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

J. Urban*, D.P. Murtagh*, A. Jones*, P. Eriksson*, M. Ekström*, M. Pommier*, U. Frisk**, M. Shiotani***, Y. Kasai****, N. Livesey*****, M.L. Santee*****

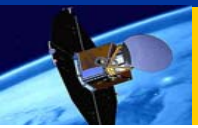
* *Department of Radio and Space Science, Chalmers University of Technology, Göteborg / Sweden*

** *Swedish Space Corporation, Solna / Sweden*

*** *University of Kyoto / Japan*

**** *National Institute for Information and Communications Technology, Koganei, Tokyo / Japan*

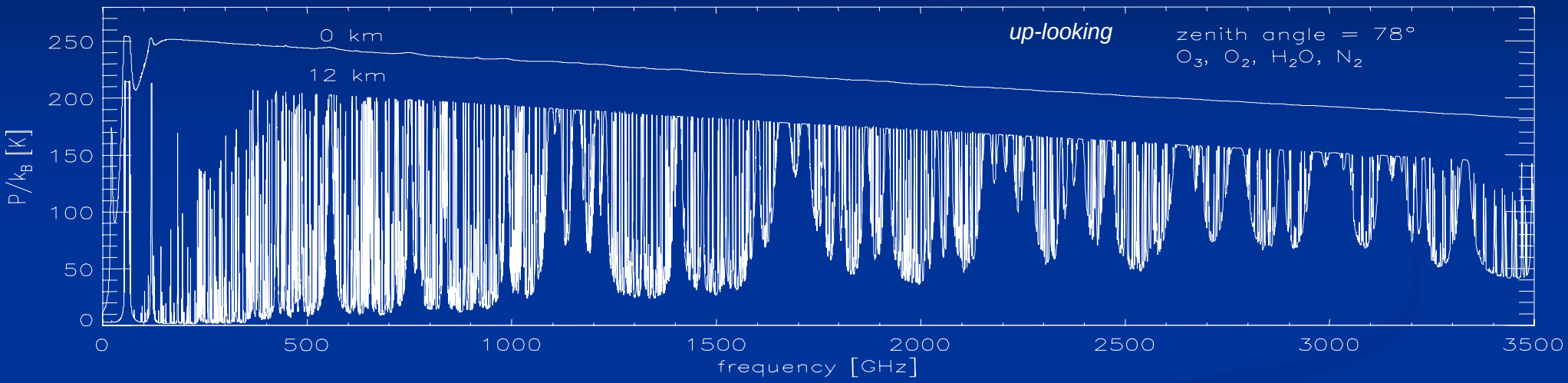
****** *Jet Propulsion Laboratory, California Institute of Technology, Pasadena / USA*



CHALMERS
Radio and Space Science

Passive Microwave Radiometry

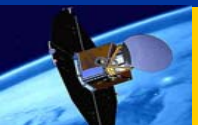
- High quality measurements of key species having rotational transitions at mm- and sub-mm wavelengths (0-3000 GHz)



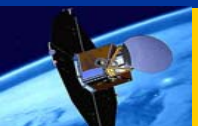
  - **stratosphere+mesosphere**: ***O_3, ClO, HCl, CH_3Cl, BrO, N_2O, HNO_3, NO, HCN, CH_3CN, CO, H_2O, HO_2, OH, isotopes, (temperature/pressure) …***
  - **UT/LS**: ***H_2O, O_3, CO, cirrus, (temperature/pressure), …***

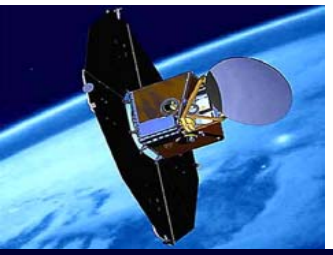
⇒ ***atmospheric composition and variability, past and present evolution***

- Ground-based, airborne, space-borne sensors
- Up-looking, nadir-, and limb-sounding observation geometries



Microwave limb-sounding





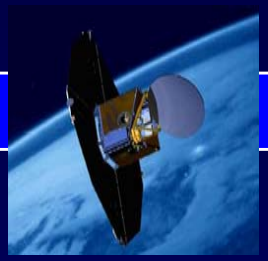
Development mm/Sub-mm Limb Emission Sounder

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".

1991

UARS/MLS
MAS/ATLAS (Space Shuttle)

2001

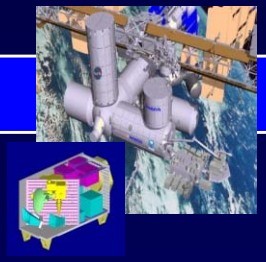


Odin/SMR

2004

Aura/MLS

2009



JEM/SMILES

Name of instrument	Receiver	Trec [K]*
Aura/MLS	Schottky	6000@650GHz DSB
Odin/SMR	Schottky	3000@500GHz SSB
JEM/SMILES	SIS	500@650GHz SSB

Sensitivity

Low

↓

High

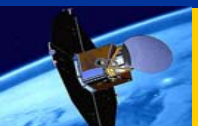
National Institute of Information and Communications Technology

CHALMERS
Radio and Space Science

courtesy: Y. Kasai

JAXA

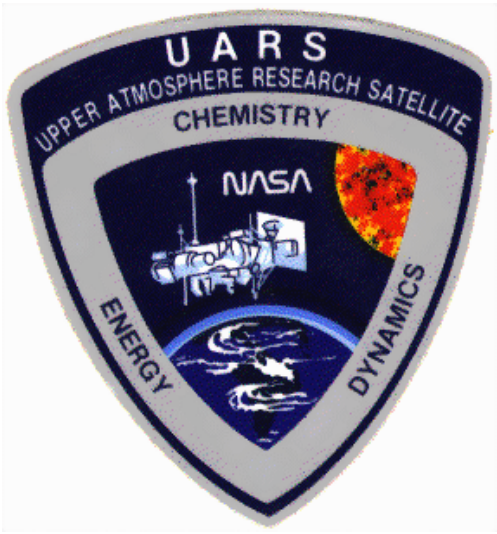
Microwave Limb Sounder on UARS

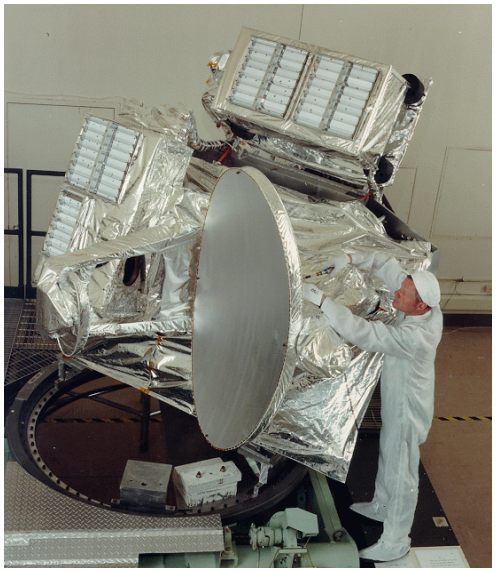


courtesy:
N. Livesey

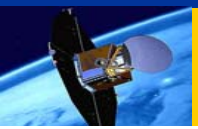
The Upper Atmosphere Research Satellite

- 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 O_3, ClO, and H_2O
- It also measured stratospheric HNO_3, temperature, SO_2, and CH_3CN, upper tropospheric H_2O and cloud ice, and gravity waves

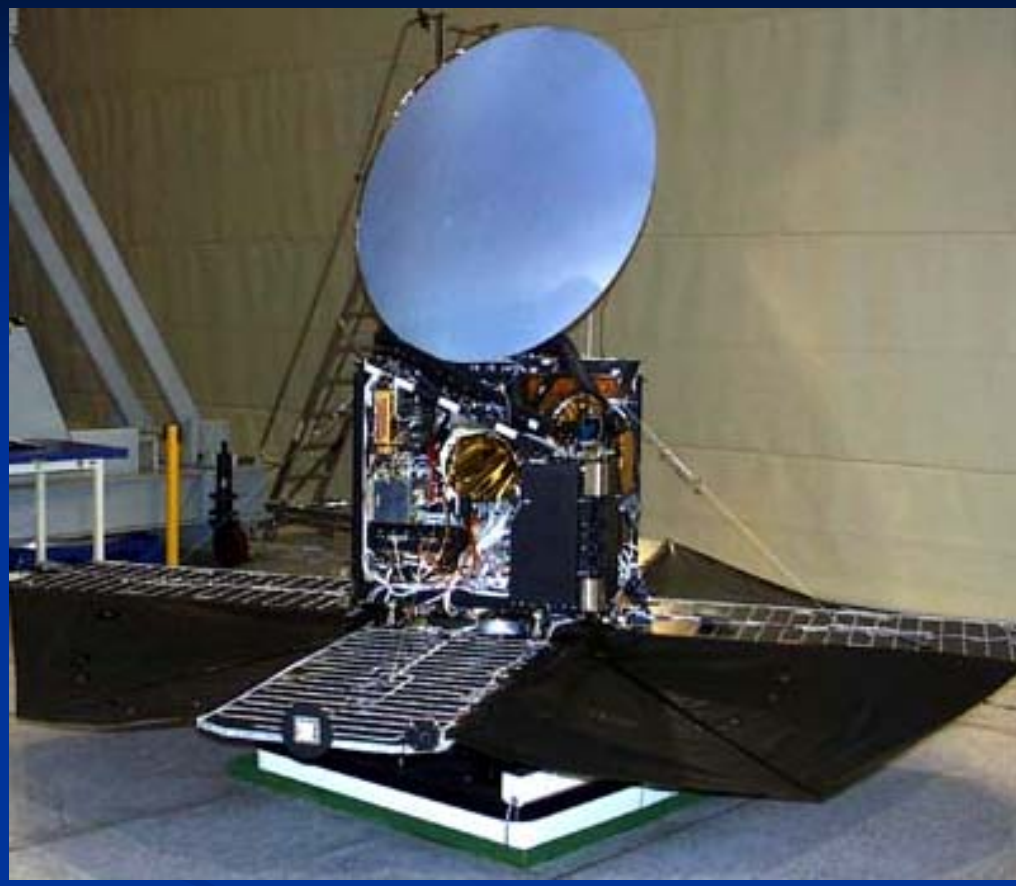




Odin Sub-Millimetre Radiometer

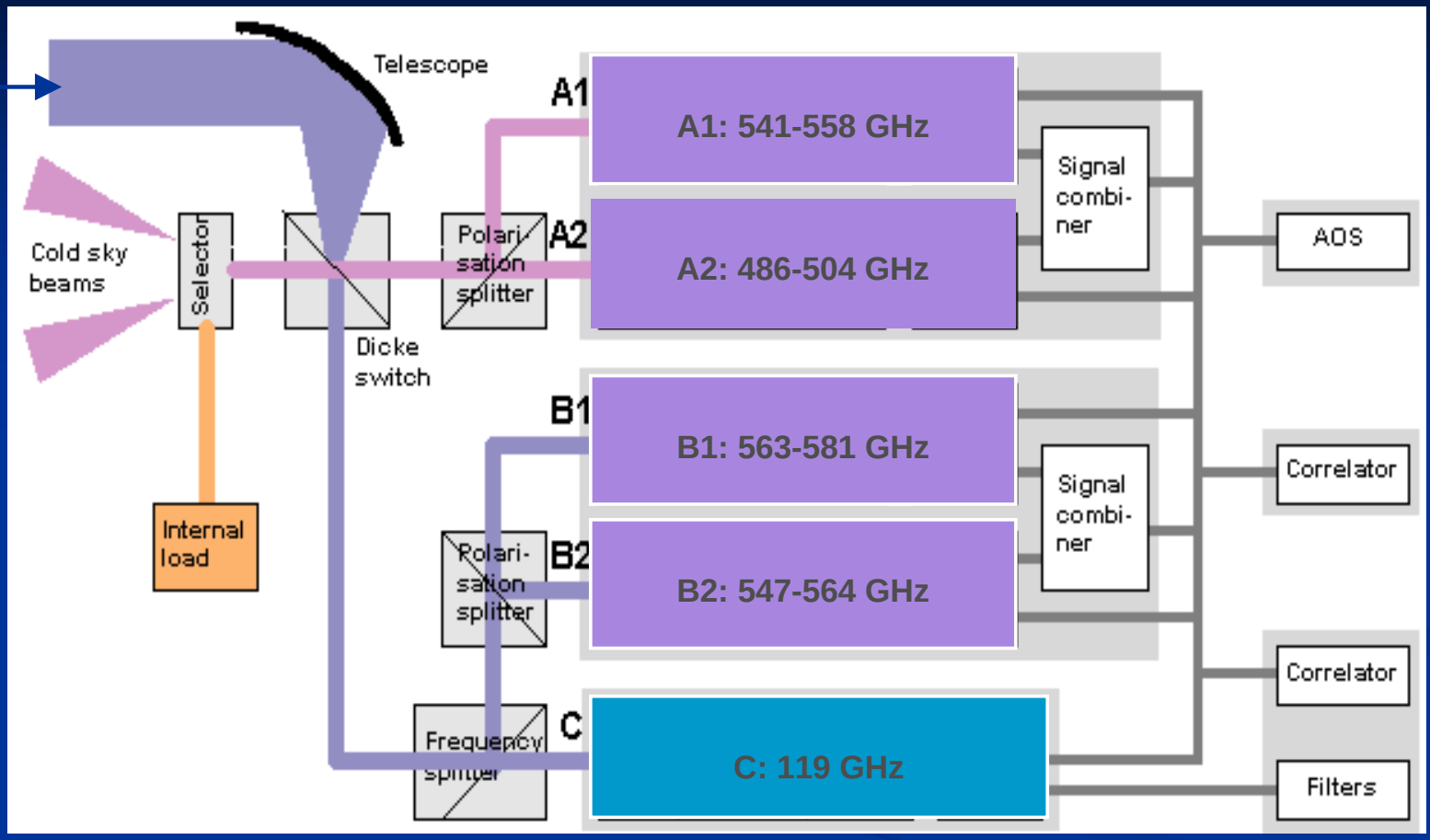


The Odin satellite



- 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"

Odin Sub-Millimetre Radiometer



- **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.

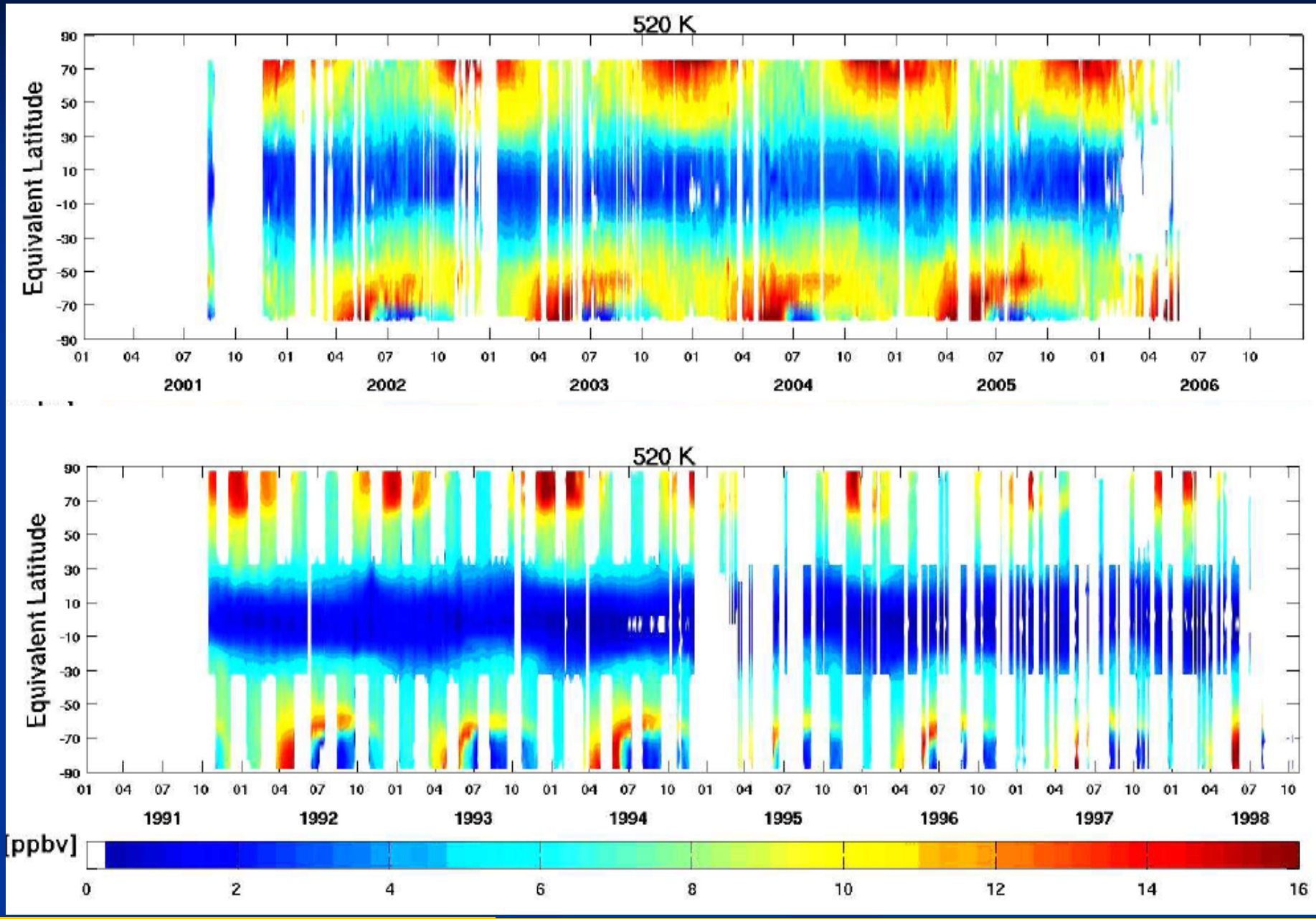
The Odin Sub-Millimetre Radiometer **[Frisk et al., A&A, 402, 3, 2003]**

courtesy: SSC

Stratospheric chemistry: HNO3

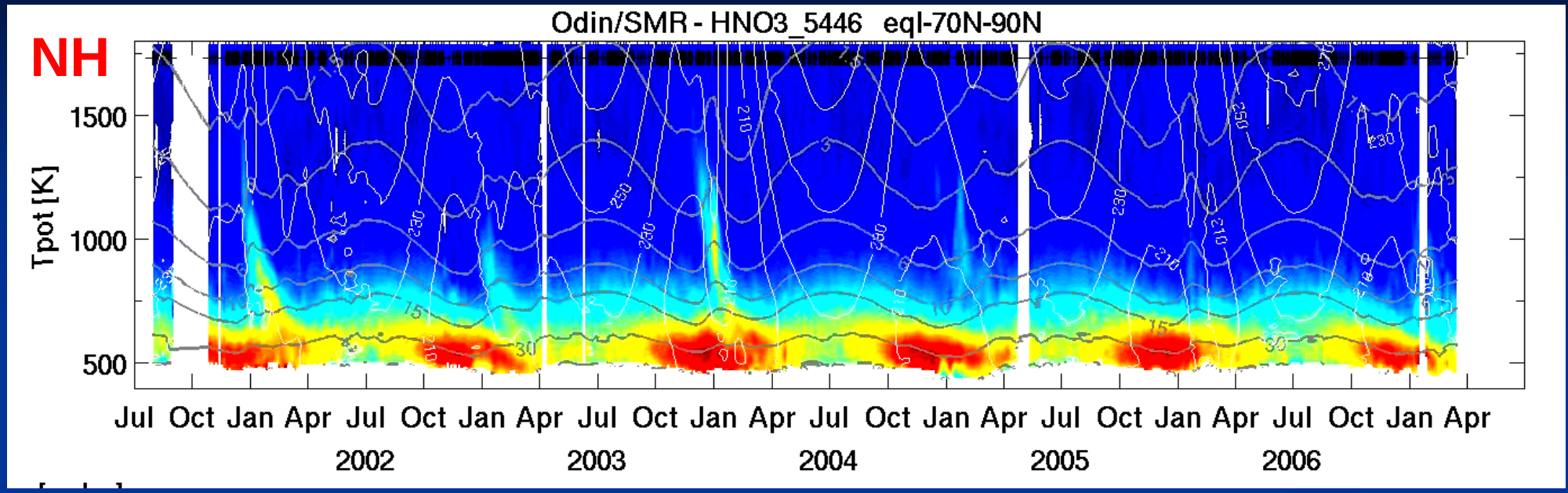
Odin/SMR
2001- ...

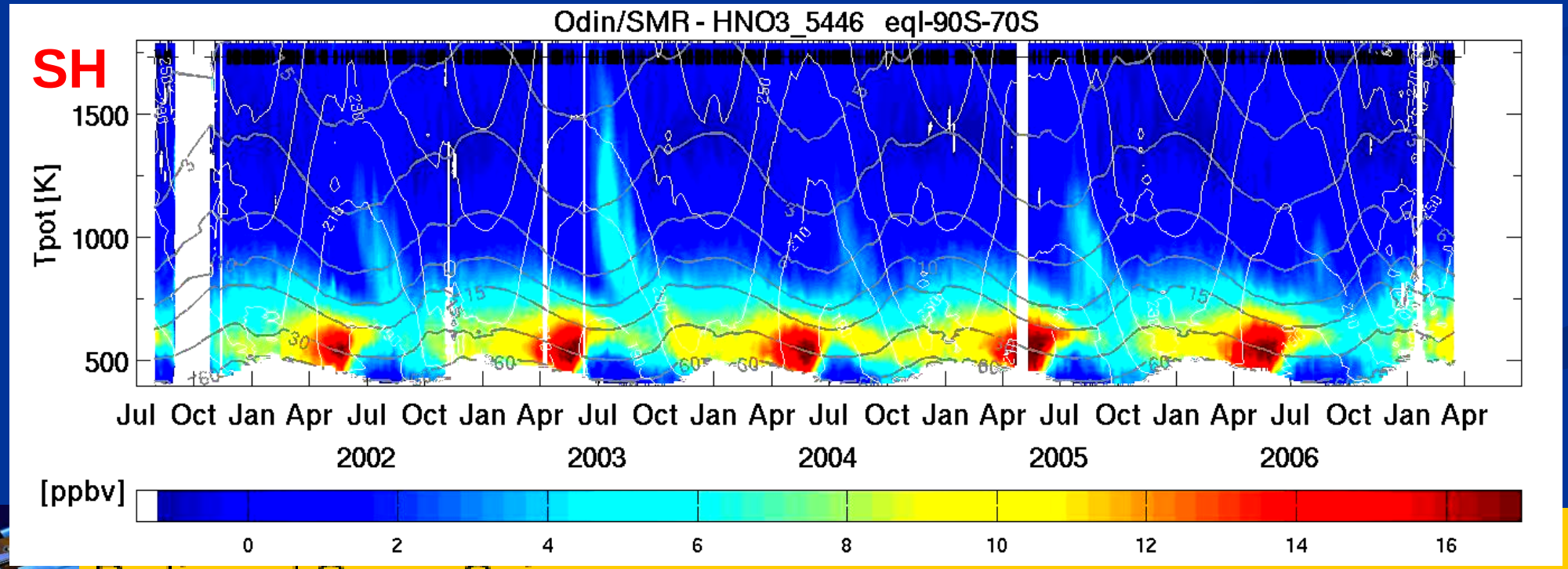
UARS / MLS
1991-1998



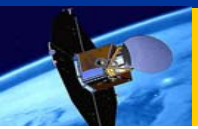
courtesy: M. Pommier, M. Santee

Odin HNO3 high-latitude time-series





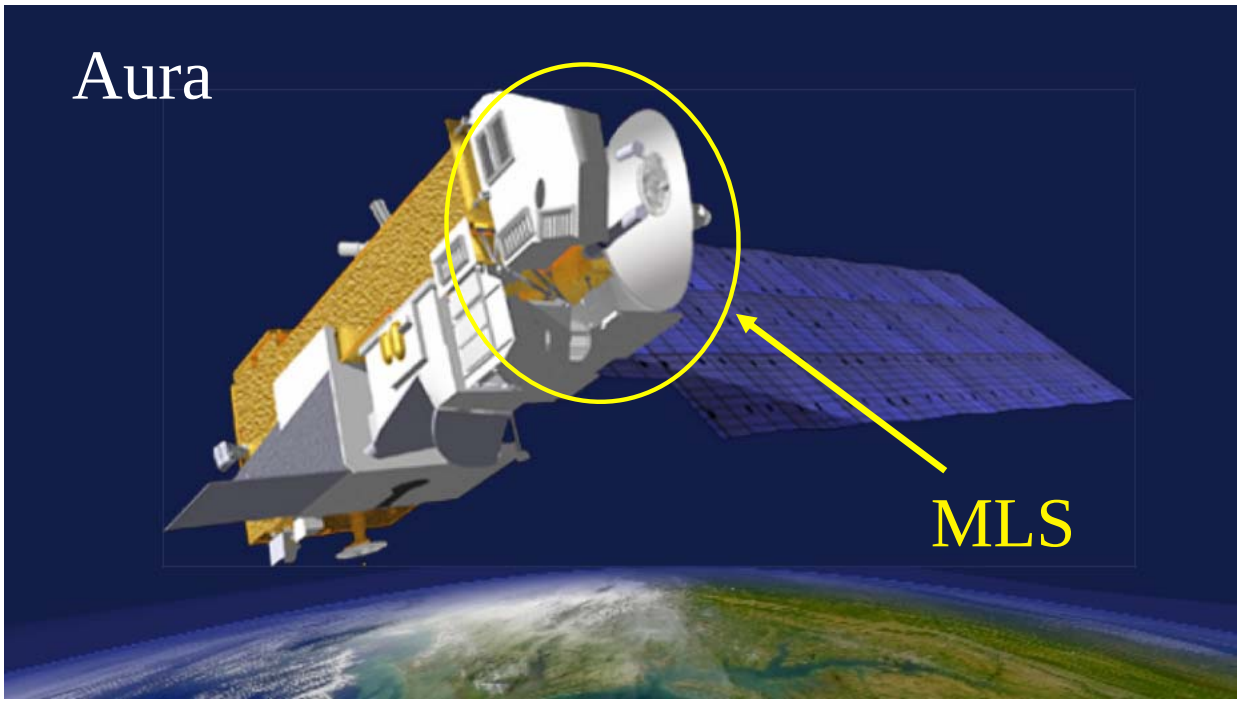
Microwave Limb Sounder on Aura

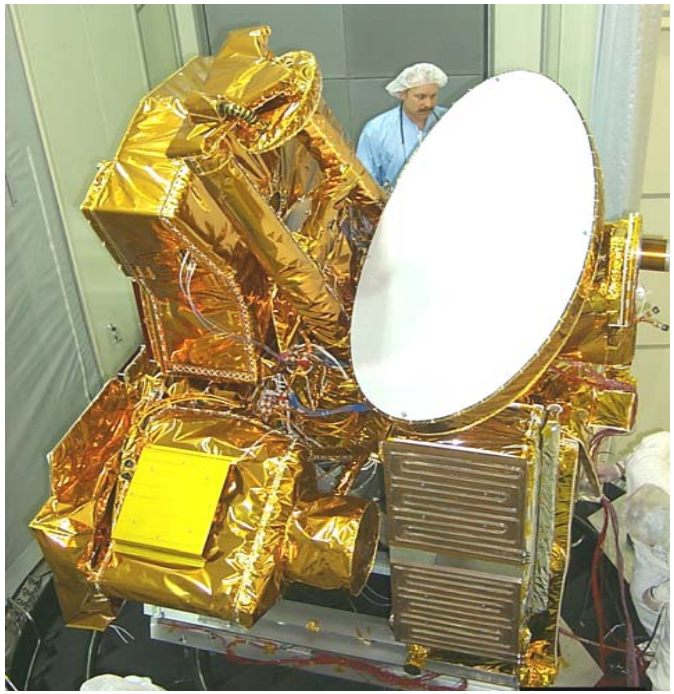


courtesy:
N. Livesey

Aura Microwave Limb Sounder objectives

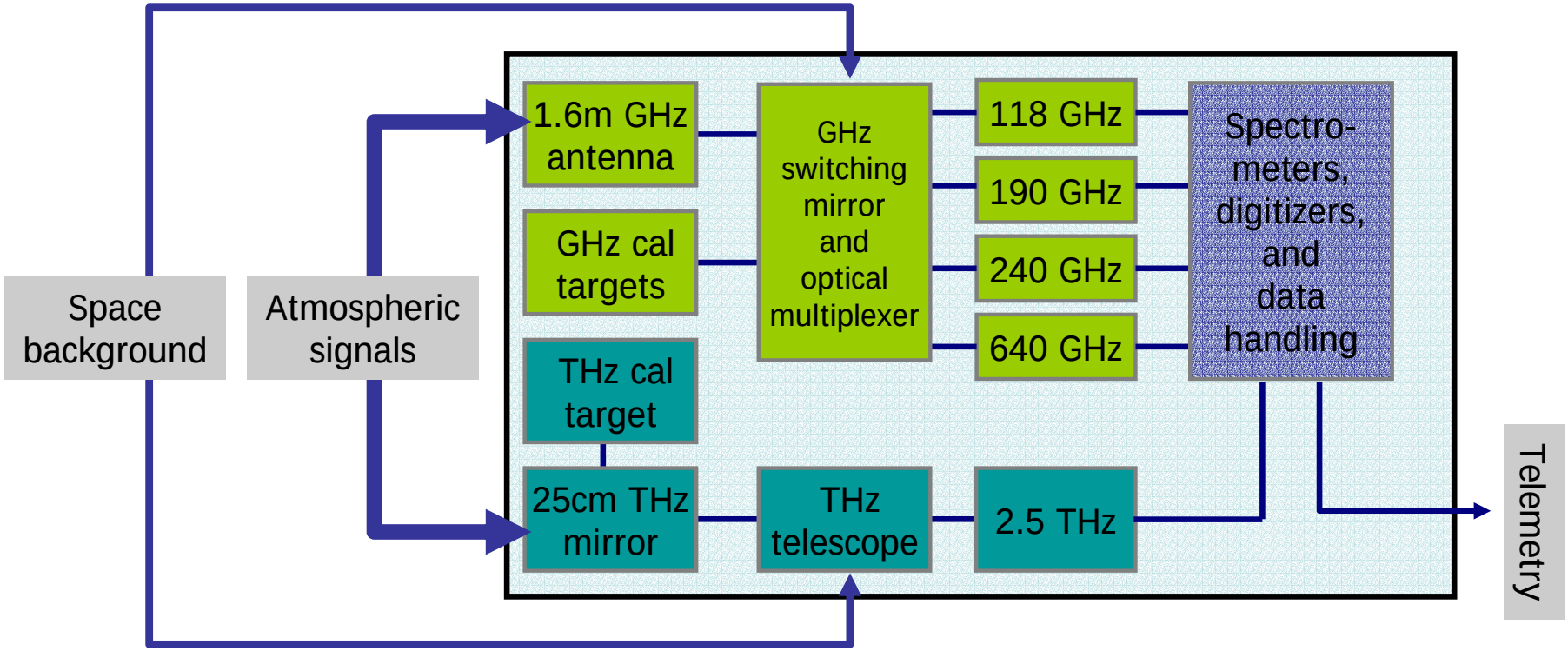
- Track the recovery of the ozone layer
- Understand aspects of how atmospheric composition affects climate
- Quantify aspects of pollution in the *upper* troposphere





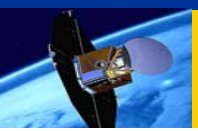
courtesy:
N. Livesey

Overview of the AURA/MLS instrument



Receiver	Frequency	Main objectives
R1A, R1B	118 GHz	Temperature and pressure (from O_2)
R2	190 GHz	Upper tropospheric water vapor
R3	240 GHz	Upper tropospheric O_3, CO and cloud ice
R4	640 GHz	Stratospheric chemistry
R5H, R5V	2.5 THz	Stratospheric and mesospheric OH

Evolution of stratospheric water vapour



Boulder balloon time-series / 17-22km

middle latitudes

Boulder
40N / 105 W

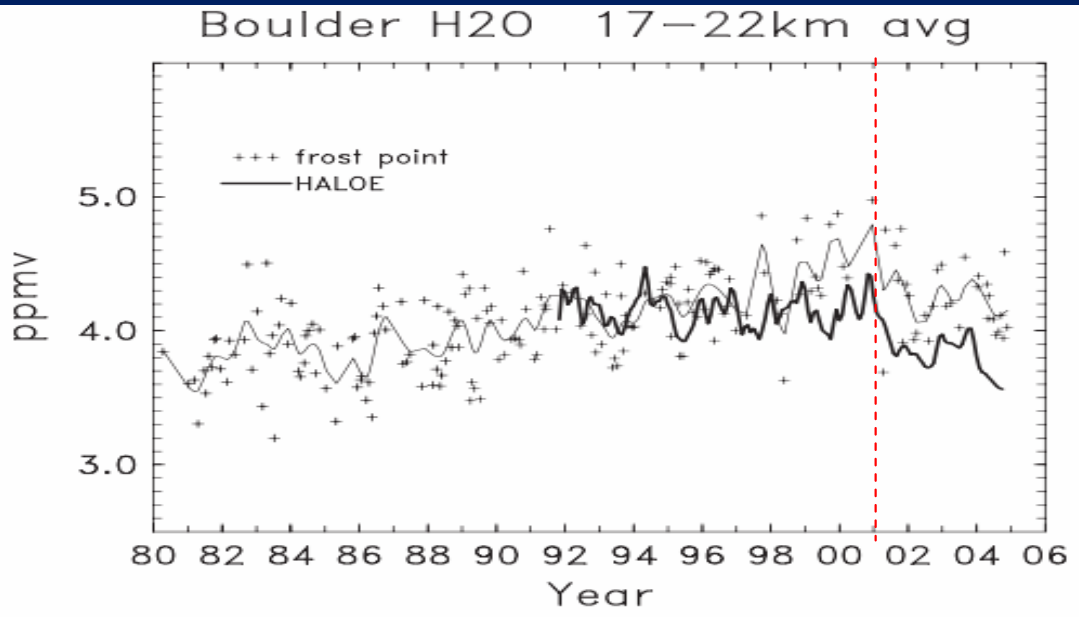
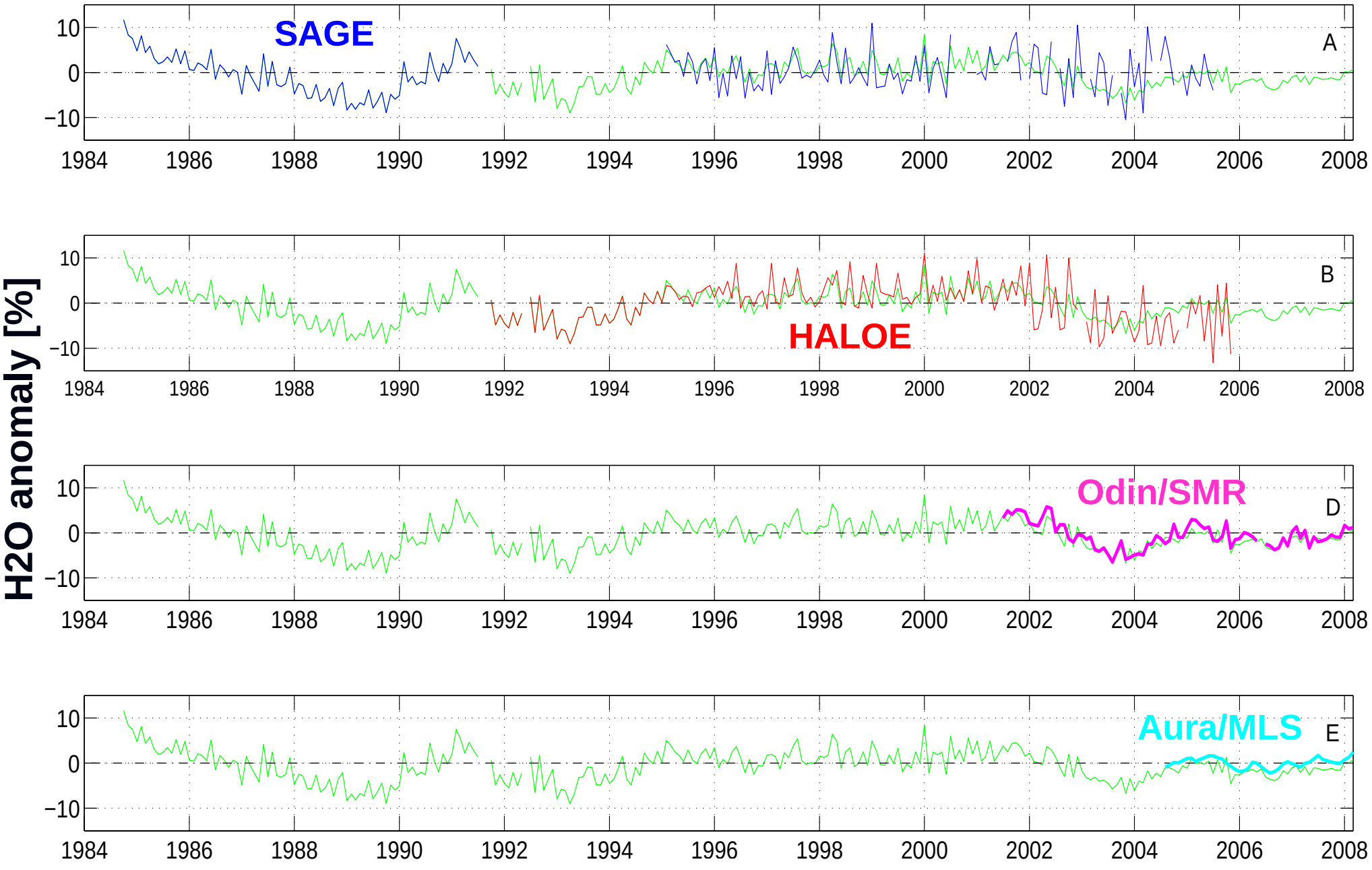


Figure 5-4. Evolution of stratospheric water vapor mixing ratio (in ppmv, averaged over 17-22 km) at Boulder, Colorado (40°N, 105°W), derived from balloonborne frost point hygrometer measurements covering 1980-2005. The thin line shows a smooth fit through the data points, using a running Gaussian window 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.

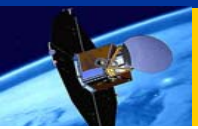
from Randel et al, 2004

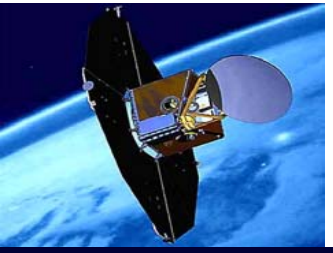
Water vapour / 30°S to 30°N / 25-35 km



Ashley Jones - Chalmers

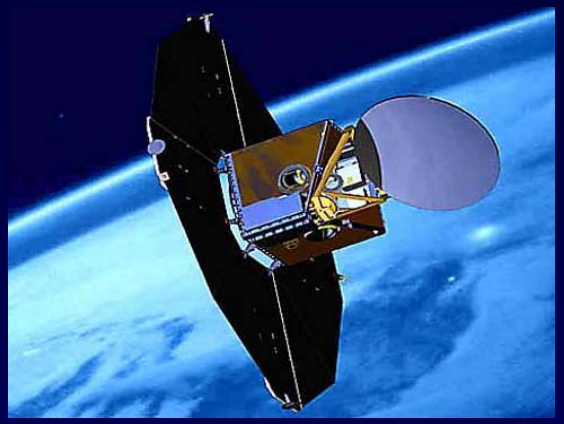
JEM / SMILES



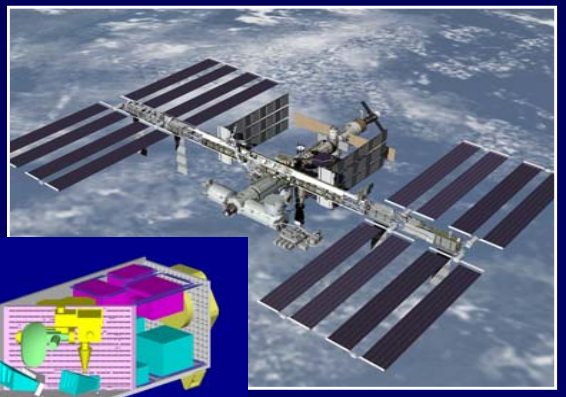


Odin/SMR and JEM/SMILES

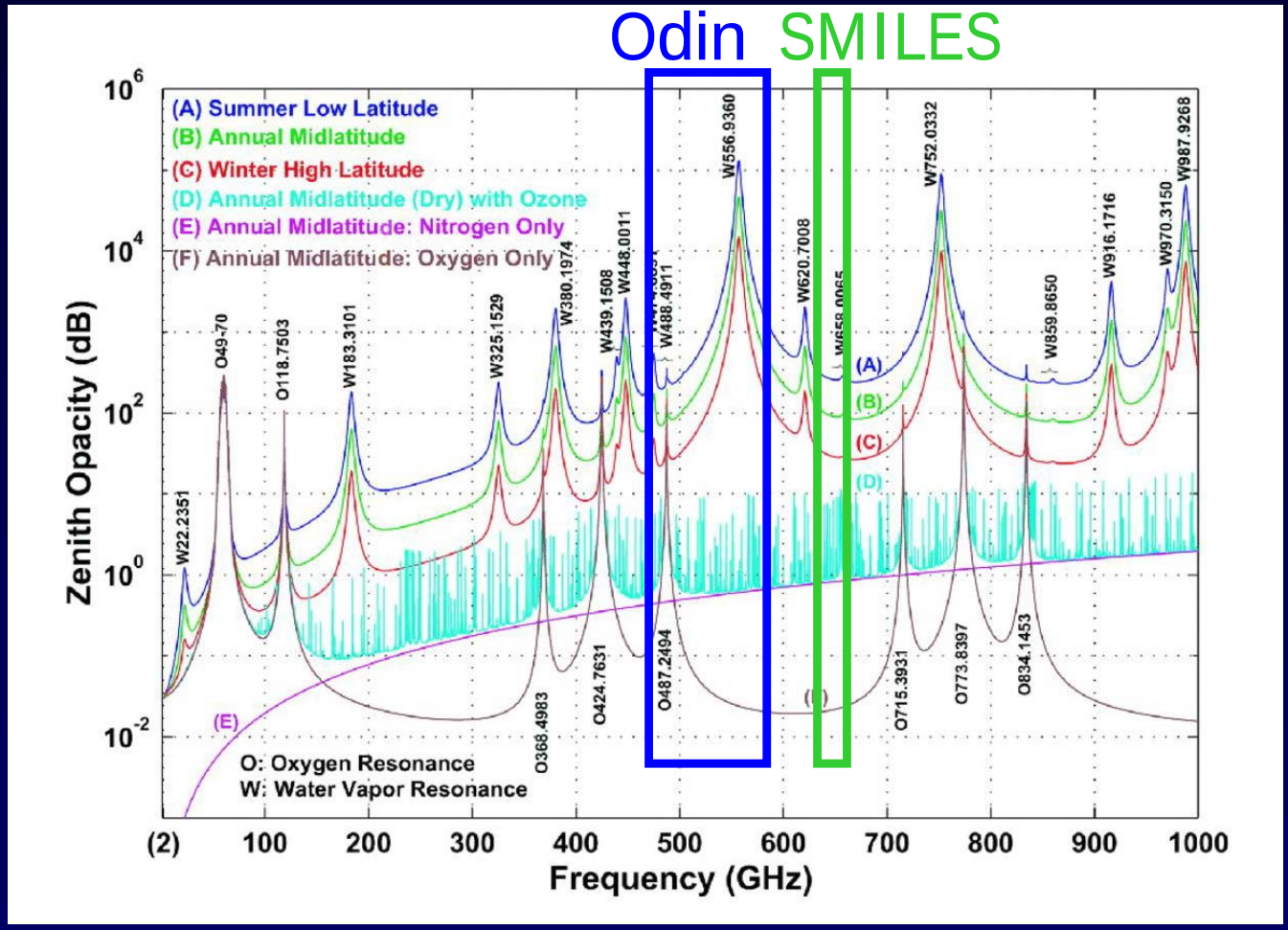
Odin/SMR



JEM/SMILES



Odin SMILES



A.J. Gasiewski and M. Klein, “The sensitivity of millimeter and sub-millimeter frequencies to atmospheric temperature and water vapour variations”, Journal of Geophysical Research-Atmospheres, 13, pp. 17 481-17 511, 2000

NiCT National Institute of Information and Communications Technology

CHALMERS Radio and Space Science

courtesy: Y. Kasai

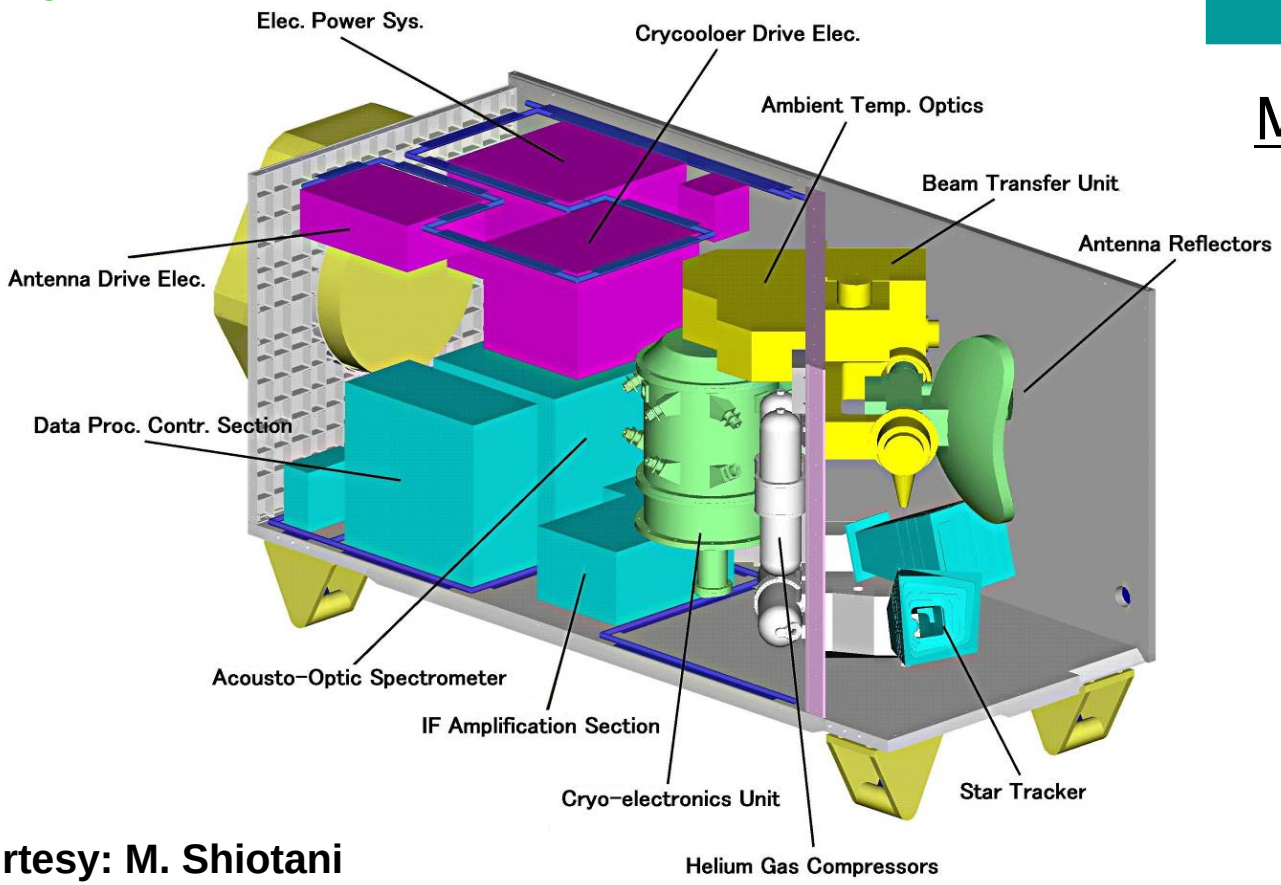
JAXA

JEM/SMILES

Science

1. Inorganic Chlorine Chemistry (ClO, HCl, HOCl)
2. Bromine budget (BrO)
3. HO_x budget (HO2)
4. Cirrus Clouds (Het. reactions & rad. budget)
5. O_3 isotopes, ...

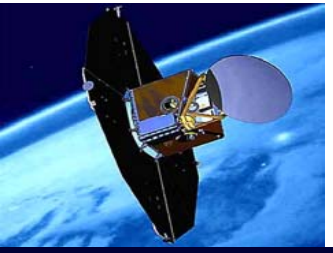
Flight Model



courtesy: M. Shiotani

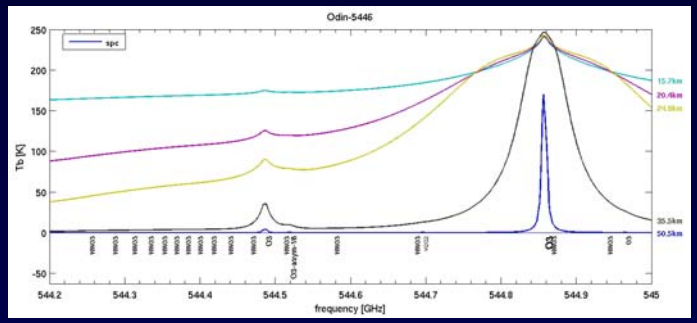
Major Design Parameters

- 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



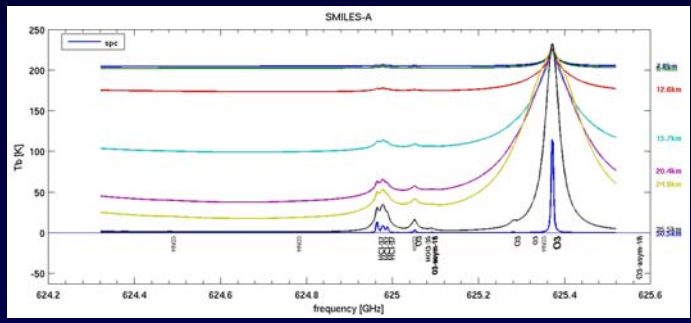
Odin/SMR vs JEM/SMILES: UT/LS water vapour

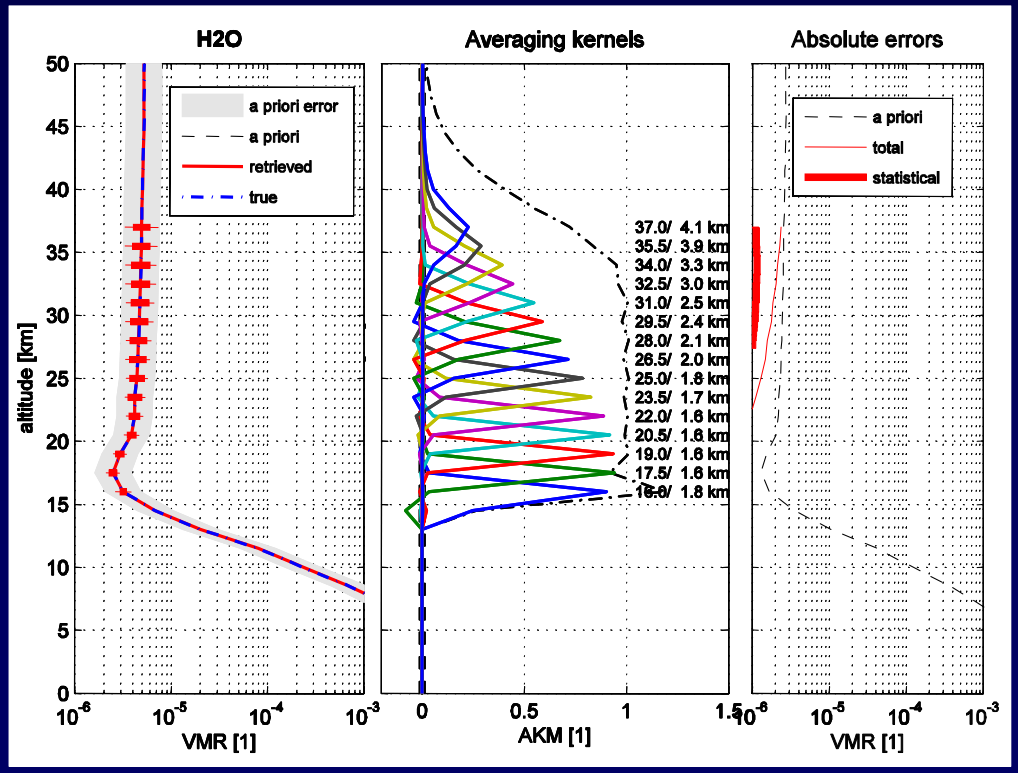
Odin/SMR - 544.6 GHz

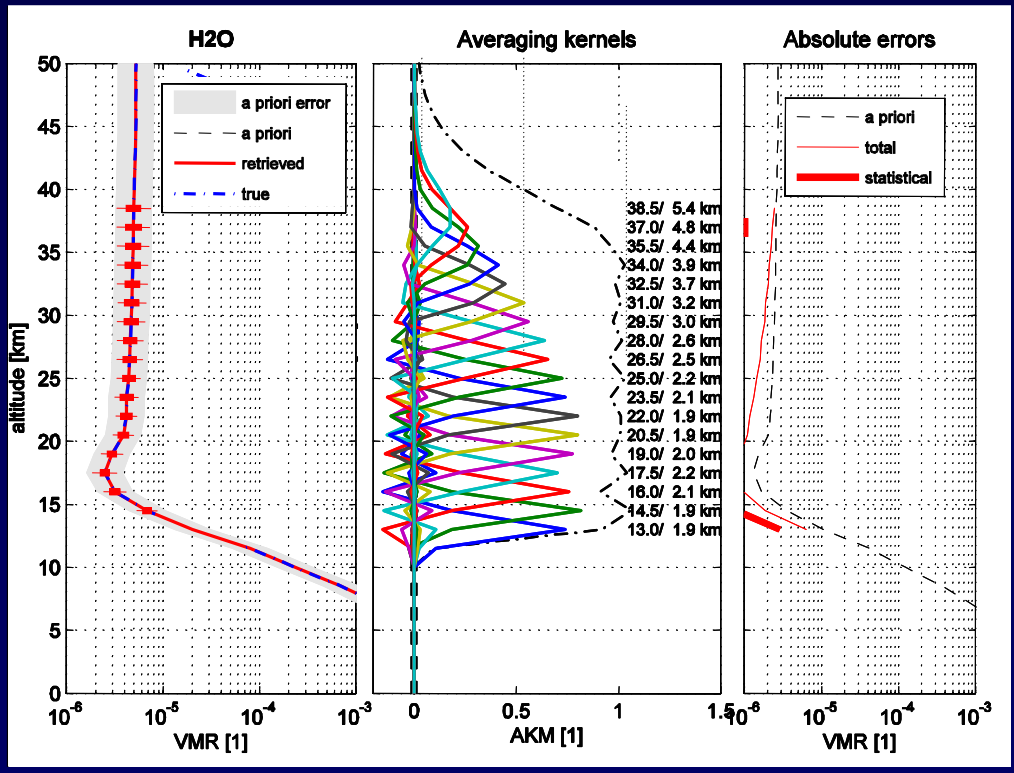


theoretical retrieval capabilities from continuum emissions (out-of-band H2O lines) in the tropics

JEM/SMILES - A - 624.9 GHz







NiCT National Institute of Information and Communications Technology

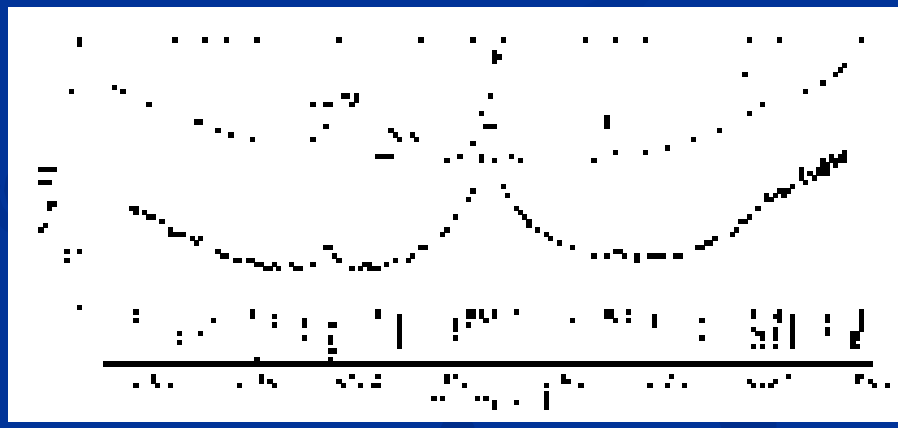
CHALMERS Radio and Space Science

JAXA

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, O_3, N_2O, ...
- **Operation on DLR-FALCON:** up-looking observation geometry, Arctic campaigns
- **Research objectives (stratosphere):**

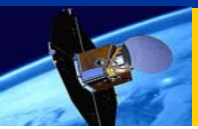
  Determination of chlorine activation, investigation of small scale structures, quantification of chemical ozone losses, time-dependent reaction mechanism (ClO diurnal variation), minor species, **validation of 3-d models and satellite instruments**
- **Other radiometers:** **500GHz-SIS** (ClO, BrO,...) and **2.5THz** (OH, H_2O)



ClO@649.45GHz - 26/2/1996 - Arctic vortex

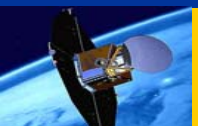
STEAM

Stratosphere-**T**roposphere **E**xchange **A**nd climate **M**onitor



Scientific objectives

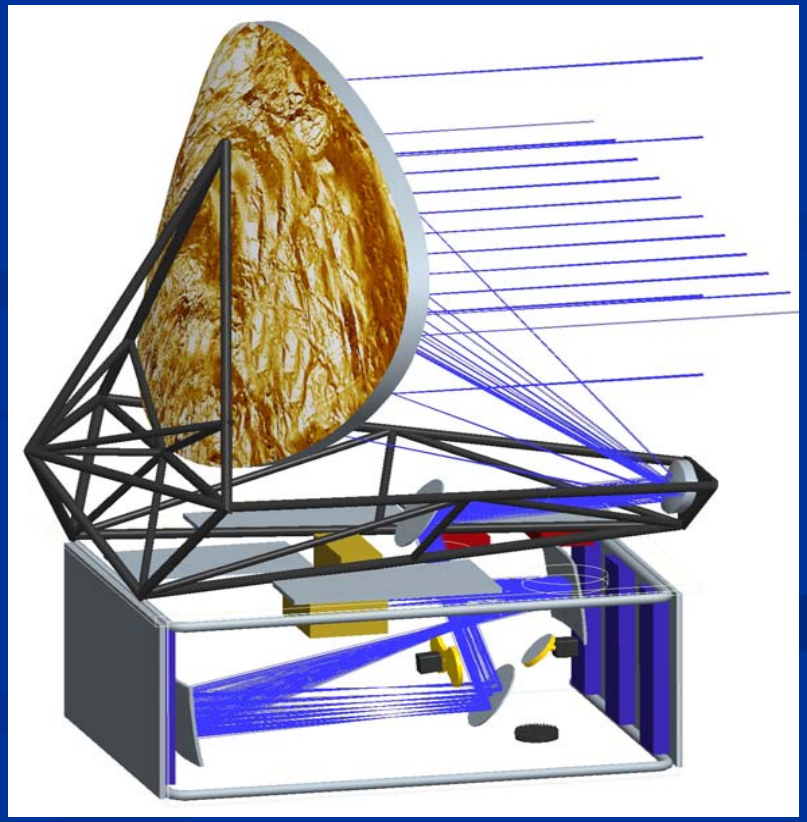
- **Climate Change**
  - Detailed measurements of **upper tropospheric H_2O**
  - IPCC identified lack of knowledge of the water vapour cycle particularly in the upper and middle troposphere as a major uncertainty in climate models
  - Water feedback provides a doubling of the CO_2 temperature increase in current climate models
- **Stratosphere-Troposphere Exchange**
  - Highly spatially resolved measurements of **O_3, H_2O** 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
  H2O, **HDO**, **O3**, **CO**, **HCN**,
  N2O, HNO3, CH3CN, CH3Cl, 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

UT/LS band

a6

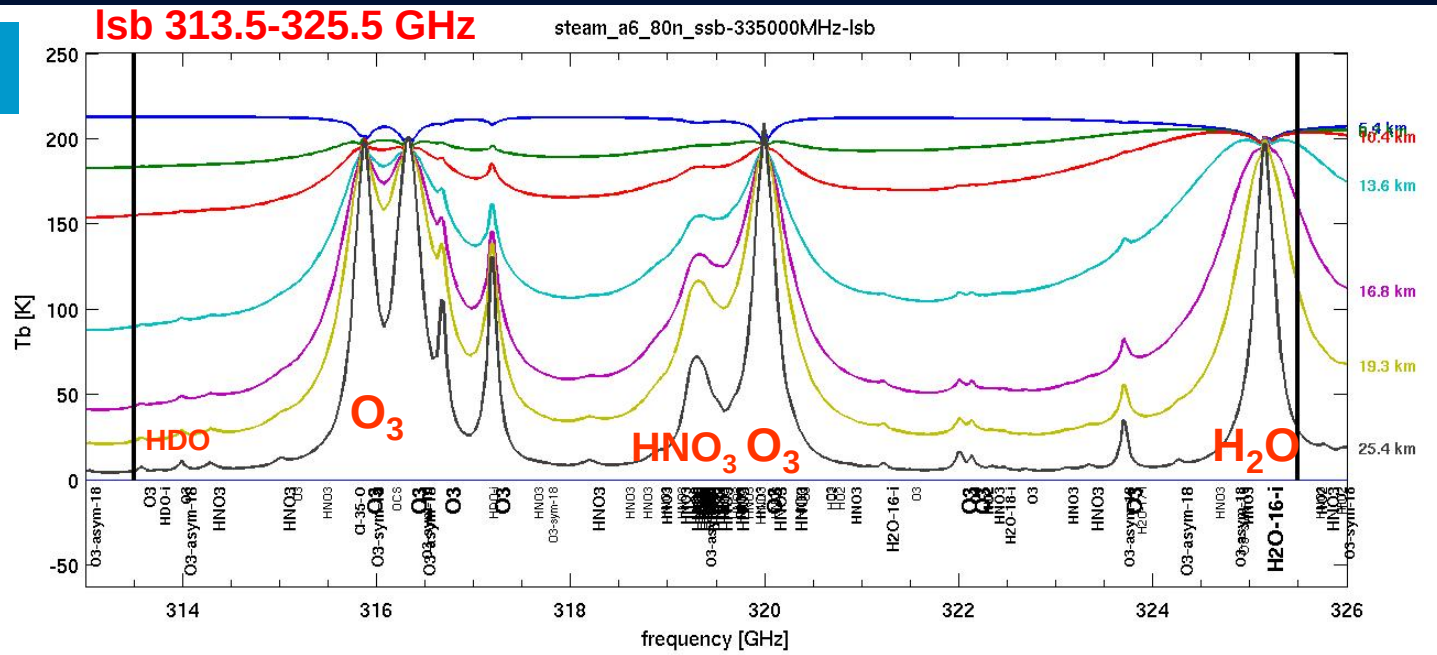
12 GHz SSB option

lo 335.000 GHz

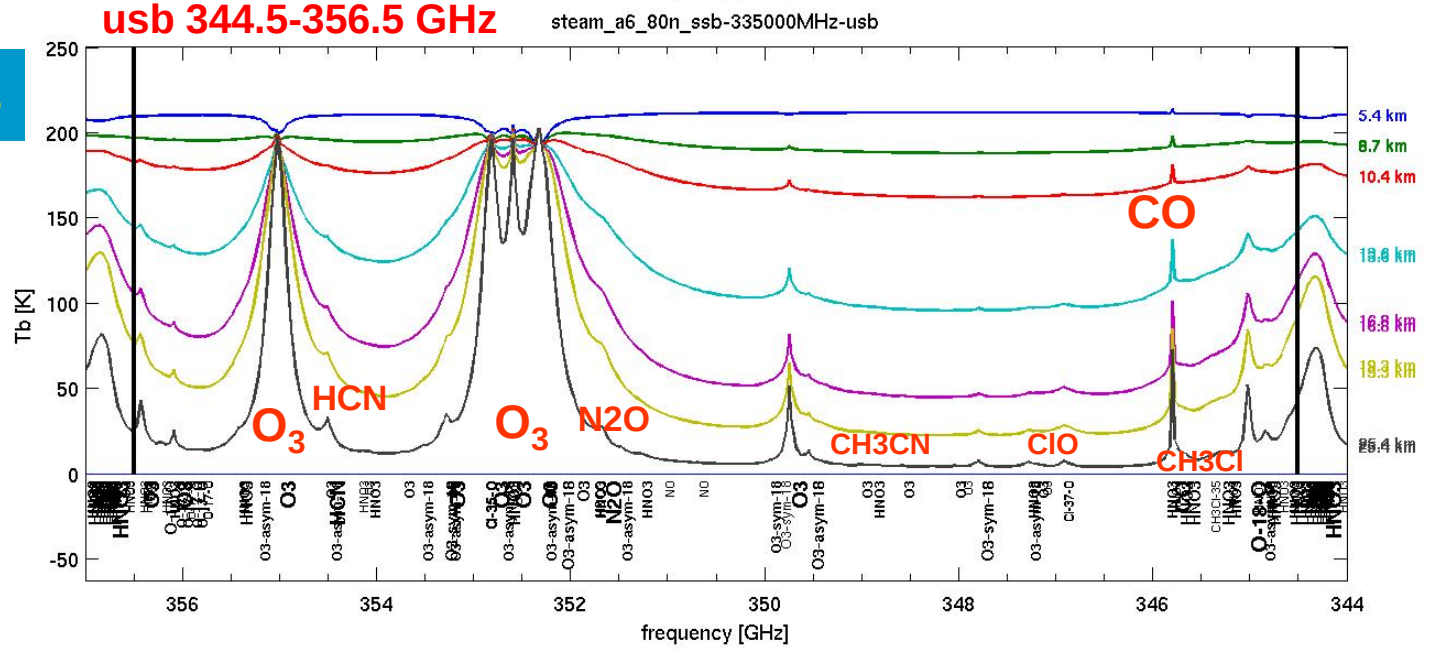
H2O, O3, CO

N2O, HNO3, CH3CN, CH3Cl, HCN, ClO, HDO

LSB

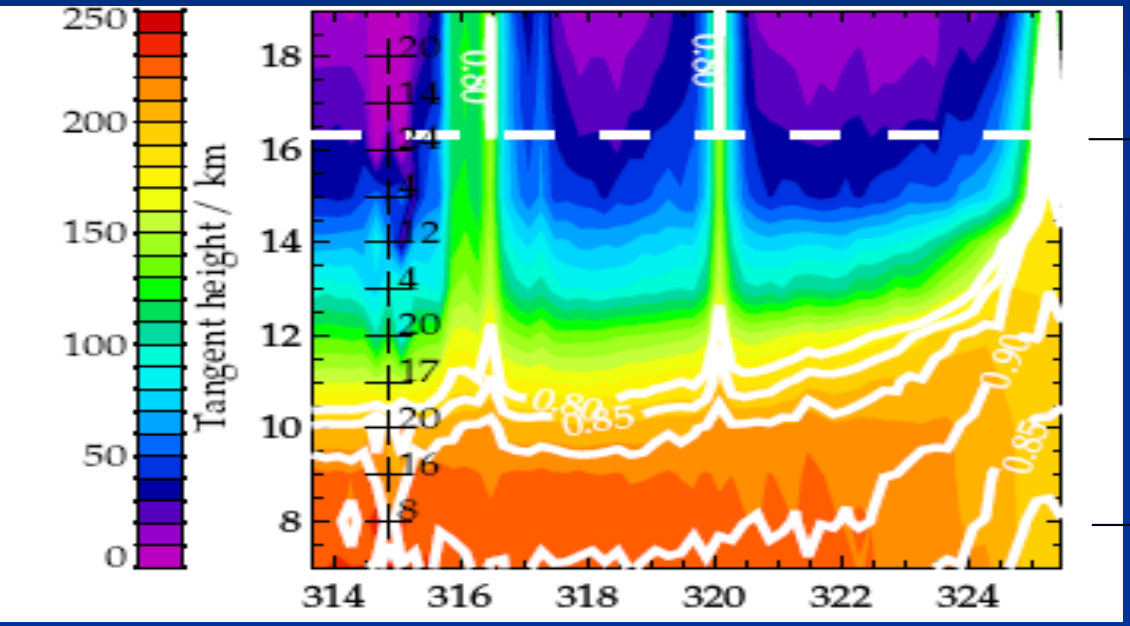


USB

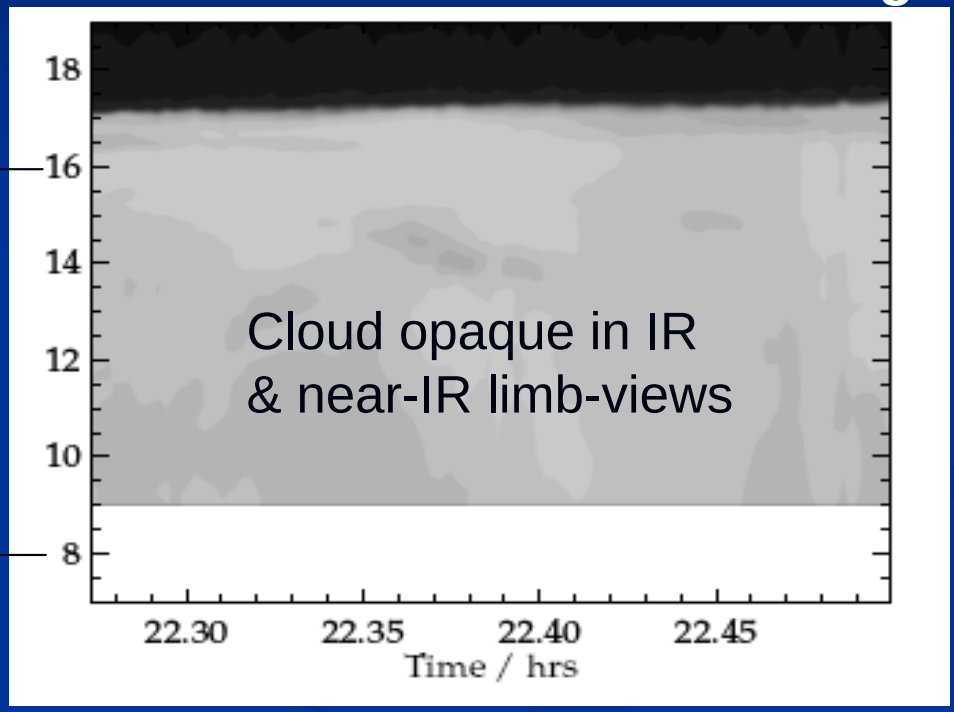


MM-wave limb sounding of UT/LS in presence of clouds

320 GHz mm-wave limb spectra



co-located 0.75mm nir limb imager



H_2O

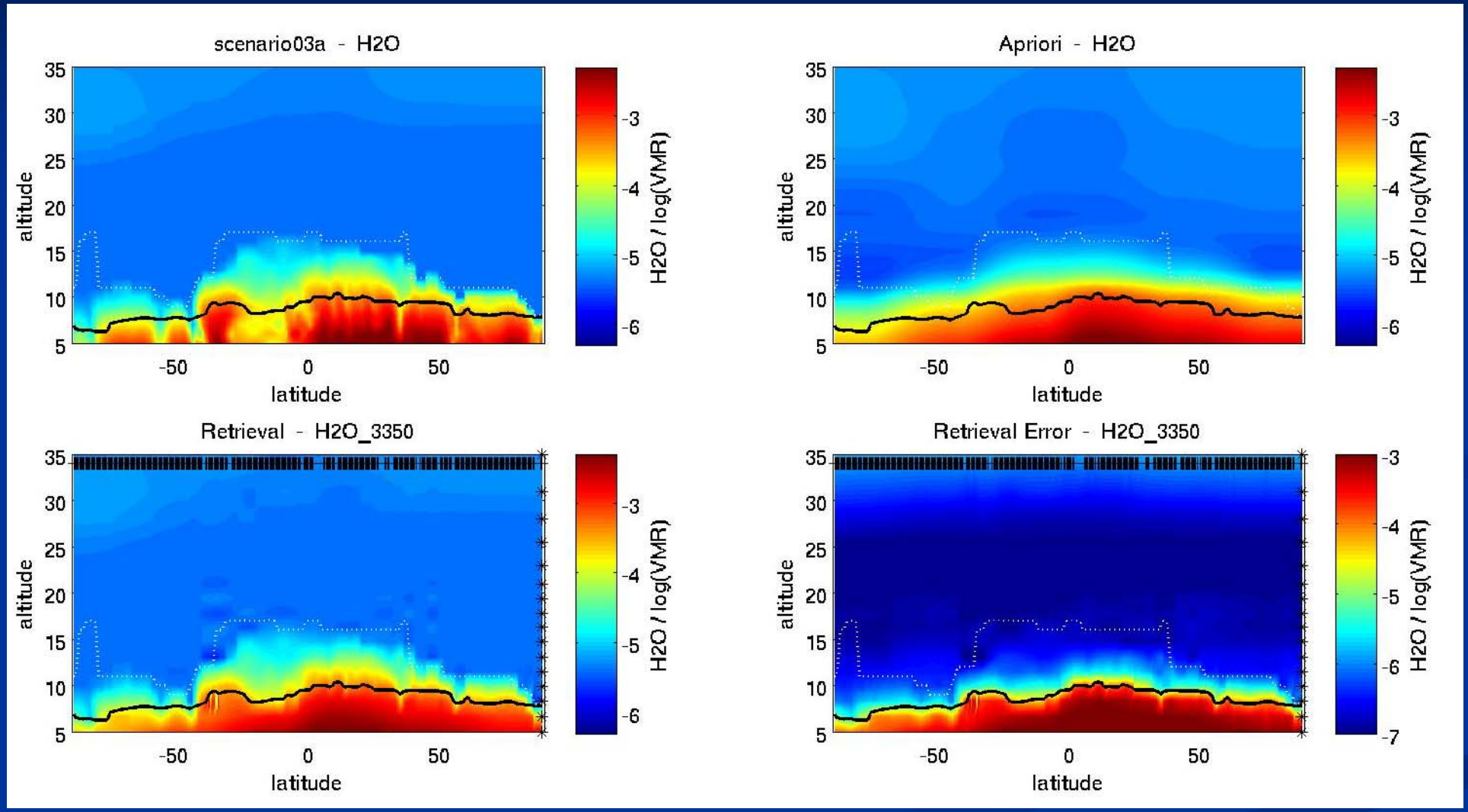
MARSCHALS

on GEOPHYSICA aircraft at ~20km

tropics (Darwin campaign)

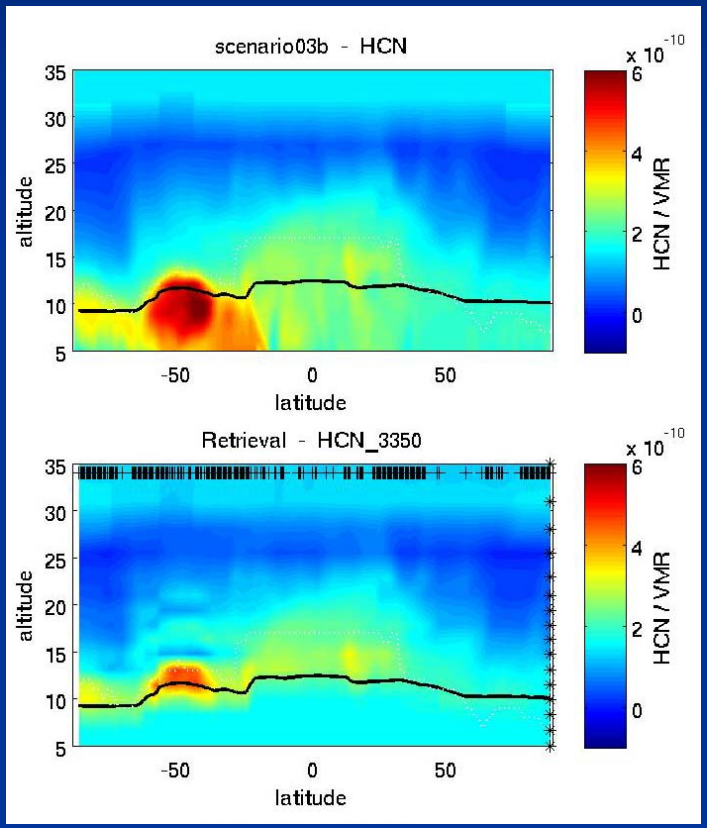
courtesy: B. Kerridge

STEAM/PREMIER study - H2O

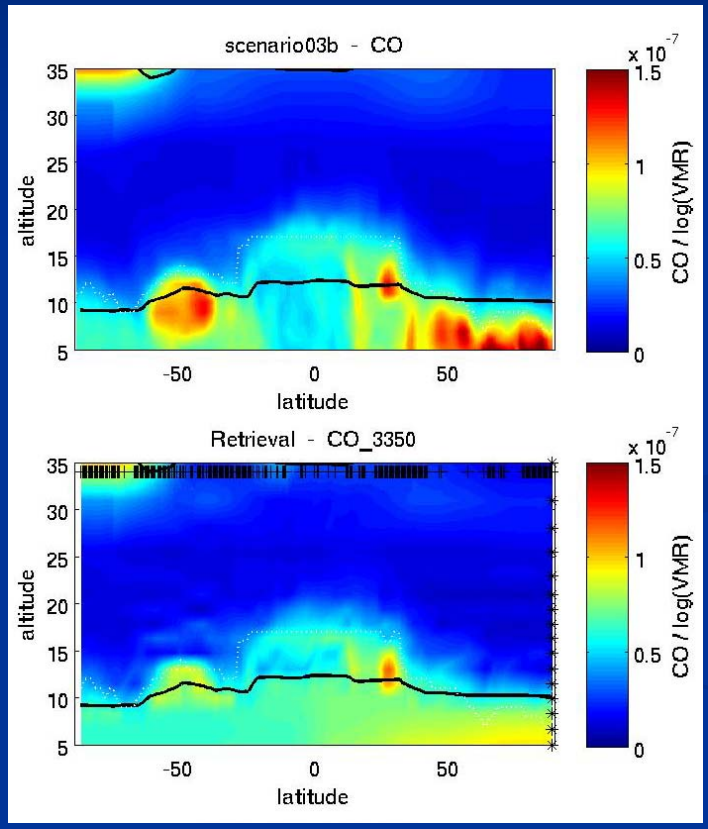


STEAM/PREMIER - Scenario 03b

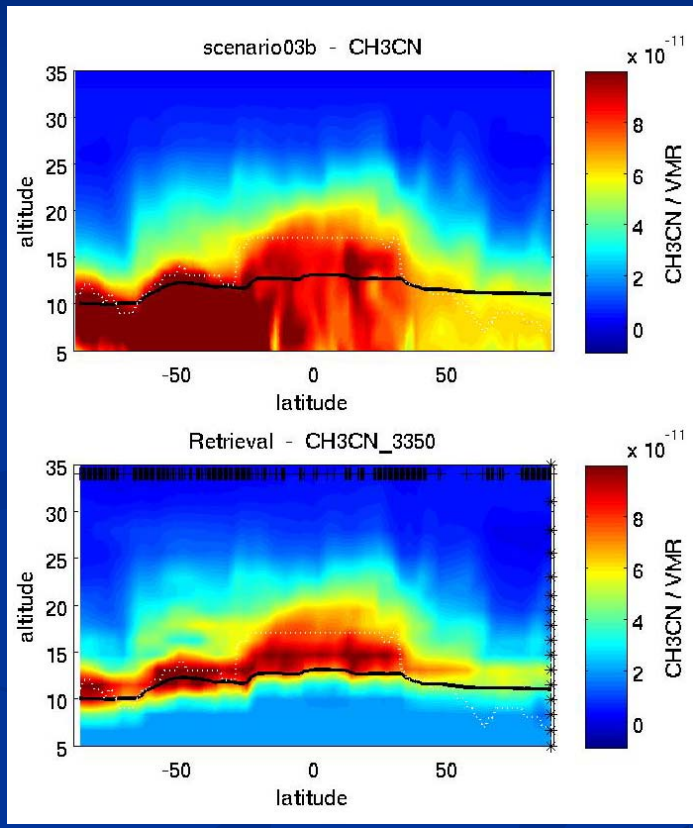
HCN



CO



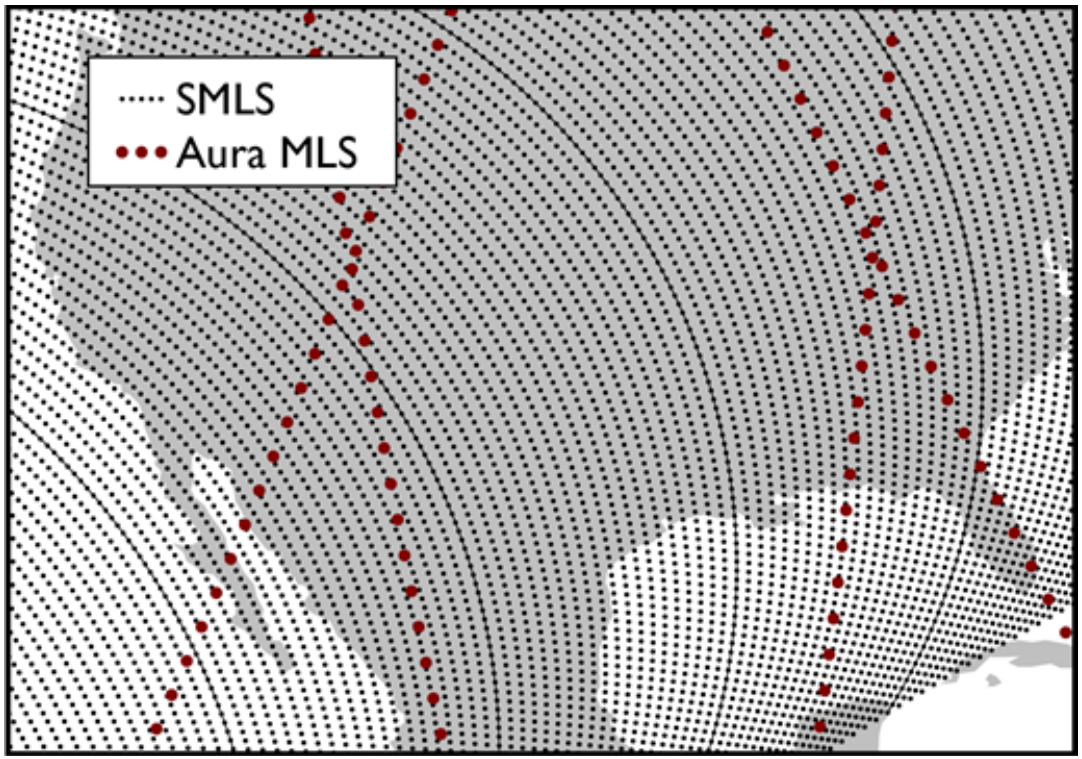
CH3CN

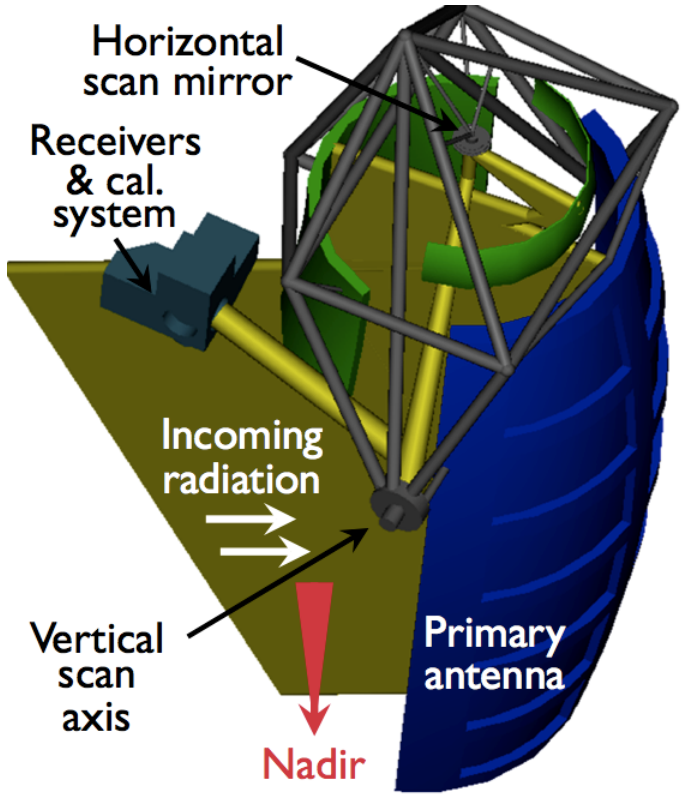


courtesy:
N. Livesey

The Scanning Microwave Limb Sounder

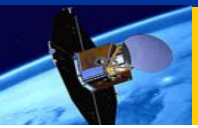
- The Scanning Microwave Limb Sounder (SMLS) is a new instrument concept that provides the needed high spatial / temporal resolution observations of the upper troposphere and lower stratosphere
- SMLS adds azimuth-scanning, combined with low-noise 'SIS' receivers
  - As used in ground-based and airborne applications for ~20 years, enabled by newly-available flight-qualified 4 K coolers
- This gives 50 x 50 km horizontal sampling



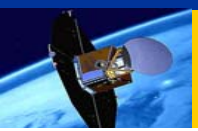


Summary

- Succesfully 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

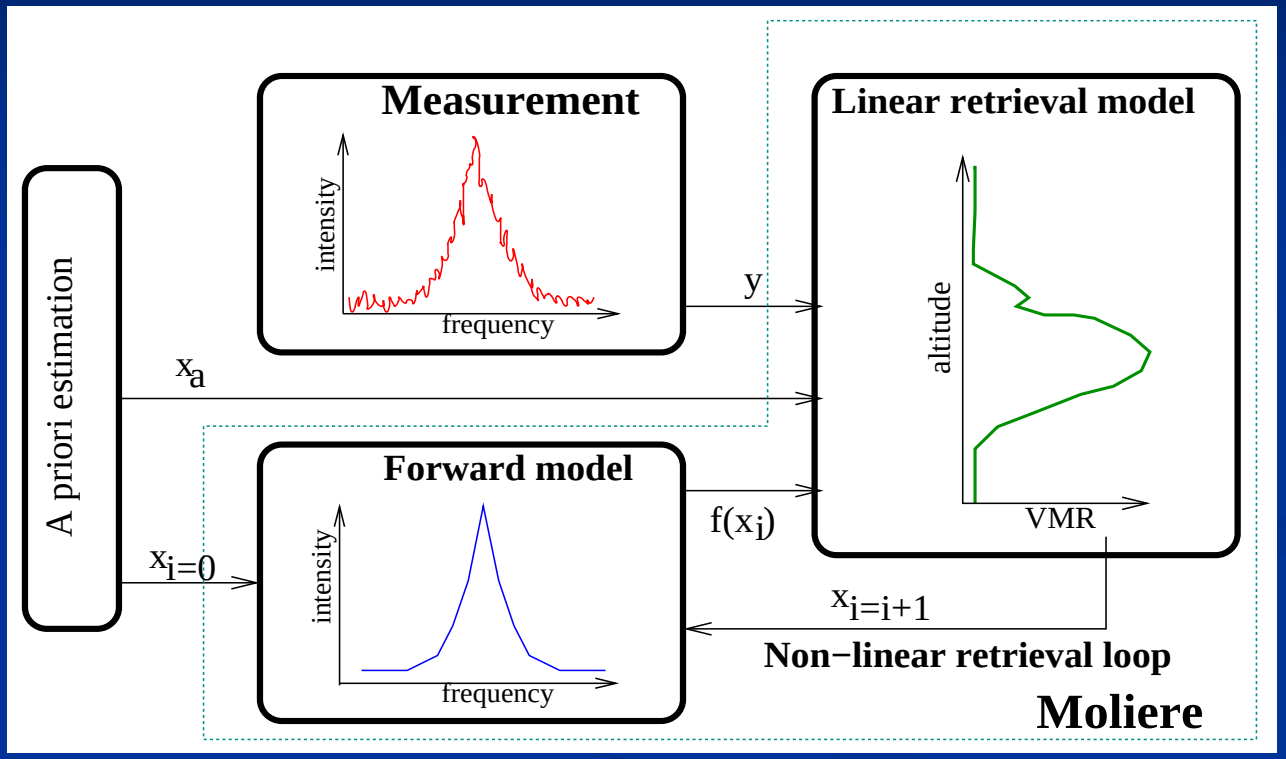


MOLIERE-5

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

Modules:

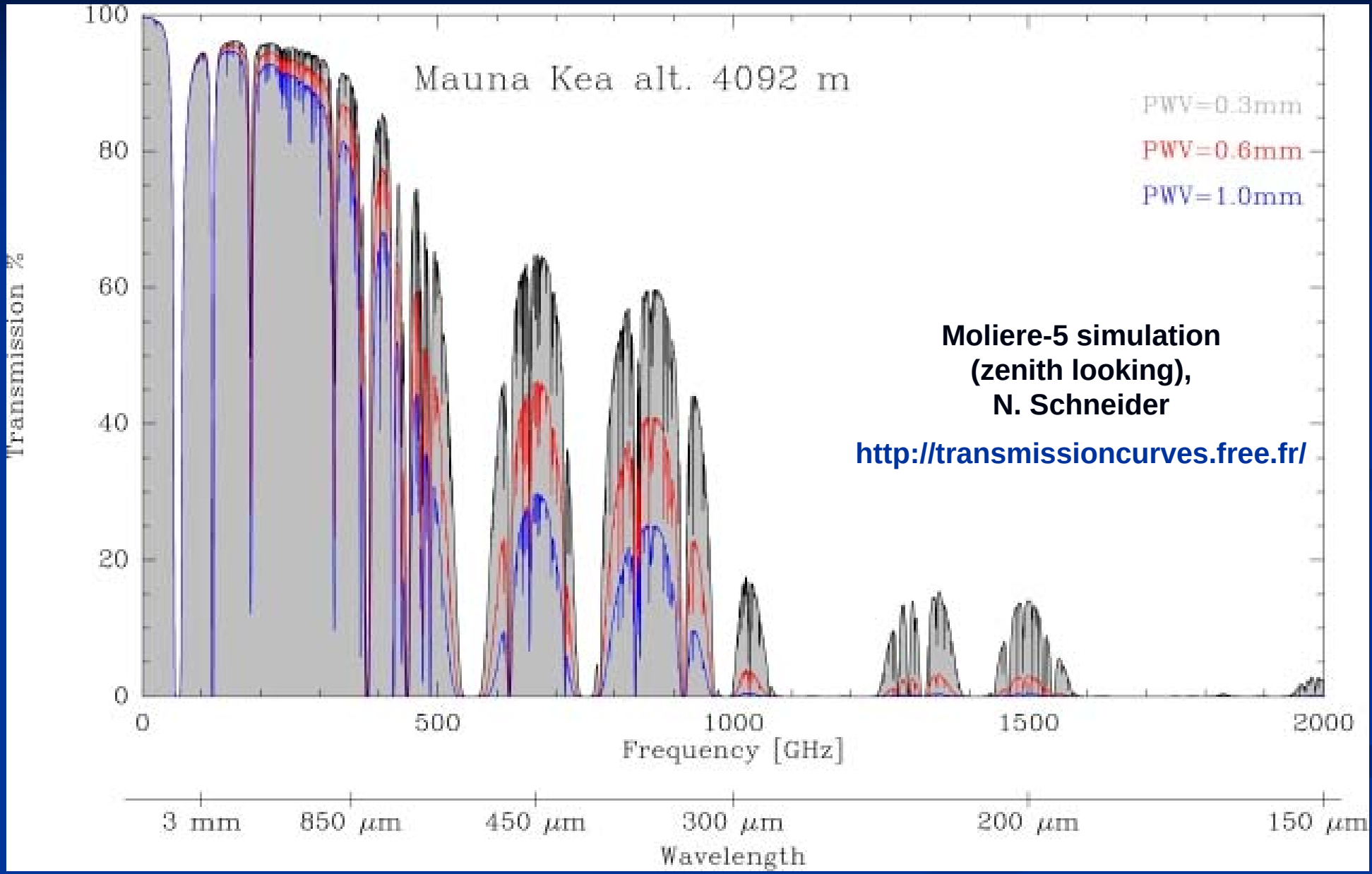
1. **ABS**. **Spectroscopic model**: line-by-line, continua.
2. **RT**. **Radiative transfer**: limb, nadir, up-looking geometry. Refraction. Differential weighting functions.
3. **INST**. **Sensor model**: antenna, sideband, spectrometer.
4. **OEM**. **Linear inversion model**: *Optimal Estimation Method*.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



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

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).**

Atmospheric transmission



Moliere-5 simulation (zenith looking), N. Schneider

http://transmissioncurves.free.fr/

Thank you!