Microwave limb-sounding of the middle atmosphere: past, present, future


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Passive Microwave Radiometry

- High quality measurements of key species having rotational transitions at mm- and sub-mm wavelengths (0-3000 GHz)

- **stratosphere+mesosphere**: O₃, ClO, HCl, CH₃Cl, BrO, N₂O, HNO₃, NO, HCN, CH₃CN, CO, H₂O, HO₂, OH, isotopes, (temperature/pressure) …

- **UT/LS**: H₂O, O₃, CO, cirrus, (temperature/pressure), …

⇒ *atmospheric composition and variability, past and present evolution*

- Ground-based, airborne, space-borne sensors

- Up-looking, nadir-, and limb-sounding observation geometries
Microwave limb-sounding
UARS/MLS was the first satellite mission for “Microwave Limb Emission”. Odin/SMR is the first "Sub-Millimetre-wave Radiometer”. JEM/SMILES will be the first “super-conductive (SIS) limb sensor".

<table>
<thead>
<tr>
<th>Name of instrument</th>
<th>Receiver</th>
<th>Trec [K]*</th>
</tr>
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<tbody>
<tr>
<td>Aura/MLS</td>
<td>Schottky</td>
<td>6000@650GHz DSB</td>
</tr>
<tr>
<td>Odin/SMR</td>
<td>Schottky</td>
<td>3000@500GHz SSB</td>
</tr>
<tr>
<td>JEM/SMILES</td>
<td>SIS</td>
<td>500@650GHz SSB</td>
</tr>
</tbody>
</table>

Sensitivity

Low

High

courtesy: Y. Kasai
Microwave Limb Sounder on UARS
The first MLS was one of ten instruments on the Upper Atmosphere Research Satellite (UARS) launched in 1991.

The original scientific goal of UARS MLS was to improve understanding of stratospheric ozone chemistry in the upper stratosphere.

UARS MLS was designed to measure stratospheric O₃, ClO, and H₂O.

It also measured stratospheric HNO₃, temperature, SO₂, and CH₃CN, upper tropospheric H₂O and cloud ice, and gravity waves.
Odin Sub-Millimetre Radiometer
The Odin satellite

- Swedish led **mini-satellite**.
  Cooperation with Canada, Finland, France.

- **Launched in February 2001.**
  Design lifetime: 2 years.

- **Circular quasi-polar sun-synchronous orbit:**
  ~600km altitude, 96min/orbit,
  6h/18h equator crossing.

- Time sharing: **50% astronomy, 50% aeronomy**
  100% aeronomy since April 2007!

- **Limb-sounding** in aeronomy mode:
  ~45-65 scans/orbit, ~15 orbits per day.

- 2 instruments:
  **SMR** (*Sub-Millimetre Radiometer*),
  **OSIRIS** (Optical Spectrograph and *InfraRed Imaging System*).

- Science objectives: **stratospheric and mesospheric processes**
  "stratospheric ozone", "water vapour and its isotopes", "global circulation"
1.1 m telescope.

- 4 sub-mm (ssb) radiometers in 485-580 GHz range, 1 mm channel at ~119 GHz.
- 2 auto-correlators, 1 acousto-optical spectrometer, 1 (3 channel) filter-bank.

Stratospheric chemistry: HNO3

courtesy: M. Pommier, M. Santee

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Odin HNO3 high-latitude time-series

NH

SH

[ppbv]
Microwave Limb Sounder on Aura
Aura Microwave Limb Sounder objectives

- Track the recovery of the ozone layer
- Understand aspects of how atmospheric composition affects climate
- Quantify aspects of pollution in the upper troposphere
Overview of the AURA/MLS instrument

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Frequency</th>
<th>Main objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1A, R1B</td>
<td>118 GHz</td>
<td>Temperature and pressure (from O₂)</td>
</tr>
<tr>
<td>R2</td>
<td>190 GHz</td>
<td>Upper tropospheric water vapor</td>
</tr>
<tr>
<td>R3</td>
<td>240 GHz</td>
<td>Upper tropospheric O₃, CO and cloud ice</td>
</tr>
<tr>
<td>R4</td>
<td>640 GHz</td>
<td>Stratospheric chemistry</td>
</tr>
<tr>
<td>R5H, R5V</td>
<td>2.5 THz</td>
<td>Stratospheric and mesospheric OH</td>
</tr>
</tbody>
</table>

GHz cal targets, THz cal target, 25 cm THz mirror, THz telescope, 118 GHz, 190 GHz, 240 GHz, 640 GHz, Spectrometers, digitizers, and data handling, Telemetry.
Evolution of stratospheric water vapour
middle latitudes
Boulder
40N / 105 W

Figure 5-4. Evolution of stratospheric water vapor mixing ratio (in ppmv, averaged over 17-22 km) at Boulder, Colorado (40°N, 105°W), derived from balloonborne frost point hygrometer measurements covering 1980-2005. The thin line shows a smooth fit through the data points, using a running Gaussian window with a half-width of three months. The heavy line shows HALOE satellite water vapor data during 1992-2005 for the same altitude region, using measurements near Boulder (over latitudes 35°N-45°N, and longitudes 80°W-130°W). Note the difference between the two datasets after about 1997. Updated from Randel et al., 2004a.
Water vapour / 30°S to 30°N / 25-35 km

Graph showing the anomaly of water vapour from 1984 to 2008, with data from SAGE, HALOE, Odin/SMR, and Aura/MLS.
Science
1. Inorganic Chlorine Chemistry (ClO, HCl, HOCl)
2. Bromine budget (BrO)
3. HO\textsubscript{x} budget (HO\textsubscript{2})
4. Cirrus Clouds (Het. reactions & rad. budget)
5. O\textsubscript{3} isotopes, ...

Major Design Parameters
- RF: 640 GHz band
- Trec: 500 K (ssb)
- Mechanically cooled SIS
- Spectral Coverage: 1200 MHz x 2
- Antenna: 40 cm x 20 cm
- Weight: < 500 kg
- Mission Life: 1 year
Odin/SMR vs JEM/SMILES: UT/LS water vapour

Theoretical retrieval capabilities from continuum emissions (out-of-band H2O lines) in the tropics.
Airborne sub-mm radiometry

- **ASUR**: University of Bremen (Germany), SRON Groningen/Utrecht (The Netherlands)
- **624-632GHz** (lsb), **646-654GHz** (usb) (→1997)
- Key components: LHe cooled SIS mixer (Trec/SSB 450-750K), tunable solid state local oscillator, Martin-Puplett single sideband filter, filterbank, CTS and acousto-optical spectrometer
- Target species: ClO, HCl, O₃, N₂O, ...
- Operation on DLR-FALCON: up-looking observation geometry, Arctic campaigns
- Research objectives (stratosphere):
  - Determination of chlorine activation, investigation of small scale structures, quantification of chemical ozone losses, time-dependent reaction mechanism (ClO diurnal variation), minor species, validation of 3-d models and satellite instruments
- Other radiometers: **500GHz-SIS** (ClO, BrO,...) and **2.5THz** (OH, H₂O)

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STEAM

Stratosphere-Troposphere Exchange And climate Monitor
Scientific objectives

- **Climate Change**
  - Detailed measurements of *upper tropospheric H₂O*
  - IPCC identified lack of knowledge of the water vapour cycle particularly in the upper and middle troposphere as a major uncertainty in climate models
  - Water feedback provides a doubling of the CO₂ temperature increase in current climate models

- **Stratosphere-Troposphere Exchange**
  - Highly spatially resolved measurements of O₃, H₂O and CO

- **Ozone Changes**
  - Continued surveillance of *ozone* and *ClO* in post Odin and EOS-Aura era
STEAM - Stratosphere-Troposphere Exchange And climate Monitor

STEAM-R / PREMIER

- Optimized 12GHz (SSB) UT/LS channel:
  lsb 313.5-325.5 GHz, usb 344.5-356.5 GHz
  \( \text{H}_2\text{O}, \text{HDO}, \text{O}_3, \text{CO}, \text{HCN}, \)
  \( \text{N}_2\text{O}, \text{HNO}_3, \text{CH}_3\text{CN}, \text{CH}_3\text{Cl}, \text{ClO}, \) temperature

- Sun-synchronous orbit
  (820km as Metop),

- 14 simultaneous limb views 5-28 km,

- Auto-correlators: 12 GHz / 25 MHz

- Options: ssb (baseline), 2sb, dsb
STEAM – Stratosphere-Troposphere Exchange And climate Monitor

STEAM-R

LSB
UT/LS band
a6
12 GHz
SSB option
lo 335.000 GHz
H2O, O3, CO
N2O, HNO3, CH3CN, CH3Cl, HCN, ClO, HDO

USB

lsb 313.5-325.5 GHz
usb 344.5-356.5 GHz

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MM-wave limb sounding of UT/LS in presence of clouds

320 GHz mm-wave limb spectra

co-located 0.75mm nir limb imager

Cloud opaque in IR & near-IR limb-views

MARSCHALS

on GEOPHYSICA aircraft at ~20km

tropics (Darwin campaign)

H$_2$O
STEAM/PREMIER - Scenario 03b

HCN

CO

CH3CN
The Scanning Microwave Limb Sounder (SMLS) is a new instrument concept that provides the needed high spatial / temporal resolution observations of the upper troposphere and lower stratosphere.

- SMLS adds azimuth-scanning, combined with low-noise ‘SIS’ receivers
  - As used in ground-based and airborne applications for ~20 years, enabled by newly-available flight-qualified 4 K coolers

- This gives 50 x 50 km horizontal sampling
Summary

- Successfully flown microwave limb-sounder missions:
  - UARS/MLS, ATLAS/MAS (1991), mm-wave Schottky
  - Odin/SMR (2001 - ), Aura/MLS (2004 - ), mm / sub-mm

- Next mission: JEM/SMILES (2009), sub-mm SIS

- Planned/proposed: STEAM, SMLS (~2015-2020?), mm / sub-mm Schottky or SIS

- Airborne demonstrators important for testing and demonstrating measurement capabilities
Forward and inversion modelling
MOLIERE-5

- General, modular 1-d forward and retrieval code for the mm- and sub-mm range.

Modules:

1. **ABS.** Spectroscopic model:
   - line-by-line, continua.
2. **RT.** Radiative transfer:
   - limb, nadir, up-looking geometry.
   - Refraction.
   - Differential weighting functions.
3. **INST.** Sensor model:
   - antenna, sideband, spectrometer.
4. **OEM.** Linear inversion model:
   - *Optimal Estimation Method.*
5. **NLIN.** Non-linear retrievals:
   - *Levenberg-Marquardt* iteration scheme.

Applications:
* Odin Sub-Millimetre (level-2 processing),
* Ground-based observations, airborne observations
* Preparatory studies for MASTER & SOPRANO (ESA), STEAM (CNES, SNSB, ESA), SMILES (NICT), Sounding of Martian atmosphere (CNES, JAXA).

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[Urban, Baron, Lautié et al., JQSRT 83, 3-4, 529, 2004]
Atmospheric transmission

Moliere-5 simulation (zenith looking), N. Schneider
http://transmissioncurves.free.fr/
Thank you!