $\alpha = 45°$, $\zeta = 53.2°$, fore- and aft-views by >±45° in azimuth, swath ~1400 km
Sampling	1 scan / 2 s
Antenna	$L = 160$ cm
Resources	Mass: 160 kg, volume (stowed): cylindrical diameter = 90 cm, $h = 180$ cm; power: 170 W; data rate 208 kbps

Channel centre (GHz)	Band-width (GHz)	Along-track IOFV (km)	Along-scan IOFV (km)	Average IFOV (km)	Samples/ scan	Integration time (ms)	Polar-ization	ΔT (required) (K)	ΔT (estimated) (K)
118.75 ± 1.0	1.0	13.0	7.8	10	800	2.5	one	0.5 @ 230	1.0 @ 230
118.75 ± 1.5	1.0	13.0	7.8	10	800	2.5	one	0.5 @ 250	1.0 @ 250
118.75 ± 2.0	1.0	13.0	7.8	10	800	2.5	one	0.5 @ 270	1.0 @ 270
118.75 ± 4.0	1.0	13.0	7.8	10	800	2.5	one	0.5 @ 290	1.2 @ 290
89.0	3.0	6.5	3.9	5	1600	1.25	four	1.0 @ 300	1.0 @ 300
55	0.5	13.0	7.8	10	800	2.5	one	0.5 @ 230	1.0 @ 230
54	0.5	13.0	7.8	10	800	2.5	one	0.5 @ 250	1.0 @ 250
53	0.5	13.0	7.8	10	800	2.5	one	0.5 @ 270	1.0 @ 270
50	0.5	13.0	7.8	10	800	2.5	one	0.5 @ 290	1.0 @ 290
36.5	1.0	15.8	9.5	12	800	2.5	four	0.7 @ 300	0.6 @ 300
23.8	0.4	24.3	14.6	19	400	5	two	0.6 @ 250	0.6 @ 250
18.7	0.2	30.1	18.6	24	400	5	four	0.5 @ 300	0.6 @ 300
10.6	0.1	54.6	32.7	42	200	10	four	0.4 @ 300	0.4 @ 300
6.9	0.3	83.8	50.3	65	200	10	two	0.3 @ 300	0.3 @ 300

water budget of the land–ocean–atmosphere system in the tropics has an influence on global climate. The exchanges of energy in the intertropical zone influence the climate of the rest of the planet. These systems interact with the general circulation of the atmosphere in ways which are not fully understood, thus precluding reliable prediction of the events. Interactions with oceanic and continental surfaces have also to be accounted for, as for example the consequences in various regions of the El Niño – La Niña events (Philander, 1990; Raschke and Jacob, 1993; Sadourny *et al.*, 1999; Sharkov, 1998).

Knowledge of the life cycle of tropical convective systems is limited by the lack of information from over the tropical oceans and many areas of tropical continents. Geostationary satellites provide a good space–time sampling of the cloud cover, but no information about water vapour profiles, deep cloud water content, or precipitation. Instruments to retrieve these quantities, based on microwave techniques, exist on polar orbiters, but they do not provide adequate sampling in the tropics (ESA, 1996b; Desbois, 1995, 1999; Gairola, 1999; Roca, 1999). TRMM, which was launched in 1997, is concerned mainly with estimation of tropical rainfall. The instruments used in TRMM are very well adapted to the study of tropical systems, but the low level of the orbit, and its inclination at 35°, do not allow a sampling of the equatorial region. Therefore the follow-up of this experiment calls for better sampling of the whole planet with passive instruments, using a constellation of satellites.

The principle of MEGHA-TROPIQUES is to get a satisfactory sampling of the intertropical band, and specially the latitudes between 10° and 20°, with instruments relevant for the water and energy budget of the tropical convective systems. This implies a low inclination orbit. The instruments have to be complementary to those that exist on geostationary satellites (VIS-IR imagers). Microwave instruments are, then, the right choice.

The basic principles of the MEGHA-TROPIQUES mission are therefore as follows:

- to provide simultaneous measurements of several elements of the atmospheric water cycle: water vapour, clouds, condensed water in clouds, precipitation and evapouration;
- to measure the corresponding radiative budget at the top of the atmosphere;
- to ensure high-temporal sampling in order to characterize the life cycle of the convective systems and to obtain significant statistics.

Given the general objectives and the principle of improved time sampling of the MEGHA-TROPIQUES experiment, the parameters that are specifically required by MEGHA-TROPIQUES are listed below. Different types of quantities are considered, according to the time scale (instantaneous, cumulated or time-averaged) and to the possibility of getting quantitative or qualitative information:

Instantaneous data:

- integrated water vapour: $\sim$5% to 10% $\sim$2 kg/m^2 (outside clouds);
- water vapour by layer (5 to 7 layers): 10% to 20%, (outside clouds);
- temperature, altitude of cloud top: 1 to 2 K, $<$500 m;
- precipitation: $\sim$50% depending on rain, size of precipitating areas, convective/stratiform precipitation, range 0.5 to 50 mm/hour;
- latent heat release: indication on some classes, convective stratiform separation;
- liquid water content: 0.05 to 0.1 kg/m^2;

- cloud ice content: absence/presence, size of anvil clouds, indication on particle size;
- radiation budget terms: $\sim 10\,\mathrm{W/m^2}$;
- sea surface wind: 2 to $5\,\mathrm{m\,s^{-1}}$;
- vertical structure of systems: an indication of the vertical distribution of liquid water and precipitation in several layers (around 5).

SAPHIR is a continuous cross-track scanning. The mission specifications calls for determination with an accuracy of 10% to 20% of the humidity in six layers of the troposphere, over 10 km pixels, from 2 km up to 12 km height. To realize that performance, it is necessary to choose channels for which the atmospheric contribution to the radiance comes from different levels of the troposphere. This can be obtained by sampling an absorption line of water vapour by channels more or less close to the centre of the line. The selected line, already chosen for other instruments, is the strong line at 183.3 GHz. The sensitivity requirement is around 1.5 K.

MADRAS (Microwave Analysis and Detection of Rain And Atmosphere) is a canonical scanning radiometre; the microwave radiation from a scene is collected by antenna beams and then focused via a single dish to different horns. The requirement of two polarizations for most channels, classical in microwave radiometry, implies that the scenes have to be observed over a constant incidence angle. This incidence angle is between 50° and 55° (upper limit for each channel), in order to get the widest swath while keeping a manageable incidence angle.

The requirements for the channels and their respective mission is the following (frequency/resolutions):

10.6 GHz (50 × 80 km);
18.7 GHz (50 × 80 km);
23.8 GHz (40 × 65 km);
36.5 GHz (40 × 65 km);
89 GHz (10 × 16 km);
157 GHz (6 × 9 km).

The polarization is H + V, except for 23.8 GHz which is H or V. Sensitivity requirement is around 1 K for the highest channels (89 GHz and 157 GHz) and 0.5 K for the others. The dish effective (along the beam axis) diametre is 76 cm. The ratio focal/diametre is 0.8. The beam efficiency is 0.95. A single horn will be used for the three channels: 18, 23 and 36 GHz.

MEGHA-TROPIQUES satellite launch is foreseen for late-2005.

14.3.4 NPOESS program

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) is a program currently in development for the purpose of providing global environmental measurements for use by the National Weather Service and other civil agencies, the Department of Defense (DoD), and the scientific research community (Flaming, 2000). NPOESS will replace the Polar-orbiting Operational

Environmental Satellite (POES) constellation currently operated by the National Oceanic and Atmospheric Administration (NOAA) and the DoD's Defense Meteorological Satellite Support Program (DMSP), a constellation of satellites which are also in polar orbit performing operational environmental measurements. International agreements are also pending with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) to incorporate and consolidate portions of that program with NPOESS.

The first NPOESS satellite is projected to be launched in 2008. The program will include replenishment satellites, and will provide measurements for at least a 10-year period.

Five of the NPOESS critical sensors are currently in development. These five are the Ozone Mapping and Profiler Suite (OMPS), the Cross-track Infrared Sounder (CrIS), the Global Positioning System Occultation Sensor (GPSOS), the Visible/Infrared Imager Radiometre Suite (VIIRS) and the Conical Microwave Imager Sounder (CMIS).

The environmental data records (EDRs) measured by CMIS are extensive, and include the following:

- atmospheric vertical moisture profile;
- atmospheric vertical temperature profile;
- sea surface temperature;
- sea surface winds (speed and direction);
- soil moisture;
- precipitable water;
- precipitation (type/rate);
- pressure profile;
- total water content;
- cloud base height;
- cloud ice water path;
- cloud liquid water;
- snow cover/depth;
- fresh water ice;
- ice surface temperature;
- tea ice age and sea ice edge motion;
- surface wind stress;
- land surface temperature;
- vegetation/surface type.

These EDRs will be collected on a global basis approximately every 6 hours when the complete constellation of satellites is in place. These satellites will have nodal crossing times of 0530, 0930, and 1330, and will have CMIS on a satellite in each orbit.

It should be noted that CMIS will incorporate into a conical scan system both a surface measurement and atmospheric sounding capability; earlier instrumentation frequently performed surface measurements with a conical scan system, and employed a cross-track scan system for atmospheric soundings. CMIS represents a

Table 14.9. Microwave sensor comparison.

Mission	SSM/I	TMI	SSMIS	AMSR-E	CMIS
Antenna diametre (m)	0.6	0.6	0.7	1.6	2.5
Number of measurement channels	7	9	24	12	77
Mass (kg)	56	62	96	324	250
Power (W)	45	50	135	350	225
Operational design life (years)	3	3	5	6	7

continuation in the trend of microwave instruments that are more capable, but also more complex. In Table 14.9 some of the physical characteristics of the conical scan sensors mentioned above are compared with CMIS. The analysis of the table has distinctly guided the development of future microwave sensing instruments.

The approaches used by other instruments for satisfying measurement requirements suggest similar design characteristics may be used by CMIS. Soil moisture and sea surface temperature are measured by AMSR with a 6.9-GHz channel; atmospheric vertical temperature profiles are measured by AMSU-A using a series of channels in the 50–60 GHz range. The SSMIS (DMSP F16 satellite) is a instrument in terms of its development, and measures atmospheric water vapour using 150 GHz and 183 GHz channels; similar channels are also being used by AMSU-B to make the same measurements. Although not used in operational instruments constructed to date, the phenomenology suggests that frequencies greater than 183 GHz may have an application, if the appropriate technology can be developed. Thus, the measurements that CMIS must perform may span the frequency range from 6 to 183 GHz, or more, and may employ 77 channels and polarimetry methods for the measurement of vector winds. The physical size of the instrument, the large number of measurement channels required for the 20 EDRs, the sensitivity required for the measurement channels, and the very long operating life (7 years), all suggest the development of an extremely complex instrument.

14.3.5 OSIRIS concept

A concept Ocean-salinity Soil-moisture Integrated Radiometre-radar Imaging System (OSIRIS) has been deeply studied for remote sensing of sea surface salinity from space using a large deployable mesh antenna system (Wilson *et al.*, 2000). The antenna has a 6-m diametre offset-fed parabolic reflector with multichannel feedhorns and radiometres and a radar, operating at L and S bands. The entire system rotates about the nadir axis, providing a conical scan across a 900-km wide swath at a spatial resolution of about 40 km from a 600-km orbit altitude. The study includes evaluation of deployable mesh antennas and preferred antenna, spacecraft, and launch vehicle configurations. The key system characteristics are

Table 14.10. Key baseline system characteristics of OSIRIS concept.

Radiometre frequencies (GHz)	1.41 and 2.69
Radiometre polarization	H, V; (1.41 GHz polarimetric)
Radar frequency (GHz)	1.26
Radar polarization	VV, HH, VH, HV
Antenna type	Offset-fed, parabolic, deployable mesh reflector
Aperture diametre (m)	6
Ocean incidence angle (degrees)	40
Number of feedhorns	2 (each L/S-band, V/H-polarization)
Beam widths (degrees)	2.6° (approx. equal all channels)
Antenna gain (dB)	35
Beam efficiency (%)	>90
Orbit type	Polar, Sun-synchronous, 6 a.m./6 p.m.
Altitude (km)	600
Spatial resolution (km)	35×45
Swath width (km)	900
Rotation rate (rpm)	6
Global coverage (days)	2–3
Radiometre ΔT per footprint (K)	0.2
Radiometre absolute accuracy and stability (K)	1 and 0.2
Radar precision/stability (dB)	0.2
Power (W)	350
Data rate (kbit/s)	25
Mass (kg)	530
Mission duration (years)	3

summarized in Table 14.10. The antenna conical scan system is a rotating, offset-fed, parabolic-mesh reflector, with two identical multichannel feedhorns, which feed the L- and S-band radiometres and the L-band radar. The two feedhorns provide separate beams that give overlapping contiguous footprints at the surface, and allow the antenna system to rotate at 6 rpm which is half as fast as would be necessary with a single beam. The combined antenna and feed system rotates about the vertical axis, with antenna beams at an incidence angle of 40°. As the spacecraft moves, the 3-dB antenna footprints provide overlap along and across track in a helical coverage pattern. At an orbit altitude of 600 km, the 6-m antenna provides $\sim$40-km spatial resolution, and a swath width of 900 km.

Another possible concept consists in using an inflatable antenna. Such an inflatable structure could enable the deployment of a large-aperture, low-mass, and low-cost antenna system in space, suitable for operation in the 1–3 GHz band needed for soil and salinity sensing (Njoku *et al.*, 1999).