Passive microwave observations

Overview:

- Definitions, basic effects
- Platforms and viewing geometries
- Detectors
- Measurement examples
  - ground based
  - air borne
  - satellite
Passive microwave observations

The term ‘Microwave’ is typically used to denote measurements at centimeter, millimeter and submillimeter wavelengths.

\[ \lambda = 0.1 - 10 \text{ cm} \quad \nu \sim 3 - 300 \text{GHz} \quad (3 \text{ THz}) \]

**Figure 6-3** Regions of the electromagnetic spectrum.
Absorption/Emission by molecules

UV/Vis and near IR: Electronic and vibrational transisions (typ. Absorption)
Thermal IR: Vibrational transisions (typ. Emission)
Microwaves: Rotational transisions (typ. Emission)
Scattering and absorption by particles

- Scattering and absorption by aerosols is usually negligible.
- Especially, scattering on molecules can be neglected.
- Scattering and absorption on liquid and solid particles can be observed.
Passive microwave observations

Advantages:
- Pressure broadening can yield profile information
- Usually (depending on the wavelength), microwave observations are not affected by clouds and rain, because the wavelengths are much larger than the droplet sizes
- Measurements possible during day and night

Measurement modes:
- Typically emissions are measured (day and night)
- Also absorption measurements are possible (e.g. using direct sun light)
- Spectroscopic measurements allow the observation of atmospheric trace gases (and other parameters like temperature)
- Measurements are made from ground aircraft, balloon and satellite
Black body radiation:

\[ B_\nu(T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{\exp\left(\frac{\hbar \nu}{k_B T}\right) - 1} \]

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with \( \frac{h \nu}{kT} \ll 1 \)  

\[ B(\nu) \approx \frac{2kT \nu^2}{c^2} \]  

Rayleigh Jeans radiation law

- linear in T
- square dependence in \( \nu \)
Brightness Temperature

-In the microwave spectral range the measured power is proportional to the temperature of the emitter. Thus the observed quantity is usually the so called **brightness temperature** $T_B$

-for a black body (emissivity = 1) the brightness temperature equals the temperature of the black body: $T_B = T_{\text{blackbody}}$

-for gray bodies with emissivities $\varepsilon$ between 0 and 1 the observed brightness temperature is $T_B = \varepsilon T_{\text{blackbody}}$

-selective emitters are bodies whose emittance is not constant as a function of wavelength [$\varepsilon = \varepsilon(\lambda)$]. Then $T_B$ also becomes dependent on wavelength:

$$T_B (\lambda) = \varepsilon(\lambda) T_{\text{blackbody}}$$
2.1 Microwave absorption due to atmospheric gases  

3.2.2 Microwave attenuation at various rain rate
### Overview on microwave observation products

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>monitoring target</th>
</tr>
</thead>
<tbody>
<tr>
<td>around 1.4</td>
<td>soil moisture content, salinity</td>
</tr>
<tr>
<td>around 2.7</td>
<td>salinity, soil moisture content</td>
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<td>around 5</td>
<td>temperature of estuary</td>
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<tr>
<td>around 6</td>
<td>sea surface temperature</td>
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<tr>
<td>around 11</td>
<td>rain, snow, lake ice, sea surface condition</td>
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<tr>
<td>around 15</td>
<td>water vapor, rain</td>
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<tr>
<td>around 18</td>
<td>rain, sea surface condition, sea ice, water vapor</td>
</tr>
<tr>
<td>around 21</td>
<td>water vapor, liquid water</td>
</tr>
<tr>
<td>22.24</td>
<td>water vapor, liquid water</td>
</tr>
<tr>
<td>around 24</td>
<td>water vapor, liquid water</td>
</tr>
<tr>
<td>around 30</td>
<td>sea ice, water vapor, oil slick, cloud, liquid water</td>
</tr>
<tr>
<td>around 37</td>
<td>rain, cloud, sea ice, water vapor</td>
</tr>
<tr>
<td>around 55</td>
<td>temperature</td>
</tr>
<tr>
<td>around 90</td>
<td>cloud, oil slick, ice, snow</td>
</tr>
</tbody>
</table>

### General rule:

- Molecular signatures are measured at high frequencies
- Surface properties are measured at low frequencies

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The observed power as function of viewing angle is:

\[ dP_v = \frac{1}{2} d\nu \int_\Omega I_v(\theta, \phi) A_e(\theta, \phi) d\Omega \]

- If only one polarisation direction is measured
- Intensity received from direction \( \theta, \phi \)
- Effective antenna area for direction \( \theta, \phi \)

\[ I_v = B_v(T) \varepsilon \ e^{-\tau(0,L)} + \int_0^L \alpha \cdot B_v(T) \cdot \ e^{-\tau_v(s,L)} \cdot ds \]

- Surface term = 0 if only atmospheric emission is observed
- Atmospheric term

In the microwave spectral region (and also in the thermal IR) typically emission and absorption have to be considered.
Optical depth:

\[ \tau_{\nu}(s, L) = \int_{s}^{L} \alpha_{\nu}(s) \, ds \quad \alpha: \text{absorption coefficient} \]

\[ \alpha_{ij}(\nu, p, T, N) = N \cdot \sigma(\nu_{ij}, T) \cdot S(\nu - \nu_{ij}, p, T) \]

\( N \): Number density  
\( T \): Temperature  
\( p \): Pressure  
\( \sigma \): absorption cross section  
\( S \): Line width

\[ \sigma(\nu_{ij}, T) = \frac{8\pi^{3}\nu_{ij}\mu^{2}}{3hc} \frac{1}{Q} \left( e^{-\frac{E_{i}}{k_{B}T}} - e^{-\frac{E_{j}}{k_{B}T}} \right) g_{j} \mid \Phi_{ij} \mid^{2} \]

\( g_{j} \) is the degeneracy and \( E_{j} \) the energy for state \( l \),  
\( \mu \) is the overall dipole (or other) moment coupling to the radiation field  
\( Q(T) = \Sigma g_{l} \exp(-E_{l}/k_{B}T) \) is the partition function  
\( \phi_{ij}^{2} \) is the transition matrix element
Without the surface term and with $d\tau = ds \cdot \alpha$:

$$I_v = \int_0^L \alpha \cdot B_v(T) \cdot e^{-\tau_v(s,L)} \cdot ds = \int_0^{\tau_v(0,L)} B_v(T) e^{-\tau_v(s,L)} \ d\tau_v(s)$$

$$= B_v(T) \cdot \left(1 - e^{-\tau_v(0,L)}\right)$$

for $\tau(0,L) \ll 1$

For small optical depth the observed signal becomes proportional to the optical depth.
Effects of line broadening

- natural line width
- pressure broadening
- doppler broadening
Natural line width: \[ \Delta \nu = \frac{\Delta E}{\hbar} \approx \frac{1}{2\pi \Delta t} \]

It can usually be ignored compared to collision (pressure) broadening at lower altitudes and Doppler (thermal motion) broadening at higher altitudes.

Collision (pressure) broadening:

- Collision between molecules shortens lifetimes for specific states
- For increasing pressure towards lower altitudes the probability of collisions increases
- The line shape for pressure broadening can be approximated by a Lorentzian line shape:

\[
S_{\text{Lorentz}}(\nu, \nu_{ij}, p, T) = \frac{1}{\pi} \left( \frac{\nu}{\nu_{ij}} \right)^2 \frac{\Delta \nu_p}{(\nu - \nu_{ij})^2 + \Delta \nu_p^2}
\]

(\(\Delta \nu_p\): line width for pressure broadening)

The Lorentzian line shape can be retrieved from the van Vleck and Weisskopf line shape assuming that the duration of a collision is much shorter than the time between two collisions (impact-approximation)
The Lorentian line width is temperature dependent

Lorentian line width:

\[ \Delta \nu_r = \Delta \nu_{r0} \frac{p}{p_0} \left( \frac{T}{T_0} \right)^\kappa \]

Typical value: 2.5 MHz

\[ p_0: 1\text{hPa} \]
\[ T_0: 300\text{K} \]

Typical value: 0.75
Doppler broadening

-is caused by thermal motion of molecules. The Maxwell distribution depends on temperature and the molecular mass:

\[ f(v) = \left( \frac{m}{2\pi k_B T} \right)^{3/2} e\left( -\frac{m}{2k_B T} v^2 \right) \]

According to the Doppler-effect, the line function becomes:

\[ S_{\text{Doppler}}(v, \nu_{ij}, T) = \frac{1}{\Delta \nu_D} \sqrt{\frac{ln2}{\pi}} \cdot e\left( -ln2 \cdot \left( \frac{\nu - \nu_{ij}}{\Delta \nu_D} \right)^2 \right) \]

With line width:

\[ \Delta \nu_D = \frac{\nu_{ij}}{c} \sqrt{\frac{2k_B T}{m} \cdot ln2}. \]

Heavy molecules have smaller velocities

By convolution of the Lorentian and Doppler line shape one gets the so called Voigt line shape:

\[ S_{\text{Voigt}} = \int_{-\infty}^{\infty} S_{\text{Doppler}}(\nu - \nu', \nu_{ij})S_{\text{Lorentz}}(\nu, \nu')d\nu' \]
collision line widths generally increase with dipole moment; O2 has a very small (magnetic) one

Heavy molecules have smaller velocities

Line width (half width at half maximum) versus altitude for some representative microwave spectral lines.
Microwave emission lines for the same mixing ratio of a gas at the bottom (100 hPa, ~15 km), middle (10 hPa, ~30 km), and top (1 hPa, ~50 km) of the stratosphere.

For trace gases close to the surface (1000 hPa), the measurements often become insensitive.
Possible viewing geometries:

- Ground based observations
- Aircraft or balloon observations
- Satellite limb observations
- Satellite nadir observations
Possible viewing geometries:

**Satellite nadir observations:**

- depending on the atmospheric transparency and the surface emissivity either atmospheric absorptions or emissions are observed (or both)

- at high frequencies emissions of atmospheric molecules dominate (atmospheric sounders)

- at low frequencies surface emission dominates ( imagers)
Possible viewing geometries:

Ground based observations:

- From direct sunlight observations, atmospheric absorptions are measured.
- From viewing angles off the sun, atmospheric emissions are measured.
- Any effects of the surface can be ignored.
- Especially at high humidity, the atmosphere is not transparent.
Possible viewing geometries:

Aircraft / balloon observations:

- usually atmospheric emissions from different (uplooking) viewing angles are measured
- effects of the surface can be ignored
- at high altitudes the atmosphere becomes more and more transparent
Possible viewing geometries:

**Satellite limb observations:**

- Atmospheric emissions from different viewing angles are measured.
- Effects of the surface can be ignored.
- The long light paths allow detection of trace gases with very low concentrations.
Spectrometers and detectors

- Radiometers and heterodyne techniques
- Frequency transformation using non-linear mixing
- Acousto-optical detectors
- Calibration
Spectrometers and detectors

In the microwave region, the atmospheric emission is measured in small spectral channels using so-called radiometers or heterodyne techniques. (The discrimination between spectrometers and radiometers is not strict)

Radiometers

Passive microwave imaging radiometers (usually called microwave imagers) collect Earth's natural radiation with an antenna and typically focus it onto one or more feed horns that are sensitive to particular frequencies and polarizations. From there, it is detected as an electrical signal, amplified, digitized.

Radiometers are usually used for satellite observations

The observations are sensitive to environmental parameters such as soil moisture content, precipitation, sea-surface wind speed, sea-surface temperature, snow cover and water content, sea ice cover, atmospheric water content, and cloud water content. Observations are typically made in nadir geometry.
Spectrometers and detectors

In the microwave region, the atmospheric emission is measured in small spectral channels using so-called radiometers or heterodyne techniques. (The discrimination between spectrometers and radiometers is not strict)

**heterodyne techniques - spectrometers**

‘Heterodyne’ indicates multiplying a weak input signal by a strong local oscillator signal to translate - without loss of information - the input signal to a portion of the spectrum more convenient for further processing. This process allows measurements of weaker signals, and better spectral resolution, than generally can be obtained with other techniques. Technology for low-noise submillimeter heterodyne measurements has become available only recently, and is advancing rapidly.

The observations are sensitive to atmospheric trace gas emissions, especially from the stratosphere. Observations are typically made in limb geometry.
Satellite microwave observations made at discrete channels

Measured (crosses, bars) and calculated (thin line) stratospheric emission spectrum in bands measured simultaneously near 626 and 649 GHz. ‘USB’: upper sideband, ‘LSB’: lower sideband, ‘IF’: intermediate frequency. LSB spectral lines are in sans serif font; USB lines are in italicized roman font

heterodyne techniques - spectrometers

Typical block diagram of an instrument for microwave observations of stratospheric chemistry. The ‘radio frequency’ amplifier is currently available only at lower frequencies and does not appear in many systems; a filter is sometimes placed at this position to eliminate unwanted signals in one of the mixer’s sidebands. The portion of the instrument between the antenna and spectrometer is called the ‘receiver’ or ‘radiometer’.
State-of-the-art mixers are based on planar Schottky-diodes (either cooled or at room temperature), superconductor-insulator-superconductor (SIS) tunnel junctions, or superconducting hot electron bolometer (HEB) devices.

The I-V dependence of a diode has an exponential form,

\[ I = I_0 \left( e^{\eta V/kT} \right) - 1 \]

\( I_0 \) and \( \eta \) are constants depending on the details of the diode, \( T \) is the diode's temperature and \( k \) is Boltzmann's constant. In practice, many real diodes only approximate to exponential behaviour.

For simplicity, here we assume that we have a Square Law diode:

\[ I = aV^2 \text{ when } V \geq 0, \quad I = 0 \text{ when } V < 0 \]
The input voltages to a square law diode is the combination of three terms:

\[ V = V_{DC} + V_S + V_{LO} \]

Atmospheric signal \[ V_S = A \cdot \sin(2\pi f_s t + \Theta) \]

Oscillator signal \[ V_{LO} = A \cdot \cos(2\pi f_L t) \]
The signal of the difference frequency $f_s - f_L$ can be easily filtered out and further processed.

\[ I(t) = a(V_{DC} + A \sin(2\pi f_s t + \Theta) + B \cos(2\pi f_L t))^2 \]

This can be rearranged into the form

\[ I(t) = \frac{aB^2}{2} \cos\left(2\pi(2f_L) t\right) - \frac{aA^2}{2} \cos\left(2\pi(2f_s) t + 2\Theta\right) + aAB \sin\left(2\pi(f_s + f_L) t + \Theta\right) + aAB \sin\left(2\pi(f_s - f_L) t + \Theta\right) + 2aV_{DC} \left[A \sin(2\pi f_s t + \Theta) + B \cos(2\pi f_L t)\right] + \frac{aA^2}{2} + \frac{aB^2}{2} + aV_{DC}^2 \]
Acousto-optical spectrometer (AOS)

- IF signal is transformed in ultrasonic signal

- ultrasonic signal is connected to transparent crystal

- the sound waves cause density fluctuations with different wavelength and amplitude

- laser illuminates the crystal homogeneously

- the density fluctuations act like a diffractive grating

- the microwave signal is transformed into an 'optical spectrum' and is read out using a CCD array
Acousto optical spectrometer:
Calibration is performed by inserting targets (typically blackbody targets - with ‘cold space’ generally used for one target when possible) in the signal path near the instrument input, ideally before the antenna.

\[ P = P_{sys} + P_{atm} \]  

\[ P = P_{sys} + G T_{atm} \]  

Total signal: atmospheric emissions and instr. offset

\[ G = \frac{P_{hot} - P_{cold}}{T_{hot} - T_{cold}} \]

\[ P_{sys} = P_{cold} - G T_{cold} \]

Kleinböhl, 2003: Calibration principle and definition of the system noise temperature

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Figure 2.3: The liquid helium dewar containing the SIS-detector of the ASUR instrument.
Measurement examples

- Ground based observations
- Aircraft and balloon observations
- Satellite limb observations
- Satellite nadir observations
Ground based observations

-can provide continuous monitoring at selected sites

-vertical resolution is obtained from the spectral line shape, it is typically around one atmospheric pressure scale height (~6-8 km)

-Initial ground-based microwave measurements in the 1970s:
  - stratospheric and mesospheric O3 from lines near 100 GHz
  - stratospheric temperatures from rotational lines of O2 (60 GHz)

-Ground-based microwave instruments are currently used by several research groups, and are deployed in the international Network for the Detection of Stratospheric Change to measure stratospheric ClO, O3 and H2O.
Atmospheric transparency is important for ground based observations.

Atmospheric zenith transmission above a 4 km high mountain (top) and above an aircraft at 12 km (bottom). The absorption features seen here are due to H2O and, to a lesser extent, O2.

The atmospheric transparency depends strongly on the atmospheric water vapor content
Ground based observations of stratospheric ClO

Ground-based microwave measurements have provided important results for understanding stratospheric chlorine chemistry.

- In 1981 they gave the first definitive remote measurements of ClO, the key chlorine radical involved in ozone depletion. Early results also included the first measurement of ClO diurnal variation, testing crucial aspects of upper stratospheric chlorine chemistry.

- In 1986 the technique gave the first evidence of greatly enhanced ClO in the Antarctic lower stratosphere, firmly connecting chlorine chemistry to the ozone hole.

- Measurements of ClO diurnal variation tested chemical models for formation and photolysis of the ClO dimer in the Antarctic lower stratosphere. Enhanced ClO in the Arctic winter stratosphere also has been measured.
First observation of ClO

a) Raw spectrum  
b) O3-Spectrum  
c) Difference  
d) Nighttime spectrum (no ClO)  
e) Nighttime spectrum (d) subtracted from Daytime spectrum (c)

278.631 GHz

De Zafra et al, Nature, 1987

Fig. 1 Steps used in processing raw data, shown as curve (a). Curve (b) is a synthesized ozone background, including the $v_2 = 1$, $J = 18_{1,17} \rightarrow 18_{0,18}$ transition (left) and the much weaker $v_1 = 1$, $J = 14_{4,10} \rightarrow 15_{3,13}$ transition (near centre). Curve (c) = (a) – (b) and shows that residual instrumental curvature remains. Curve (d) is night-time data for >4 h after sunset at 45 km, with the remaining ClO signal suppressed. It contains the same instrumental curvature as (c). Curve (e) = (c) – (d).
Fig. 2  Diurnal variation of ClO line-shape in 2-h time blocks. Curve (a) covers the last two night-time hours before dawn at 20 km, (b) the first two after sunrise, and so on. Curve (i) covers the first two hours after sunset at 45 km, curve (h) the preceding two hours, and so on. Curve (e), only, represents a variable length period bridging the midday interval, never more than four hours long.

De Zafra et al,
Nature, 1987

2-h-Intervals
Averages of 22 days
Increase of broad wings of line
→ ClO at low altitudes
Ground-based 278 GHz measurement of stratospheric ClO over Antarctica. The left panel shows day-night differences of the spectral line measured during several days in 1992. The right panel shows a height-time cross section of the retrieved ClO mixing ratio profile, where contours are in parts per billion by volume.

Dynamical and photochemical development in the stratosphere during polar winter

Transport
CFC → Stratosphere → Reservoir compounds (HCl, ClONO₂) → active comp. (Cl, ClO) → OClO

hv (UV)

PSC

BrO

Ozone destruction

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Catalytic ozone destruction cycle through chlorine

2(Cl + O₃) → ClO + O₂

ClO + ClO + M → Cl₂O₂ + M

Cl₂O₂ + hv → Cl + ClOO

ClOO + M → Cl + O₂ + M

Net: 2O₃ → 3O₂

Quadratic dependence on ClO
Dependence on sun light
Temperature differences between both hemispheres

*Envelope of minimum temperature 1980-1988 at about 90 mb from MSU measurements [WMO 1991].*
The radiometer MIAWARA on the roof of the Institute of Applied Physics at Bern, Switzerland (46.95° N / 7.45° E, 550 m. above sea level).

**Measured balanced spectrum from April 2002**

The measured spectra (blue: narrowband spectrometer; green: broadband spectrometer; integration-time: 1.4 hours) are corrected for tropospheric attenuation. The red line shows a spectrum calculated from a standard water vapor profile.
Spectra of $O_3$ and $H_2^{18}O$ measured with EMCOR from Jungfraujoch with corresponding synthetic spectrum based on the retrieved profile.

Comparison of vmr for $H_2^{18}O$ deduced from EMCOR with data from ATMOS, an IR solar occultation experiment, and data from a balloon borne Fourier transform instrument.

N. Kämpfer Institute of Applied Physics, Univ. of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

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Aircraft-based Observations

- good horizontal resolution along a measurement track over an extended spatial range.

- Instruments can observe in high-frequency spectral windows where tropospheric H2O absorption prevents ground-based measurements and where more species have spectral lines.

- Vertical resolution is obtained from spectral line shape for measurements above the aircraft altitude, and can be obtained from limb sounding techniques at heights below the aircraft.

- Initial aircraft measurements in the 1970s included stratospheric H2O and O3 from lines near 183 GHz, and an upper limit on stratospheric ClO abundance.

- Recent measurements include stratospheric HCl, ClO, O3, HNO3, N2O, H2O, HO2, BrO and volcanic SO2
Aircraft measurements of stratospheric HCl (triangles, from the 626 GHz line) and ClO (diamonds, from the 649 GHz line) from a January 2000 flight through the edge of the Arctic vortex. These results show the transition of stratospheric chlorine from the relatively-inert HCl at lower latitudes to the highly-reactive ClO at higher latitudes inside the vortex.

Figure 7.3: HNO₃ volume mixing ratios measured by ASUR and plotted against equivalent latitude between December 2 and 5, 1999. The black vertical dashes on the top horizontal axis indicate where measurements were made.
Figure 7.4: HNO$_3$ volume mixing ratios measured by ASUR and plotted against equivalent latitude between March 9 and 15, 2000. The black vertical dashes on the top horizontal axis indicate where measurements were made.
Balloon-based microwave observations

- can provide measurements throughout the stratosphere with 2-3 km vertical resolution.

- The instrument FOV is vertically-scanned through the atmospheric limb to observe a long path length and to obtain high vertical resolution.

- Balloon instruments provide measurements to higher altitudes with better resolution than can be obtained from aircraft or ground.

- They provide valuable development and tests of techniques to be deployed on satellites.

- Initial measurements in the 1980s were of ClO and O3 from lines near 205 GHz.
Balloon microwave measurements of ClO, HCl and HO2. Top panels show the spectral lines for a limb observation path through the middle stratosphere. The bottom panels show retrieved mixing ratio profiles (thick) and uncertainty limits (thin)

Satellite-based Observations

- limb observations: upper tropospheric and stratospheric profiles of atmospheric trace gases

- nadir observations (sounders): atmosphere is the light source, tropospheric profiles of trace gases and meteorological parameters are derived

- nadir observations (imagers): (also surface emissions are measured)
  - integrated tropospheric amounts of water vapor, liquid water and ice water
  - surface properties (e.g. sea ice cover)
Satellite-limb sounders

-can provide global coverage on a daily basis.

-Limb-sounding is used for chemistry observations because of its vertical resolution and long path length for observations of small concentrations.

-Low-orbit (~700 km altitude) satellites have an observation path tangent point ~3000 km from the instrument.

-Vertical resolution of ~3 km, for example, then requires an antenna having vertical dimension of ~1000 wavelengths.

<table>
<thead>
<tr>
<th>Radiometer</th>
<th>Primary measurements for which the radiometer was included in EOS MLS</th>
<th>Additional measurements that are provided, or contributed to</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 (118 GHz)</td>
<td>temperature, pressure</td>
<td>cloud ice, geopotential height</td>
</tr>
<tr>
<td>R2 (190 GHz)</td>
<td>H₂O, HNO₃</td>
<td>cloud ice, ClO, N₂O, O₃, HCN, CH₃CN, volcanic SO₂</td>
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<tr>
<td>R3 (240 GHz)</td>
<td>O₃, CO</td>
<td>cloud ice, temperature, pressure, HNO₃, volcanic SO₂</td>
</tr>
<tr>
<td>R4 (640 GHz)</td>
<td>HCl, ClO, BrO, N₂O, HO₂</td>
<td>cloud ice, O₃, HOCl, CH₃CN, volcanic SO₂</td>
</tr>
<tr>
<td>R5 (2.5 THz)</td>
<td>OH</td>
<td>O₃, cloud ice, temperature, pressure</td>
</tr>
</tbody>
</table>

It is expected that R3 measurement of the 233.9 GHz ¹⁶O¹⁸O isotopic oxygen line eventually will provide the primary MLS temperature measurement. R3 gives better vertical resolution for temperature than R1.
The figures above show a photo and sketch of UARS MLS. The instrument has three assemblies: sensor, spectrometer and power supply. The overall instrument mass is 280 kg, power consumption is 163 W fully-on, and data rate is 1250 bits/second.
Earth’s lower stratosphere in the Northern Hemisphere on 20 February 1996 (top) and in the Southern Hemisphere on 30 August 1996 (bottom). White contours show the dynamical edge of the polar vortices. HNO3, ClO and O3 are from MLS. Temperature data are from U.S. National Center for Environmental Prediction.

Very small signals can be extracted by averaging many observations:

The weak 204 GHz H2O2 line from satellite measurements made over a period of 38 days, (~2 days averaging time). Horizontal bars give the spectral resolution of individual filters and vertical bars give the $\Delta Trms$ measurement uncertainty. The 0.353 K background is emission from the lower atmosphere received through the antenna sidelobes.
CIO amounts at different altitudes

lower stratosphere

upper stratosphere
Altitude information is retrieved from the line width

Upper stratosphere

Lower stratosphere

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Since 2003: EOS-MLS on the AURA satellite

It is an improved version compared to the *UARS* MLS in providing
1) more and better upper-tropospheric and lower-stratospheric measurements,
2) additional stratospheric measurements for chemical composition and long-lived dynamical tracers,
3) better global coverage and spatial resolution, and
4) better precision for many measurements.

These improvements are possible because of
1) advances in microwave technology that provide measurements to higher frequencies where more molecules have spectral lines and spectral lines are stronger, and provide greater instantaneous spectral bandwidth for measurements at lower altitudes;
2) a better understanding of the capabilities of the measurement technique as a result of the *UARS* experience; and
3) the EOS near-polar (98° inclination, sun synchronous) orbit that allows nearly pole-to-pole coverage on each orbit, whereas the *UARS* orbit (57° inclination) and its precession forces MLS to switch between northern and southern high-latitude measurements on an approximate monthly basis.
Illustrating coverage of the EOS MLS ‘standard’ 25-channel spectrometer. Each filter in the spectrometer is shown as a horizontal bar whose width gives the filter resolution. Vertical bars, too small to be seen except in the narrow center channels, give the $\pm 1\sigma$ noise for the $1/6$ s individual integration time of the MLS instrument and a double-sideband radiometer noise temperature of 1000 K. The signal shown here is a simulated ozone line for a limb observation path with tangent height in the lower stratosphere. The 11 filters between the dotted vertical lines also occur in the ‘mid-band’ spectrometers.

Table III: Nominal Positions and Widths of Filters for Channels in the MLS ‘Standard’ Spectrometers

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Position (MHz)</th>
<th>Width (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.175</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>0.379</td>
<td>96</td>
</tr>
<tr>
<td>3</td>
<td>0.383</td>
<td>96</td>
</tr>
<tr>
<td>4</td>
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<td>64</td>
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<td>0.739</td>
<td>64</td>
</tr>
<tr>
<td>6</td>
<td>1.175</td>
<td>64</td>
</tr>
<tr>
<td>7</td>
<td>1.179</td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>0.379</td>
<td>32</td>
</tr>
<tr>
<td>9</td>
<td>0.51</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>0.51</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>0.51</td>
<td>16</td>
</tr>
<tr>
<td>12</td>
<td>0.51</td>
<td>16</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>14</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>15</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>16</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>17</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>18</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>19</td>
<td>1.19</td>
<td>48</td>
</tr>
<tr>
<td>20</td>
<td>1.19</td>
<td>48</td>
</tr>
<tr>
<td>21</td>
<td>1.75</td>
<td>64</td>
</tr>
<tr>
<td>22</td>
<td>2.35</td>
<td>64</td>
</tr>
<tr>
<td>23</td>
<td>3.03</td>
<td>64</td>
</tr>
<tr>
<td>24</td>
<td>3.83</td>
<td>96</td>
</tr>
<tr>
<td>25</td>
<td>5.75</td>
<td>96</td>
</tr>
</tbody>
</table>

Values are the full width at half power points in the local vertical and horizontal planes at the tangent point. See [21] and [22] for more information.

Filter positions are relative to the center of the targeted spectral line. Widths are full widths between half power points. The positions and widths for channels 8 to 18 are also the nominal values for channels 1-11 of the MLS ‘midband’ spectrometers. See [20] for more information.
Examples of target spectral lines measured by five different MLS radiometers and ‘standard’ 25-channel spectrometers. The target line, centered in the band, is labeled in each panel. Additional lines of O3 evident in some bands, and the vibrationally-excited O2 line in band 1 are indicated. The two fine structure components for OH are easily seen, and the three for HCl can be seen with more scrutiny. These are EOS MLS ‘first light’ measurements: OH on 24 July 2004, the others on 27 July.
AURA MLS observations of H2O, CO and HCN in the Tropics (shown are anomalies to the long year mean). For all species the so called tape-recorder effect is seen: concentration signatures are slowly transported to higher altitudes.

- H2O concentrations vary with season because of the change in tropopause temperature
- CO concentrations vary with season because of changes of the emission sources (combustion processes, both anthropogenic and natural)
- HCN concentrations vary with season because of changes of the emission sources (forest fires)
AURA MLS observations of H2O, CO and HCN in the Tropics (shown are anomalies to the long year mean). For all species the so called tape-recorder effect is seen: concentration signatures are slowly transported to higher altitudes.

- H2O concentrations vary with season because of the change in tropopause temperature

- CO concentrations vary with season because of changes of the emission sources (combustion processes, both anthropogenic and natural)

- HCN concentrations vary with season because of changes of the emission sources (forest fires)

The cycle for HCN does not repeat every year; the data so far suggest that the dominant period is about two years. The reason for this periodicity is not yet fully understood. Comparisons with MODIS fire-count data suggest that it may be connected to inter-annual variations in biomass burning in Indonesia and the surrounding region. [Pumphrey et al., 2008]
Satellite-nadir sounders/imagers

-can provide global coverage on a daily basis.

-nadir-sounding is used for observations of total amounts of water vapor, liquid water and ice water

-also profiles of water vapor and temperature can be retrieved

-especially at low frequencies surface properties are analysed

-Low-orbit (~700 km altitude) satellites
Figure 4.8.2 Microwave scanning radiometer 2)
SSM/I consists of seven separate total-power radiometers, each simultaneously measuring the microwave emission coming from the Earth and the intervening atmosphere. Dual-polarization measurements are taken at 19.35, 37.0, and 85.5 GHz, and only vertical polarization is observed at 22.235 GHz. Spatial resolutions vary with frequency. The table below gives the frequencies, polarizations and temporal and spatial resolutions of the seven channels.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Polarization</th>
<th>Integration Period</th>
<th>3 dB Footprint Size</th>
<th>Along-track</th>
<th>Cross-track</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.35</td>
<td>vertical</td>
<td>7.95 ms</td>
<td>69 km</td>
<td>43 km</td>
<td></td>
</tr>
<tr>
<td>19.35</td>
<td>horizontal</td>
<td>7.95 ms</td>
<td>69 km</td>
<td>43 km</td>
<td></td>
</tr>
<tr>
<td>22.235</td>
<td>vertical</td>
<td>7.95 ms</td>
<td>50 km</td>
<td>40 km</td>
<td></td>
</tr>
<tr>
<td>37.0</td>
<td>vertical</td>
<td>7.95 ms</td>
<td>37 km</td>
<td>28 km</td>
<td></td>
</tr>
<tr>
<td>37.0</td>
<td>horizontal</td>
<td>7.95 ms</td>
<td>37 km</td>
<td>29 km</td>
<td></td>
</tr>
<tr>
<td>85.5</td>
<td>vertical</td>
<td>3.89 ms</td>
<td>15 km</td>
<td>13 km</td>
<td></td>
</tr>
<tr>
<td>85.5</td>
<td>horizontal</td>
<td>3.89 ms</td>
<td>15 km</td>
<td>13 km</td>
<td></td>
</tr>
</tbody>
</table>
### Microwave imagers

- **SSM/I:** -19, 22, 37, and 85 GHz  
  - at 53°, both H and V polarizations

- **AMSR:** - 6, 10, 19, 22, 37, and 85 GHz  
  - at 53°, both H and V polarizations

### Table 1: AMSU channel characteristics.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.8</td>
</tr>
<tr>
<td>2</td>
<td>31.4</td>
</tr>
<tr>
<td>3</td>
<td>50.3</td>
</tr>
<tr>
<td>4</td>
<td>52.8</td>
</tr>
<tr>
<td>5</td>
<td>53.596 ± 115</td>
</tr>
<tr>
<td>6</td>
<td>54.4</td>
</tr>
<tr>
<td>7</td>
<td>54.94</td>
</tr>
<tr>
<td>8</td>
<td>55.5</td>
</tr>
<tr>
<td>9</td>
<td>$f_0 = f_0 \pm 0.217$</td>
</tr>
<tr>
<td>10</td>
<td>$f_0 = f_0 \pm 0.322 \pm 0.048$</td>
</tr>
<tr>
<td>11</td>
<td>$f_0 = f_0 \pm 0.322 \pm 0.022$</td>
</tr>
<tr>
<td>12</td>
<td>$f_0 = f_0 \pm 0.322 \pm 0.010$</td>
</tr>
<tr>
<td>13</td>
<td>$f_0 = f_0 \pm 0.322 \pm 0.0045$</td>
</tr>
<tr>
<td>14</td>
<td>89.0</td>
</tr>
</tbody>
</table>

### Table 1: The main nadir microwave radiometers for temperature sounding 1972-1998

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Year of launch</th>
<th>Frequencies</th>
<th>Nadir field of view</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMS</td>
<td>1972</td>
<td>53.6, 54.9, 58.8</td>
<td>200 km</td>
</tr>
<tr>
<td>SCAMS</td>
<td>1975</td>
<td>52.8, 53.8, 54.4</td>
<td>150 km</td>
</tr>
<tr>
<td>SSM/T</td>
<td>1978</td>
<td>50.5, 53.2, 54.3, 54.9, 58.4, 58.8, 59.0</td>
<td>175 km</td>
</tr>
<tr>
<td>MSU</td>
<td>1978</td>
<td>50.3, 53.7, 55.0, 57.9</td>
<td>110 km</td>
</tr>
<tr>
<td>AMSU</td>
<td>1998</td>
<td>50.3-57.293</td>
<td>48 km</td>
</tr>
</tbody>
</table>

Remote sensing of the atmosphere thomas.wagner@mpic.de http://joseba.mpch-mainz.mpg.de/index.htm
The measured signal ($T_B$) depends on several quantities:

$$T_B = \varepsilon T_S e^{-\tau} + T_{UP} + (1 - \varepsilon) T_{DOWN} e^{-\tau} + (1 - \varepsilon) T_{SP} e^{-2\tau}$$

- **Measured signal**
- **Surface emission**
- **Atmospheric emission**
- **Reflected space emission**
- **Reflected atmospheric emission**
The measured signal \( T_B \) depends on several quantities:

**Case 1:**

**Ocean**

- low and rather constant emissivity
- at low frequencies (22GHz) the total water vapor column is retrieved using the atmospheric emission signal
- at these frequencies the effect of scattering and absorption of cloud droplets is small

\[
T_B = \varepsilon T_s e^{-\tau} + T_{up} + (1 - \varepsilon) T_{down} e^{-\tau} + (1 - \varepsilon) T_{sp} e^{-2\tau}
\]
The measured signal ($T_B$) depends on several quantities:

\[ T_B = \varepsilon T_S e^{-\tau} + T_{\text{up}} + (1 - \varepsilon) T_{\text{down}} e^{-\tau} + (1 - \varepsilon) T_{\text{sp}} e^{-2\tau} \]

**Case 2:**

Ocean

- low and rather constant emissivity
- at higher frequencies (183 GHz) water vapor profile is retrieved using the atmospheric emission signal
- because of the rather strong atmospheric emission/absorption the surface emissions are not visible from space
- from measurements at different distance from the line center altitude information is retrieved
Figure 4.6. Monochromatic weighting functions for selected frequencies near the 57 GHz O₂ band (left), the 118 GHz O₂ line (centre) and the 183 H₂O line (right), calculated for nadir sounding over land (a surface emissivity of 1 is assumed) for a mean standard atmosphere. Weighting functions show the sensitivity as a function of altitude. [Prigent et al. 2005].
The measured signal ($T_B$) depends on several quantities:

\[
T_B = \varepsilon T_S e^{-\tau} + T_{\text{up}} + (1 - \varepsilon) T_{\text{down}} e^{-\tau} + (1 - \varepsilon) T_{\text{sp}} e^{-2\tau}
\]

**Case 3:**

**Ocean**

- Low and rather constant emissivity
- At low frequencies (19 – 85 GHz) the total liquid water (and/or rain) is retrieved using the atmospheric emission signal
- Emission signal is strong at low frequencies; at higher frequencies also scattering contributes to the signal
The measured signal \( T_B \) depends on several quantities:

**Brightness Temperature \( T_B \)**

\[
T_B = \varepsilon T_S e^{-\tau} + T_{up} + (1 - \varepsilon) T_{down} e^{-\tau} + (1 - \varepsilon) T_{sp} e^{-2\tau}
\]

**Case 4:**

Ocean

- low and rather constant emissivity

- at low frequencies (19 – 85 GHz) the total ice water is retrieved using the atmospheric reflection signal, because in contrast to liquid particles, ice particles have high scattering efficiency

- scattering signal is strong at high frequencies; at lower frequencies also emission contributes to the signal
Modelled spectra over ocean (left) and land (right)

Outside the atmospheric emission lines the brightness temperature is low because of the low emissivity (about 0.5) of the ocean.

Outside the atmospheric emission lines the brightness temperature is high because of the high emissivity (about 1) of the land surface.

Only over ocean information about atmospheric constituents (water vapor, liquid water, ice water, rain rate) can be obtained, because the surface emissivity is small.

(Pardo et al., 2001)
Differences between measurements over clouds compared to clear sky over ocean

Water cloud between 2 and 3 km
Emission from liquid cloud droplets increases brightness temperature (outside molecular emission / absorption lines)

Ice cloud between 7 and 8 km
scattering on ice particles decreases brightness temperature (reflection of cold temperatures from space)
Difference between measurements over clouds compared to clear sky

**over land**

Water cloud between 2 and 3 km

Emission from liquid cloud droplets does not increase the brightness temperature, because of high surface emissivity

Ice cloud between 7 and 8 km

Scattering on ice particles strongly decreases the brightness temperature (reflection of cold temperatures from space)
SSM/I observations from 15.05.2010
http://www.ssmi.com

Images currently shown: 2010/05/15, Local Morning Passes, SSM/I - F15

Surface Wind Speed (m/s)

Atmospheric Water Vapor (mm)

Cloud Liquid Water (mm)

Rain Rate (mm/hr)
SSM/I observations for April 2010

http://www.ssmi.com
The measured signal \( T_B \) depends on several quantities:

\[
T_B = \varepsilon T_s e^{-\tau} + T_{up} + (1 - \varepsilon) T_{down} e^{-\tau} + (1 - \varepsilon) T_{sp} e^{-2\tau}
\]

**Case 5:**

Ocean / land

- at low frequencies (<40 GHz), surface properties can be retrieved using the surface emission, because the atmospheric transmission is high
- scattering signal is strong at high frequencies; at lower frequencies also emission contributes to the signal
Figure 4.8.1 Sensitivity of physical parameters in oceanography with respect to frequency and the optimum channels as symbols arrow. 1)
Emissivity variation of pure water and sea water at 20° C with smooth surface.
Effects of vegetation

When vegetation is present, there are two sources of emissions – vegetation and the soil below the vegetation.

Vegetation serves to attenuate the soil signature: as vegetation density increases, soil contribution decreases.

Soil emissions are **strongly polarised**

Vegetation emissions are **almost not polarised**
emissivity examples (SSM/I)

Vegation: Low polarization differences

Desert: Large polarization differences
This image was acquired over Tropical Atlantic and U.S. East Coast regions on Aug. 22 - Sept. 23, 1998. Sea Surface Temperature (SST) data were collected aboard the NASA/NASDA Tropical Rainfall Measuring Mission (TRMM) satellite by The TRMM Microwave Imager (TMI). TMI is the first satellite microwave sensor capable of accurately measuring sea surface temperature through clouds.
Spectra of Polar Oceanic Surfaces over the SMMR Wavelengths

Key: O = Open Water, FY = First Year Ice, MY = Multi-year Ice
H = horizontal polarization, V = Vertical Polarization

GHz  85  37  22  19  SSM/I
Brightness temperature map from ESMR
The Weddell Polynya as Seen with ESMR

• This was the first and only time the Weddell Polynya was ever observed.

Remote sensing of the atmosphere  thomas.wagner@mpic.de  http://joseba.mpch-mainz.mpg.de/index.htm
24 years of multiyear sea ice observations (observations in February)
From IPCC report 2007
Summary microwave (passive) observations:

- large wavelength:
  - small effect of aerosols and clouds
  - observed signal is proportional to temperature of the measured object (Rayleigh-Jeans approximation)
  - rotational transitions are measured

- molecular emissions are typically measured at high frequency

- altitude information from pressure broadening

- surface properties are typically measured at low frequencies

- observations from ground, aircraft/balloons or satellites
Summary microwave (passive) observations:

-in general complex retrievals, because different effects contribute to the measured signal (emission, absorption, scattering)

-many satellite nadir observations are possible only over ocean

-measurements are (almost) not affected by clouds

-measurements are possible during day and night

-spectrometers/detectors are complex and expensive
Where can spectral parameters be obtained?

- Line frequencies are typically known to \(~0.1\) MHz or better; strengths to \(~1\%\) or better.

- Dipole (and other) moments are measured from Stark and Zeeman splitting of spectral lines, allowing line strengths to be determined without requiring measurement of the gas abundance in a laboratory cell.

- Line width parameters can be measured with \(~3\%\) accuracy.

Data bases of these parameters exist and are continuously updated (e.g. catalog maintained by the Molecular Spectroscopy Group at the California Institute of Technology Jet Propulsion Laboratory (see world wide web site http://spec.jpl.nasa.gov)
Spectra of some stratospheric molecule and atomic oxygen. Vertical axis is the logarithm of the optical depth for an observation path through the atmospheric limb with the indicated volume mixing ratios (vmr).

Diffraction limits the received power:

-for microwave observations, typically the aperture angle of the telescope is determined by diffraction

-it is approximately inverse proportional to the collecting area

-thus the effective collective area (integrated over all viewing angles) for isotropic radiation is independent from the size of the antenna.

\[ \int A_{\text{eff}} = \lambda^2 \]
Diffraction limits the received power:

\[ \int A_{\text{eff}} = \lambda^2 \]

-for temperatures in the Earth's atmosphere

\[ B(v) \approx \frac{2kT_v^2}{c^2} \approx 1 / \lambda^2 \]

Thus \( \lambda^2 B(T) \) is nearly constant with frequency up to \( \sim 5 \) THz. Beyond it drops rapidly. Microwave measurements of atmospheric thermal emission are, thus, relatively efficient at frequencies up to \( \sim 5 \) THz (\( \lambda > \sim 6 \times 10^{-5} \) m) but not much beyond.
The power per unit frequency interval at frequency $v$ from a blackbody radiation field at 200 and 250 K (in units of W / MHz).

For $\tau(0, L) \ll 1$ and frequencies $< \sim 5$ THz

$$P_{sig} \propto \tau_v(0, L) \cdot \Delta v$$
The sensitivity of a microwave radiometer is usually specified and determined by its ‘receiver noise temperature’. The root mean square measurement noise, expressed in temperature units, for integration time $\Delta t$ and spectral resolution $\Delta \nu$ is given by

$$\Delta T_{rms} \approx a \cdot \frac{T_{rec} + T_{sig}}{\sqrt{\Delta t \cdot \Delta \nu}}$$

- $T_{rec}$ is the receiver noise temperature
- $a$ is typically between 1 and 2
- $T_{sig}$ is usually much smaller than $T_{rec}$ for thermal emission measurements

- The value of $T_{rec}$ is primarily set by noise in the first amplifier, typical values are ~400 K for cooled radiometers and 2000K for room temperature radiometers at ~200 GHz.

Typical values for $\Delta t=1$ s integration:

- $\Delta T_{rms} \approx 1$ K for $T_{rec} \approx 4000$ K
- $\approx 0.1$ K for $T_{rec} \approx 400$ K

$=>$ MW detectors are usually cooled!