International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R RS.2194

(10/2010)

Passive bands of scientific interest to EESS/SRS from 275 to 3 000 GHz

RS Series

Remote sensing systems

International Telecommunication Union

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.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Annex 1 of Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from http://www.itu.int/ITU-R/go/patents/en where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Reports

(Also available online at http://www.itu.int/publ/R-REP/en)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	Mobile, radiodetermination, amateur and related satellite services
P	Radiowave propagation
RA	Radio astronomy
RS	**Remote sensing systems**
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management

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

Electronic Publication
Geneva, 2010

REPORT ITU-R RS.2194

Passive bands of scientific interest to EESS/SRS from 275 to 3 000 GHz

(2010)

TABLE OF CONTENTS

1 Introduction

This Report provides relevant passive bands of interest to Earth exploration-satellite service (passive) (EESS(passive)) and space research service (passive) (SRS (passive)) in the 275-3 000 GHz frequency range and the corresponding scientific rationale.

It also provides information on EESS (passive) systems that are currently operating or planned to operate in the 275 to 3 000 GHz frequency range. Information on current and planned spaceborne passive remote sensing systems was reviewed for applicable information. Scientific literature and personnel were surveyed and consulted to determine currently known frequency bands of interest.

In addition, studies were conducted to examine possible interference to the Earth observing passive sensors from stations that may operate in the active services, both terrestrial and space-based, in the 1 000-3 000 GHz band.

2 Primary EESS measurement classes

There are two primary EESS measurement "classes", 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 (there is a direct correlation between the temperature and the sub-millimetre emissions from oxygen). The atmospheric chemistry sensing measures the many smaller spectral lines of the various atmospheric chemical species.

An important difference between the two classes is in the geometry of the measurement. Most meteorology/climatology measurements are performed using vertical nadir sounders at lower frequencies (typically below 600 GHz) and limb sounders at higher frequencies whereas atmospheric chemistry measurements are mostly performed using limb sounding across the whole frequency range.

In some cases, apparent redundant coverage (a single molecule is observed in several different bands) is needed for several reasons, such as different bands being sensitive to different altitudes.

2.1 Meteorology/climatology

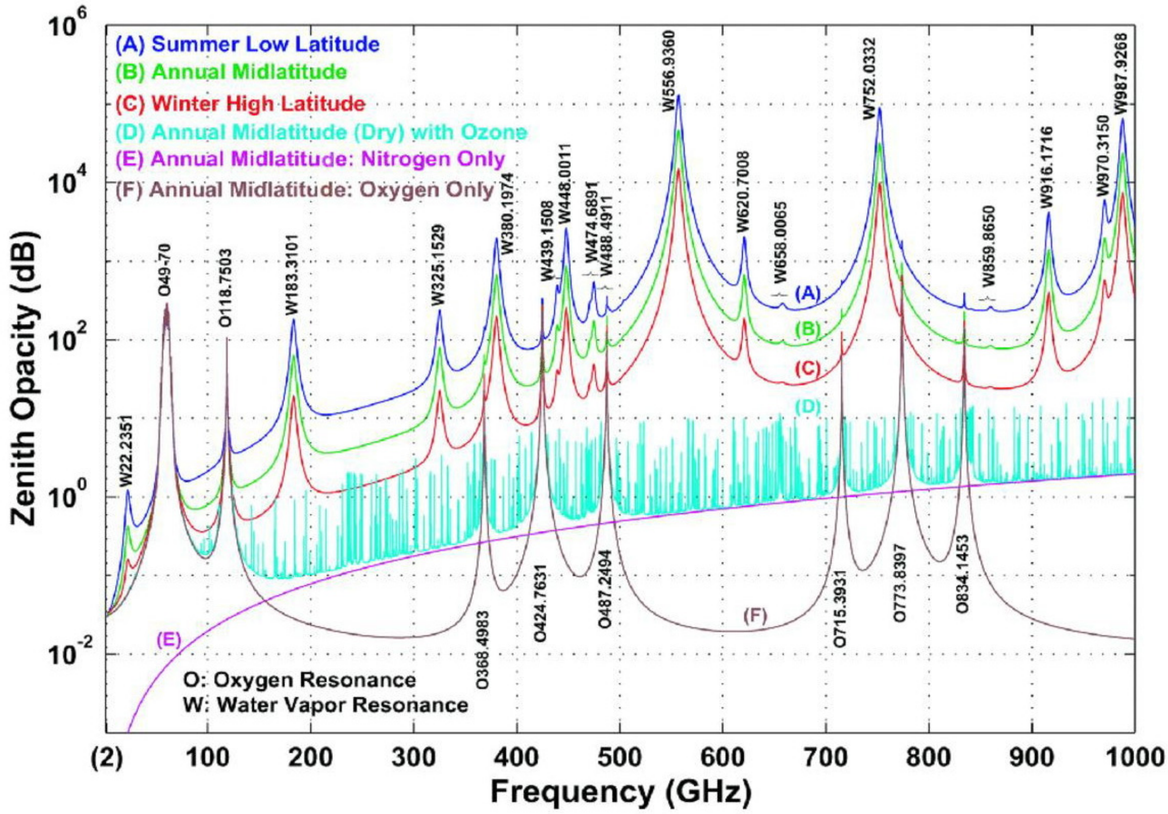
Figure 1 shows the sensitivity of millimetre and sub-millimetre frequencies to atmospheric temperature and water vapour variations between 2 and 1 000 GHz. The water vapour and oxygen resonance spectral lines are indicated in the figure as well.

The figure shows the increasing atmospheric attenuation at higher frequencies and the sizable variability of the attenuation due to water vapour.

For this reason the low frequencies (below 200 GHz) are the most suitable for vertical nadir measurements of the lower layers of the atmosphere, while the higher frequencies are better suited for 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.

FIGURE 1

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



Among these bands, it has to be stressed that ranges around the water vapour resonance at 325 and 380 GHz and the 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 for technology to provide 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 the retrieval of precipitation over snow-covered mountains and plains and in the driest polar areas where even the most opaque 183 GHz channels become transparent. The only remedy for transparency is a more opaque water vapour band and 380 GHz seems to be a uniquely good choice.

Among oxygen lines, one can also note that the resonance line at 368 GHz is not considered since it is masked by the nearby 380 GHz water vapour resonance line.

Cloud ice and water vapour are two components of the hydrological cycle in the upper troposphere, and both are currently poorly measured. The hydrological cycle is the most important subsystem of the climate system for life on the planet and its understanding is of the utmost importance. The use of passive sub millimetre-wave measurements to retrieve cloud ice water content and ice particle size was suggested years ago by Evans and Stephens (*Evans KF, Stephens GL. 1995. Microwave radiative transfer through clouds composed of realistically shaped ice crystals. Part II: Remote sensing of ice clouds. J. Atmos. Sci. 52: 2058–2072*) and refined in subsequent publications. Since then, a number of missions have been proposed that focus on this technique to measure cloud ice water path, ice particle size and cloud altitude to US and European Space Agencies.

---

[1] The sensitivity of millimeter and sub-millimeter frequencies to atmospheric temperature and water vapour variations. Journal of Geophysical Research-Atmospheres, 13, from A.J. GASIEWSKI and M. KLEIN.

Currently, these measurements focus on the 183 GHz, 243 GHz, 325 GHz, 340 GHz, 380 GHz, 425 GHz, 448 GHz, 664 GHz and 874 GHz. The vertical water vapour and oxygen sounding measurements are typically performed using a set of channels, composed of so-called "wings" and associated "window".

The "window" corresponds to a frequency range where the effect of the resonance line is minimal. Corresponding measurements are used to determine the component that are not linked to the specific resonance line under investigation and that will then be eliminated from the "wings" measurements.

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 and providing therefore the water vapour and oxygen vertical profiles.

The measurements on the wings around the main resonance lines are sometimes presented individually, while in other cases the frequency requirement is expressed as the whole range needed to cover all the individual measurements. Indeed, for a given resonance curve, there is not always consistency in the definition of the offsets needed for these wing measurements, depending on the different instruments characteristics (bandwidth, offset and number of slots) or investigation strategies. To cover all cases, the required total frequency band can hence be defined as the maximum bandwidth (BW) plus twice the maximum offset, centred on the resonance frequency.

It should be noted that the frequency band corresponding to the "wings" measurements is not necessarily contiguous to the associated "window".

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 as demonstrated in Jimenez *et al.* (Performance simulations for a sub-millimetre wave cloud ice satellite instrument, Q.J.R. Meteorol. Soc , Vol. 133, No. S2, p. 129-149, 2007), Mech *et al.* (Information content of millimetre observations for hydrometeor properties in mid-latitudes, IEEE Trans. Geosci. Remote Sens., 45, 2287-2299, 2007) or Defer *et al.* (Development of precipitation retrievals at millimetre and sub-millimetre wavelengths for geostationary satellites, J. Geophys. Res., 113, D08111, doi:10.1029/2007JD008673, 2008).

2.2 Atmospheric chemistry

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 a large number of chemical species in the atmosphere and refer to spectral lines that are much narrower and larger in numbers than the water vapour and oxygen resonance lines.

Among others, the following ones represent a subset of important species to be studied:

HNO_3: **Nitric acid**

The most important reservoir for odd nitrogen in the atmosphere is nitric acid. It plays an important role in heterogeneous chemistry in polar stratospheric clouds. It comprises 90% of NO_y in the lower stratosphere. HNO_3 plays role in air quality, atmospheric oxidation efficiency and stratospheric ozone depletion. This acid also shows a strong latitudinal gradient and is a useful tracer of stratospheric dynamics.

SO_2: **Sulphur dioxide**

A key species in formation of sulphate particles is sulphur dioxide. It is produced from the oxidation of biogenic compounds and emitted directly by volcanoes. SO_2 is an important tropospheric pollutant involved in rainfall acidification, smog formation and aerosol formation. Monitoring mid-upper tropospheric concentrations is important in understanding trans-national pollutant transport. Anthropogenic emissions stem mainly from fossil-fuel combustion. They continue to be globally very large despite the effective desulphurisation technology developed and applied in most developed countries.

CH_3Br: **Methyl bromide**

Methyl bromide has both natural and anthropogenic sources and accounts for about 50% of the global organic bromine emissions. There are large uncertainties in the global trend of total organic bromine in the troposphere. It plays role in the stratospheric ozone layer depletion.

CH_3Cl: **Methyl chloride**

Methyl chloride is important halogen source which plays a role in atmospheric ozone layer depletion.

NO, NO_2: **Nitric oxide, nitric dioxide**

These two reactive nitrogen species are often referred to as NOx, play a critical role in atmospheric chemistry. NOx is released into the troposphere by biomass burning, combustion of fossil fuels and lightning. In troposphere NOx is a dominant factor in the in situ photochemical catalytic production of O_3. Nitric oxide.

BrO: **Bromine monoxide**

BrO is an active halogen compound. Its principal importance is in the stratosphere where it participates in chain reactions which destroy ozone. The details of the variation of BrO are essential in the verification of the models used to describe the atmosphere, and to obtaining accurate picture of the state of the atmosphere, particularly the dynamics in the stratosphere.

N_2O: **Nitrous oxide**

There are natural land-surface sources and anthropogenic sources of nitrous oxide. It is a greenhouse gas with a tropospheric mean residence time of 120 years. Its concentration is increasing in the atmosphere at a rate of 0.25% per year. There are major unknowns in its global cycle that remain to be resolved. N_2O is often used as a tracer for stratospheric dynamics and stratospheric/tropospheric exchange studies.

CO: **Carbon monoxide**

The origin of CO is predominantly anthropogenic. It is mainly being produced by the combustion of fossil fuel. CO has a direct influence on the greenhouse gas concentrations of CO_2 and O_3.

HCl/HOCL: **Hydrochloric acid / Hypochlorous acid**

HCl is a major reservoir compound for inorganic stratospheric chlorine, which plays a role in ozone depletion. Current observations show that the total column abundances of HCl are currently starting to decrease. These results provide robust evidence of the impact of the regulation of the Montreal protocol and its subsequent amendments on the inorganic chlorine loading of the stratosphere. HOCl is also a chlorine reservoir. Reservoir forms of chlorine (HCl, $ClONO_2$ and

HOCl) are converted to ClO by heterogeneous reactions on polar stratospheric clouds.

ClO: **Chlorine monoxide**

ClO is the main trace gas involved in the catalytic destruction of stratospheric ozone at high latitudes. ClO is an active halogen compound. Its principal importance is in the stratosphere where it participates in chain reactions which destroy ozone. The details of the variation of ClO are essential in the verification of the models used to describe the atmosphere, and to obtaining accurate picture of the state of the atmosphere.

O_3: **Ozone**

The 623-661 GHz band (technically, a set of 3 bands with gaps between them) is viewed as being critical to protect above 275 GHz. This band is particularly well suited for microwave limb sounding and contains good spectral lines for most of the species contributing to ozone chemistry as it is currently understood.

OH: **Hydroxyl**

The EOS Microwave Limb Sounder, or MLS, produces an extensive dataset for tracking stratospheric ozone chemistry. It provides the first global measurements of OH and HO, the chemically reactive species in hydrogen chemistry that dominates ozone destruction at 20-25 km outside winter polar regions, and at heights above 45 km. Our present understanding of hydrogen chemistry in the upper stratosphere is in question due to some observations of OH that are in disagreement with current theory (R.R. Conway, M.E. Summers, M.H. Stevens, J.G. Cardon, P. Preusse, and D. Offermann, "Satellite observations of upper stratospheric and mesospheric OH: The HO dilemma," Geophys. Res. Lett., Vol. 27, pp. 2613–2616, 2000). One MLS objective is to resolve this discrepancy.

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 required for a measurement at 300 GHz). This is essentially due to the fact that the sensor filtering capability is limited 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 side of the spectral line would be sufficient for measurements between 500 and 1 000 GHz.

2.3 Specificities of the 1 000 to 3 000 GHz range

Water vapour and oxygen resonance lines above 1 000 GHz are not expected to be of interest for meteorological/climatological investigations.

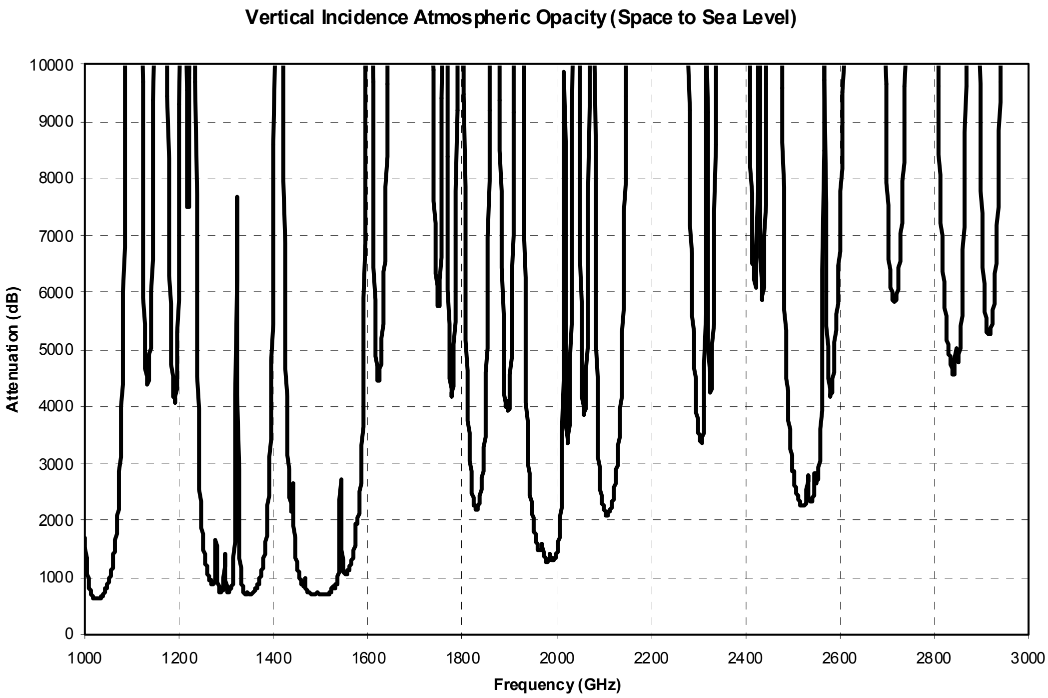
There are a large number of spectral lines that may be of interest for chemistry atmospheric limb sounding between 1 000 GHz and 3 000 GHz. A good source for information on these spectral lines is the Jet Propulsion Laboratory (JPL) Molecular Spectroscopy Catalogue which can be accessed at: http://spec.jpl.nasa.gov/.

Due to the very large number of stratospheric and tropospheric molecules spectral absorption lines that are found in this frequency range, the atmospheric chemistry spectral lines become extremely dense above 1 000 GHz, meaning that, potentially, any frequency above 1 000 GHz could be used for future measurements from satellites. The hydroxyl lines (OH) around 1 836 and 2 508 GHz are identified as lines of particular interest.

On the other hand, the Earth's atmosphere is virtually opaque at frequencies above 1 000 GHz. Figure 2 shows atmospheric absorption calculated for a mid-latitude location that is moderately wet.

FIGURE 2

Total vertical atmospheric opacity between 1- and 3- TeraHertz



From Fig. 2, the minimum atmospheric absorption is hundreds of dB. Consequently, terrestrial services would not present interference potential to spaceborne passive sensors. Similarly, such instruments are expected to be limb sounding, rather than nadir pointing, measurements and potentially subject only to interference from space-to-space communications, should any exist.

Because of the above, no specific spectral lines above 1 000 GHz are identified from a scientific point of view, but it is generically indicated that the whole 1 000-3 000 GHz range is of interest for EESS (passive) chemistry measurements. At the same time it is notable that this passive use of the spectrum between 1 000 and 3 000 GHz will not put any constraint on systems of active terrestrial services that may be deployed in the future in this frequency range.

2.4 Ground-based and balloon-based sensors

In case of ground-based passive remote sensing, observation upward is made only in atmospheric windows. Balloon-based passive remote sensing is much freer from the tropospheric heavy absorption by water vapour and oxygen, so that observations of various molecules and atmospheric properties in the stratosphere can be made in the same frequency bands used by EESS satellite sensors. Balloon-based passive remote sensing system has some advantages comparing with satellite measurements. It gives better vertical resolution for the middle and the lower stratosphere, and can measure diurnal change of atmosphere state around a specific location, which is generally difficult to measure from a satellite.

3 Compatibility with active service systems

In applications above 275 GHz, there can be communications as well as scientific applications. This study examines the geometries of example systems to illustrate the frequency sharing feasibility, between an inter-satellite service (ISS) system and an EESS system.

3.1 Atmospheric absorption

3.1.1 275-1 000 GHz

The 275-1 000 GHz frequency range is characterized by windows of transparency interlaced with windows of opacity. Strong absorption peaks exist due to the presence of diatomic oxygen (O_2) and water vapour (H_2O) in the atmosphere. The windows of transparency are in frequency regions between these widely separated peaks. In these bands, atmospheric attenuation is about equal to free space loss.

The 275-1 000 GHz frequency range should be considered as a distinct band from the frequency range above 1 000 GHz regarding propagation. Short-range radio systems can be designed with centre frequencies in frequency windows of transparency. Such designs can neglect noise contributions due to adjacent band interference (if such adjacent bands exist in absorption peaks). In the 275-1 000 GHz bands, if the frequencies are between absorption peaks, consideration of sharing with other services or systems may be required.

Earth-space link budgets have two loss components: free space loss and atmospheric loss. Free space loss extends over the entire path length between Earth and space. Atmospheric loss occurs mostly within the troposphere. Slant range is a function of elevation angle. The slant range d to the upper reach of the troposphere has been modelled as:

$$d = r_{eff}^2 \sin^2(E) + r_{eff}(r_{eff} + r_T)^2 - r_{eff}\sin(E)$$

where:

- d: the slant range through the troposphere (km)
- r_{eff}: the effective Earth radius (km)
- r_T: the nominal height of the troposphere, usually taken as 10 km
- E: the elevation angle.

The effective Earth radius is 4/3 times the Earth radius, which is approximately 8 500 km. The atmospheric loss is equal to the specific attenuation times the slant range.

3.1.2 1 000-3 000 GHz

In the range 1 000-3 000 GHz, propagation through Earth's atmosphere is strongly affected by absorption due to atmospheric molecules. The molecular species most responsible for the absorption are oxygen (O_2) and water vapour (H_2O). Non-resonant absorption creates a general continuum of absorption that steadily increases with frequency, while exceedingly large values of attenuation are found at specific frequencies corresponding to natural resonances of the molecules. At sea level, the general continuum of absorption ranges from approximately 300 dB/km at 1 000 GHz to approximately 4 000 dB/km at 3 000 GHz. At specific molecular resonances, the attenuation can be as large as 500 000 dB/km or more.

Attenuation will decrease with altitude due to lower concentrations of oxygen and water vapour. Figure 3, using the assumed atmospheric properties found in Table 1, shows attenuation in dB/km at 4 different altitudes: sea level, 300 m, 1 000 m, and 3 000 m. The curve assumes the 1976 Standard Atmosphere model[2, 3], with the addition of a column of 2 cm total precipitable water vapour with a scale height of 2 km, at a sea-level relative humidity of 50%.

---

[2] U.S. Standard atmosphere [1976] U.S. Government Printing Office, Washington DC, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539_1977009539.pdf.

[3] Standard atmosphere calculator available at: http://www.luizmonteiro.com/StdAtm.aspx.

FIGURE 3

Atmospheric attenuation computed over horizontal paths of 1 km at four different altitudes, assuming the atmospheric properties of Table 1

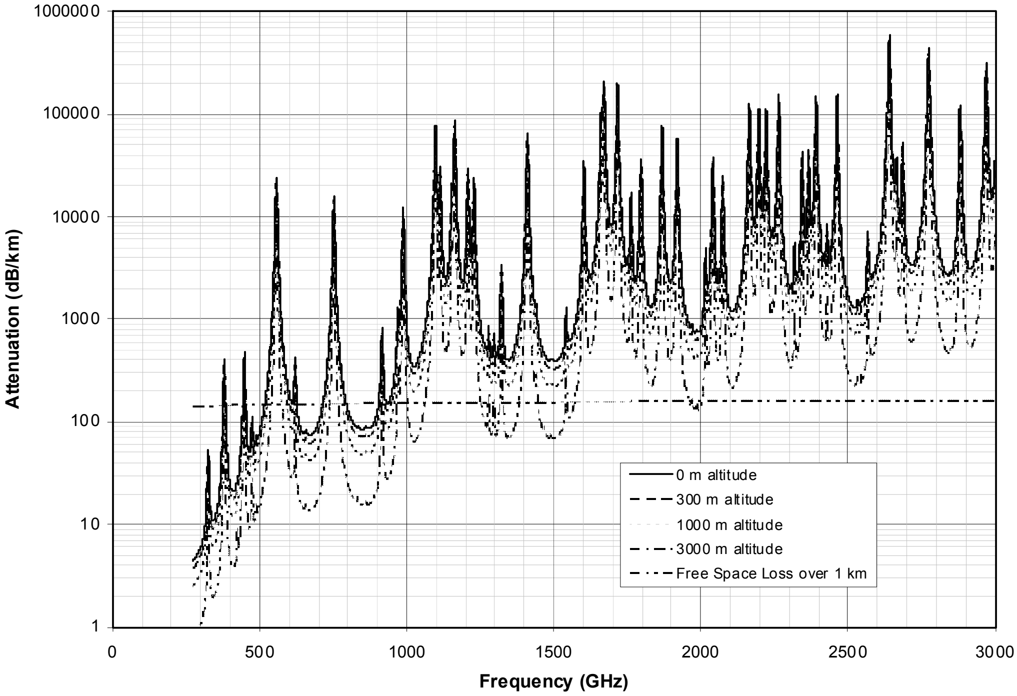


TABLE 1

Assumed atmospheric properties for calculating absorption over a horizontal path of 1 km in length

Altitude (m)	Temperature (K)	Pressure (mbar)	Column density of dry air (cm^{-2})	Column density of water vapour (cm^{-2})
0	288.15	1013.25	2.55×10^{24}	3.34×10^{22}
300	286.20	977.73	2.47×10^{24}	2.87×10^{22}
1 000	281.65	898.75	2.31×10^{24}	2.03×10^{22}
3 000	268.65	701.09	1.89×10^{24}	7.45×10^{21}

The atmospheric parameters were used in the *am* atmospheric transmission model to compute the absorption curves. Based on the assumed atmospheric characteristics, the following inputs were used in the *am* model.

Because atmospheric absorption is a strong factor for terrestrial systems at frequencies above 1 000 GHz, calculation of path loss between a transmitter and receiver must include this factor. The signal level at the receiver is:

$$P_R = P_T + G_T + G_R - P_L - A$$

where:

P_R: the power at the output port of the receive antenna

P_T: the power at the input port of the transmit antenna

G_T: the gain of the transmit antenna in the direction of the receive antenna

G_R: the gain of the receive antenna in the direction of the transmit antenna

PL: the "normal" path loss between transmit and receive antennas due to geometric spreading and terrain blockage

A: the additional loss factor due to atmospheric absorption.

All terms are expressed in logarithmic units.

Due to extreme atmospheric absorption, typically the only possible interference scenarios involve a transmitter and victim receiver that are line-of-sight to one another, and therefore the *PL* factor is free space loss:

$$PL(\text{dB}) = 20 \log D_{km} + 20 \log f_{\text{GHz}} + 92.44$$

where:

D_{km}: the distance between the transmitter and the receiver (km)

f_{GHz}: the frequency (GHz).

At sea level, the minimum baseline absorption rate is approximately 300 dB/km at 1 000 GHz (i.e. $A \approx 300\ D_{km}$). Solving for D_{km} at which $PL = A$ shows that atmospheric absorption A will be greater than free space loss PL for any distance greater than approximately 0.5 km (free space loss and atmospheric absorption are both ~150 dB). At 3 000 GHz, the baseline absorption rate is approximately 4 000 dB/km, and the corresponding distance at which absorption is greater than the calculated free-space loss is about 33 m (loss/absorption are both ~132 dB), although this is less than the near field distance of a small 10 cm diameter antenna and the free-space loss formula breaks down. At specific absorption resonance peaks, these distances shrink dramatically. Consider for example a resonance near 1 411 GHz, where sea level attenuation exceeds 65 000 dB/km. Attenuation exceeds the calculated free space loss at a distance of only 1.6 m, which is again less than the near field distance of a very small antenna.

At higher elevations the conclusions are similar. At 3 000 m altitude and 1 000 GHz frequency, the baseline absorption rate is approximately 100 dB/km, and atmospheric attenuation exceeds free-space loss for distances over about 1.6 km. At 3 000 GHz, the baseline absorption rate is approximately 1 000 dB/km, and the distance is about 150 m.

Due to these atmospheric absorption rates it can be concluded that based on distance, sharing between EESS and ground based active services in the range 1 000-3 000 GHz should not be problematic.

3.2 Sharing in the 1 000-3 000 GHz Region

3.2.1 Antenna beamwidth

One factor common to all applications in the 1 000 to 3 000 GHz range is small antenna beam sizes, which greatly reduces the possibility of accidental interference. The beamwidth of a dish antenna, measured in degrees, is given by the approximate formulae:

$$\theta_{deg} \approx (1\ 720) / (\alpha\, f_{\text{GHz}}\, d_{cm})$$

where:

θ_{deg}: the approximate beamwidth (degrees)

f_{GHz}: the frequency (GHz)

d_{cm} the antenna's physical diameter (cm)

α: a parameter (≤ 1) that is effectively the fraction of the diameter of the dish illuminated by the feed.

A given size antenna will produce a smaller beamwidth with increasing frequency; alternatively, at a given frequency, a larger dish will create a smaller beamwidth (assuming α remains constant). Some example beamwidths for 5 cm, 10 cm, and 30 cm antennas are provided in Table 2.

TABLE 2

Example beamwidths ≥ 1 000 GHz

	Frequency (GHz)				
Antenna size (cm)	**1 000**	**1 500**	**2 000**	**2 500**	**3 000**
5	0.46°	0.31°	0.23°	0.18°	0.15°
10	0.23°	0.15°	0.11°	0.09°	0.08°
30	0.08°	0.05°	0.04°	0.03°	0.03°

The systems selected for this study all use the 5 cm antenna at 1 000 GHz since this provides the largest beamwidth, and the greater probability of interference and interaction between systems.

3.2.2 EESS sensor

At frequencies above 275 GHz there are EESS applications where systems monitor the edge of the Earth's atmosphere. Typically, these missions are polar-orbiting missions. For this study, a limb scanning instrument was affixed to a polar-orbiting satellite. Orbit and instrument details are provided in Table 3. Figure 4 illustrates the instrument installation and geometry of such a system.

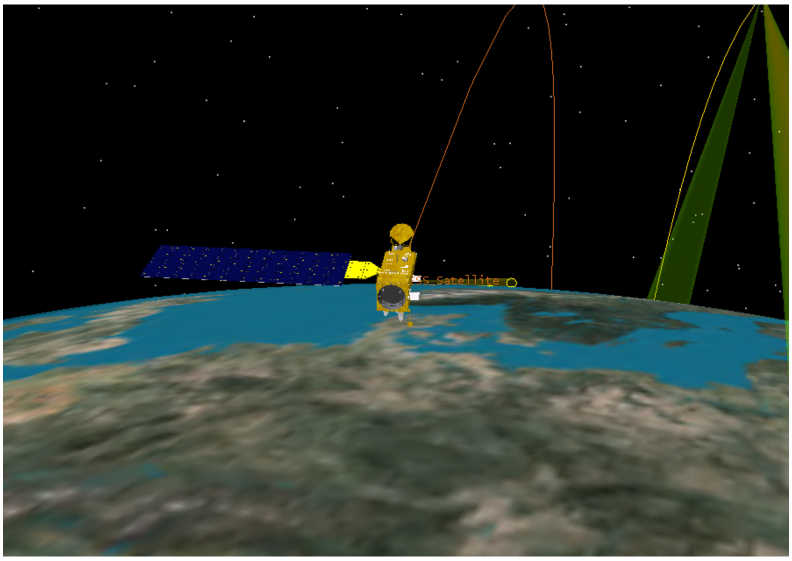
TABLE 3

EESS satellite orbit and instrument parameters

EESS satellite parameters	**Values**
Altitude (km)	705
Inclination (degrees)	98.2
EESS sensor parameters	
Beamwidth (degrees)	0.46
Pointing in azimuth (degrees)	0.0
Pointing in elevation (degrees)	–25.9

FIGURE 4

EESS satellite with a limb scanning sensor



3.2.3 ISS applications

One potential future use for systems above 275 GHz is for ISS communications links. These links would typically be short links between satellites in LEO. In the simulation provided, a conservative assumption of an ISS receiver with a 0.46° field of view was made. Satellite and receiver details are provided in Table 4. The ISS satellite used has four sensors, two for tracking satellites in the same plane (one forward and one aft) and two receive signals from the port and starboard sides of the spacecraft. Figure 5 illustrates the system geometry.

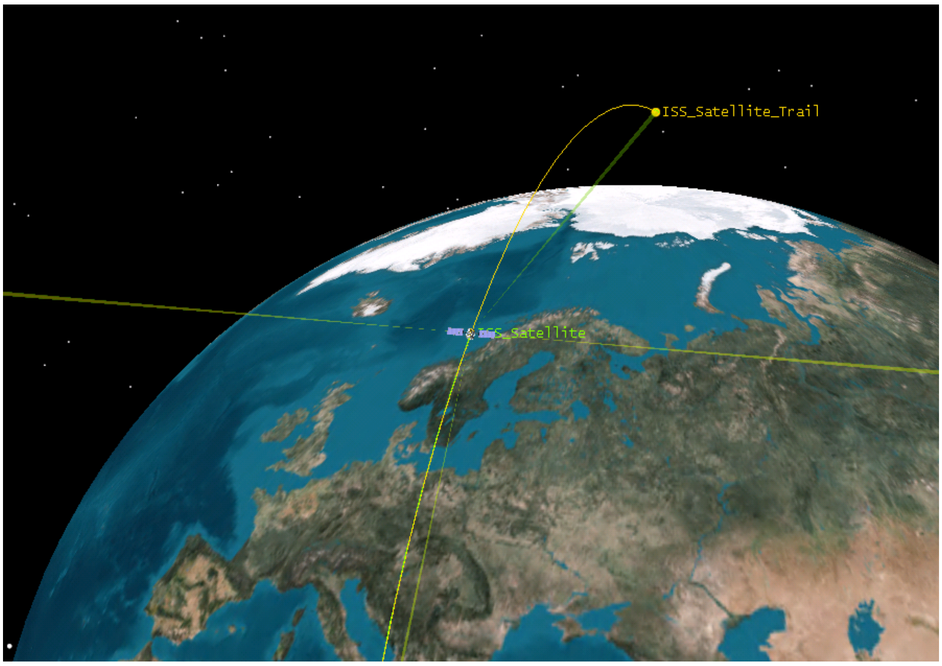
TABLE 4

ISS satellite orbit and receiver parameters

ISS satellite parameters	Values
Altitude (km)	780
Inclination (degrees)	86.4
ISS receiver parameters	
Receiver beamwidth (degrees)	0.46
Forward receiver azimuth (degrees)	0
Forward receiver elevation (degrees)	–17.5
Starboard receiver azimuth (degrees)	90
Starboard receiver elevation (degrees)	0
Rear receiver azimuth (degrees)	180
Rear receiver elevation (degrees)	–17.5
Port receiver azimuth (degrees)	270
Port receiver elevation (degrees)	0

FIGURE 5

ISS satellites and receiver fields of view

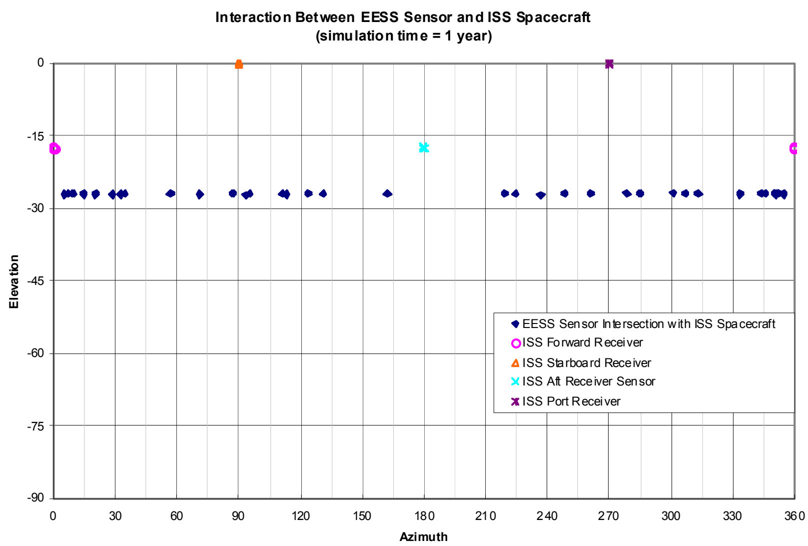


3.3 Simulation

During the 1-year simulation period, although there are instances when the ISS satellite is within the field of view of the ESSS sensor, the ESSS sensor's beam never intersects with any of the four ISS receivers. The ISS satellite comes into the ESSS FOV 114 times, for a total of 187.4 s or 0.00059% of the year. The minimum duration of an occurrence was 0.73 s, the maximum duration was 17.8 s, and the mean duration was 5.07 s. And as shown in Fig. 6, all of those occurrences are well beyond the various ISS receiver fields of view. The result of this simulation indicates that sharing between EESS systems and short range ISS links in the range 1 000 to 3 000 GHz is feasible due to the relative speeds of the spacecraft, and very small beamwidths.

FIGURE 6

Summary of occurrences when ISS satellite enters EESS sensor FOV



3.4 Conclusion

Sharing between EESS and active services in the range 1 000-3 000 GHz should be feasible. Atmospheric absorption rates dictate that ground-based active systems will have no detrimental effects on an orbiting spacecraft's operations. Additionally, space-based active systems are very unlikely to have any detrimental effect on passive remote sensing operations due to the relative speeds of spacecraft and the very small beamwidths, greatly limiting possibilities for any main beam-to-main beam interaction.

4 Consolidated tables

The Table in Annex 1 presents a consolidation of different frequency bands of scientific interest for satellite passive sensing between 275 and 1 000 GHz, taking into account requirements for meteorology/climatology and atmospheric chemistry, subdivided into two measurement classes.

For each of the two classes, the relevant frequency ranges are different but, in many cases, they overlap each other so that, at the end, the corresponding band requirement results in a large single frequency band covering multiple measurements in both classes (e.g. 312.65-355.6 GHz band). Detailed information on how the resulting frequency ranges are derived can be found in the column "Supporting information".

In addition, the Table in Annex 2 addresses "non-traditional" passive sensors such as ground-based and balloon-based sensors.

5 Summary

Between 275 and 1 000 GHz, a number of bands of scientific interest for studies of meteorology/climatology and atmospheric chemistry have been identified and are listed in Annex 1.

Between 1 000 and 3 000 GHz, studies show that sharing between EESS and active services should be feasible. The strong atmospheric absorption in that region of the spectrum effectively shields passive spaceborne instruments from terrestrial-based active services, while space-based active services have minimal opportunity to cause interference lasting a significant length of time.

Annex 1

Passive bands of scientific interest for EESS between 275 and 1 000 GHz

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		**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 (PREMIER), CLOUDICE , MWI (ICI), GOMAS, GEM	**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), **MWI (ICI)** (313.95-336.35) **Window** (339.5-348.5), **GEM Chemistry** (342-346), **STEAMR**(4) **(PREMIER) 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)

(4) Due to the instrument needs for the tuning of the local oscillator in order to achieve optimal measurement accuracy, the frequency band indicated for this instrument (STEAMR) exceeds the one shown in the corresponding first column.

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	**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	MWI (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), MWI (ICI)(439.1-456.9), **Chemistry** (442-444), **Window** (458.5-466.64),
477.75-496.75	19 000	487.25 **(O_2)**	OXYGEN, Temperature Profiling			Limb	ODIN	**Oxygen line** (477.75-496.75, BW: 3 GHz, max. offset: 8 GHz), **ODIN Oxygen** (486-489)
497-502	5 000	497.6, 497.9 **(BrO)**, 497.9 **($N_2{}^{18}O$)**, 498.6 **(O_3)**	Wing channel for water vapour profiling	498-502	O_3, $N_2{}^{18}O$, BrO,	Limb, Nadir	ODIN	**Chemistry ODIN** (497-499), **Water window** (498-502)
523-527	4 000	Window for 556.9	Wing channel for water vapour profiling	523-527		Nadir		
538-581	43 000	541.26, 542.35, 550.90, 556.98 **(HNO_3)**, (544.99, 566.29, 571.0) **(O_3)**, 556.93 **(H_2O)**, 575.4 **(ClO)**	WATER Vapour Profiling	538-542	HNO_3, O_3, ClO	Nadir, Limb	ODIN	**Water window** (538-542), **Chemistry** (541-558), **ODIN water vapour profiling** (546-568), **ODIN water vapour sounding** (552-562), **ODIN Chemistry** (563-581)

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			
611.7-629.7	18 000	620.7 **(H_2O)**, 624.27 **(ClO_2)**, 624.34, 624.89, 625.84, 626.17 **(SO_2)**, 624.48, 624.78 **(HNO_3)**, 624.77 **(^{81}BrO)**, 624.8 **(CH_3CN)**, 624.98 **($H^{37}Cl$),** 625.04 **(H_2O_2)**, 625.07, 628.46 **(HOCl),** 625.37 **(O_3)**, 625.66 **(HO_2),** 625.92 **($H^{35}Cl$)**, 627.18 **(CH_3Cl)**, 627.77 **($O^{18}O$)**,	WATER Vapour Profiling, OXYGEN		OXYGEN, ClO_2, SO_2, BrO, O_3, $H^{35}Cl$, CH_3Cl, $O^{18}O$, HOCl, HO_2, HNO_3, CH_3CN, H_2O_2	Limb	MLS, SMILES,	**Water line** (611.7-629.7, BW: 3 GHz, max. offset: 7.5 GHz), **MLS/SMILES Chemistry** (624-629)
634-654	20 000	635.87 **(HOCl)**, 647.1 **($H_2{}^{18}O$)**, 649.24 **(SO_2)**, 649.45 **(ClO)**, 649.7 **(HO_2)**, 650.18 **(^{81}BrO)**, 650.28 **(HNO_3)**, 650.73 **(O_3)**, 651.77 **(NO)**, 652.83 **(N_2O)**	Wing channel for water vapour profiling	634.8-651	$H_2{}^{18}O$, HOCl, ClO, HO_2, BrO, HNO_3, O_3, NO, N_2O, SO_2	Limb, Nadir	MLS, SMILES	**MLS/SMILES Chemistry** (634-654), **Window** (634.8-651)
656.9-692	35 100	658 **(H_2O)**, 660.49 **(HO_2)**, 687.7 **(ClO),** 688.5 **(CH_3Cl)**, 691.47 **(CO)**	WATER Vapour Profiling, CLOUD	676.5-689.5	HO_2, ClO, CO, CH_3Cl	Limb, Nadir, Conical	CLOUDICE, MWI (ICI), MLS	**Water line** (669.7-676.5)**, Window** (658.3-669.7, 676.5-689.5), **Cloud Measurements** (665.2-671.2, 677-692), **CLOUDICE** (657.3-670.7)**,** **MWI (ICI)(656.9-671.1),** **MLS Chemistry** (659-661)
713.4-717.4	4 000	715.4 **(O_2)**	OXYGEN			Limb		
729-733	4 000	731 **(HNO_3)**, 731.18 **($O^{18}O$)**	OXYGEN		$O^{18}O$, HNO_3	Limb		
750-754	4 000	752 **(H_2O)**	WATER			Limb		
771.8-775.8	4 000	773.8 **(O_2)**	OXYGEN			Limb		
823.15-845.15	22 000	834.15 **(O_2)**	OXYGEN					**Oxygen line** (823.15-845.15, BW: 3 GHz, max. offset: 9.5 GHz)
850-854	4 000	852 **(NO)**			NO	Limb		
857.9-861.9	4 000	859.9 **(H_2O)**	WATER			Limb		
866-882	16 000		CLOUD, WINDOW			Conical		**Cloud Measurements** (866.5-869.5, 868-881, 878.5-881.5), **Window** (866.9-881.9)
905.17-927.17	22 000	916.17 **(H_2O)**	WATER					

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			
951-956	5 000	952 **(NO)**, 955 **($O^{18}O$)**	OXYGEN		$O^{18}O$, NO	Limb		
968.31-972.31	4 000	970.3 **(H_2O)**	WATER			Limb		
985.9-989.9	4 000	987.9 **(H_2O)**	WATER			Limb		

Annex 2

Passive bands of scientific interest for terrestrial sensors between 275 and 3 000 GHz

Frequency band(s) (GHz)	Total bandwidth required (MHz)	Spectral line(s) (GHz)	Platform
275-294	19 000	275.0: NO_2 275.2: SO_2 276.3: N_2O 278.6: ClO 281.8: HNO_3 293.5: O_3	Ground
624-629	5 000	624.3: SO_2 624.8: BrO 625.9-625.94: HCl 625.0: H_2O_2 625.4: O_3 627.8: O_2 628.5: HOCl	Balloon
649-653	4 000	649.5: ClO 649.7: HO_2 650.3: HNO_3 650.7: O_3 651.8: NO 652.8: N_2O	Balloon
2 500-2 600	100 000	2 502.3: O_2 2 504.7: CO 2 509.6: O_3 2 510.0: OH 2 510.7: NO 2 514.3: OH 2 516.9: CO 2 518.1: O_3 2 523.5: O_3 2 526.4: O_2 2 528.2: CO 2 529.3: HDO	Balloon