Overview

- Introduction
  - Motivation
  - Challenges
  - Radiation Source and Techniques
  - Spectroscopy

- Instruments
  - SSM/T2, AMSU-B, MHS
  - MLS
  - HIRS, AIRS, IASI, Meteosat
  - MIPAS
  - GOME, SCIAMACHY
  - GRAS
  - ACCURATE
  - WALES

- Summary and Conclusions
Overview

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- **Summary and Conclusions**
The Water Vapor Feedback

- Models predict that relative humidity stays nearly constant → absolute humidity increases with surface T
- Responsible for roughly half the predicted warming
- Frequent subject of “climate skeptic” arguments

Evaporation ➔ Atmospheric H_2O ➔ OLR

Surface T ➔ Radiation Balance

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Water vapor and CO₂ are the most important greenhouse gases

Ample opportunities for remote sensing

Challenges

Clouds

Gradients

Temperature
Gradients

Figure from Inverse Theory Lecture.

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Temperature

Buehler, S. A. and N. Courcoux (2003),
The Impact of Temperature Errors on Perceived Humidity
Supersaturation,
Temperature Errors may Map to RH Errors

Buehler, S. A. and N. Courcoux (2003),
The Impact of Temperature Errors on Perceived Humidity Supersaturation,
Viewing Geometries

**Down**
- Mostly operational meteorology
- Good horizontal resolution
- LEO or GEO orbit
- Mostly troposphere

**Limb**
- Mostly research
- Good vertical resolution
- LEO orbit
- Mostly stratosphere
Radiation Source

- Thermal
  - Passive mm-wave, IR (limb and nadir)
- Sun
  - UV/Vis DOAS
  - Solar occultation
- Artificial
  - Transmitter on another satellite (occultation)
  - LIDAR
Lambert-Beer’s Law

Absorption by a gas:

\[ I = I_0 e^{s \alpha} \]

Distance

Intensity

Absorption Coefficient

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Absorption coefficient $\alpha$ determined by

- Continua
- Electronic transitions ($10^{15}$ Hz, UV visible)
- Vibrational transitions ($10^{13}$ Hz, Infrared)
- Rotational transitions ($10^{11}$ Hz, mm / sub-mm)
Absorption coefficient $\alpha$ given by

$$\alpha(\nu) = n S(T) F(\nu)$$

- **Number density of absorber**
- **Temperature**
- **Line intensity**
- **Line shape function**
- **Frequency**
N2O P:1000 hPa T:300 K

Model: ARTS (www.sat.uni-bremen.de/arts)

Abs. Coeff [m⁻¹]

Frequency [GHz]

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- Summary and Conclusions
Satellite H$_2$O Observations

Passive
- MM-Wave
  - Down AMSU
  - Limb MLS
  - Limb MIPAS
  - Down HIRS IASI

Active
- UV/Vis
  - Down GOME
  - IR Laser ACCURATE
- Occultation
  - Radio GRAS
  - Occultation HALOE

Down
- LIDAR WALES
Thermal Radiation

Can be measured by a microwave or IR sensor

\[ B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \]

Planck Function

\[ I_\nu = \int \alpha_\nu(s) B_\nu(T(s)) e^{-\tau_\nu(s)} ds \]

Opacity

\[ \tau_\nu(s) = \int_0^s \alpha_\nu(s') ds' \]

No external source, continuous measurement by day and by night.

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Down-looking - Limb-Looking
The Radiometer Challenge

- The absolute power of thermal radiation in the mm-wave spectral range is low.
The Radiometer Challenge

- The absolute power of thermal radiation in the mm-wave spectral range is low. (The peak of the Planck function is in the infrared.)
- Need to amplify the signal by many orders of magnitude for detection.
- No good amplifiers for frequencies above approximately 100 GHz (technology constantly moving)
- State of the art: Heterodyne Receivers
A Typical Heterodyne Radiometer

Antenna → Mixer → Amplifier → Spectrometer

RF = Radio frequency
LO = Local oscillator
IF = Intermediate frequency

(Figure: Oliver Lemke)
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The Heterodyne Principle

- Mixer generates signal with $v_{IF} = |v_{RF} - v_{LO}|$
- This can then be amplified and analyzed with a spectrometer
- Intensity unit: **Brightness temperature** = The temperature a black body would need to generate the same intensity of radiation

(Figure: Oliver Lemke)

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The Radiometer Formula

\[ T_{\text{NET}} = \frac{T_{\text{Sys}}}{\sqrt{\Delta B \times \Delta t}} \]

\( T_{\text{NET}} \) = Noise equivalent temperature (noisiness of individual measurement)

\( T_{\text{Sys}} \) = System noise temperature (characteristic noise of measurement system)

\( \Delta B \) = Frequency bandwidth

\( \Delta t \) = Integration time
The Radiometer Challenge (2)

\[ T_{\text{NET}} = \frac{T_{\text{Sys}}}{\sqrt{\Delta B \times \Delta t}} \]

- We cannot make \( \Delta B \) and \( \Delta t \) as large as we want. (We want spectral resolution, and the satellite flies by fast.)
- Need low noise receivers.
- Mixer and first amplifier most critical, because their noise is amplified by subsequent stages.
- Cool mixer to low operation temperature. Best: Superconducting (SIS) mixers at 4 K.
- Cooled HEMT amplifiers.
DOWNLOOKING SENSORS
SSM/T2, AMSU-B, MHS
Microwave Satellite Data

- SSM-T2 since 1995
- AMSU-B since 1999
- Passive microwave instruments (measuring thermal radiation from the atmosphere)
- Less affected by cloud than infrared
- Well calibrated
AMSU-B (MHS is very similar)

- Cross-track scanner
- 90 pixels per scan line
- Outermost pixels 49° off-nadir
- Swath with $\approx 2300$ km
- Global coverage twice daily
- 16 km horizontal resolution (at nadir)
AMSU-B Channels

(Details: John and Buehler, GRL, 31, L21108, doi: 10.1029/2004GL021214)

Water vapor

Oxygen

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AMSU-B Channels

(Figure by Viju O. John)

Water vapor

Oxygen

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AMSU-B Jacobians

(Figure by Viju O. John)

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AMSU-B Data (Channel 18)

Dry areas in the UT

Figure: Oliver Lemke)
- Retrieving humidity usually requires a priori, problematic for climate applications
- Humidity Assimilation can destroy information on absolute value due to the bias corrections applied
- Solution: Look for a humidity product that is related as closely as possible to the radiances
Regression UTH Retrieval

- UTH = Jacobian-weighted relative humidity ≈ mean relative humidity between 500 and 200 hPa
- Simple relation:
  \[ \ln(UTH) = a + b T_b \]
- Determine \( a \) and \( b \) by linear regression with training data set
- Details:
  Buehler and John, JGR, 2004

- Method originally invented by Brian Soden for IR data.

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- Coefficients independent of training data set
- Basically another unit for radiance
- Other humidity data must be processed in same way for comparison
Humidity Climatology

An Upper Tropospheric Humidity Data Set From Operational Satellite Microwave Data,

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# Available instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Satellite</th>
<th>Useable data</th>
<th>LTAN (@launch)</th>
</tr>
</thead>
<tbody>
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<td>SSM/T 2</td>
<td>DMSP F14</td>
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<td>DMSP F15</td>
<td>01/2000 - 08/2001</td>
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<td>NOAA-15</td>
<td>01/1999 - present</td>
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<td>NOAA-16</td>
<td>09/2000 - present</td>
<td>14:00</td>
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<td>AMSU-B</td>
<td>NOAA-17</td>
<td>07/2002 - present</td>
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<td>NOAA-18</td>
<td>06/2005 - present</td>
<td>1:30</td>
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<tr>
<td>MHS</td>
<td>NOAA-19</td>
<td>04/2009 - present</td>
<td>13:37</td>
</tr>
</tbody>
</table>

Slide by Mathias Milz, Luleå University of Technology
Megha-Tropique

- French-Indian Satellite (CNES, ISRO)
- Tropical orbit (20° incl.)
- SAPHIR (183 GHz)

Slide by Mathias Milz, Luleå University of Technology
MILLIMETER/SUBMILLIMETER-WAVE (MICROWAVE) LIMB SOUNDERS: MLS, ODIN, SMILES,…
Geometry

$h_o$: Platform altitude
$\theta$: Scan angle
$h_t$: Tangent altitude

typically:
$R_E = 6000 \text{ km}$
$h_o = 600 \text{ km}$
$h_t = 6-60 \text{ km}$

- Measure thermal radiation from the atmosphere (passive!)
- Good altitude resolution, because we can scan vertically
Small $\Delta \theta \leftrightarrow$ large $\Delta h_i$.

**Accurate Pointing** necessary.

**Narrow Field of View** necessary.
Antenna

- Field of view diameter = “beam width”, even for passive instrument
- Given by angle of half power of received (or transmitted) radiation
- Diffraction theory:
  \[ \theta_{\text{HPBW}} \sim \frac{\text{Wavelength}}{\text{Antenna size}} \]

(Figure: Oliver Lemke)
Antenna Technology

- $\theta_{HPBW} \sim \text{Wavelength} / \text{Antenna size}$
- Needs large antenna, particularly for low frequencies
- Scan angle small
- Needs accurate scanning mechanism (or wobble the whole satellite)

The Odin reflector mounted on the spacecraft body. (Source: PREMIER mission proposal)
Overview of the 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

Slide by Bill Read, JPL
Selected radiances for Band 2 on 2010-010

Slide by Bill Read, JPL
12S--12N Aura MLS H2O Anomaly

Pressure (hPa)

% deviation from mean

H2O (ppmv)

Slide by Bill Read, JPL
Level of Agreement on Stratospheric H2O

- MLS and ACE-FTS agree within about 5%
- SAGE II and HALOE are 10% drier
- Balloon cryogenic frostpoint hygrometer shows 5% agreement
- Larger disagreement with aircraft data
  - Harvard aircraft hygrometer 30% drier than MLS
  - MLS agrees within 10% with JPL's tunable diode laser instrument
  - FISH—Schiller Lyman alpha agrees within 10% with CFH
- Bottom line: Mostly within around 10%

All estimates here by Bill Read, JPL
Weather vapor and CO$_2$ are the most important greenhouse gases

Ample opportunities for remote sensing


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HIRS, AIRS, IASI, METEOSAT
NOAA 14 HIRS Channel Positions

Big differences between the different data sets, for example:

+/-15 %RH difference between IR satellite and radiosonde

= 40% relative difference in humidity, as RH values are low in the UT.

(Soden and Lanzante, JGR 1996)

Mostly due to radiosonde network inhomogeneity, much better results ~5 %RH when concentrating on a single sonde type.
Clouds

**Biases in satellite infra-red estimates of upper tropospheric humidity and its trends,**
*J. Geophys. Res.*
IR Dry Bias compared to MW

*Biases in satellite infra-red estimates of upper tropospheric humidity and its trends,*
*J. Geophys. Res.*
Impact on Timeseries

**Biases in satellite infra-red estimates of upper tropospheric humidity and its trends,**
*J. Geophys. Res.*
Geostationary IR Sensors

- Comparable products to HIRS, e.g. UTH
- Studies of the diurnal cycle
- Studies on the evolution of convective systems
HOW WELL DO DIFFERENT MET SENSORS AGREE?
<table>
<thead>
<tr>
<th>Model</th>
<th>[\int \Delta T [K]] AIRS</th>
<th>[\int \Delta T [K]] ECMWF</th>
<th>[\int \frac{\Delta q}{q} [%]] AIRS</th>
<th>[\int \frac{\Delta q}{q} [%]] ECMWF</th>
<th>[\int \frac{\Delta R}{R} [%RH]] AIRS</th>
<th>[\int \frac{\Delta R}{R} [%RH]] ECMWF</th>
<th>[\int \frac{\Delta q}{q} [%]] (AIRS) 1000–200</th>
<th>[\int \frac{\Delta q}{q} [%]] (AIRS) 850–200</th>
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<td>4.96</td>
<td>7.92</td>
<td>−8.83</td>
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<td>GFDL_CM2_0</td>
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<td>−1.83</td>
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<td>20.84</td>
<td>24.64</td>
<td>3.14</td>
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<td>4.70</td>
<td>6.88</td>
<td>−4.75</td>
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</tbody>
</table>

\(^{a}\)Columns from 2 to 7 presents vertically integrated global mean bias (\(\int \Delta x\), where \(\Delta x = x_{\text{model}} - x_{\text{obs}}\) and \(x\) is \(T\), \(q\) or \(R\); note \(\Delta q\) is in percent) from 1000 to 100 hPa for \(T\) [K], \(q\) [%], and \(R\) [%RH] for all 16 models and the mean model with respect to AIRS and ECMWF. Columns from 8 to 10 show \(\int \Delta q\) with respect to AIRS for different layers of the atmosphere.

John, V. O. and B. J. Soden (2007),
Temperature and humidity biases in global climate models and their impact on climate feedbacks,

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AIRS versus AMSU-B

- Comparison for upper tropospheric humidity (UTH)
- Roughly mean relative humidity between 500-200 hPa.
- AIRS has a slight (1-3 %RH) moist bias against AMSU-B in the UT.
- Models moist bias even larger against AMSU-B.


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Comparison HIRS/AMSU upper tropospheric humidity (UTH)

HIRS has a 7-9 %RH dry bias against AMSU.

But 2-7 %RH of this difference is due to HIRS’ higher sounding altitude.


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Upper tropospheric relative humidity (UTH) summary

- Model mean: 10-11 %RH
- AIRS data: 1-3 %RH
- AMSU data: 0-7 %RH
- HIRS data

moistest

driest
Satellite H₂O Observations

Passive
- MM-Wave
  - Down AMSU
  - Limb MLS
  - Down HIRS IASI

- IR
  - Limb MIPAS

Active
- UV/Vis
  - Down GOME

- Occultation
  - Radio GRAS
  - Occultation HALOE
  - IR Laser ACCURATE

- Down
  - LIDAR WALES
MIPAS

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MIPAS

- On board Envisat
- Launched 1 March 2002
- Data available since July 2002
- Nominal operation (high resolution): until March 2004
- Reduced resolution: since beginning 2005
MIPAS

Figure courtesy ESA

Slide by Mathias Milz, Luleå University of Technology
Mipas Spectral Channels, measured Spectra for 18.7 km

Copyright 2003 IMK Forschungszentrum Karlsruhe

Figure courtesy IMK

ARTS calculation
MIPAS

- One spectrum: >50000 spectral points
- To get information on a certain species, small sections of the spectrum are used:
  - Maximum information on target species
  - Minimum influence of interfering species
  - Minimum influence of external error sources
  - Wide enough to reduce measurement noise
  - Individual 'channel' selection for each species and altitude
Comparison to Microwave Limb Sounder

Annual global mean probability of limb transmittance >3%, as estimated from ECMWF fields of temperature, water vapour, water and ice clouds sampled globally one day in ten over a year (Kerridge et al., ESA UTLS study final report).

- IR more affected by clouds than microwave
PREMIER

- Candidate Earth Explorer mission
- Featuring an advanced MIPAS-type instrument, plus an advanced MLS-type instrument
GOME, SCIAMACHY
Air Mass Corrected DOAS (AMC-DOAS)

- Similar to standard DOAS:
  - Does not rely on absolute radiometric calibration
  - Uses differential structures to derive trace gas column

- Main differences:
  - Considers **saturation** effect for water vapour (non-resolved lines):
    Non-linear relation between absorption depth and absorber amount
  - **Air mass factor (AMF) correction** (from O₂ absorption):
    Considers uncertainties in radiative transfer calculation caused by insufficient knowledge of atmospheric conditions (esp. cloudiness)

  - Retrieval also possible for partly cloudy pixels

  - AMF correction also used as quality check

Slide by Stefan Noël, University of Bremen
Fitting Window

- 688 to 700 nm
- Absorptions of both water vapour and O$_2$ of same magnitude (required for air mass correction)
- Further advantage: „Harmless“ region w.r.t. calibration of GOME, SCIAMACHY & GOME-2

⇒ very stable
Characteristics of the AMC-DOAS Products

- **Limitations:**
  - Only measurements on the dayside can be used
  - No total column data for too cloudy scenes (removed by AMF correction factor check)
  - Limited spatial and temporal resolution
  - Currently no data for high mountain areas (masked out by quality check; can be avoided by use of external surface elevation data base)

- **Advantages:**
  - Retrievals possible over land and ocean (with same algorithm)
  - No external calibration sources required

⇒ Completely independent data set!

Slide by Stefan Noël, University of Bremen
Quality of AMC-DOAS Water Vapour Products

- Precision estimate:
  - 3-5% for columns > 0.6 g/cm²
  - Lower columns: up to 10%
  - Absolute precision always better than 0.2 g/cm²

- Accuracy estimate:
  - Difficult to determine because of large spatial/temporal variability of water vapour, resulting in a large scatter (~0.5 g/cm²)
  - Systematic deviations to e.g. ECMWF and SSM/I data ~ 0.1 – 0.5 g/cm²
  - SCIAMACHY data typically lower (cloud free bias?)

Data and more information are available via the AMC-DOAS web site: http://www.iup.uni-bremen.de/amcdoas

Slide by Stefan Noël, University of Bremen
The Combined GOME & SCIAMACHY Water Vapour Data Set 1996-2008

GOME: 1996 – 2002
SCIAMACHY: 2003 – 2008

Time series to be continued with SCIAMACHY and GOME-2 until 2020.

Annual Means

Slide by Stefan Noël, University of Bremen
Satellite H₂O Observations

Passive

- MM-Wave
  - Down AMSU
  - Limb MLS
  - Limb MIPAS
  - Down HIRS IASI

Active

- UV/Vis
  - Occultation
    - Down GOME
  - IR
    - Occultation
      - HALOE
  - Radio GRAS
  - IR Laser ACCURATE
  - LIDAR WALES

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OCCULTATION:
SAGE II, HALOE, ACE-FTS
Solar Occultation Instruments

- High accuracy / self calibrating
- Relatively few profiles
- In UT affected by clouds

- **SAGE II**
  - 1984-2005

- **HALOE**
  - 1991-2005

- **ACE-FTS**
  - 2003-
Satellite H$_2$O Observations

Passive
- MM-Wave
  - Down AMSU
  - Limb MLS
  - Limb MIPAS
  - Down HIRS IASI
- IR

Active
- UV/Vis
- Occultation
  - Radio GRAS
  - Down GOME
  - Occultation HALOE
  - IR Laser ACCURATE
- Down
  - LIDAR WALES

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RADIO-OCCULTATION
GRAS

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Introduction: RO Principle

- GRAS Radio Occultation instrument
- observing GPS satellites:
  - 2 rising, 2 setting (atmosphere)
  - 8 zenith (orbit)
- observations:
  - about 650 profiles / day
  - 0.2km – 1km vertical resolution
- level 1b products (EUMETSAT):
  - bending angle (2h 15 min)
- level 2 products (GRAS SAF):
  - refractivity (3h, pre-operational)
  - T, WV (3h, ~ end-2009)
  - climate applications (~ 2010)

Radio Occultation Principle:
Observation of e.g. GPS satellite signals through the atmosphere; changing refractivity leads to bending of rays

Actually measured is the Doppler shift in the GPS carrier frequency.

Slide by Axel von Engeln, EUMETSAT
Introduction: Benefits / Applications of RO

- **Benefits:**
  - all weather capability
  - high vertical resolution
  - Time/frequency measurement (no bias correction required)

- **Applications:**
  - Numerical Weather Prediction (NWP)
    - low latency required (< 3 hours)
    - highest possible number of observations
  - Climate
    - consistent processing / long term data set required

Refractive index ➔ Temperature in stratosphere
H2O in lower troposphere

Slide by Axel von Engeln, EUMETSAT
GRAS / Troposphere: Wave Optics Calculation

Open loop / Wave Optics processed GRAS data (30th Sep. 2007) from different processing Centres

Slide by Axel von Engeln, EUMETSAT
GRAS / Troposphere: Signal Dynamics

Radio-Hologram of GRAS Raw Sampling Data; Left: Surface Reflection, Right: Cross Channel Interference and Data Gaps

Slide by Axel von Engeln, EUMETSAT
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IR Laser ACCURATE

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RADIO-OCCULTATION WITH AMPLITUDE MEASUREMENT: ACCURATE
ACCURATE: Microwave+IR Occultation Measurements

Figure from ACCURATE Mission Proposal, Kirchengast et al., 2010
Figure 4.1-3: Spectral ranges for ACCURATE LMO illustrating the major absorption features and the mandatory K band channels (blue solid, left panel) and the optional 183 GHz channels (blue dashed, right panel). The dotted channels (X band, left; 195 GHz, right) are further best-effort channels (ACCU, 2009) that might play a role in extended LMO designs but are not relevant here.
Figure 4.1-4: Spectral ranges for ACCURATE LIO illustrating the selected laser frequencies in the 2.3–2.5 μm “SWIR B” band (upper left) and the ~2.1 μm “SWIR A” band (upper right). A zoom into a narrow sub-range of the SWIR A band highlights a special “demo” band of only ~4 nm (10 cm⁻¹) width (lower left) suitable to probe the key variables CO₂ (incl. isotopes), H₂O, and I.o.s. wind within the mode-hop free tuning range of single DFB lasers. A further zoom in this band highlights a small “wind line” band of only ~0.4 nm (1 cm⁻¹) width (lower right) where the selected two wind measurement frequencies sit at the points of inflection of the highly symmetric and stable C¹⁸O₂ line (left sub-panel) and where also the spectral derivative of the transmission is shown (right sub-panel), confirming that the wind frequencies sit at maximum gradient providing highest sensitivity to wind-induced Doppler shift of the line exploited for the I.o.s. wind measurements.

Figure from ACCURATE Mission Proposal, Kirchengast et al., 2010
Satellite H$_2$O Observations

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Down

LIDAR WALES

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LIDAR:
WALES
Water Vapour Lidar Experiment in Space (WALES)

Candidate for the next Generation of ESA Earth Explorer Core Missions

Benefit of WALES

• Numerical weather prediction
• Climate change analysis
• Atmospheric model validation

Core Instrument

• H₂O-DIAL at 940 nm wavelength

Proposed by:

DLR, Institut für Physik der Atmosphäre

Slide by Christoph Kiemle, DLR
**Observational Geometry**

**Instrument**
- 4 wavelength H2O-DIAL at 935 nm
- 1040 W, 588 kg, 385 Mbits/Orbit

**Orbit**
- polar, dawn/dusk, 450 km height

**Nature of Data**
- profile of water vapour
- 1 km vertical resolution
- 100 km horizontal resolution
- small bias < 5 %
- high accuracy RMS < 10 %
- 6000 profiles/day
- aerosol profiles, cloud boundaries
Observation technique of WALES
4 wavelengths to cover large dynamic range

Slide by Christoph Kiemle, DLR
DLR Airborne Demonstrator: Water Vapour Differential Absorption Lidar (DIAL) "DLR-WALES" on Falcon Aircraft

New DIAL:
4 wavelengths, 9 W @ 935 nm

Slide by Christoph Kiemle, DLR

Overview

» Introduction
  » Motivation
  » Challenges
  » Radiation Source and Techniques
  » Spectroscopy

» Instruments
  » SSM/T2, AMSU-B, MHS
  » MLS
  » HIRS, AIRS, IASI, Meteosat
  » MIPAS
  » GOME, SCIAMACHY
  » GRAS
  » ACCURATE
  » WALES

» Summary and Conclusions
Summary and Conclusions

- H2O, T, and clouds basic meteorological variables
- Measured by an amazing number of techniques and instruments
- Tropospheric RH measurement agree to within approximately 10 %RH (but are affected by clouds)
- Stratospheric VMR measurements agree to approximately 10%
- Use of most datasets not trivial

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