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(09/2018)

Technical and operational characteristics of EESS (passive) systems in the frequency range 275-450 GHz

RS Series

Remote sensing systems

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Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R RS.2431-0

Technical and operational characteristics of EESS (passive) systems in the frequency range 275-450 GHz

(2018)

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1 Introduction

The agenda item 1.15 of the WRC-19 resolves to consider the identification of frequency bands for the use of land-mobile and fixed services applications operating in the frequency range 275-450 GHz. Within this frequency range there are a number of bands which by RR No. **5.565** have been identified for use by administrations for passive services, such as the radio astronomy service, the Earth exploration-satellite service EESS (passive) and the space research service SRS (passive). RR No. **5.565** states that the use of the range above 275 GHz by the passive services does not preclude use of this range by active services.

Preparation for WRC-19 AI 1.15 requires conducting sharing and compatibility studies between the land-mobile, fixed and passive services in the frequency range 275-450 GHz while maintaining protection of the passive services identified in RR No. **5.565**.

As far as EESS (passive) is concerned, the sharing and compatibility studies need to address the following frequency bands within the frequency range 275-450 GHz:

- 275-286 GHz
- 296-306 GHz
- 313-356 GHz
- 361-365 GHz
- 369-392 GHz
- 397-399 GHz
- 409-411 GHz
- 416-434 GHz
- 439-467 GHz

2 Scope

This Report provides the technical and operational characteristics of Earth Observation (passive) sensors in the frequency range 275-450 GHz to be used for sharing and compatibility studies between EESS (passive) remote sensing, and land-mobile and fixed services applications.

3 Related ITU-R Recommendations and Reports

- Recommendation ITU-R RS.2017 – Performance and interference criteria for satellite passive remote sensing.
- Recommendation ITU-R RS.515 – Frequency bands and bandwidths used for satellite passive sensing.
- Report ITU-R RS.2194 – Passive bands of scientific interest to EESS/SRS from 275 to 3 000 GHz.

For convenience, Table 1 provides an extract of Recommendation ITU-R RS.2017 summarizing the interference protection criteria for EESS (passive) sensors in the frequency range 275-450 GHz.

TABLE 1

Extract of Rec. ITU-R RS.2017 showing the interference criteria for satellite passive remote sensing in the frequency range 275-450 GHz

Frequency band(s) (GHz)	**Reference bandwidth (MHz)**	**Maximum interference level (dBW)**	**Percentage of area or time permissible interference level may be exceeded [(1)] (%)**	**Scan mode (N, C, L)[(2)]**
275-285.4	3	−194	1	L
296-306	200/3[(3)]	−160/−194[(3)]	0.01/1[(3)]	N, L
313.5-355.6	200/3[(3)]	−158/−194[(3)]	0.01/1[(3)]	N, C, L
361.2-365	200/3[(3)]	−158/−194[(3)]	0.01/1[(3)]	N, L
369.2-391.2	200/3[(3)]	−158/−194[(3)]	0.01/1[(3)]	N, L
397.2-399.2	200/3[(3)]	−158/−194[(3)]	0.01/1[(3)]	N, L
409-411	3	−194	1	L
416-433.46	200/3[(3)]	−157/−194[(3)]	0.01/1[(3)]	N, L
439.1-466.3	200/3[(3)]	−157/−194[(3)]	0.01/1[(3)]	N, C, L

(1) For a 0.01% level, the measurement area is a square on the Earth of 2 000 000 km^2, unless otherwise justified; for a 0.1% level, the measurement area is a square on the Earth of 10 000 000 km^2 unless otherwise justified; for a 1% level, the measurement time is 24 h, unless otherwise justified.

(2) N: Nadir. L: Limb, C: Conical.

(3) First number for nadir or conical scanning modes and second number for microwave limb sounding applications.

4 List of acronyms and abbreviations

BW	Bandwidth
C	Conical scanning
EE	Earth explorer
EESS	Earth exploration satellite service
GSO	Geostationary-satellite orbit
HPBW	Half power beam width
IR	Infra-red
LEO	Low earth orbit
N	Nadir scanning
L	Limb scanning
OZA	Observation zenith angle
SSO	Sun-synchronous orbit
UT/LS	Upper troposphere / lower stratosphere

5 Primary EESS (passive) measurement classes in the range 275-450 GHz

There are two primary EESS measurement "classes" for passive sensors operating in the 275-450 GHz, namely meteorology/climatology and atmospheric chemistry:

- The meteorology/climatology measurements mainly focus around the water vapour and oxygen resonance lines and the associated windows to retrieve necessary physical parameters, such as humidity, pressure, cloud ice and temperature.

  When operating below 600 GHz, the meteorology/climatology measurements are typically performed using vertical nadir sounders or conical scanning radiometers.
- The atmospheric chemistry sensing measurements focus in the many smaller spectral lines of the various atmospheric chemical species, and are mostly performed using limb sounding across the whole frequency range.

5.1 Meteorology/climatology

Figure 1 shows the sensitivity of millimetre and sub-millimetre frequencies to atmospheric temperature and water vapour variations between 2 and 1 000 GHz. The water vapour and oxygen resonance spectral lines are indicated in the Figure as well. The Figure shows the increasing atmospheric attenuation at higher frequencies and the sizable variability of the attenuation due to water vapour:

- Frequencies below 200 GHz are the most suitable for vertical nadir measurements of the lower layers of the atmosphere.
- Frequencies between 200 and 600 GHz are better suited for vertical nadir measurements of the higher layers of the atmosphere.
- Above 600 GHz the oxygen lines are only visible over regions with very dry atmosphere. Measurements at these frequencies are therefore typically from limb sounders and, in any case, exclusively for the top atmospheric layers.

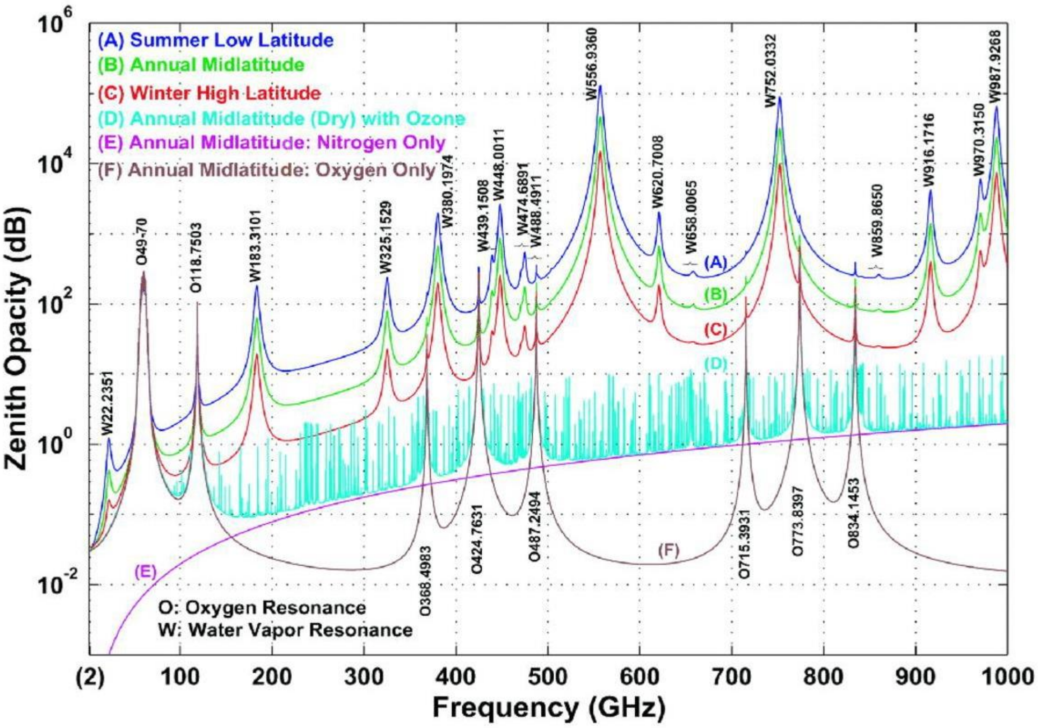
The retrieval of atmospheric properties (e.g. ice cloud content, ice cloud altitude, rain rate, rain profiles, etc.) requires the use of simultaneous multiple frequency observations for better accuracy. Some important considerations among these bands:

- Frequencies around the water vapour resonance at 325 and 380 GHz and oxygen at 424 and 487 GHz are unique in their opacity and high enough in frequency to permit practical antennae to be used at geosynchronous altitudes, yet low enough in frequency for current technology solutions to allow for practical, sensitive instrumentation.
- Use of the 380 GHz water vapour band helps avoid false alarms over super-dry air masses. Adding channels in the 380 GHz band to operational polar-orbiting satellites allows for the retrieval of precipitation over snow-covered mountains and plains and in the driest polar areas where even the typically opaque 183 GHz channels become transparent. The only remedy to this transparency is a more opaque water vapour band and 380 GHz is the only suitable choice.
- Cloud ice and water vapour are two components of the hydrological cycle in the upper troposphere, and both are currently poorly measured. A number of missions have been proposed to measure cloud ice water path, ice particle size and cloud altitude. Currently, these measurements will focus on the 183 GHz, 243 GHz, 325 GHz, 340 GHz, 380 GHz, 425 GHz, 448 GHz, 664 GHz and 874 GHz bands. The vertical water vapour and oxygen sounding measurements are typically performed using a set of channels, composed of so-called "wings" and associated "windows".
- The vertical sounding measurements along the "wings" of the resonance curve under investigation are performed in frequency slots (with a given bandwidth BW) at symmetrical

distance (Offset) from the central resonance frequency. This allows characterizing the resonance curve slope at the various atmospheric heights which in turn allows observing the water vapour and oxygen vertical profiles. The required total frequency band can be defined as the maximum bandwidth (BW) plus twice the maximum offset, centred on the resonance frequency.

FIGURE 1

The sensitivity of millimetre and sub-millimetre frequencies to atmospheric temperature and water vapour variations [1]



5.2 Atmospheric chemistry

Atmospheric attenuation occurs among many atmospheric layers of varying temperature. The temperature values can be sensed at different heights or distances along the path by selecting frequencies near the edges of the opaque regions with different attenuations, which provide different weighting functions or multipliers of the atmospheric temperature at a given point. Atmospheric chemistry measurements are typically made with limb sounders, scanning the atmosphere layers at the horizon as viewed from the satellite orbital position. These measurements relate to the spectral lines of a large number of chemical species in the atmosphere. Limb sounding is more sensitive and allows for better vertical resolution than nadir sounding. Sub-millimetre frequencies, from about 500 GHz and higher, allow sounding down to the lower stratosphere. Millimetre frequencies, notably between 180 and 360 GHz, allow sounding to even lower altitudes, i.e. to the upper troposphere (Recommendation ITU-R RS.515).

A number of different frequencies are typically chosen to provide a reasonable set of weighting functions for atmospheric temperature, water vapour, ozone, chlorine oxide, nitrous oxide and carbon monoxide profile measurements. The minimum bandwidth required for measurements of atmospheric spectral lines is proportional to the frequency of the spectral line (i.e. a measurement around 600 GHz requires more bandwidth than what is required for a measurement at 300 GHz). This is essentially due to the fact that the sensor filtering capability corresponds to a certain percentage absolute value of the frequency.

As a first order approximation, this implies a bandwidth requirement of about 1 GHz on both sides of the spectral line for measurements up to 500 GHz, while 2 GHz on both sides of the spectral line is needed for measurements between 500 and 1 000 GHz.

5.3 EESS (passive) scanning modes

There are two types of sounding modes and three types of scanning modes used by passive sensors in NGSO orbits. Additionally, there are two scanning modes used in geostationary orbit.

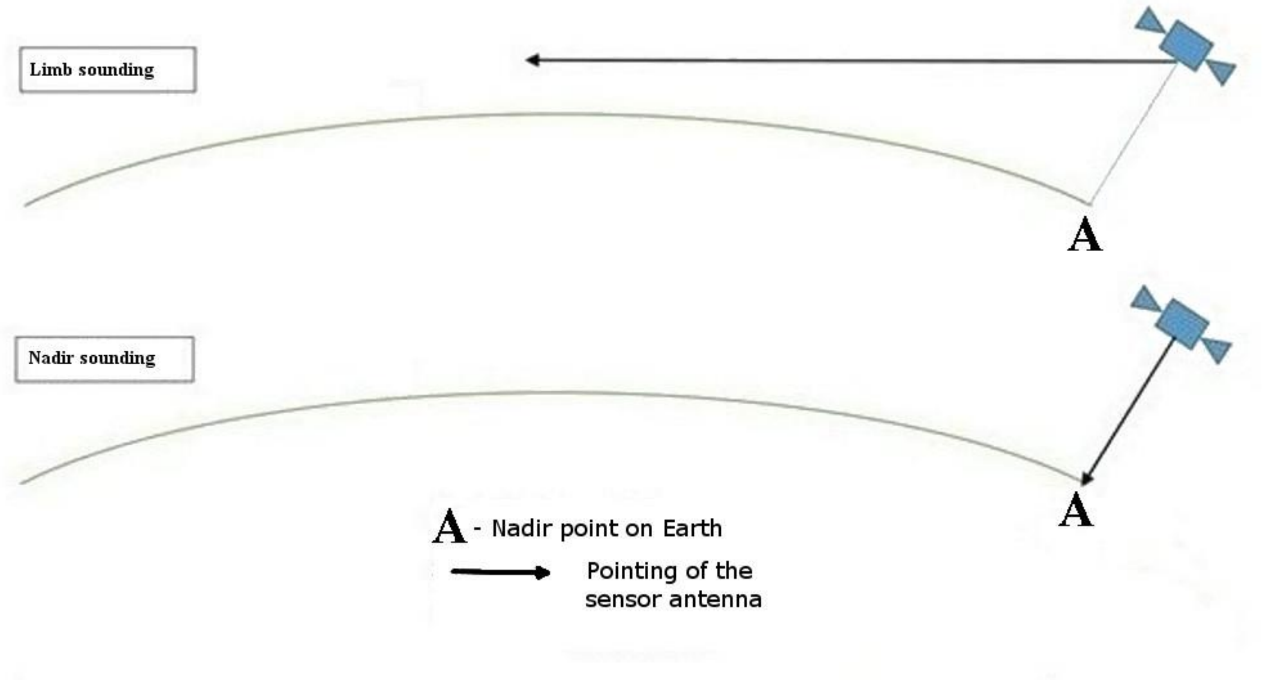
The NGSO sounding modes provide profiles of atmospheric constituents from one fixed orientation relative to the satellite. Figure 2 provides a depiction of the NGSO sounding modes which are:

– Limb sounding modes, which observe the atmosphere at a tangential angle to the Earth's surface. The field of view terminates in space rather than at the surface of the Earth. However, some limb sounding radiometers also perform elevation scanning of the Earth's limb in order to cover the whole vertical range and improve the vertical resolution.

– Nadir sounding modes, which provide atmospheric soundings or views of the Earth's surface at angles of nearly perpendicular incidence to the Earth's surface.

FIGURE 2

NGSO sounding modes



The NGSO scanning modes view the Earth from various angles and cover a range of terrestrial locations from a single satellite location. The three NGSO scanning modes are:

– conical scanning modes, which view the Earth's surface by rotating the antenna at an offset angle from the nadir direction;

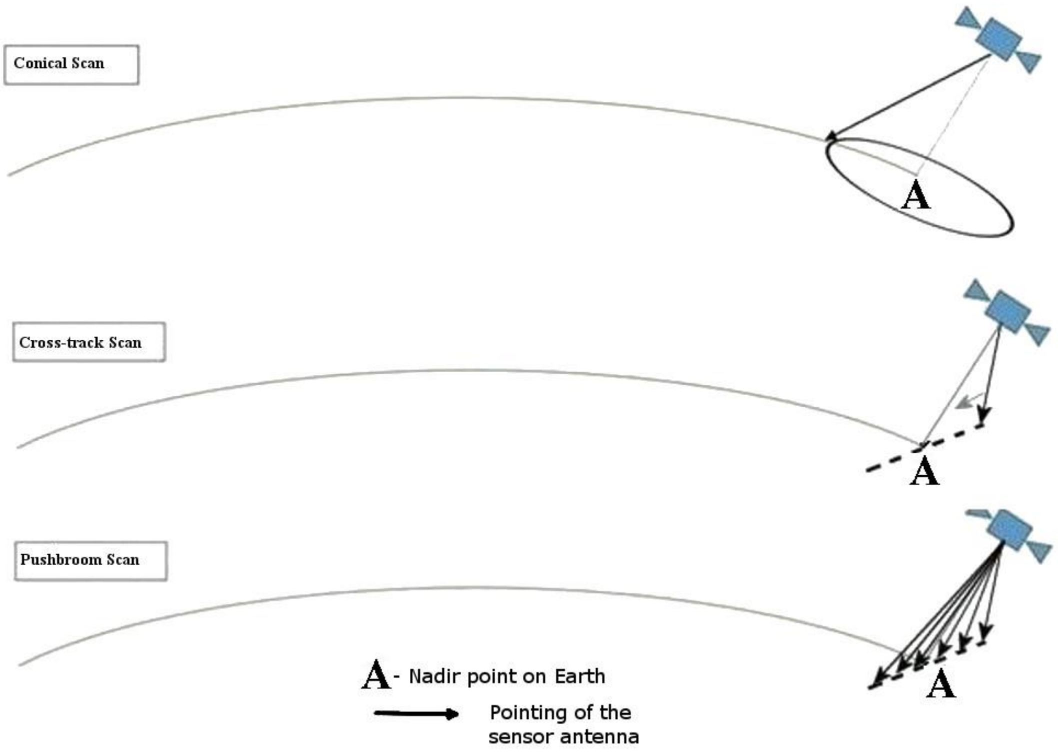
– cross track scanning modes, which provide measurements in swaths perpendicular to the track of the satellite. These swaths may provide scanning in one direction or in a back-and-forth direction (whisk-broom scan) for which the raw zig-zag pattern must be eliminated; and

– push-broom scanning modes, which utilize multiple sensors to observe the Earth in multiple parallel along-track swaths.

A schematic of the three types of NGSO scanning modes is presented in Fig. 3.

FIGURE 3

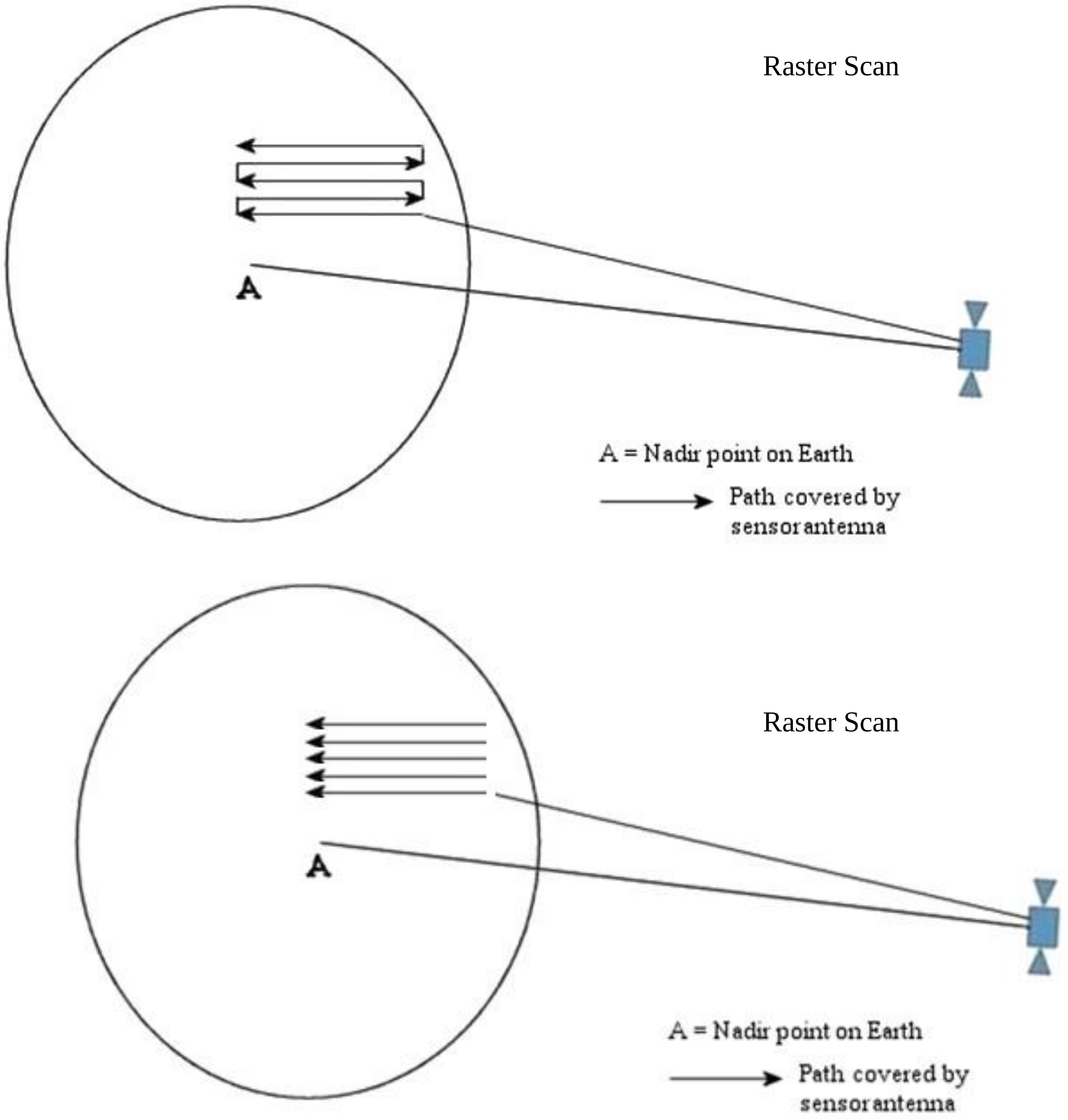
NGSO Scanning Modes



In a geostationary orbit, the orbital path of the instrument does not provide the movement in the second dimension required to perform a scan of an area. Therefore the two-dimensional scanning mechanism must be built into the instrument hardware. Examples of this type of scanning mode is depicted in Fig. 4.

FIGURE 4

GSO Scanning Mode



The type of scanning strategy employed by the sensor will have impact in the analysis of the frequency sharing scenario.

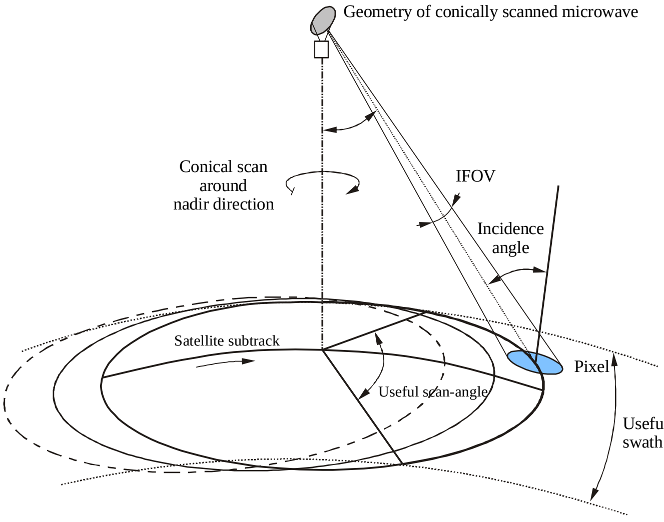
5.3.1 Conical scanning radiometers

Many passive microwave sensors designed for imaging the Earth surface features use a conical scan configuration turning around the nadir direction because it is important, for the interpretation of surface measurements, to maintain a constant ground incidence angle along the entire scan-lines.

A conical scan configuration produces measurement footprints that are constant in size and, since the polarization characteristics of the signal have a dependence on ground incident angle, a constant ground incidence angle removes the variation of return polarization from the gathered data. Conical scanning antennas gather information over wide areas as shown in Fig. 5. Scans are typically performed by rotating the antenna at an offset angle from the nadir direction.

FIGURE 5

Geometry of conical scan passive microwave radiometers (Rec. ITU-R RS.1861)



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5.3.2 Cross-track scanning

Scanning radiometric measurements gather information over wide areas which are used in creating virtual maps of the parameter being measured. Scanning measurements are also typically performed at multiple frequencies and polarizations.

Scans are typically performed in a cross-track pattern across the surface of the Earth as shown in Fig. 6. Cross-track scanning may be performed by physically rotating a reflector 360 degrees. As the reflector is directed away from the surface of the Earth, sensor channels remain operating for calibration purposes, as shown in Fig. 7. An alternate approach is to swing the sensor back and forth, never looking away from the surface. This alternate motion would produce a zig-zag pattern of coverage measurements which must be removed, usually by a mechanism within the instrument.

FIGURE 6

Typical cross-track Earth scanning pattern (Rec. ITU-R RS.1861)

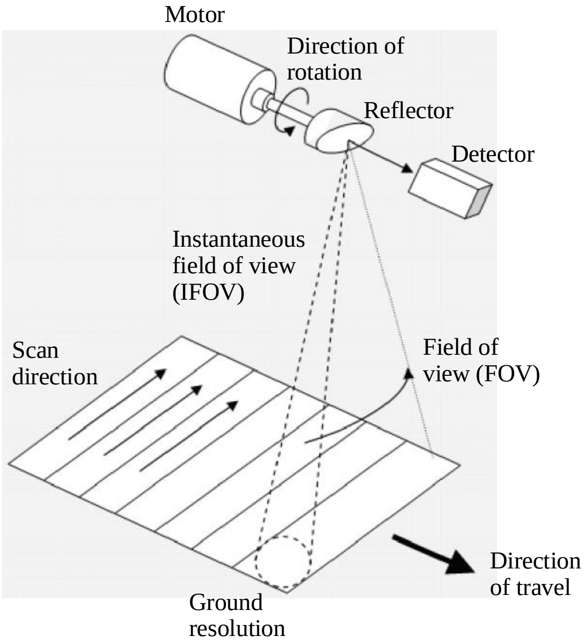

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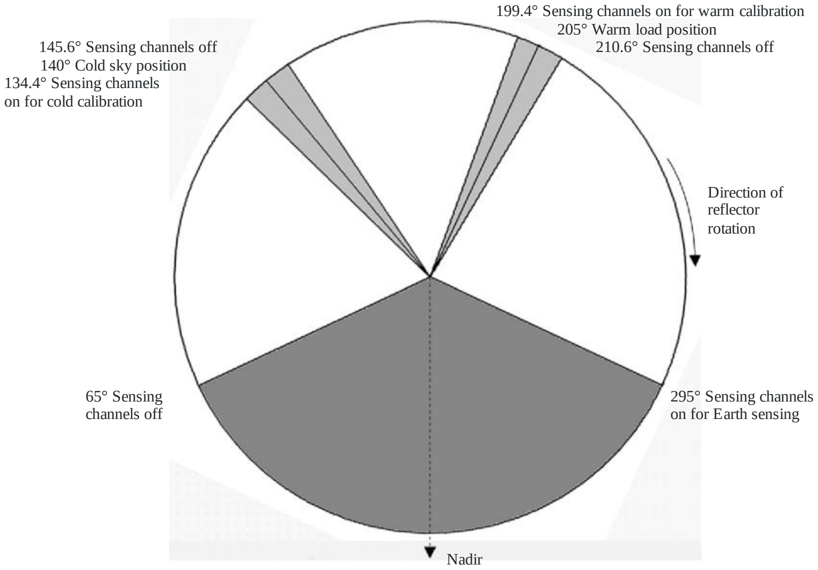
FIGURE 7

Typical sensing scanning pattern over 360 degrees (Rec. ITU-R RS.1861)



Note 1 – All angles with respect to nadir.

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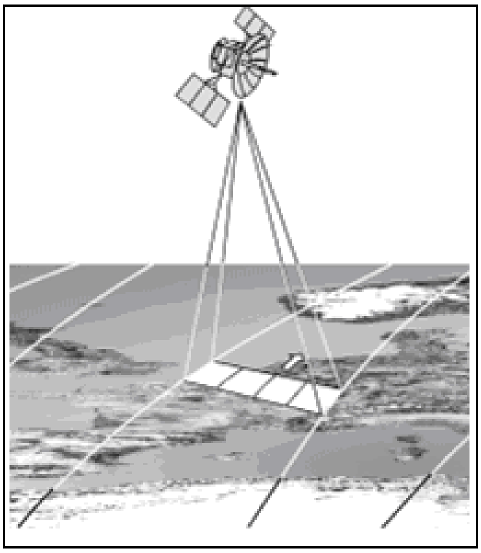
5.3.3 Push-broom scanning

A “push-broom” (along track) sensor consists of a line of sensors arranged perpendicular to the flight direction of the spacecraft, as illustrated in Fig. 8. Different areas of the surface of the Earth are detected as the spacecraft flies forward. The push-broom sensor is a purely static instrument with no moving parts. The major feature of the push-broom sensor is that all resolution elements in a scan line are acquired simultaneously, and not sequentially as with mechanically scanned sensors, enabling this type of sensor to significantly increase the achievable radiometric resolution.

FIGURE 8

Typical push-broom radiometer configuration



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5.3.4 Raster scanning

Raster scanning modes sweep horizontally left-to-right at a steady rate, then blanks and rapidly moves back to the left (or down), where it turns back on and sweeps out the next line, as shown in

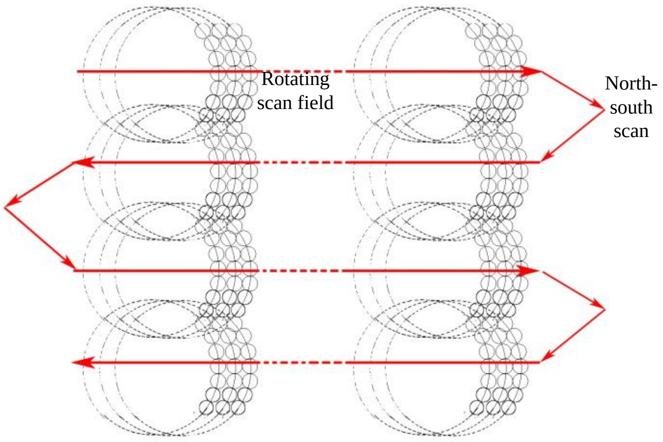
Fig. 3. During this time, the vertical position is also steadily increasing (downward). GSO raster scanning radiometers can provide temperature and humidity profiles, cloud ice/liquid water columnar amount and gross profile, precipitation rate (particularly in cyclone or convection) with very high temporal resolution.

5.3.5 Wide strip and thin circle combined scanning

GSO radiometers also focus on rapidly changing weather phenomenon observation. It needs to use real aperture design to ensure the calibration accuracy and the observation reality of dynamic targets. The wide strip and thin circle combined scanning radiometer, as illustrated in Fig. 9, can realize calibration in every one second and scan on stable satellite platform in GSO. This scan mode combines the general scan (wide strip) of satellite and detail local scan (thin circle) of sensor. Accompanied with satellite the sensor makes east-west recycling movement and steps forward line by line along south-direction, forming the general scan in two dimensional stripes, as shown in Fig. 9 with the red line. At the same time, the sensor makes its footprint move as a circle, in which total 110-degrees angle range are used for observation, forming the detail local scan to meet the requirements of region coverage and time resolution, as shown in Fig. 9 with the black line. One footprint movement step of the general scan and one circle of the detail local scan spend the same time.

FIGURE 9

Typical wide strip and thin circle combined scanning configuration



6 EESS (passive) systems in the frequency range 275-450 GHz

A number of bands between 275 and 450 GHz are identified in Recommendation ITU-R RS.2194 that are of scientific interest for studies of meteorology/climatology and atmospheric chemistry. The relevant bands between 275 and 450 GHz, along with key characteristics of those bands, are listed in Annex 2.

Table 2 provides an overview of different remote passive sensing instruments, the type of measurements obtained, and the missions that they are incorporated into. A summary Table with the main characteristics of these systems is presented in Annex 1.

TABLE 2

Instruments with radiometric channels between 275 and 450 GHz

Instrument	Short description and main objective	Mission/Sponsor
Remote Sensor-1 (ICI)	Ice Cloud Imager (ICI): Conical scanning radiometer. Main objective: cloud ice retrieval, with emphasis on cirrus clouds, and water vapour profile measurement capability Submillimetre wave sensor with channels from 183 to 664 GHz	Instrument selected for MetOp Second Generation –B (EUMETSAT). Under development. Operational system for 2020 – 2040
Remote Sensor-2 (TWICE)	Tropospheric Water and Cloud ICE (TWICE): Conical scanning radiometer. Main objective: Water vapour and ice clouds in upper troposphere, and study of circulation models for climate modelling	On-going development for CubeSat deployment. NASA
Remote Sensor-3 (SMM)	Passive submillimetre wave (SMM) ice cloud radiometer. Main objective: measurement of ice clouds, namely cloud ice mass, particle size, and mean cloud altitude.	Completed feasibility study. Preparation for mission proposal was supported by JAXA.
Remote Sensor-4 (STEAMR)	STEAMR Millimetre wave multi-beam Limb sounder Main objective: 3D limb sounding with embedded cloud imaging capability	One of the payloads of PREMIER for an Earth Explorer Core Mission
Remote Sensor-5 (GEM)	Geosynchronous Microwave (GEM) sensor Main objective: Temperature and moisture profiling from the lower stratosphere down to ~2-5 km altitude.	Sensor on GOES-class satellites
Remote Sensor-6 (GOMAS)	Geostationary Observatory for Microwave Atmospheric Sounding (GOMAS). Main objective: Temperature and moisture profiles, cloud ice/liquid water gross profile.	Earth Explorer Opportunity Mission
Remote Sensor-7 (CAMLS)	Compact Adaptable Microwave Limb Sounder (CAMLS) Main objective: understanding the composition and structure of UT/LS.	On-going development for next generation of microwave Limb Sounders. NASA
Remote Sensor-8 (GMS)	Geostationary Microwave Sounder (GMS)	Chinese FY-4 microwave satellite
Remote Sensor-9 (MASTER)	MASTER- Millimetre wave multi-beam Limb sounder Main objective: 3D limb sounding	Earth Explorer Core Mission

6.1 Remote Sensor-1: Ice Cloud Imager (ICI)

In order to obtain global coverage observation data for Earth atmospheric weather forecasting, ESA & EUMETSAT are jointly planning the next generation of weather satellite series: Meteorological Operational Satellite-Second Generation (MetOp-SG). MetOp-SG consists of two series of satellites (termed Satellite A and Satellite B series), with three satellites in each series (3+3 configuration). A total of ten different instruments will be flown onboard the two series of satellites. The Ice Cloud Imager (ICI) instrument is a millimetre and sub-millimetre wave conically scanning radiometer, providing brightness temperature measurements in a total number of 13 channels ranging from 183 GHz up to 664 GHz. ICI is designed to monitor the exchange mechanisms in Earth's upper troposphere and lower stratosphere, and will focus, in particular, on the remote sensing of high altitude ice clouds. This will be accomplished using several double sideband heterodyne receiver channels centred at 183 GHz, 243 GHz, 325 GHz, 448 GHz and 664 GHz, with two window channels (243 GHz and 664 GHz) which will be measured at both V and H polarizations. The use of channels around weak absorption lines (i.e. 325.15 GHz and 448 GHz) allows performing cloud slicing.

The ICI instrument is composed of a rotating part that includes the main antenna, the feed assembly and the receiver electronics, and a fixed part that contains the hot calibration target, the reflector for viewing the cold sky and the electronics for the instrument control and interface with the platform. Between the fixed and the rotating part is the scan mechanism. ICI is a conical scanner with a constant observation zenith angle (OZA) at 53° ± 2°. ICI provides footprints of 15 km at all channels.

The antenna is based on single offset reflector geometry and the feed cluster has 7 horns distributed in two rows. ICI obtains measurements from the upper and lower sidebands for each channel over an azimuth scan angle range of ±65 degrees around the nadir for scene view. The ICI rotates at uniform speed. Channels at 243 GHz and 664 GHz are measured at V and H polarizations, while all other channels are measured in V polarization only. Contrary to traditional conical scanners, ICI will be mounted on the nadir side of the spacecraft [2], [3].

TABLE 3

Main technical and operational characteristics of Remote Sensor-1 (ICI)

Type of mission	Payload on Metop-SG. Operational mission. In orbit from 2023 up to the 2040
Type of orbit	SSO LEO
Altitude	817 km
Inclination	98.7 degrees
Scanning geometry (N, C, L)	Conical scanning. Scan rate: ~ 27 scan/min = ~ 16 km/scan. Scan angle over ±65 degrees. See Fig. 10
Observation zenith angle (OZA)	53 degrees ± 2 degrees
Channels centre frequency	183.31 GHz, 243.2 GHz, 325.15 GHz, 448 GHz & 664 GHz
Channels bandwidth	See Table 4
Antenna peak gain	55 dBi, Beam efficiency > 95%
Antenna 3 dB beamwidth	Consistent with an antenna diameter of ~ 0.5 m
Footprint area	Projected footprint of 16 km for all channels (Oval shape, can be approximated to circle 16 km diameter)
Coverage	Global coverage once/day

TABLE 4

Channel specifications for Remote Sensor-1 (ICI)

Channel No	**Frequency $f_0 \pm \Delta f$ (GHz) (*)**	**Bandwidth (MHz) (**)**	**Polarization**	**Utilization**
ICI-1	183.31±7.0	2 × 2 000	V	Water vapour profile and snowfall
ICI-2	183.31±3.4	2 × 1 500	V	
ICI-3	183.31±2.0	2 × 1 500	V	
ICI-4	243.2±2.5	2 × 3 000	V, H	Quasi-window, cloud ice retrieval, cirrus clouds
ICI-5	325.15±9.5	2 × 3 000	V	Cloud ice effective radius

TABLE 4 (*end*)

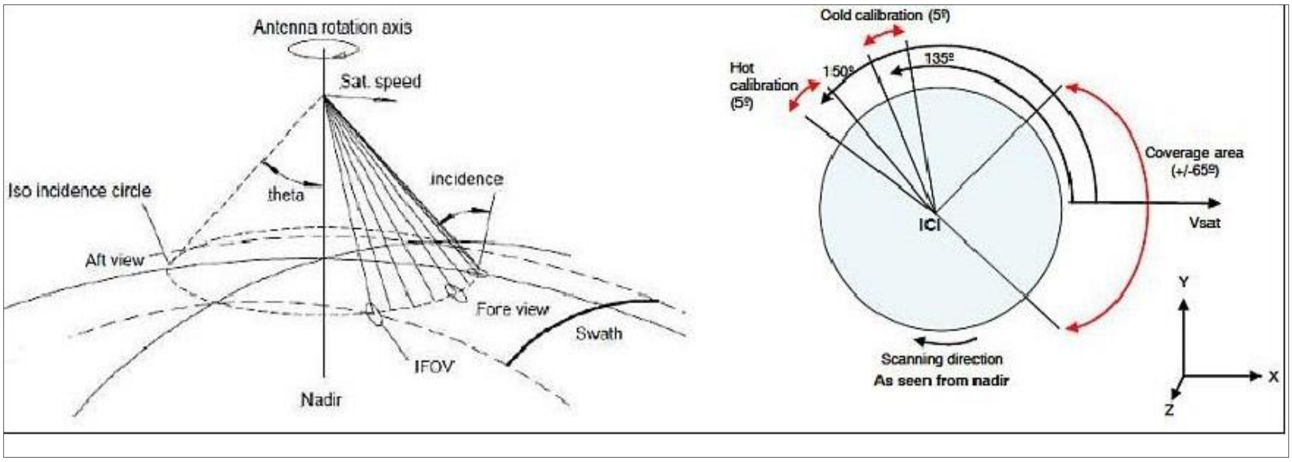
Channel No	Frequency $f_o \pm \Delta f$ (GHz) (*)	Bandwidth (MHz) (**)	Polarization	Utilization
ICI-6	325.15±3.5	2 × 2 400	V	
ICI-7	325.15±1.5	2 × 1 600	V	
ICI-8	448±7.2	2 × 3 000	V	Cloud ice water path and cirrus
ICI-9	448±3.0	2 × 2 000	V	
ICI-10	448±1.4	2 × 1 200	V	
ICI-11	664±4.2	2 × 5 000	V, H	Quasi-window, cirrus clouds, cloud ice water path

(*) For each ICI channel, measurements are performed at both sides of the centre frequency ($f_o + \Delta f$ and $f_o - \Delta f$)

(**) Total bandwidth per channel, considering both sides around the centre frequency f_o.

FIGURE 10

Scanning geometry and measurement/calibration sectors [2]



6.2 Remote Sensor-2: Tropospheric Water and Cloud ICE (TWICE)

The Tropospheric Water and Cloud ICE (TWICE) radiometer instrument is currently under development. TWICE is designed with size, mass, power consumption and downlink data rate compatible with deployment aboard a 6U-Class nanosatellite.

The TWICE instrument will perform conical scanning of the atmosphere at an incidence angle near 53 degrees as well as two-point integrated ambient and cold-sky calibration once each scan, i.e. once per second. The TWICE instrument will provide 15 radiometer channels, including window frequencies near 240, 310 and 670 GHz to perform ice particle sizing and determine total ice water content, as well as four sounding channels each near 118 GHz for temperature sounding and near 183 GHz and 380 GHz for water vapour sounding during nearly all weather conditions. This will prove particularly useful for measurements in the upper troposphere in the presence of ice clouds. The TWICE instrument has three direct-detection receivers, with dual-polarization capability at the 670 GHz. Ice particle size and total ice water content will be retrieved from measured antenna temperatures at these frequencies [4], [5].

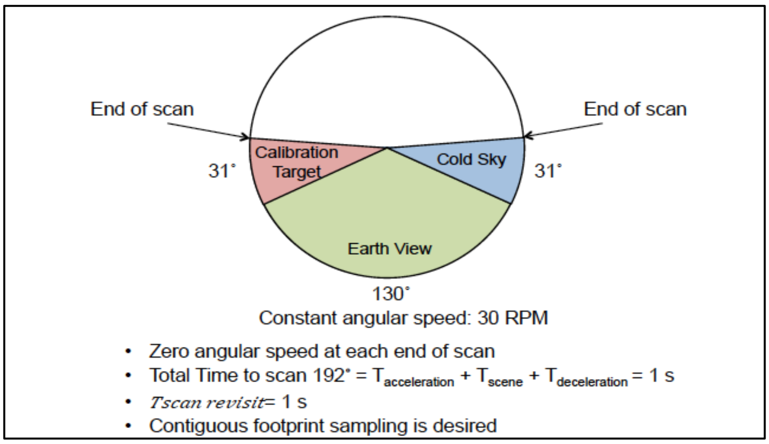
TABLE 5

Main technical and operational characteristics of Remote Sensor-2 (TWICE)

Type of mission	6U-Class nanosatellite
Type of orbit	SSO LEO
Altitude	400 km
Inclination	High inclination
Scanning geometry (N, C, L)	Conical scanning. See Fig. 11 Total scan angle 130 degrees (Earth view)
Observation Zenith Angle (OZA)	53 degrees
Channels centre frequency	Sounding: 118 GHz (4 channels), 183 GHz (4 channels) and 380 GHz (4 channels) Window channels: 240 GHz (1 channel), 310 GHz (1 channel) and 670 GHz (2 channels)
Channels bandwidth	See Table 6
Antenna peak gain	46-48 dBi
Antenna 3 dB beamwidth	At 310 GHz: 0.64 degrees HPBW At 380 GHz: 0.56 degrees HPBW
Footprint area	At 310 GHz: 6.5 km (cross-track) and 9.9 km (along-track) At 380 GHz: 5.8 km (cross-track) and 8.7 km (along-track) Swath width = 749 km See Fig. 12
Coverage	Nearly global coverage once/day

FIGURE 11

TWICE Scanning and calibration strategy [5]



Constant angular speed: 30 RPM

- Zero angular speed at each end of scan
- Total Time to scan 192° = $T_{acceleration} + T_{scene} + T_{deceleration} = 1$ s
- *Tscan revisit*= 1 s
- Contiguous footprint sampling is desired

FIGURE 12

TWICE Surface Footprint for 400 km orbit [5]

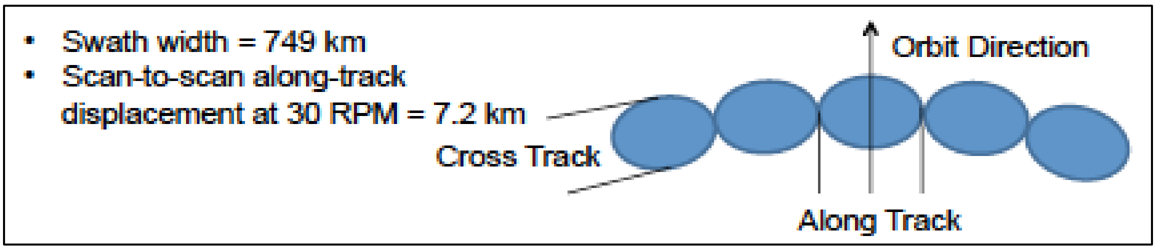


TABLE 6

Channel specifications for Remote Sensor-2 (TWICE)

Channel	Frequency $f_0 \pm \Delta f$ (GHz) (*)	Bandwidth (GHz)	Polarization	Utilization
1	118.75 ± 1.1	2 × 0.4 = 0.8	linear	Water vapour retrievals
2	118.75 ± 1.5	2 × 0.4 = 0.8	linear	
3	118.75 ± 2.1	2 × 0.8 = 1.6	linear	
4	118.75 ± 5.0	2 × 2.0 = 4.0	linear	
5	183.31 ±1.0	2 × 0.5 = 1.0	linear	Water vapour profile in the troposphere and UTLS
6	183.31 ± 3.0	2 × 1.0 = 2.0	linear	
7	183.31 ± 6.6	2 × 1.5 = 3.0	linear	
8	243.20 ± 2.5	2 × 3.0 = 6	linear	Ice particle sizing and total ice water content
9	310.00 ± 2.5	2 × 5.0 = 10	linear	Ice particle sizing and total ice water content
10	380.20 ± .75	2 × 0.7 = 1.4	linear	Water vapour sounding and ice clouds
11	380.20 ±1.80	2 × 1.0 = 2.0	linear	
12	380.20 ± 3.35	2 × 1.7 = 3.4	linear	
13	380.20 ± 6.20	2 × 3.6 = 7.2	linear	
14	664.00 ±4.20	2 × 4.0 = 8.0	H,V	Ice particle sizing and total ice water content

6.3 Remote Sensor-3: Sub-MilliMeter Ice Cloud sensor (SMM)

The sub-millimetre (SMM) ice cloud remote sensor targets global coverage measurements of important micro- and macrophysical properties for all types of ice clouds, namely cloud ice mass, particle size, and mean cloud altitude. These parameters have not been measured with sufficient coverage and accuracy by other sensor types including active instruments.

One of the key issues in SMM ice cloud remote sensing is to solve the trade-offs between spatial resolution, coverage, and sensor sensitivity in a satisfactory manner. Ice cloud sensing requires a spatial resolution in the order of cloud characteristic sizes, i.e. a few kilometres or better. With currently used single field-of-view scanning receivers, wide coverage of 1 000 km or more requires fast scanning when improvement of spatial resolution is targeted. Fast scanning on the other hand decreases signal integration time, increases signal noise, and decreases sensor sensitivity. To improve or solve these issues, this concept applies receiver arrays for SMM imaging.

Covering a wider area in a "single shot" observation this setup allows for slower scanning of an equivalent area compared to conventional single field-of-view receivers. Hence, sensitivity of the observation is improved. In turn, when keeping sensor sensitivity constant a finer spatial resolution can be realized.

The sensor has two observation frequencies: around the 325 GHz water vapour line and in the 660 GHz window region. Beside technological reasons, these spectral positions have been chosen because they exhibit similar clear-sky atmospheric opacities. That means, observed brightness temperatures are nearly identical for clear-sky conditions, and deviations in the signals can be attributed solely to clouds. The 325 GHz channels will be more sensitive to large particle fractions, while the high frequency channel senses smaller particles. Table 7 provides preliminary characteristics for the SMM Ice cloud remote sensor and Fig. 13 illustrates the concept of the receiver array. The channel specifications are presented in Table 8 [6].

TABLE 7

Main technical and operational characteristics of Remote Sensor-3 (SMM)

Type of mission	Proposed, preferably in line with other instruments
Type of orbit	SSO LEO
Altitude	600 to 800 km
Inclination	High inclination
Scanning geometry (N, C, L)	Conical or across track scan scanning. See Fig. 6.3-1
Observation Zenith Angle (OZA)	Dependent on final design configuration.
Channels centre frequency	325 GHz (H_2O-line) + 660 GHz (window) (possibly H/V polarizations for window receiver)
Channels bandwidth	See Table 8
Footprint area	5 km^2
Coverage	Global

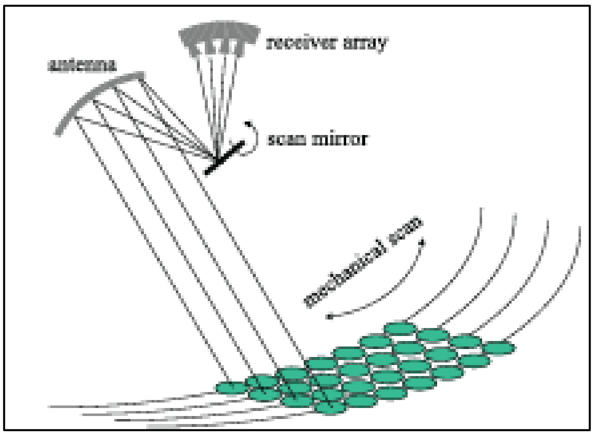
TABLE 8

Channel specifications for Remote Sensor-3 (SMM)

Channel No.	Centre frequency (GHz)	Polarization	Utilization
SMM-1	325	Single pol	(H2O-line) Ice clouds mass, ice particle sizing, mean cloud altitude
SMM-2	325	Single pol	
SMM-3	325	Single pol	
SMM-4	325	Single pol	
SMM-5	660	V, H	(Window) Ice particle sizing (for smaller ice particles) and total ice water content

FIGURE 13

Illustration of the SMM receiver array concept



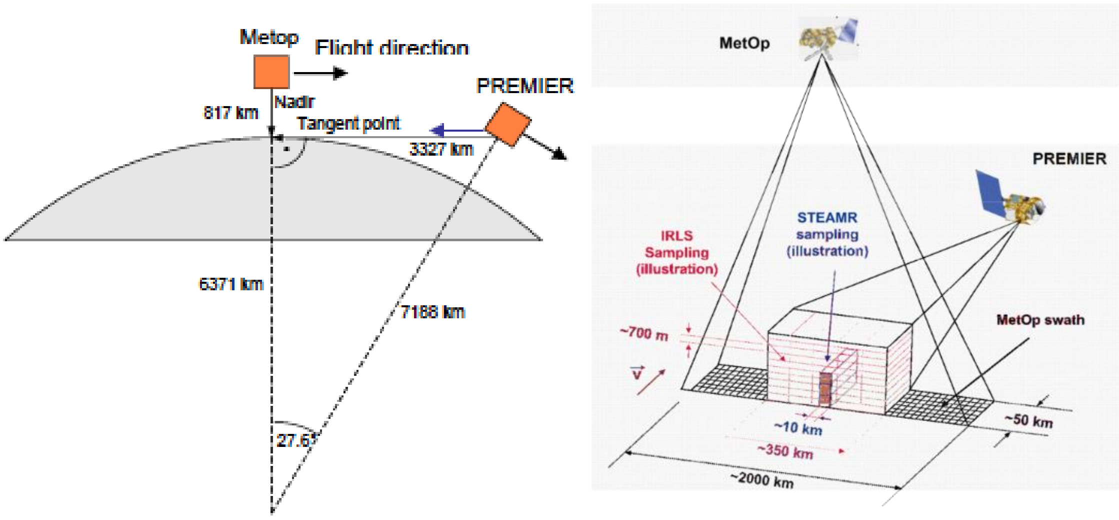
6.4 Remote Sensor-4: Millimetre-Wave Limb sounder (STEAMR)

STEAMR is one of the payloads of PREMIER, which was proposed to ESA as an Earth Explorer Core mission. The main objective of PREMIER is to measure vertical volume mixing profiles of atmospheric constituents in the mid/upper troposphere and the lower stratosphere (UT-LS), and their variation over time. The mission concept is based on a payload with three complement instrument functions: Millimetre-Wave Limb Sounder (known as STEAMR), IR limb sounder (IRLS) and IR limb cloud imager (IRCI).

The mission concept considers PREMIER flying in a tandem formation looking backwards to METOP’s swath and therefore PREMIER data would need to be temporally co-registered at the tangent point with METOP data at nadir. The geometry of the METOP and PREMIER orbits is shown in Fig. 14 [7], [8].

FIGURE 14

Geometry of METOP and PREMIER orbits



STEAMR is a multi-beam limb sounder operating in the 310-360 GHz range, using an 8-beam array of receivers to improve sensitivity and instrument data retrieval. The main objective of STEAMR is to provide vertically (1-2 km) and horizontally (30-50 km) information on the distribution of UT-LS constituents such as water vapour, ozone and carbon monoxide on the global scale.

The quasi-optical system consists of one primary reflector of 1.6 × 0.8 m with an offset Gregorian sub reflector. Three mirrors link the beam from the sub reflector to the focal plane unit, accommodating 8 receiver front-ends in an array configuration [9].

STEAMR observation principles require the highest altitude resolution at the lower end of the atmospheric altitudes observed. The STEAMR measurement concept is based on multi-beam limb sounding in the orbital plane using Schottky-diode heterodyne receivers. The instrument limb view follows a staring concept, observing simultaneously an altitude range of 22 km with 14 beams spaced vertically: every 1.5 km in the lowest 12 km and every 2 km in the highest 10 km as shown in Fig. 15 [8]. Two polarisations are used. There is no need to scan the limb mechanically or by spacecraft manoeuvring. Instead, the spacecraft antenna pointing follows the tropopause altitude.

FIGURE 15

STEAMR limb imaging principles

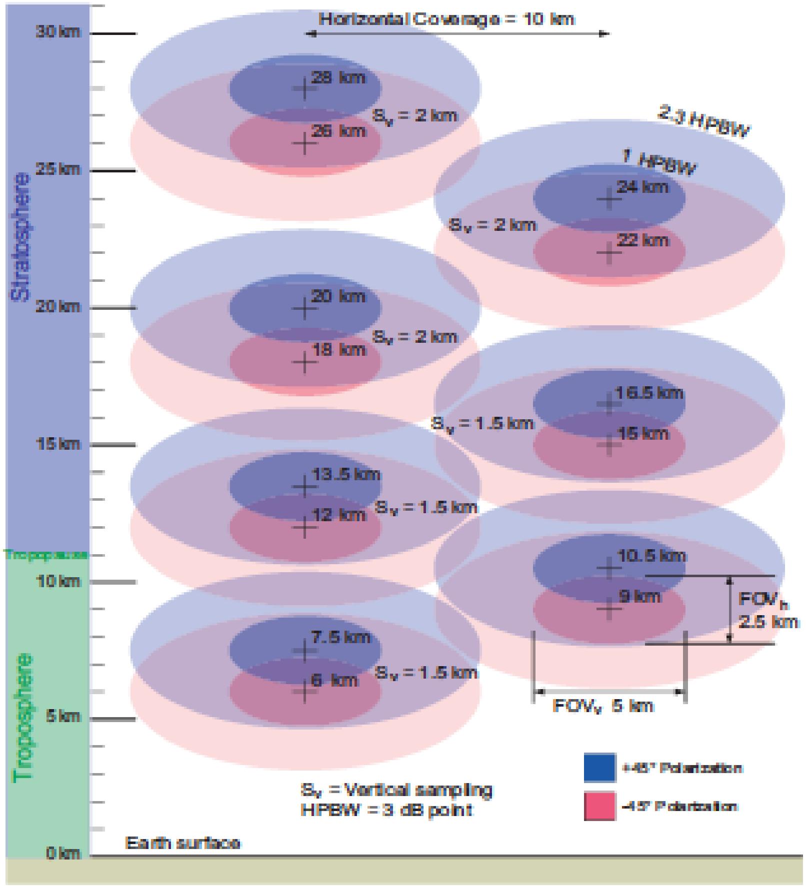


TABLE 9

Main technical and operational characteristics of Remote Sensor-4 (STEAMR)

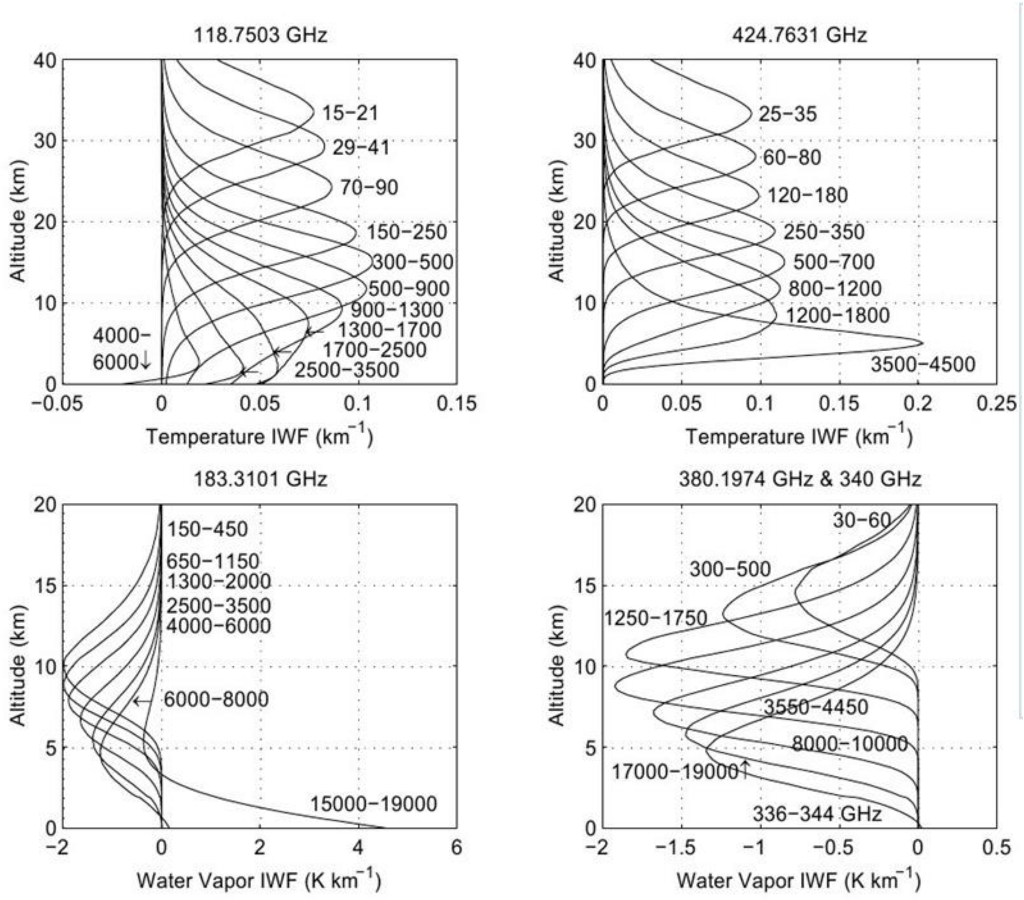
Type of mission	Satellite in tandem formation with Metop.
Type of orbit	SSO LEO
Altitude	817 km
Inclination	98.7 degrees
Scanning geometry (N, C, L)	Limb sounder. See Fig. 14
Observation Zenith Angle (OZA)	Not applicable
Channels centre frequency	Spectral instrument (continuous measurement over large bandwidth
Channels bandwidth	Lower side band: 313.5-325.5 GHz Upper side band: 343.6-355.6 GHz (12 GHz for each spectral sideband)
Antenna peak gain	Reflector antenna 1.6 m × 0.8 m; Gain = 70 dBi First side lobe < –35 dB
Footprint area	FOVh = 5 km, FOVv = 2.5 km See limb imaging schematic in Fig. 15
Coverage	Global

6.5 Remote Sensor-5: Geosynchronous Microwave sensor (GEM)

The Geosynchronous Microwave (GEM) sensor was proposed to be flown on a GSO satellite. The technical and operational characteristics of the sensor were defined. The GEM observation principle is based on the use of three absorption bands of oxygen (54, 118 and 425 GHz) and two bands of water vapour (183 and 340/380 GHz). A series of narrow-bandwidth channels implemented within these bands for a total of 37 channels would provide temperature and moisture profiling capability from the lower stratosphere down to ~2-5 km altitude. Owing to the wide frequency range spanned by the five GEM bands, each of these bands is differently affected by liquid and ice water amount and drop size (see Fig. 16). These additional observable degrees of freedom provide information on cloud and precipitation type and amount.

FIGURE 16

GEM vertical response



The baseline GEM concept uses a 2-metre Cassegrain antenna with a dual-stage scanning system. The dual-stage system consists of a slow momentum-compensated azimuth mechanism and fast nodding/morphing subreflector scanning system to provide both wide-area synoptic coverage and fast regional coverage with adaptive scan capabilities. Oversampling and super-resolution techniques are expected to improve GEM spatial resolutions by an additional ~20-30% for high-interest events such as hurricanes or localized mesoscale convection. Further reductions in the ΔT_{rms} are achievable via additional downsampling and/or time averaging. Regional scanning covering a 1 500 × 1 500 kilometres square is expected to take 12-15 minutes, while scanning the entire continental United States, an area 3 000 × 5 000 kilometres, is estimated to take 90 minutes.

TABLE 10

GEM Instantaneous FOV per channel

Band (GHz)	**3 dB IFOV (km)**
50-56	138.6
118.75	60.2
183.31	41.9
380.153	20.5
424.763	16.4

Thermal and inertial deformations are monitored by a series of sensors on the antenna structure. Phase errors caused by such deformations will be actively compensated using a nodding/morphing sub-reflector with approximately five degrees of freedom. The sub-reflector also provides for high rate beam scanning over a limited range. Larger movements to change the observation sector are performed by momentum-compensated elevation and azimuth motors, although the possibility of using the satellite attitude control system in combination, or as an alternative, is also considered. A single feed horn path is baselined so as to provide hardware co-alignment of all feeds for the five bands. The baseline receiver uses a quasi-optical multiplexer and includes five individual radiometer modules, one for each band [10].

6.6 Remote Sensor-6: GEO Atmospheric Sounding (GOMAS)

The Geostationary Observatory for Microwave Atmospheric Sounding (GOMAS) mission was proposed to ESA as an Earth Explorer Opportunity Mission. GOMAS and GEM mission concepts are similar, although adapted to different platforms and with differences in the frequency bands selected. The instrument is intended to be flown on a dedicated satellite.

The objective is to explore the capabilities of very high frequency microwaves and sub-millimetre waves to provide observations, at 15-min intervals, of:

– Nearly-all-weather temperature and humidity profiles.

– Cloud ice/liquid water, columnar amount and gross profile.

– Precipitation rate (particularly within convection).

Considerations for the frequency selection:

– For O_2, above the 54 GHz band, the desirable temperature sounding bands are at 118 GHz and 425 GHz.

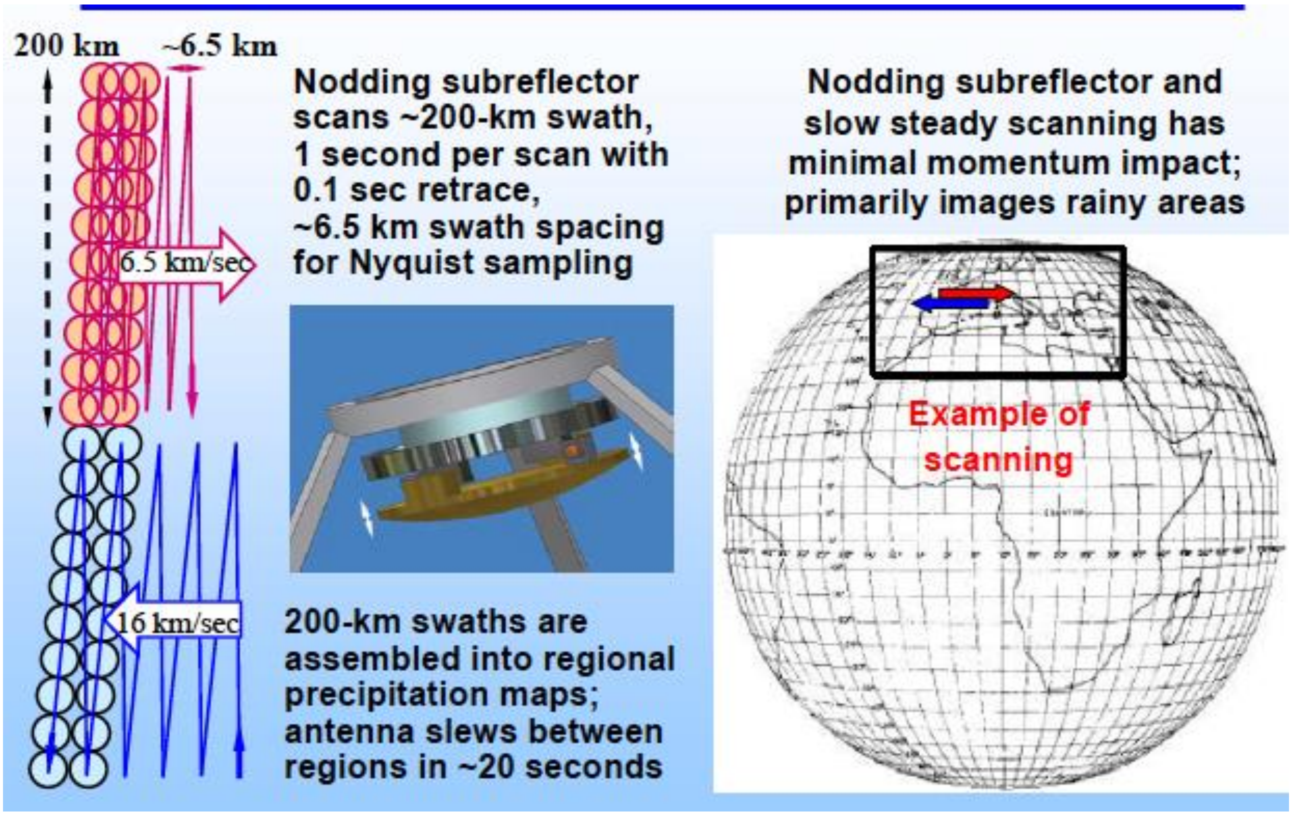
– For H_2O, above the band at 183 GHz, there are several others, the first at 325 GHz, then at 380 GHz and higher.

The choice of bands for GOMAS is 54 GHz, 118 GHz, 183 GHz, 380 GHz and 425 GHz. GOMAS has 40 channels distributed over these five frequency bands.

The GOMAS concept is based on a 3-m antenna diameter. The problem of sensitivity is solved by limiting the scanned area of the Earth's disk. Within the current technological state-of-art it is not possible to scan the full Earth disk in the required short time at the required resolution. A compromise is achieved by scanning a sector of about 1/12 of the disk (250 × 500 pixels) with an integration time of ~6 ms per pixel (see Fig. 17). The scanning mechanism may be driven with different speeds and over areas of different sizes. The reference sector of 1/12 of the disk can be selected everywhere within the disk of the Earth so as to track events of particular interest. In addition, during the satellite lifetime the longitude of geostationary position can be shifted so as to allow observation over the American continents to the Indian Ocean, following seasonal events [11].

FIGURE 17

GEM/GOMAS reference coverage and illustration of the micro-scan concept



(Source: *Application of a CubeSat based passive microwave constellation to operational meteorology, by Prof A.J. Gasiewski, Eumetsat seminar, 2016*).

TABLE 11

Main technical and operational characteristics of Remote Sensor-6 (GOMAS)

Type of mission	The instrument is intended to be flown on a dedicated satellite Proposed to ESA as an Earth Explorer Opportunity Mission.
Type of orbit	Geostationary
Altitude	35,786 km
Inclination	Not applicable
Scanning geometry (N, C, L)	The scanned area can be moved within the Earth disk, and the longitude of geostationary position can be shifted during the satellite lifetime.
Channels centre frequency	54 GHz, 118 GHz, 183 GHz, 380 GHz and 425 GHz
Channels bandwidth	See Table 12
Footprint area	IFOV at s.s.p: 12 km @ 380 GHz, and 10 km @ 425 GHz
Coverage	1/12 of the earth disk can be scanned at any one time. Global with repositioning of GEO location and selection of scan area.

TABLE 12

Channel specifications for Remote Sensor-6 (GOMAS) within the 275-450 GHz range

Channel No.	**Frequency (GHz)**	**Bandwidth (GHz)**	**Utilization**
GOMAS-1	380.17 ± 0.3	0.3	Water
GOMAS-2	380.17 ± 0.9	0.5	
GOMAS-3	380.17 ± 1.65	0.7	
GOMAS-4	380.17 ± 3	1	
GOMAS-5	380.17 ± 5	2	
GOMAS-6	380.17 ± 7	2	
GOMAS-7	380.17 ± 17	4	
GOMAS-8	424.76 ± 0.15	0.06	Oxygen
GOMAS-9	424.76 ± 0.3	0.1	
GOMAS-10	424.76 ± 0.6	0.2	
GOMAS-11	424.76 ± 1	0.4	
GOMAS-12	424.76 ± 1.5	0.6	
GOMAS-13	424.76 ± 4	1	

6.7 Remote Sensor-7: Compact, Adaptable Microwave Limb Sounder (CAMLS)

The CAMLS family of instruments makes measurements needed to address key outstanding issues associated with the composition and structure of Earth’s upper troposphere and lower stratosphere UT/LS (i.e. 10-20 km altitude region) [12].

TABLE 13

Main technical and operational characteristics of Remote Sensor-7 (CAMLS)

Type of orbit	LEO
Altitude	Not available
Inclination	Not available
Scanning geometry (N, C, L)	Limb sounder
Observation Zenith Angle (OZA)	Not applicable
Channels centre frequency	340 GHz
Channels bandwidth	Two wideband 8 000 MHz channel digital polyphase spectrometers, sideband separation in the digital domain
Footprint area	50 km along track for continuity 50 km × 50 km 2D scan for Scanning Microwave Limb Sounding (SMLS) design.

6.8 Remote Sensor-8: Geostationary Microwave Sounder (GMS)

A geostationary microwave sounder (GMS) onboard a Chinese second generation geostationary meteorological satellite – FengYun-4 microwave satellite (FY-4MS) is being developed, which will be launched after 2021. The GMS has several channels operated in the range 275-450 GHz. The

GMS will focus on rapidly changing weather phenomenon observation. It uses real aperture design to ensure the calibration accuracy and the observation reality of dynamic targets. The GMS adopts wide strip and thin circle combined scanning mode. It can scan 7.2 × 7.2° area in 90 minutes, which consists of 8 scan strip, i.e. each strip is 0.9 × 2°. The speed of the detail local scan formed thin circles is 25.75 rpm and the circle diameter is 1.1°. Table 14 summarizes the parameters of the GMS sensor.

TABLE 14

Main technical and operational characteristics of GMS

Type of mission	Payload on FY-4 MS. Operational mission after 2021.
Type of orbit	Geostationary
Altitude	35 800 km
Inclination	Not applicable
Scanning geometry (N, C, L)	Wide strip and thin circle combined scan.
Observation Zenith Angle (OZA)	Not applicable
Channels centre frequency	338 GHz, 380 GHz and 425 GHz
Channels bandwidth	See Table 15
Antenna peak gain	76.5 dBi
Antenna 3 dB beamwidth	0.027°
Footprint area	16 km
Coverage	Any 7.2°×7.2° area within the earth disk

TABLE 15

Channel specifications for Remote Sensor-8 (GMS) within the 275-450 GHz range

Channel No.	Frequency (GHz)	Bandwidth (MHz)	Polarization	Utilization
1	338	4 000	V	Window
2	380.197 ± 18.0	4 000	H	Water vapour
3	380.197 ± 9.0	4 000	H	
4	380.197 ± 4.0	1 800	H	
5	380.197 ± 1.5	1 000	H	
6	380.197 ± 0.4	400	H	
7	380.197 ± 0.045	60	H	
8	424.763±4.0	2 000	H	Oxygen
9	424.763±1.5	1 200	H	
10	424.763±1.0	800	H	
11	424.763±0.6	400	H	
12	424.763±0.3	200	H	
13	424.763±0.15	120	H	
14	424.763±0.07	40	H	
15	424.763±0.03	40	H	

6.9 Remote Sensor-9: Limb sounder MASTER

The Millimetre-wave Acquisitions for Stratosphere/Troposphere Exchange Research instrument (MASTER) is a limb-viewing emission-sensing spectrometer with three millimetre wave and a sub-millimetre wave channel. MASTER was one of the payloads of ACECHEM, a mission proposed to ESA as Earth Explorer Core mission.

The objectives of ACECHEM are to measure and understand the human impact on the chemistry and composition of the lower and middle atmosphere, and to investigate the interactions between atmospheric chemistry, atmospheric composition and climate. This demands the simultaneous and accurate observation of numerous species in the upper troposphere and lower stratosphere, globally and with high vertical resolution. A multi-instrument payload is required to meet the objectives of ACECHEM, including an mm-wave limb sounder called MASTER with four bands in the 296-505 GHz range.

MASTER is designed to make high sensitivity measurements with good vertical resolution (2 km) and frequent along-orbit track sampling. The wavelength range chosen makes it much less sensitive to cloud and aerosol than instruments that target shorter wavelengths. The frequency range selected for MASTER requires the application of the super-heterodyne principle to down-convert the received radiation for further spectral analysis. The proposed instrument concept is a single side-band design. Sampling of the same atmospheric volume as observed by MetOp is achieved by flying the ACECHEM satellite carrying the MASTER instrument in formation with MetOp. The ACECHEM satellite would fly ahead of MetOp and its instruments would look backwards.

The MASTER antenna (offset Cassegrain type) is shared by all five receivers. The vertical and horizontal directivity requirements lead to a system with a large elliptical main reflector of 1 × 2 m. Elevation scanning of the Earth's limb in the standard tangent-height range is achieved by a combination of manoeuvring the complete satellite to the three atmospheric domains indicated in Fig. 18 and moving the main reflector at a constant speed to cover the vertical range of a given domain [13], [14], [15].

FIGURE 18

MASTER observation geometry, showing the standard and extended scan ranges achieved by the platform [14]

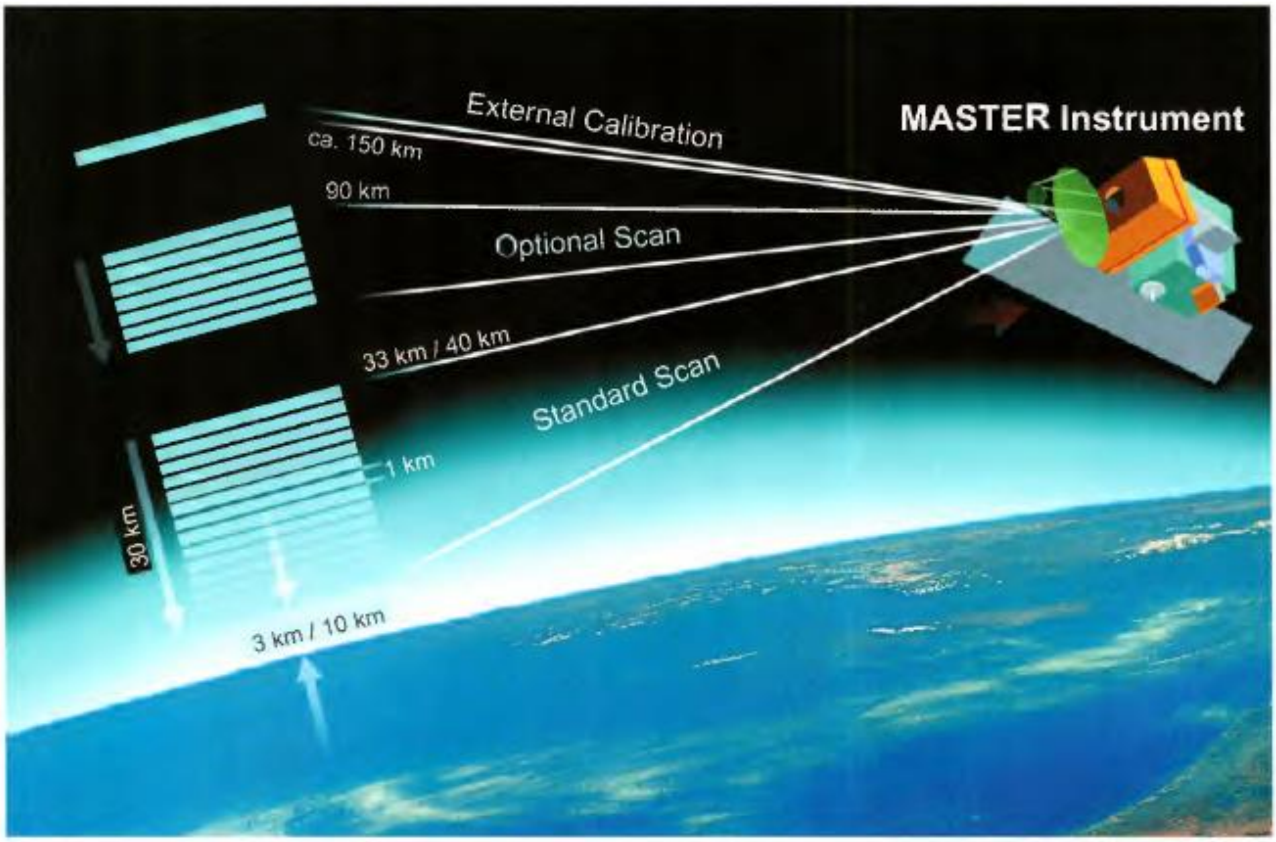


TABLE 16

Main technical and operational characteristics of Remote Sensor-9 (MASTER)

Type of mission	Proposed to ESA as an Earth Explorer Core Mission.
Type of orbit	SSO LEO
Altitude	817 km
Inclination	98.7 degrees
Scanning geometry (N, C, L)	Limb sounder. A vertical profile is measured every 15 s by scanning the instrument's antenna over a tangent height range of 30 km; varying from 33 km down to 3 km at the poles, to 40 km down to I0 km in the tropics.
Observation Zenith Angle (OZA)	Not applicable
Channels centre frequency	(A) 299.75 GHz, (B) 320.0 GHz, (C) 345.6 GHz, (D) 501.5 GHz and (E) 625.25 GHz
Channels bandwidth	(A) 11.5 GHz, (B) 9.0 GHz, (C) 6.5 GHz, (D) 9.0 GHz, (E) 2.5 GHz
Antenna peak gain	Offset Cassegrain reflector (1 m × 2 m)
Footprint area (IFOV)	(A), (B), (C) 2.3 km × 4.6 km, (D), (E) 1.6 km × 3.3 km

7 Characteristics of EESS (passive) systems to be considered in sharing studies in the frequency range 275-450 GHz

The following Table provides a band-by-band summary of EESS (passive) systems to be considered in sharing studies in the frequency range 275-450 GHz. The detailed characteristics of these EESS (passive) systems have been presented in previous sections and have been summarised in Annex 1.

TABLE 17

Mapping criteria for satellite passive remote sensing in the frequency range 275-450 GHz

Frequency band(s) (GHz)	**Scan mode**	
	Scanning (Nadir, Conical, Push-Broom, Cross Track, Raster)	**Limb**
275-286	---------	Consider characteristics similar to STEAMR (Note)
296-306	Consider characteristics similar to ICI (Note)	MASTER (SSO LEO orbit, § 6.9)
313-356	ICI (SSO LEO orbit, § 6.1) SSM (SSO LEO orbit, § 6.3) GEM (GSO orbit, § 6.5) GMS (GSO orbit, § 6.8)	STEAMR (SSO LEO orbit, § 6.4) CAMLS (SSO LEO orbit, § 6.7) MASTER (SSO LEO orbit, § 6.9)
361-365	Consider characteristics similar to ICI (Note) GMS (GSO orbit, § 6.8)	Consider characteristics similar to STEAMR (Note)
369-392	TWICE (SSO LEO orbit, § 6.2) GEM (GSO orbit, § 6.5) GOMAS (GSO orbit, § 6.6) GMS (GSO orbit, § 6.8)	
397-399	Consider characteristics similar to ICI (Note) GMS (GSO orbit, § 6.8)	
409-411	---------	
416-434	GOMAS (GSO orbit, § 6.6) GMS (GSO orbit, § 6.8)	
439-467	ICI (SSO LEO orbit, § 6.1)	

NOTE – For the bands for which current operating or planned systems are not available characteristics based on systems in other bands should be used.

It should be noted that the current reference EESS (passive) antenna pattern as given in Recommendation ITU-R RS.1813 is valid in the 1.4 to 100 GHz range. However, for the time being, it is recommended that the pattern in Recommendation ITU-R RS.1813 be used in the 275-450 GHz range.

8 References

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Annex 1

Summary of technical characteristics of EESS (passive) systems in 275-450 GHz frequency range

Instrument	ICI	TWICE	SMM	STEAMR	GOMAS	GEM	CAMLS	MASTER	GMS
Type of Orbit	SSO LEO	SSO LEO	SSO LEO	SSO LEO	GSO	GSO	LEO	SSO LEO	GSO
Altitude (km)	817	400	not available	817	35 684	35 684	not available	817	35 684
Inclination (degrees)	98.7	High inclination	High inclination	98.7	0	0	not available	98.7	0
Scanning mode	Conical (Fig. 10)	Conical (Fig. 11)	Conical or cross track (Fig. 13)	Limb (Fig. 15)	Conical (Fig. 17)	Conical	Limb	Limb	wide strip and thin circle combined scan (Fig. 9)
Observation Zenith Angle (OZA) (degrees) for conical scan, or Min. pointing altitude (km), for limb scan	Conical: 53 ± 2	Conical: 53	not available	Limb: 6	not available	not available	Limb: 10	Limb: 3	**N/A**
RF Centre Frequency (GHz)	325.15 448	310 380.2	325	319.5 349.6	380.197 424.763	380.197 425.763	340	299.75 320.0 345.6	338 380.197 424.763
RF Bandwidth (GHz)	3.2 – 6 2.4 – 6 (Table 4)	10 7.2	not available	12 12	0.3 – 4 0.06 – 1 (Table 12)	0.05-18 (LSB)	16	11.5 9.0 6.5	0.03-8 0.01-1
Antenna type	Offset reflector, multiple feeds	Broadband multi-flare horns	not available	Reflector antenna	Filled aperture scanning	Filled aperture scanning	not available	Elliptical Offset reflector	Reflector Antenna
Antenna Peak Gain (dBi)	55	46-48 (TBC)	not available	70	not available	not available	not available	not available	**76**
Antenna Diameter (m)	~ 0.5	not available	not available	not available	3	2	not available	1 × 2	3
Antenna Beamwidth (degrees)	not available	0.64° 0.56°	not available	See Fig. 15	0.019° 0.017°	0.029° 0.026°	not available	not available	0.027°
FOV (km) Footprint area (km^2)	16 Area ≈ 200 km^2 (Table 3)	FOV: 6.5 × 9.9 Area ≈ 50 km^2 FOV: 5.8 × 8.7 Area ≈ 40 km^2 (Fig. 6.2-2)	not available	N/A (See Fig. 15)	IFOV: 12 Area ≈ 110 km^2 IFOV: 10 Area ≈ 75 km^2	FOV: 20.5 Area ≈ 330 km^2 FOV: 16.4 Area ≈ 210 km^2	N/A (See Table 13)	N/A (See Table 17)	IFOV: 16

Annex 2

Passive bands of scientific interest for EESS between 275 and 475 GHz (Table in Report ITU-R RS.2194 revised the column with existing/planned instruments)

Frequency band(s) (GHz)	**Total bandwidth required (MHz)**	**Spectral line(s) (GHz)**	**Measurement**			**Typical scan mode**	**Existing or planned instrument(s)**	**Supporting information**
			Meteorology – Climatology	**Window (GHz)**	**Chemistry**			
275-285.4	10 400	276.33 **(N_2O),** 278.6 **(ClO)**		276.4-285.4	N_2O, ClO	Limb		**Chemistry** (275-279.6), **Window** (276.4-285.4)
296-306	10 000	Window for 325.1, 298.5 **(HNO_3)**, 300.22 **(HOCl)**, 301.44 **(N_2O)**, 303.57 **(O_3)**, 304.5 **($O^{17}O$),** 305.2 **(HNO_3)**	Wing channel for temperature sounding	296-306	OXYGEN, N_2O, O_3 , $O^{17}O$, HNO_3, HOCl	Nadir, Limb	MASTER	**Window** (296-306), **Chemistry** (298-306)
313.5-355.6	42 100	313.8 **(HDO)**, 315.8, 346.9, 344.5, 352.9 **(ClO)**, 318.8, 345.8, 344.5 **(HNO_3)**, 321.15, 325.15 **(H_2O)**, 321, 345.5, 352.3, 352.6, 352.8 **(O_3)**, 322.8, 343.4 **(HOCl)**, 345.0, 345.4 **(CH_3Cl)**, 345.0 **($O^{18}O$)**, 345.8 **(CO)**, 346 **(BrO),** 349.4 **(CH_3CN)**, 351.67 **(N_2O),** 354.5 **(HCN)**	Water vapour profiling, cloud, Wing channel for temperature sounding	339.5-348.5	H_2O, CH_3Cl, HDO, ClO, O_3, HNO_3, HOCl, CO, $O^{18}O$, HCN, CH_3CN, N_2O, BrO	Nadir, Conical, Limb	STEAMR, MASTER, CLOUDICE, ICI, GOMAS, GEM, SSM, CAML	**Water vapour line at 325.15** (314.15-336.15, BW: 3 GHz, max. offset: 9.5 GHz), **Cloud Measurements** (331.65-337.65, 314.14-348, 339-348, 314.14-317.15, 320.45-324.45, 325.8-329.85, 336-344, 339-348), **CLOUDICE** (314.15-336.15), **ICI** (313.95-336.35), **Window** (339.5-348.5), **GEM Chemistry** (342-346), **STEAMR Chemistry** (310.15-359.85)
361.2-365	3 800	364.32 **(O_3)**	Wing channel for water vapour profiling		O_3	Nadir, Limb	GOMAS	**GOMAS Water vapour** (361-363), **Chemistry** (363-365)

Frequency band(s) (GHz)	Total bandwidth required (MHz)	Spectral line(s) (GHz)	Measurement			Typical scan mode	Existing or planned instrument(s)	Supporting information
			Meteorology – Climatology	Window (GHz)	Chemistry			
369.2-391.2	22 000	380.2 **(H_2O)**	WATER VAPOUR PROFILING			Nadir, Limb	GEM, GOMAS. TWICE	**Water vapour line** (369.2-391.2, BW: 3 GHz, max. offset: 9.5 GHz), **GEM Water vapour sounding** (379-381), **Water vapour profiling** (371-389), Polar-orbiting and GSO satellites (FY4) for precipitation over snow-covered mountains and plains (near 380) **GOMAS** (370.2-390.2)
397.2-399.2	2 000		WATER VAPOUR PROFILING				GOMAS	**GOMAS** (397.2-399.2)
409-411	2 000		Temperature sounding			Limb		
416-433.46	17 460	424.7 **(O_2)**	OXYGEN, Temperature profiling			Nadir, Limb	GEM, GOMAS	**Oxygen line** (416.06-433.46, BW: 3 GHz, max. offset: 7.2 GHz), **GEM Oxygen** (416-433) **GOMAS** (420.26-428.76)
439.1-466.3	27 200	442 **(HNO_3)**, 443.1, 448 **(H_2O)**, 443.2 **(O_3)**	WATER VAPOUR PROFILING, CLOUD	458.5-466.3	O_3, HNO_3, N_2O, CO	Nadir, Limb, Conical	ICI, CLOUDICE	**Water line** (439.3-456.7, BW: 3 GHz, max. offset: 7.2 GHz), **Cloud measurements** (452.2-458.2, 444-447.2, 448.8-452, 459-466), **CLOUDICE (**439.3-456.7), ICI (439.1-456.9), **Chemistry** (442-444), **Window** (458.5-466.64)
