On the determination of atmospheric boundary layer structures by ground-based remote sensing (SODAR, lidar/ceilometer, RASS)

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Introduction

-features of the atmospheric boundary layer

detection techniques
diurnal variation of PBL

vertical structure of PBL

internal layers in PBL

free troposphere

z_t = o(1000) - o(2500) m

Ekman sublayer

homogeneous boundary layer

constant-flux sublayer

roughness sublayer

flow

Ekman sublayer

homogeneous boundary layer

constant-flux sublayer

blending height

internal boundary layer 1

internal boundary layer 2

internal boundary layer 3

z_{e1}

z_{e2}

z_{e3}
special types of PBL

- Urban boundary layer
  - Urban plume
  - Urban canopy sublayer
  - Marine boundary layer
  - Wave sublayer

- Forest boundary layer
  - Crown sublayer
  - Stem sublayer

Prof. Dr. Stefan Emeis - Mixing-layer height by remote sensing
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## Basic remote sensing techniques

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

SODAR

wind, turbulence, temperature gradients, mixing-layer height
monostatic SODAR: measuring principles

Emission of sound waves into three directions:

- sound travel time = height
- backscatter intensity = turbulence
- Doppler-shift = wind speed

in order to measure all three components of the wind (horizontal and vertical)
The SODAR equation:

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

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

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

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

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 \( k = 2\pi/\lambda \):

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


Großes SODAR des IMK-IFU (METEK DSDR3x7)

- Frequenz: 1500 Hz
- Reichweite: 1300 m
- Auflösung: 20 m
- unterste Messhöhe: ca. 60 m
- Höhe: 4 m
- Breite: 1,50 m
- Länge: 10 m
- Gewicht: 8 t
SODAR sample plot (diurnal evolution, low-level jet)

horizontal wind speed and direction

Abb.: 10'-Mittel des Windvektors \((v_v)\) für ausgewählte Höhen \((v)\)
IFU-MiniSODAR Sachsen-Anhalt Juni 1999

IFU GAP
SODAR sample plot (daytime convective BL)

acoustic backscatter intensity

sigma w

40 – 300 m

2 days, midnight to midnight
SODAR sample plot (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
Ceilometer

aerosol detection, 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
  (available only from a Wind-LIDAR: velocity component in line of sight)
The LIDAR equation:

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

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

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

optical backscatter intensity

CL31 Augsburg LFU backscatter density on 19.05.2007 in $10^{-5}$ m$^{-1}$ sr$^{-1}$

Height in m, 160 m mean, calc limits 100-2000 m, tilted by 0°

Time on 19.05.2007, 1800 s mean, MB 150, MG -0.65

negative vertical gradient of optical backscatter intensity

CL31 AugsburgFH negative gradient density on 19.05.2007 in $10^{-9}$ m$^{-1}$ sr$^{-1}$

Height in m, 160 m mean, calc limits 100-2000 m, tilted by 0°

Time on 19.05.2007, 1800 s mean, MB 150, MG -0.65
Algorithm 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 gradient methods with labels: B, dB(z)/dz, d^2B(z)/dz^2, dlnB(z)/dz]
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
comparison of LD40 and CL31
Eyjafjallajökull ash cloud over Southern Germany
Doppler wind lidar

wind, turbulence, aerosol detection, mixing-layer height
Doppler wind lidar measuring principle

detection:

- travel time of signal = height
- backscatter intensity = particle size and number distribution
- depolarisation = particle shape
- Doppler-shift = wind speed in the line of sight
mobile Doppler windlidar from Halo Photonics
sample data from windlidar

April 16, 2010

by

Univ. of Reading

taken at

Chilbolton, UK

volcanic ash from Eyjafjallajökull
RASS

temperature, wind, turbulence, mixing-layer height
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 = $\frac{1}{2}$ electro-magnetic wavelength

dimension of atmospheric turbulent structures

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)
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^{-3} m^{-1} sr^{-1}

well-mixed
stable nocturnal boundary layer
fog
RASS data Augsburg February 2009

potential temperature (top), backscatter SODAR (middle), Ceilometer (bottom)

Feb. 3
Feb. 4
Feb. 5
RASS data Augsburg February 2009

potential temperature (top), MLH RASS (middle), MHL SODAR/Ceilo (bottom)

Feb. 3  Feb. 4  Feb. 5
Summary
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. Restricted range.**

😊😊😊 Ceilometer/windlidar 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. Wind from windlidar. **Does not work properly in extreme clear (aerosol-free) air and during precipitation events and fog.**

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


Ceilometer:


RASS:


Reviews:


Books:


Thank you very much for your attention