Passive microwave radiometry for atmospheric research and composition monitoring

A brief overview of past and present spectrum usage

Passive microwave radiometers measuring thermally emitted radiation by the Earth's atmosphere from the ground, from airborne platforms and from space are nowadays key components of global observation systems for atmospheric research and the monitoring of the ozone layer and the climate system.

Numerical weather prediction models rely on the assimilation of data obtained from operational meteorological satellites, which employ instrumentation measuring emitted or back-scattered radiation in various spectral ranges from microwaves to the ultra-violet. Amongst the important microwave bands used by meteorological nadir (downward-looking) sensors are those containing the water lines centred at 22.235 GHz and 183.310 GHz. Using spectral measurements from these bands, atmospheric humidity in the troposphere, the lowest layer of the atmosphere, can be determined. Measurements in the oxygen bands at ~63 GHz and at 118.75 GHz enable vertically resolved information on atmospheric temperatures and pressures to be obtained. These channels provide an all-weather capability for the global observing system, since millimetre waves are relatively insensitive to cloud absorption compared with other spectral ranges. Window channels in the regions of low absorption between the strong spectral lines are targeted by nadir-looking satellite sensors for near-surface atmospheric measurements and for observations of land, ocean and ice. Long-term protection of the passive bands in the spectral region below 300 GHz (centimetre and millimetre wavelength ranges) remains important to assure continuous long-term measurements of a large number of geophysical variables for meteorological and climate applications.

Surface-based radiometric monitoring of tropospheric parameters such as temperature, water vapour and cloud liquid has a long history. Multi-frequency radiometers typically utilise similar bands to the meteorological nadir-looking satellite sensors. Dual-frequency radiometers observe, for example, a channel close to the 22.235 GHz water vapour line (often at 20.6 or 23.8 GHz) in combination with a window channel (at ~31 GHz) for deriving tropospheric water vapour and cloud liquid water. Observations of channels close to the centre and in the wing of the much stronger 183 GHz water line are useful for extremely dry conditions such as at high-altitude mountain sites. Multiple bands at ~63 GHz in the lower wing of the strong oxygen line are commonly used for temperature measurements, and window channels at ~90 GHz and 150 GHz provide information on liquid water.

Ground-based microwave instrumentation is also an integral part of equipment at stations of the global Network for the Detection of Atmospheric Composition Change (NDACC). An important goal of the network, established in the early 1990s, is to provide long-term, quality-assessed measurements of the atmospheric composition, with an initial focus on monitoring of ozone and related species in the stratospheric ozone layer. Regular measurements are made of rotational lines of stratospheric ozone (e.g. at 110.836 and 142.175 GHz), of strato-mesospheric water vapour (usually at 22.235 GHz) and of the ozone destroying radical, chlorine monoxide, at 204.35 and 278.63 GHz. Neighbouring lines of carbon monoxide (at 115.271 and 230.538 GHz), nitrous oxide and nitric acid are also often measured. Vertical concentration profiles with moderate vertical resolution can be retrieved from these pressure broadened emission lines. The long-term stability of the instrumentation is essential in order to monitor atmospheric composition and to enable the detection and quantification of weak trends in the presence of natural atmospheric variability, which is both spatially and temporarily large. The long-term protection of the relevant frequency bands in the 22 GHz to 300 GHz range is therefore essential to assure continuity of these important data sets, which rely on observations of only a few weak spectral lines accessible from the ground.

Above 300 GHz absorption by tropospheric water vapour in the lowest atmospheric layer becomes too strong for year-round ground-based measurements, except for a few high-altitude sites. As spectral line strengths increase with increasing frequency, higher frequency bands (at sub-millimetre wavelengths) are widely used by limb sensors on Earth-exploration research satellites. The first millimetre-wave, limb-scanning satellite instrument providing global measurements of the composition of the middle atmosphere was the Microwave Limb Sounder (MLS). The instrument was operated from 1991 to 1998 on board NASA's Upper Atmosphere Research Satellite (UARS), measuring for example lines of oxygen (~63 GHz), ozone (at 184.378 and 206.132 GHz), water vapour (183.310 GHz), chlorine monoxide (204.35 GHz) and weaker lines of other trace gases such as nitric acid. A similar instrument, the Millimetre-wave Atmospheric Sounder (MAS), was

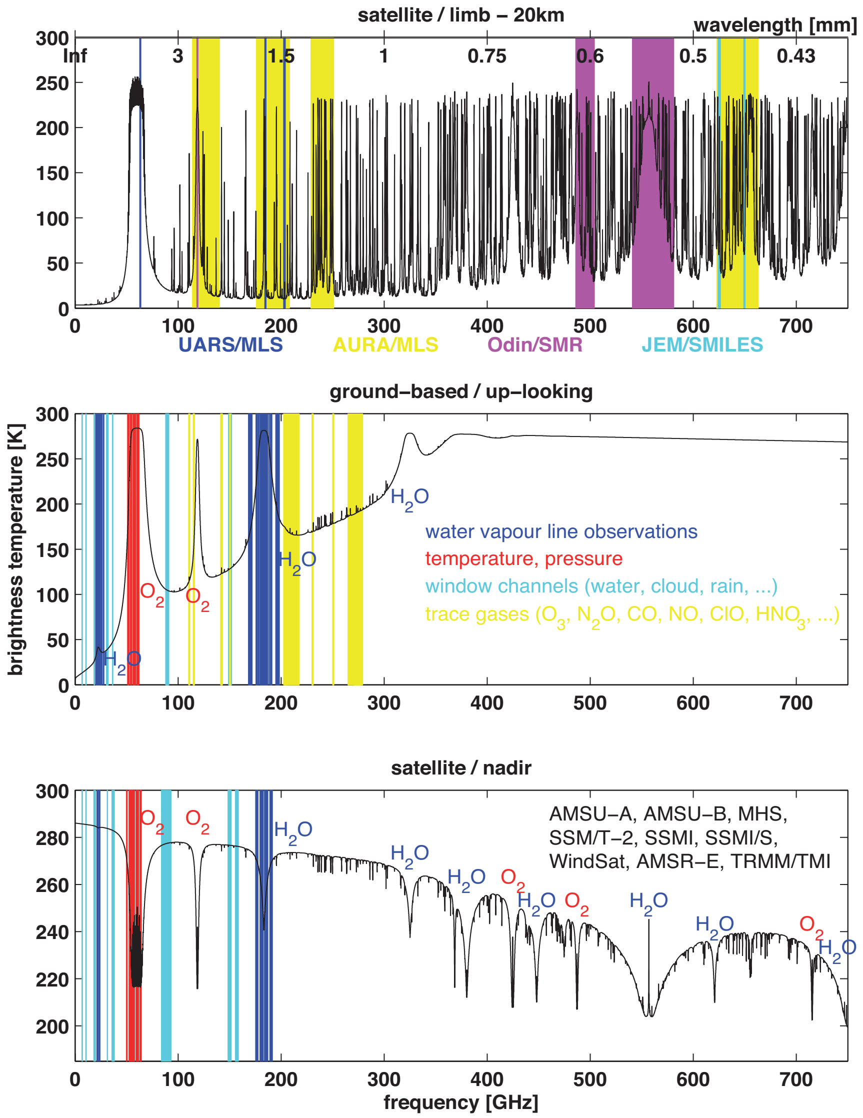

Figure 1.
Use of frequency bands for atmospheric sounding in the millimetre and sub-millimetre wavelength range. Shown are model calculations of atmospheric emission and absorption spectra up to 750 GHz for typical mid-latitude conditions and three different observation geometries.
Top: Thermal emission spectrum as observable by satellite limb sensors at a tangent-height of 20km.
Target bands of the limb sounders UARS/MLS, Aura/MLS, Odin/SMR and JEM/SMILES are shown.
Middle: Emission spectrum observable by ground-based passive microwave radiometers (zenith looking). Frequency bands used by presently deployed instruments are indicated, roughly distinguished by application.
Bottom: Absorption spectrum (against Earth surface emission) observed by nadir sounding instruments on meteorological satellites and presently employed frequency bands.

installed on the ATLAS research platform in the cargo bay of the Space Shuttle and operated during three campaigns in 1992, 1993 and 1994. The Swedish-led Odin Sub-Millimetre Radiometer (SMR), the first space-borne heterodyne radiometer operating in sub-millimetre bands for atmospheric limb observations, was launched in 2001. Four radiometers within the 486-581 GHz range and one millimetre wave radiometer at 118.8 GHz were employed for middle atmospheric measurements of O_3 (489.2, 501.5, 544.9, 551.4 and 576.5 GHz), ClO (501.3 GHz), N_2O (502.3 GHz), HNO_3 (544.4 GHz), NO (551.2 and 551.5 GHz), water isotopologues (488.5, 489.1, 490.6, 552.0 and 556.9 GHz), CO (576.3 GHz) and O_2 (118.8 GHz). A second MLS using various millimetre, sub-millimetre and far-infrared channels for measuring spectral lines including O_2 (118.8 GHz), H_2O (183.3 GHz), CO (230.5 GHz), HCl (625.9 GHz), ClO (649.5 GHz) and OH (2.514 THz) was launched in 2004 on board NASA's Aura satellite. Most recently, the Japanese Sub-Millimeter SIS Limb Emission Sounder (SMILES) was installed on board the International Space Station (ISS) and made measurements from October 2009 to April 2010. For the first time, this instrument used sensitive Superconductor-Insulator-Superconductor detector technology at 625/650 GHz together with a mechanical 4K cooler to observe O_3 (625.3 GHz), HCl (625.9 GHz), ClO (649.5 GHz) and many other important minor species such as HO_2, BrO and HOCl in the stratosphere and mesosphere. Several future projects are being planned. An example of these is the Stratosphere-Troposphere Exchange and Climate Monitor (STEAM). This radiometer will operate in bands in the lower sub-millimetre range from 310 to 360 GHz and will be dedicated to the exploration of the

Upper Troposphere/Lower Stratosphere (UT/LS) altitude region. It is currently being assessed by the Swedish Space Board and the European Space Agency. Other climate-related research projects have been proposed and are being considered in Europe, Japan and the US.

It should be emphasized that line selection is often difficult as important simple, linear molecules have only a few accessible rotational emission lines. Examples of lines typically observed by ground-based and space-borne sensors are the CO lines at 115.3, 230.5, 345.3, 576.3 and 691.4 GHz, HCl lines at 625.9 GHz, ClO transitions at 204.4, 278.6, 501.3 and 649.5 GHz and OH lines at 1.838 and 2.514 THz. As the lines are pressure broadened, enabling the determination of altitude-resolved vertical concentration profiles of the target species, frequency protection measures must also include the line wings. Required spectrometer bandwidths vary with the atmospheric target region. Whilst mesospheric observations require only very narrow bands of a few tens of MHz, lower stratospheric measurements require typically 1 GHz, and upper tropospheric observations from satellites are planned for up to 12 GHz wide bands (spectrally resolved) in order to allow far-out line wings to be accurately analysed.

The proposed frequency bands for accepted future missions for observations of key spectral lines for atmospheric research will need to be protected in order to allow for interference free measurements once these missions become operational. The use of the frequency region above 275 GHz is currently being discussed in preparation for WRC-2012 ("ITU AI 1.6: Resolution 950, Rev. WRC-07, on the use of frequencies between 275 and 3000 GHz"). Operational constraints and the future needs of atmospheric emission sounding for important weather, ozone and climate related applications will have to be taken into account.

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RFI measurements at Yebes observatory and in the Azores archipelago

The Yebes observatory has been operating a 40 metre radio-telescope since mid 2007, when the 'first microwaves' were received from the Moon and Venus using a 22 GHz receiver. A few months later, in May 2008, successful VLBI observations were made when fringes were obtained for the first time with the 100 metre Effelsberg radio telescope.

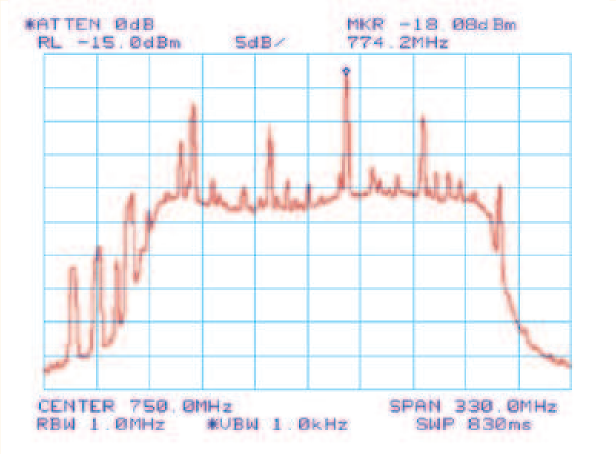

Figure 2
RFI signals in S band.

Currently, the radio telescope has 7 receivers, as shown in Table 1, which have been completely designed, developed and characterised in the Yebes laboratories (an exception is the 3mm receiver on loan from IRAM).

RFI has been seen and investigated since the beginning of operations, with a significant component coming from 'internal' sources such as the antenna servo electronics, ethernet switches, computers and mobile phones. Thus, Figure 2 shows the initial IF spectrum of the S band receiver with most, but not all of the RFI being caused by Beckhoff profibus modules and other telescope control electronics. The three broad RFI signals on the left-hand edge come from radio-links outside the observatory.

It is hoped that all this 'internally generated' interference has been removed from the observed spectra by careful shielding and filtering, although this has not been fully assessed as yet. A portable measurement system consisting of a 90 cm parabolic antenna (moveable in both azimuth and elevation) with a tripod on which is mounted an 850 MHz – 26.5 GHz log-periodic feed and a broad-band amplifier (noise figure 5 dB) was purchased last year to measure the RFI coming from outside the observatory. The characteristics of all the components and cables have been measured and, with the help of the antenna manufacturer's data, it has been possible to calibrate the measurements so as to provide results in units of electric field intensity (dBuV/m). The system backend, which is a spectrum analyser controlled by a laptop, has a sensitivity of ~30 dBuV/m.

Initial measurements made from the roof of the Yebes observatory building when pointing to the horizon have provided the calibrated RFI panorama shown in Figure 3. The bands of the 40m radio-telescope receivers are depicted in red.