Determination of mixing-layer height by ground-based remote sensing

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### Basic remote sensing techniques

<table>
<thead>
<tr>
<th>name</th>
<th>principle</th>
<th>spatial resolution</th>
<th>direction</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADAR</td>
<td>backscatter, electro-magnetic pulses, fixed profiling wave length</td>
<td>profiling</td>
<td>scanning, slanted</td>
<td>active, monostatic</td>
</tr>
<tr>
<td>SODAR</td>
<td>backscatter, acoustic pulses, fixed wave length</td>
<td>profiling</td>
<td>fixed, slanted, vertical</td>
<td>active, usually monostatic</td>
</tr>
<tr>
<td>LIDAR</td>
<td>backscatter, optical pulses, fixed wave length(s)</td>
<td>profiling</td>
<td>scanning, fixed, horizontal, slanted, vertical</td>
<td>active, monostatic</td>
</tr>
<tr>
<td>RASS</td>
<td>backscatter, acoustic, electro-magnetic, fixed wave length</td>
<td>profiling</td>
<td>fixed, vertical</td>
<td>active, monostatic</td>
</tr>
<tr>
<td>FTIR</td>
<td>absorption, infrared, spectrum path-averaging</td>
<td>fixed, horizontal, slanted</td>
<td>active, bistatic or passive</td>
<td></td>
</tr>
<tr>
<td>DOAS</td>
<td>absorption, optical, fixed wave lengths path-averaging</td>
<td>fixed, horizontal</td>
<td>active, bistatic</td>
<td></td>
</tr>
<tr>
<td>radiometry</td>
<td>electro-magnetic, fixed wave length(s) averaging, profiling</td>
<td>fixed, scanning, slanted, vertical</td>
<td>passive</td>
<td></td>
</tr>
<tr>
<td>tomography</td>
<td>travel time, acoustic, fixed wave length horizontal distribution</td>
<td>fixed, horizontal</td>
<td>active, multiple emitters and receivers</td>
<td></td>
</tr>
</tbody>
</table>

**subject of this talk**
Typical frequency bands for remote sensing of the atmosphere

- **LIDAR/Ceilometer**
  - FTIR
  - MWR
  - 10^6 cm⁻¹
  - 10^⁻⁶ cm⁻¹

- **RADAR**
  - 1 cm⁻¹
  - 10⁻⁶ cm⁻¹

- **Wind-profiler**
  - 1 THz
  - 1 GHz
  - 1 MHz

- **RASS**
  - 1 mm
  - 1 m
  - 1 km

- **SODAR**
  - aerosol
  - rain
  - turbulence

Modified from Fig. 8.1 in "Meteorologie in Stichworten", Borntraeger, Berlin Stuttgart 2000
SODAR

algorithms for mixing-layer height
Sample plot SODAR (convective BL at daytime)

acoustic backscatter intensity

sigma w

40 – 300 m

2 days, midnight to midnight
Sample plot SODAR (lifted inversion)

acoustic backscatter intensity

sigma w

40 – 400 m

1 day, midnight to midnight
Algorithms to detect MLH from SODAR data

criterion 1:
upper edge of high turbulence

criterion 2:
surface and lifted inversions

MLH = Min (C1, C2)

example 1: daytime
example 2: night-time
SODAR measurements in a wintry Alpine valley

29 January 2006

backscatter intensity

wind direction
Ceilometer

algorithms for mixing-layer height
Sample plot ceilometer (convective BL at daytime)

optical backscatter intensity

CL31 Augsburg LFU backscatter density on 19.05.2007 in $10^9 \text{ m}^{-1} \text{ sr}^{-1}$

- Gradient local minimum
- Cloud

negative vertical gradient of optical backscatter intensity

CL31 Augsburg FH negative gradient density on 19.05.2007 in $10^9 \text{ m}^{-1} \text{ sr}^{-1}$

- Gradient local minimum
- Cloud
Algorithms to detect MLH from Ceilometer-Daten

criterion

minimal vertical gradient of backscatter intensity (the most negative gradient)
Different gradient methods (see Sicard et al. 2006, BLM 119, 135-157)

logarithmic gradient minimum

gradient minimum

inflection point method (minimum of 2nd derivative)
Diurnal variation of mixing-layer height from SODAR and Ceilometer data (Budapest)

SBL: stable boundary layer (usually at night and in winter)

CBL: convective boundary layer (usually at daytime due to strong insolation)

RL: residual layer (usually at night-time)
RASS
principles of operation
examples
RASS: frequencies

Bragg condition: acoustic wavelength = $\frac{1}{2}$ electro-magnetic wavelength

RASS wavelength ratio: $\lambda_e = 2 \lambda_a$
temperature profile and pollution

comparison of RASS data (potential temperature, right)
with aerosol backscatter from a ceilometer (left)

CL31 Augsburg AVA $\log_{10}$ of backscatter with MLH on 01.03.2009 in $10^{-9}$ m$^{-1}$ sr$^{-1}$

- well-mixed
- stable nocturnal boundary layer
- fog

Prof. Dr. Stefan Emeis, IMK-IFU: MLH by ground-based remote sensing
temperature profile and pollution
comparison of RASS data (potential temperature, right) with aerosol backscatter from a ceilometer (left)

CL31 Augsburg $\log_{10}$ of backscatter with MLH on 06.04.2009 in $10^{-9}$ m$^{-1}$ sr$^{-1}$

well-mixed
stable nocturnal boundary layer
fog
Overview on methods using ground-based remote sensing for the derivation of the mixing-layer height

<table>
<thead>
<tr>
<th>method</th>
<th>short description</th>
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<tbody>
<tr>
<td>acoustic</td>
<td><strong>ARE method</strong> analysis of acoustic received echo intensity profiles</td>
</tr>
<tr>
<td>“</td>
<td><strong>HWS method</strong> analysis of horizontal wind speed profiles</td>
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<tr>
<td>“</td>
<td><strong>VWV method</strong> analysis of vertical wind variance profiles</td>
</tr>
<tr>
<td>“</td>
<td><strong>EARE method</strong> analysis of acoustic backscatter intensity and vertical wind variance profiles (enhanced acoustic received echo method)</td>
</tr>
<tr>
<td>optical</td>
<td><strong>threshold method</strong> detection of a given backscatter intensity threshold</td>
</tr>
<tr>
<td>“</td>
<td><strong>gradient method</strong> analysis of optical backscatter intensity profiles</td>
</tr>
<tr>
<td>“</td>
<td><strong>idealised backscatter method</strong> analysis of optical backscatter intensity profiles</td>
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<td>“</td>
<td><strong>wavelet method</strong> analysis of optical backscatter intensity profiles</td>
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<tr>
<td>“</td>
<td><strong>variance method</strong> analysis of optical backscatter intensity profiles</td>
</tr>
<tr>
<td>acoustic / electro-magnetic</td>
<td>ARE method applied to sodar and wind profiler data</td>
</tr>
<tr>
<td>acoustic / optical</td>
<td>EARE method plus gradient method</td>
</tr>
<tr>
<td>electro-magnetic / electro-magnetic</td>
<td>combination of a sodar-RASS and a wind profiler RASS: analysis of the vertical temperature profile plus analysis of the electro-magnetic backscatter intensity profile</td>
</tr>
<tr>
<td>acoustic / in situ</td>
<td>ARE method plus in-situ surface flux measurement</td>
</tr>
<tr>
<td>RASS</td>
<td>analysis of the temperature profile from the measured speed of sound</td>
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</tbody>
</table>
Conclusions:

**RASS** directly delivers temperature profiles. MLH, inversions, and stable layers can easily be detected, wind profiles are additionally available. Only remote system that measures inversion strengths. Does not work properly with high wind speeds.

**SODAR** detects temperature fluctuations and gradients, but no absolute temperature. Inversions and stable layers can indirectly be inferred with a MLH algorithm. Does not work properly with perfectly neutral stratification, with very high wind speeds, and during stronger precipitation events.

**Ceilometer** detects aerosol distribution and water droplets. It has to be assumed that the aerosol follows the thermal structure of the atmosphere. Inversions and MLH can indirectly be inferred with a MLH algorithm. Does not work properly in extreme clear (aerosol-free) air and during precipitation events and fog.
SODAR:


Ceilometer:


RASS:


Reviews:
