Different methods to derive the mixing-layer height by remote sensing (including RASS)

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Introduction

- relevance for wind energy
- definition of mixing layer
- remote sensing
Diurnal variation of vertical wind profiles

Day

well-mixed boundary layer

Night

stable boundary layer
Nocturnal low-level jet and the turning of wind direction with height

Day

Night

well-mixed boundary layer

stable BL

$\vec{T}$

$\vec{P}$

$\vec{C}$

$\vec{R}$

$\vec{H}$
Mean diurnal variation of wind turning

IFU-MiniSODAR, level terrain, June 1999

turning in degrees

time [h]

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KIT – die Kooperation von Forschungszentrum Karlsruhe GmbH und Universität Karlsruhe (TH)
extreme example for wind turning

Abb.: 10^\textdegree\textsuperscript{h} Mittel des Windvektors ($v_\text{r}$) für ausgewählte Höhen ($\times$)
IFU–MiniSODAR Sachsen–Anhalt Juni 1999

3 m/s Westwind
The vertical wind profile

logarithmic law
(with stability correction) \[ u(z) = \left(\frac{u_s}{\kappa}\right) \left(\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L^*}\right)\right) \]

power law \[ u(z) = u(z_A) \left(\frac{z}{z_A}\right)^n \]

New proposal
(Gryning et al. 2007)

needs information on the PBL or mixing-layer height

# Mixing-layer height

<table>
<thead>
<tr>
<th>Inversion height</th>
<th>literally: inversion in the temperature profile, increase of temperature with height, strong decrease of moisture, radiation inversions, sinking inversions, surface inversions, lifted inversions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing-layer height</td>
<td>defined by the turbulence profile, upper boundary for vertical exchange (mixing), upper boundary of the well-mixed layer, entrainment</td>
</tr>
</tbody>
</table>
| Boundary layer height | SBL: at night, height of the near-surface layer influenced by surface friction  
CBL: at day, height of convective plumes |

boundary layer height ≈ mixing-layer height

boundary layer height ≥ inversion height
## 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>scanning, slanted</td>
<td>active, monostatic</td>
<td></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</td>
<td>path-averaging</td>
<td>fixed, horizontal, slanted</td>
<td>active, bistatic or passive</td>
</tr>
<tr>
<td>DOAS</td>
<td>absorption, optical, fixed wave lengths</td>
<td>path-averaging</td>
<td>fixed, horizontal</td>
<td>active, bistatic</td>
</tr>
<tr>
<td>radiometry</td>
<td>electro-magnetic, fixed wave length(s)</td>
<td>averaging, profiling</td>
<td>fixed, scanning, slanted, vertical</td>
<td>passive</td>
</tr>
<tr>
<td>tomography</td>
<td>travel time, acoustic, fixed wave length</td>
<td>horizontal distribution</td>
<td>fixed, horizontal</td>
<td>active, multiple emitters and receivers</td>
</tr>
</tbody>
</table>
Typical frequency bands for remote sensing of the atmosphere

- **LIDAR/Ceilometer**
  - $10^6$ cm$^{-1}$
  - 1 cm$^{-1}$

- **RADAR**
  - 10$^{-6}$ cm$^{-1}$

- **Wind Profiler**
  - 1 THz
  - 1 GHz
  - 1 MHz

- **FTIR**
  - 10$^6$ cm$^{-1}$
  - 1 cm$^{-1}$

- **MWR**
  - 10$^{-6}$ cm$^{-1}$

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

- **SODAR**
  - 1 mm
  - 1 m
  - 1 km

- **Electromagnetic**
  - 1 KHz
  - 1 Hz

- **Acoustic**
  - 1 KHz

- **Aerosol**
  - 1 mm

- **Rain**
  - 1 m

- **Turbulence**
  - 1 km

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

algorithms for mixing-layer height
monostatic SODAR: measuring principles

**Deduction:**

- Sound travel time = height
- Backscatter intensity = turbulence
- Doppler-shift = wind speed

Emission of sound waves into three directions: in order to measure all three components of the wind (horizontal and vertical)
The SODAR equation:

\[ P_R = r^2 \left( c_s \tau A \varepsilon / 2 \right) P_0 \beta_s e^{-2\sigma r} + P_{bg} \]

received power \( P_R \),
emitted power \( P_0 \),
antenna efficiency \( \varepsilon \),
effective antenna area \( A \),
sound absorption in air \( \sigma \) due to classical and molecular absorption due to the collision of water molecules with the oxygen and nitrogen molecules of the air,
distance between the scattering volume and the instrument \( r \),
pulse duration \( \tau \) (typically between 20 and 100 ms),
backscattering cross-section \( \beta_s \) (typically in the order of \( 10^{-11} \, \text{m}^{-1} \, \text{sr}^{-1} \)),
sound speed \( c_s \),
background noise \( P_{bg} \).

Emitted power: \( \sim 10^3 \, \text{W} \), received (backscattered) power: \( 10^{-15} \, \text{W} \)
The SODAR equation:

\[ P_R = r^2 (c_s \tau A \varepsilon/2) P_0 \beta_s e^{-2\sigma r} + P_{bg} \]

The ratio of the two terms on the right-hand side of the SODAR equation is called signal-to-noise ratio (usually abbreviated as SNR).

The backscattering cross-section \( \beta_s \) is a function of the temperature structure function \( C_T^2 \) (Tatarskii 1961).

For a monostatic SODAR we find (Reitebuch 1999) when using the wave number \( k = 2\pi/\lambda \):

\[ \beta_s(180^\circ) = 0.00408 k^{1/3} C_T^2 / T^2 \]


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)

equation: MLH = Min (C1, C2)

example 1: daytime

equation: MLH = Min (C1, C2)

example 2: night-time
Ceilometer

algorithms for mixing-layer height
Ceilometer/LIDAR measuring principle

detection:

- travel time of signal = height
- backscatter intensity = particle size and number distribution
- Doppler-shift = cannot be analyzed from ceilometer data (only from Wind-LIDAR: velocity component in line of sight)
The LIDAR equation:

\[ P_R(\lambda, r) = r^2 \left( \frac{c \tau A \varepsilon}{2} \right) P_0 \left[ \beta_m(\lambda, r) + \beta_p(\lambda, r) \right] e^{-2\sigma r} + P_{bg} \]

distance \( r \) between the LIDAR and the backscattering object, speed of light \( c \), pulse duration \( \tau \), antenna area \( A \), correction term for the detector efficiency and losses due to the lenses \( \varepsilon \), emitted energy \( P_0 \), backscatter coefficient for molecules \( \beta_m \) and for particles \( \beta_p \), absorption of light in the atmosphere \( \sigma \), background noise \( P_{bg} \).

For a ceilometer \( \beta_m \) is negligible and only \( \beta_p \) is important.
Sample plot ceilometer (convective BL at daytime)

optical backscatter intensity

negative vertical gradient of optical backscatter intensity
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)

![Graph showing different gradient methods with labels H4LGM, H4GM, and H4IPM.](image-url)
comparison of two different ceilometers

LD40

two optical axes
- wave length: 855 nm
- height resolution: 7.5 m
- max. range: 13000 m

CL31

one optical axis
- wave length: 905 nm
- height resolution: 5 m
- max. range: 7500 m
19 May 2007: ceilometer LD40 and CL31
comparison of MLH from LD40 and CL31 data

19 May 2007

20 May 2007
Comparison SODAR and Ceilometer
Measurement of the vertical structure of the boundary layer and mixing-layer height by remote sensing:

mobile surface-based acoustic and optical remote sensing yields information on:

- thermal structure of the BL and turbulence intensity
  (SODAR)
- aerosol content of the BL
  (Ceilometer)
comparison of algorithms

left: SODAR

middle and right: ceilometer

acoustic backscatter intensity

optical backscatter intensity

vertical gradient of optical backscatter intensity
negative vertical gradient of optical backscatter intensity
Application examples for SODAR and Ceilometer
Example for the joint operation of a SODAR and a Ceilometer
winter in an Alpine valley (snow-covered)

(ALPNAP-Campaign in the Inn valley in winter 2005/06)

(ALPNAP was a project in the European Programme
INTERREG III B Alpine Space, ref. no. D/III/2.1/7)
SODAR measurements in a wintry Alpine valley

29 January 2006

backscatter intensity vs. wind direction

190° 230°
optical backscatter intensity

acoustic backscatter intensity
statistical evaluations of the Inn valley measurements (1-18 Jan 06)

MLH: mean diurnal variation

MLH: frequency distribution

multiple inversions
Example for the joint operation of a SODAR and a Ceilometer

summer 2003 Budapest (Hungary)

(ICAROS NET-Campaigns)

(ICAROS NET was a project within the European Research Framework Programme FP5: IST-2000-29264)
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 nighttime)
Simultaneous operation SODAR-Ceilometer: examples for summer days

Emeis, S., K. Schäfer, 2006: Remote sensing methods to investigate boundary-layer structures relevant to air pollution in cities. Bound.-Lay Meteorol., 121, 377-385,

Free troposphere

inversions from radiosonde ascents

15 July 2003

height above ground in m

H1 Sodar
H2 Sodar
H3 Ceilo

SBL
RL

CBL

Prof. Dr. S. Emeis | IMK-IFU Garmisch | 11.06.2009
Example for the joint operation of a SODAR
and two ceilometers (LD40 and CL31 of Vaisala)

spatial variation of MLH over Augsburg (town with 250 000 inhabitants
in Germany)

(measurement campaign in Augsburg since winter 2006/07)

(cooperation with University of Augsburg, Helmholtz Centre Munich
(health impact research), State Environmental Agency of Bavaria,
City of Augsburg)
comparison of optical (top) and acoustic (below) backscatter intensity

19 May 2007

20 May 2007
comparison of MLH from Sodar and CL31 data

![Graph showing comparison of MLH from Sodar and CL31 data](image)
RASS

principles of operation

examples
RASS (radio-acoustic remote sensing)

measures vertical temperature profiles

Bragg-RASS: windprofiler plus acoustic component

Doppler-RASS: SODAR plus electro-magnetic component

UHF RASS (boundary layer)

VHF RASS (troposphere)
RASS: frequencies

Bragg condition:
acoustic wavelength = ½ electro-magnetic wavelength

RASS wavelength ratio: $\lambda_e = 2 \lambda_a$
SODAR-RASS  
(Doppler-RASS)  
(METEK)  

- acoustic frequ.: 1500 – 2200 Hz  
- radio frequ.: 474 MHz  
- resolution: 20 m  
- lowest range gate: ca. 40 m  
- vertical range: 540 m
Bragg-RASS

- acoustic frequ.: about 3000 Hz
- radio frequ.: 1290 MHz
- resolution: 50 m
- lowest range gate: ca. 200 m
- vertical range: 1000 m
example RASS data: summer day potential temperature (left), horizontal wind (right)
example RASS data: winter day
potential temperature (left), horizontal wind (right)
example RASS data: inversion potential temperature (left), horizontal wind (right)
Comparison of MLH retrievals with three different remote sensing techniques

SODAR
acoustic backscatter

Ceilometer
optical backscatter

RASS
temperature

Summary
### 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>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic</td>
<td>Analysis of acoustic received echo intensity profiles</td>
</tr>
<tr>
<td>“ HWS method</td>
<td>Analysis of horizontal wind speed profiles</td>
</tr>
<tr>
<td>“ VWV method</td>
<td>Analysis of vertical wind variance profiles</td>
</tr>
<tr>
<td>“ EARE method</td>
<td>Analysis of acoustic backscatter intensity and vertical wind variance profiles</td>
</tr>
<tr>
<td>“ (enhanced acoustic received echo method)</td>
<td></td>
</tr>
<tr>
<td>Optical threshold method</td>
<td>Detection of a given backscatter intensity threshold</td>
</tr>
<tr>
<td>“ gradient method</td>
<td>Analysis of optical backscatter intensity profiles</td>
</tr>
<tr>
<td>“ idealised backscatter method</td>
<td>Analysis of optical backscatter intensity profiles</td>
</tr>
<tr>
<td>“Wavelet method</td>
<td>Analysis of optical backscatter intensity profiles</td>
</tr>
<tr>
<td>“ Variance method</td>
<td>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>
</tr>
</tbody>
</table>
Conclusions:

**RASS** directly delivers temperature profiles, MLH, inversions, and stable layers can easily be detected, wind profiles are additionally available. Does not work properly under 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 under 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.
Literature
SODAR:


Ceilometer:


RASS:


Reviews: