Karlsruhe Institute of Technology

WindForS Wind Energy Research Alliance

Remote sensing of mixing-layer height at environmental monitoring stations

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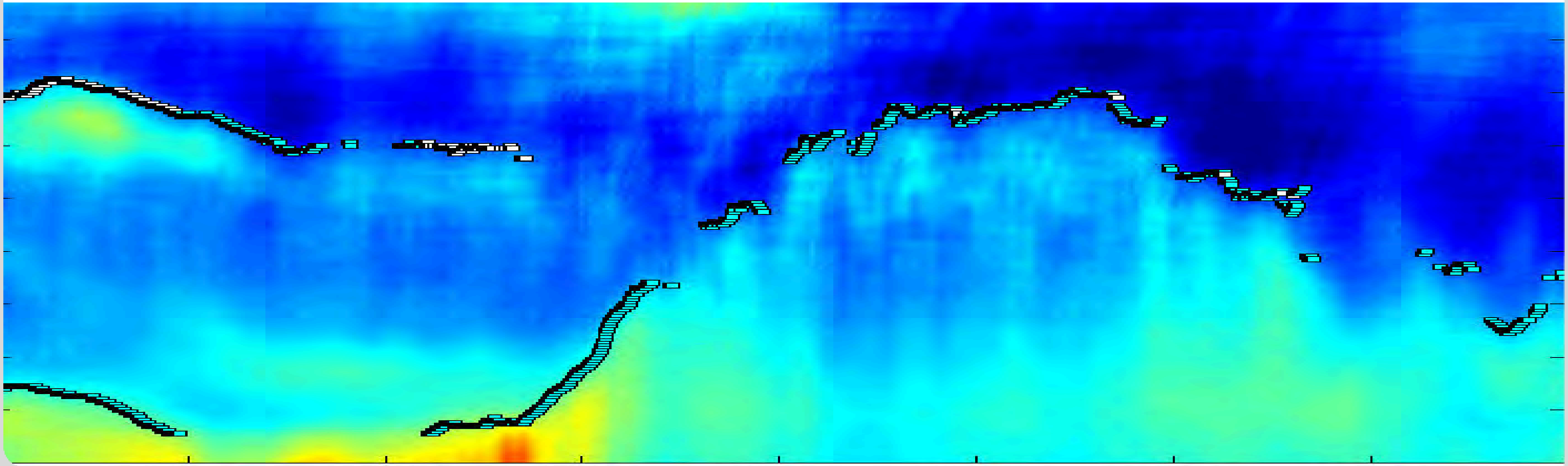

April 2012

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World Calibration Center (WCC)

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TERENO

TERRESTRIAL ENVIRONMENTAL OBSERVATORIES

The Bavarian Prealpine Observatory

Hans Peter Schmid, Harald Kunstmann,
Hans Papen, Jean Charles Munch,
Eckart Priesack

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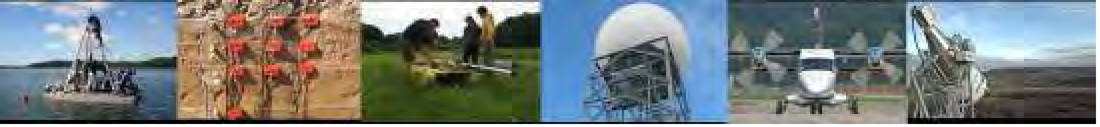
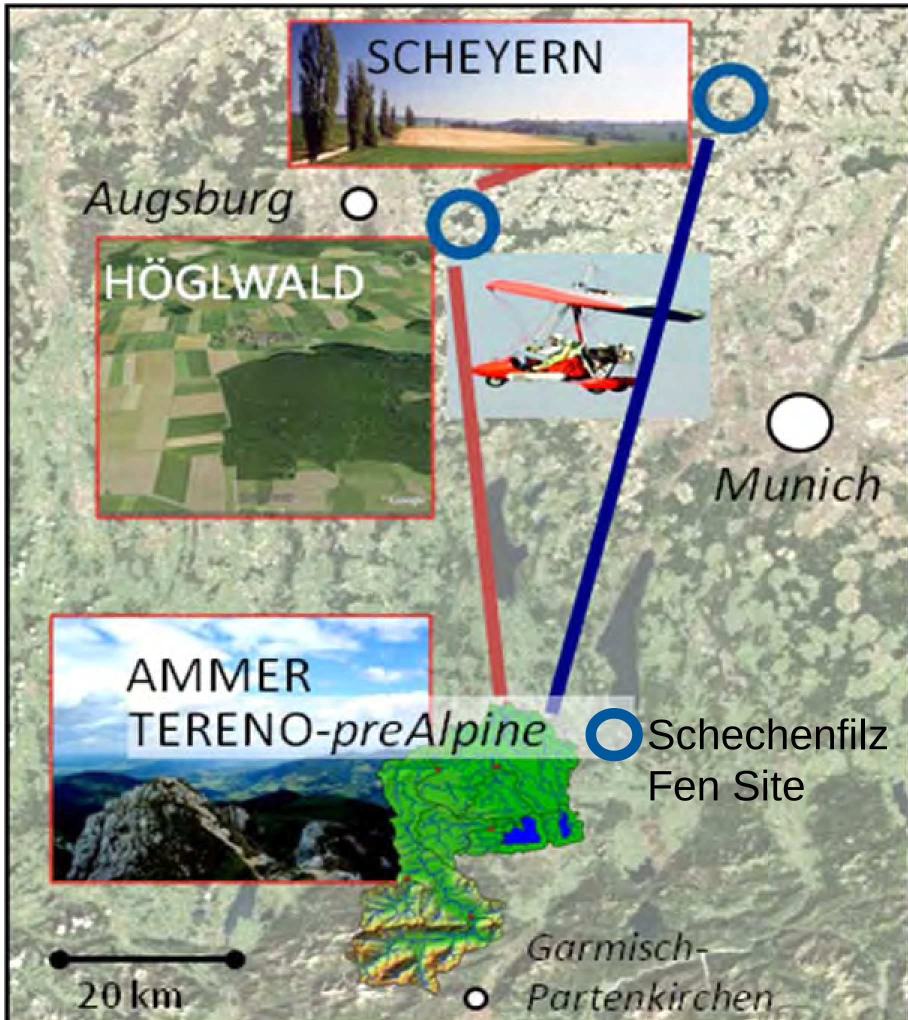
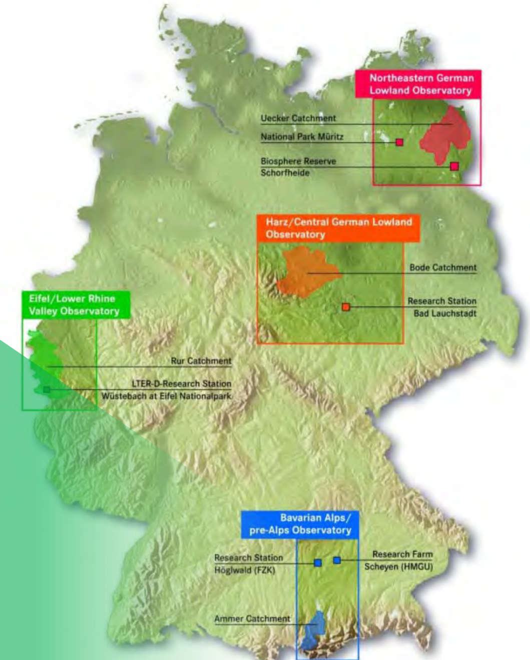


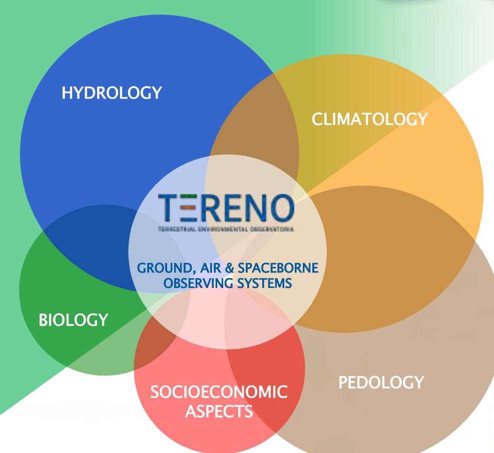
prealpine

TERENO
TERRESTRIAL ENVIRONMENTAL OBSERVATORIES

The Bavarian Prealpine Observatory







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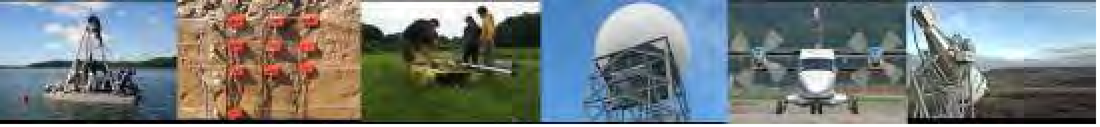

“In House” Research Goals

- Long-Term **biosphere-atmosphere exchange** (greenhouse gases, energy balance)
- Coupled **C-/N-cycles** and C-/N-storage
- **Vegetation and microbial biodiversity** (temporal dynamics, relation to matter turnover)
- **Alpine watershed hydrology** (water budget, Karst related problems, precipitation variability, floods/droughts, seepage water quality/quantity, water retention capacity)
- **Nutrient deposition** and **land use/management** (wet grasslands/fens, forests and agricultural systems).
- **Methodology development** for micrometeorological observations in complex terrain
- (planned) ecosystem-atmosphere exchange in **urban areas**

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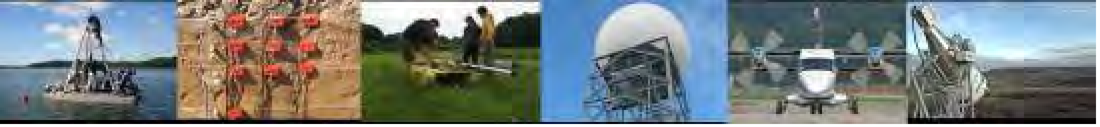

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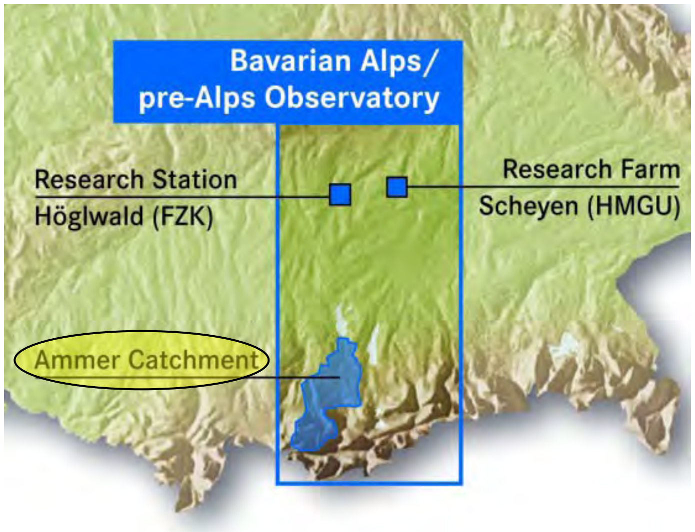
Ammer Catchment Observatory



- area of ~710 km² (601 km² above Weilheim)
- alpine and prealpine landscape with high spatial differentiation in geology and pedology
- elevations: from 533 m (a.s.l., Ammersee) to 2185 m (Kreuzspitze)
- two dominant landscape units: the prealpine hill country and moorland and the Swabian-Upper Bavarian foothills of the Alps.
- Dominant geology: lime-alpine zone (south), flysch zone (north)

TERENO Infrastructure

- **Graswang-, Rottenbuch-, Fendt Sites**
  - 3 EC towers: momentum, heat, H_2O, CO_2, plus TERENO-ICOS: N_2O, CH_4 fluxes
  - 36 Lysimeters: soil water balance, **3 ceilometers**
  - GHG (N_2O, CO_2, CH_4) measurements at lysimeters
- **Geigersau Site:** 1 X-Band precipitation radar
- **Sites to be determined:** 3 Climate stations
- **movable: 1 Doppler wind lidar**

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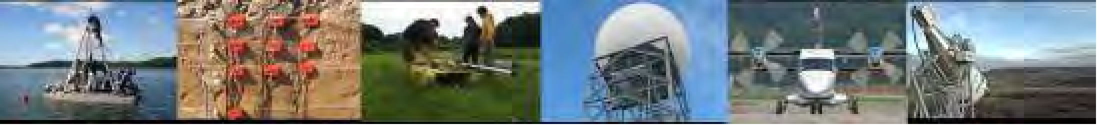

prealpine

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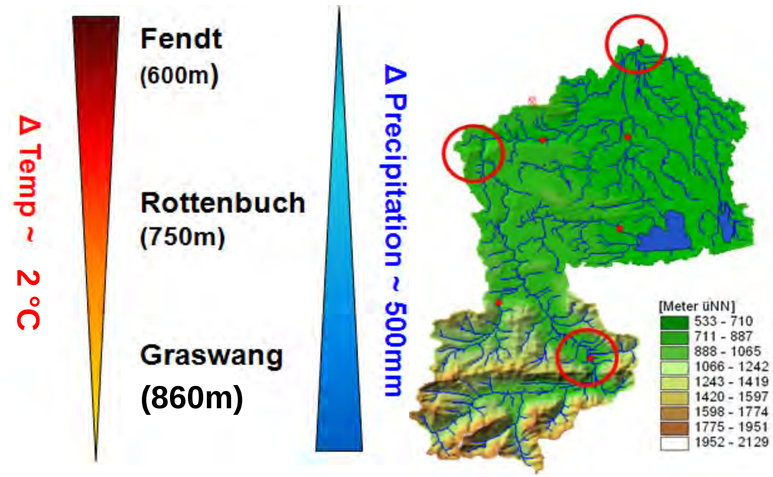
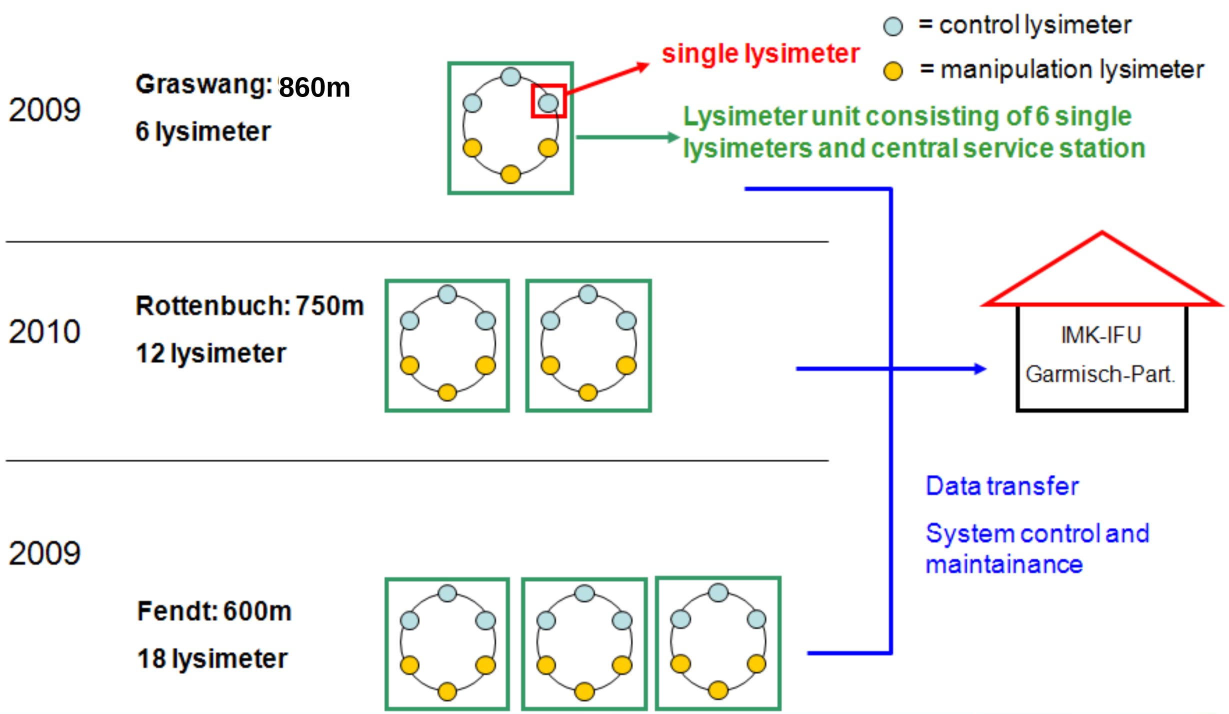
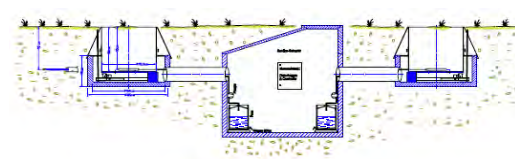
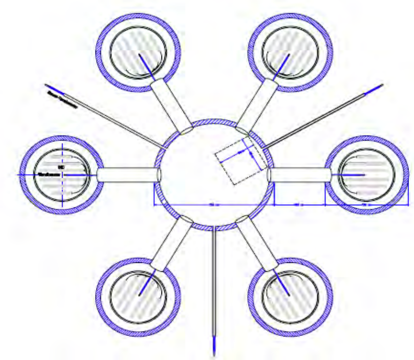
Climasequence: how do grassland ecosystems adapt to climate change?

- grassland soil monoliths transplanted along the natural gradient in temperature and precipitation
- climate change effects on C/N cycles
- associated plant and microbial processes/populations/biodiversity
- terrestrial hydrology and water quality









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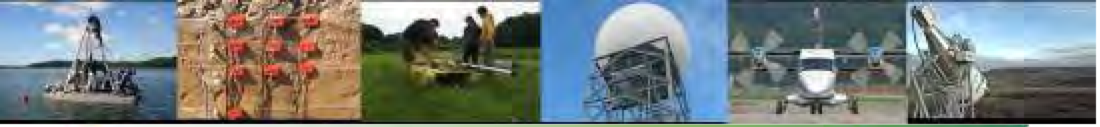
TERENO Lysimeter experiment: construction phase



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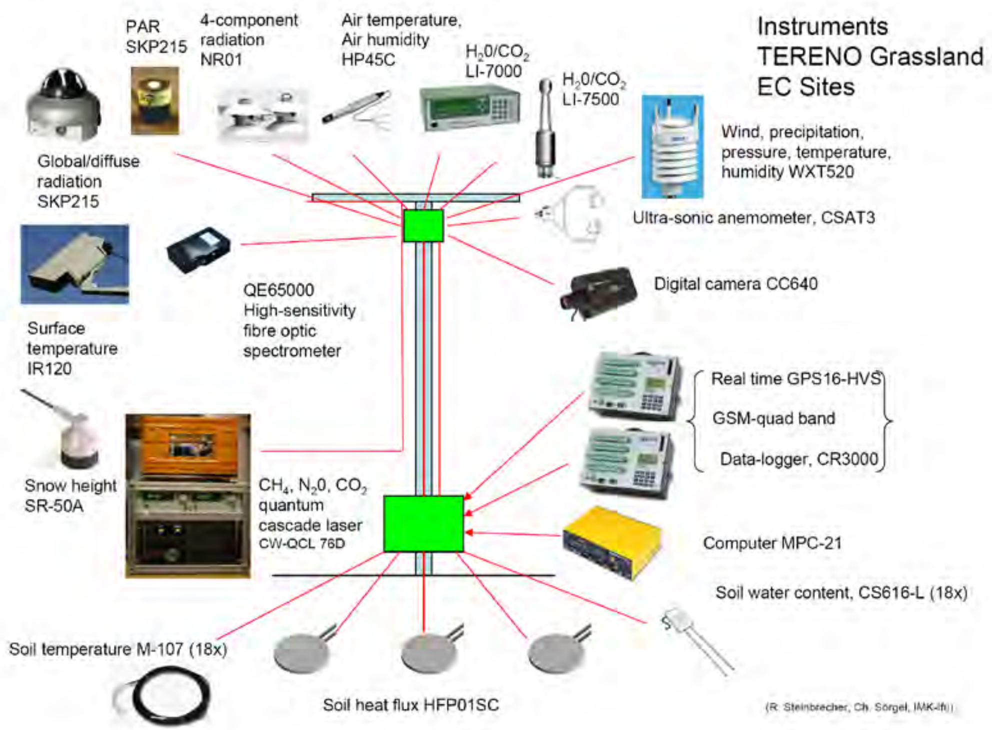
icos integrated carbon observation system

A European infrastructure dedicated to high precision monitoring of greenhouse gas fluxes

http://www.icos-infrastructure.eu/

- ICOS mission: “To provide the long-term observations required to understand the present state and predict future behavior of the global carbon cycle and greenhouse gas emissions.”
- 5 EC-sites at TERENO-prealpine, -Harz, and –Eifel received additional funding to expand instrumentation to include fluxes of CH_4 and N_2O and upgrade to ICOS standard



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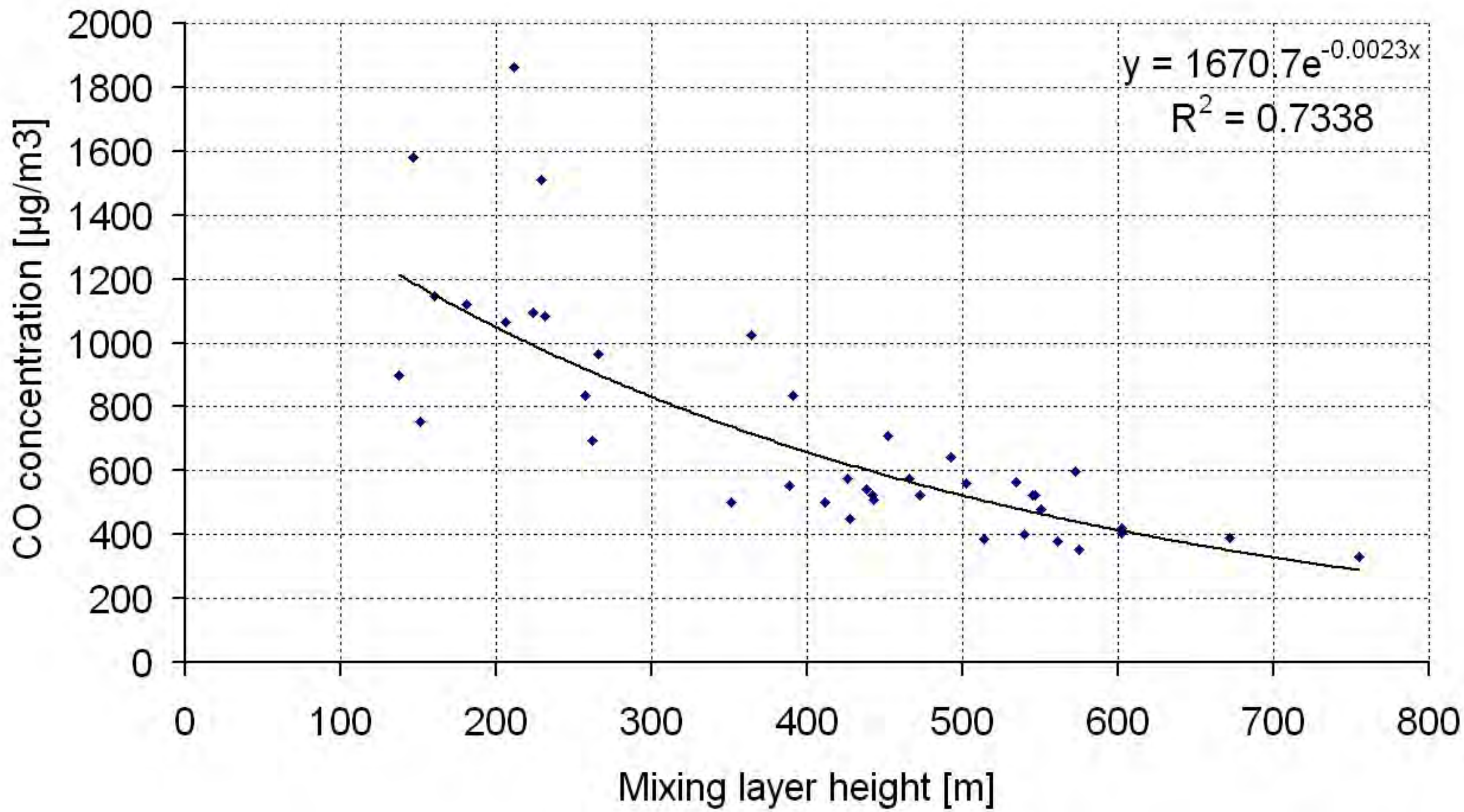
Motivation

correlation at street level pollutant - MLH



Schäfer, K., S. Emeis, H. Hoffmann, C. Jahn, 2006: Influence of mixing layer height upon air pollution in urban and sub-urban areas. Meteorol. Z., 15, 647-658.

Remote sensing

of the vertical structure of the atmospheric boundary layer

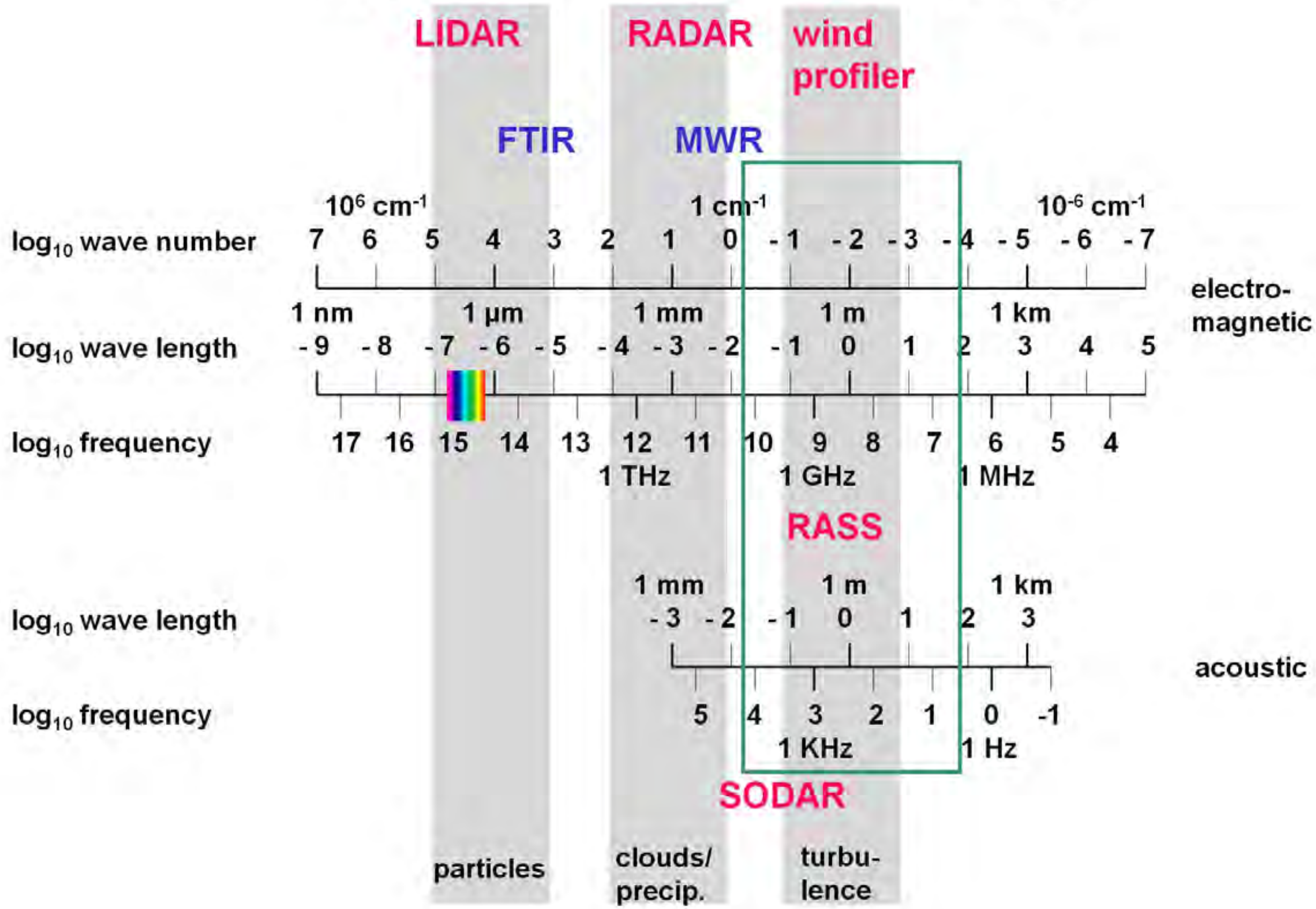
Basic remote sensing techniques

name	princple	spatial resolution	direction	type
RADAR	backscatter, electro-magnetic pulses, fixed wave length	profiling	scanning, slanted	active, monostatic
SODAR	backscatter, acoustic pulses, fixed wave length	profiling	fixed, slanted, vertical	active, usually monostatic
LIDAR ceilometer	backscatter, optical pulses, fixed wave length(s)	profiling	scanning, fixed, horizontal, slanted, vertical	active, monostatic
RASS	backscatter, acoustic, electro-magnetic, fixed wave length	profiling	fixed, vertical	active, monostatic
FTIR	absorption, infrared, spectrum	path-averaging	fixed, horizontal, slanted	active, bistatic or passive
FTIR	emission, infrared, spectrum	path-averaging	fixed, horizontal, slanted	passive
DOAS	absorption, optical, fixed wave lengths	path-averaging	fixed, horizontal	active, bistatic
radiometry	electro-magnetic, fixed wave length(s)	averaging, profiling	fixed, scanning, slanted, vertical	passive
tomography	travel time, acoustic, fixed wave length	horizontal distribution	fixed, horizontal	active, multiple emitters and receivers

subject of this lecture

subject of this lecture

Frequencies for atmospheric remote sensing



Emeis, S., 2010: Measurement Methods in Atmospheric Sciences - In situ and remote. Borntraeger, Stuttgart, 272 pp., 103 figs, 28 tables, ISBN 978-3-443-01066-9.

Surface-based Remote Sensing Systems

at IMK-IFU

SODAR (Large system), acoustic backscatter, Doppler shift analysis ➔ wind, turbulence

SODAR-RASS (Doppler-RASS), acoustic, electro-magnetic backscatter, determines speed of sound ➔ wind and temperature profiles

Ceilometer, backscatter, optical pulses, wave length ~ 0.9 µm ➔ aerosol profiles

Wind-LIDAR, optical backscatter, Doppler shift analysis, wave length ~ 1.5 µm ➔ wind and aerosol profiles

image: Halo Photonics

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SODAR

algorithms for the determination of mixing-layer height

and low-level jet observations

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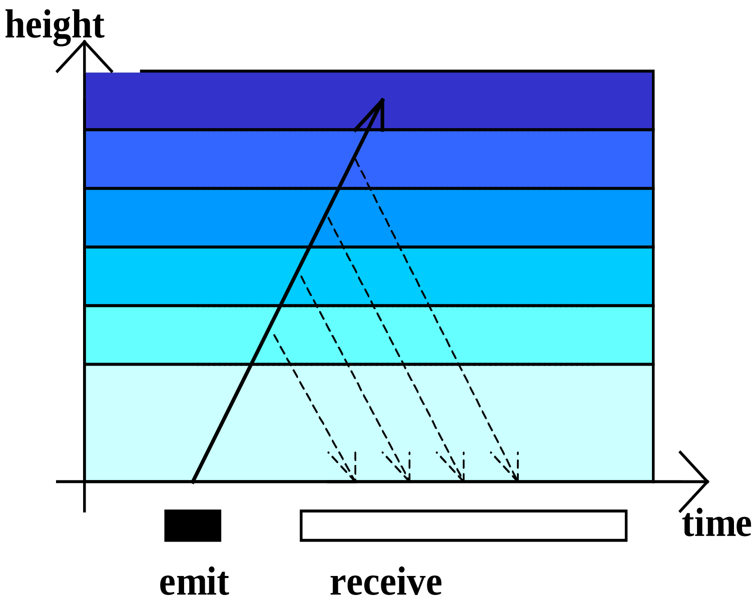
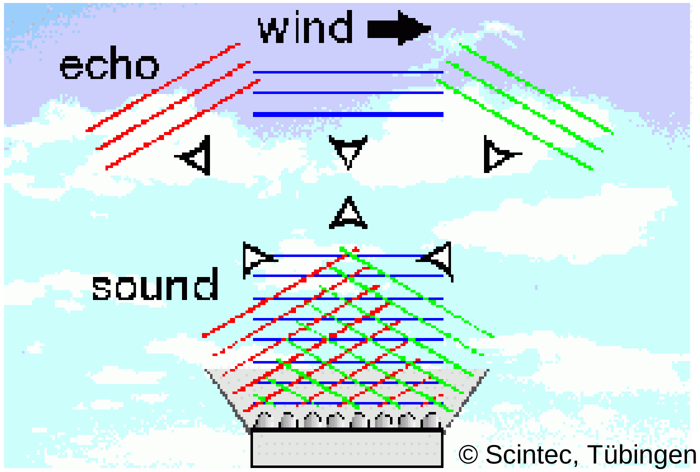
monostatic SODAR: measuring principles





deduction:

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

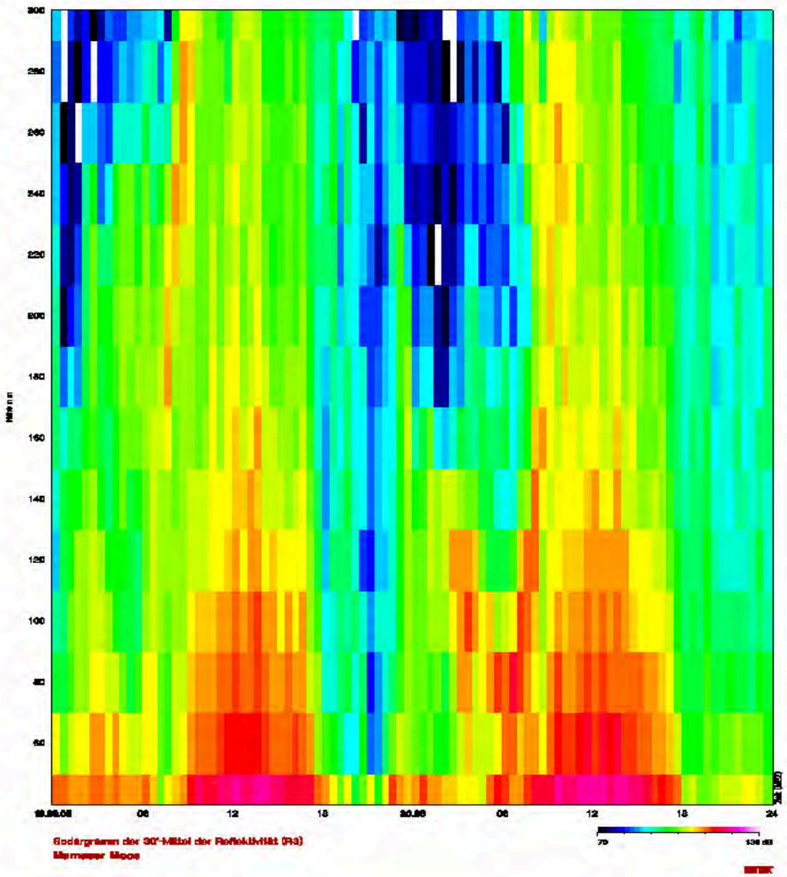
Emission of sound waves into three directions:

in order to measure all three components of the wind (horizontal and vertical)

SODAR sample plot (daytime convective BL)

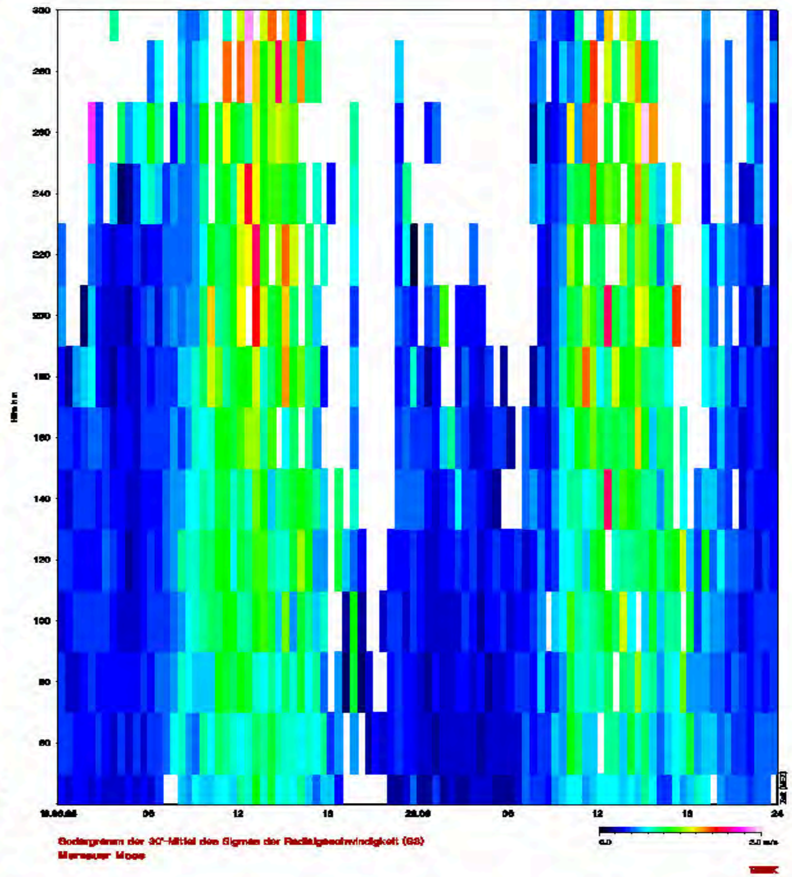
acoustic backscatter intensity

40 – 300 m



2 days, midnight to midnight

sigma w



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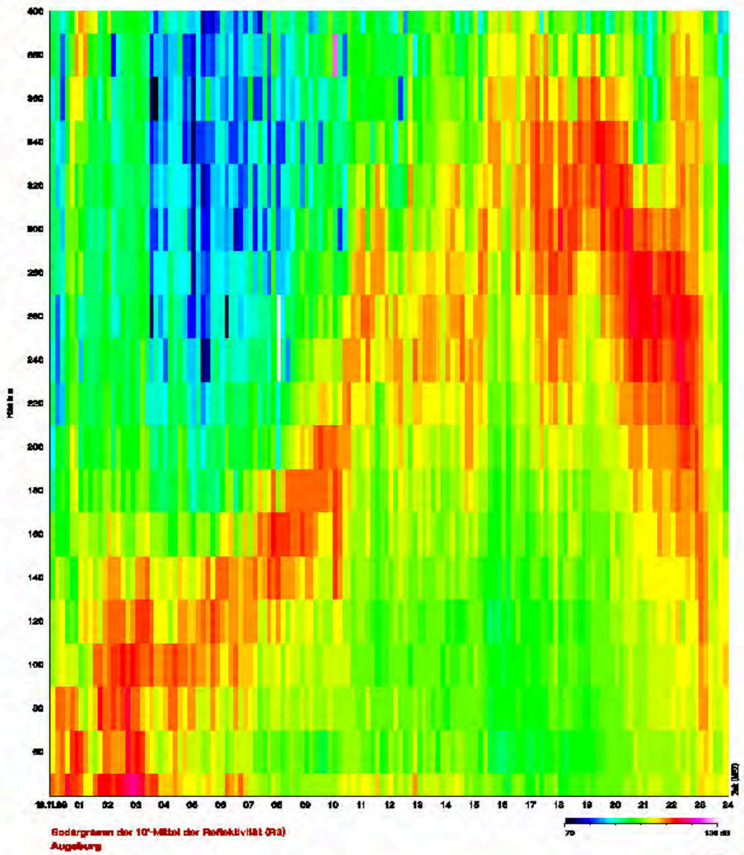
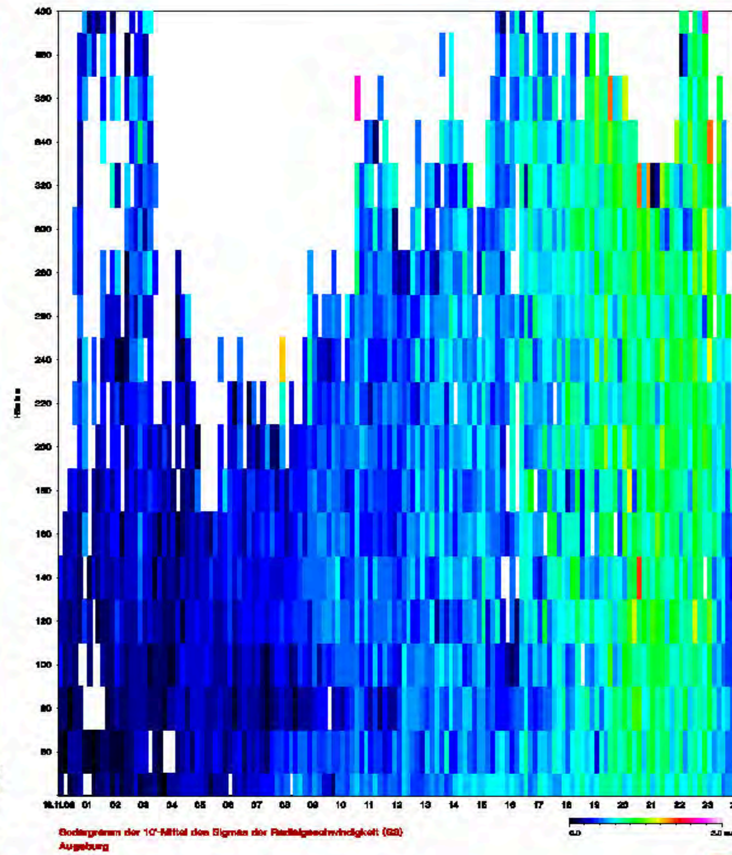
SODAR sample plot (lifted inversion)

acoustic backscatter intensity



sigma w



40 – 400 m

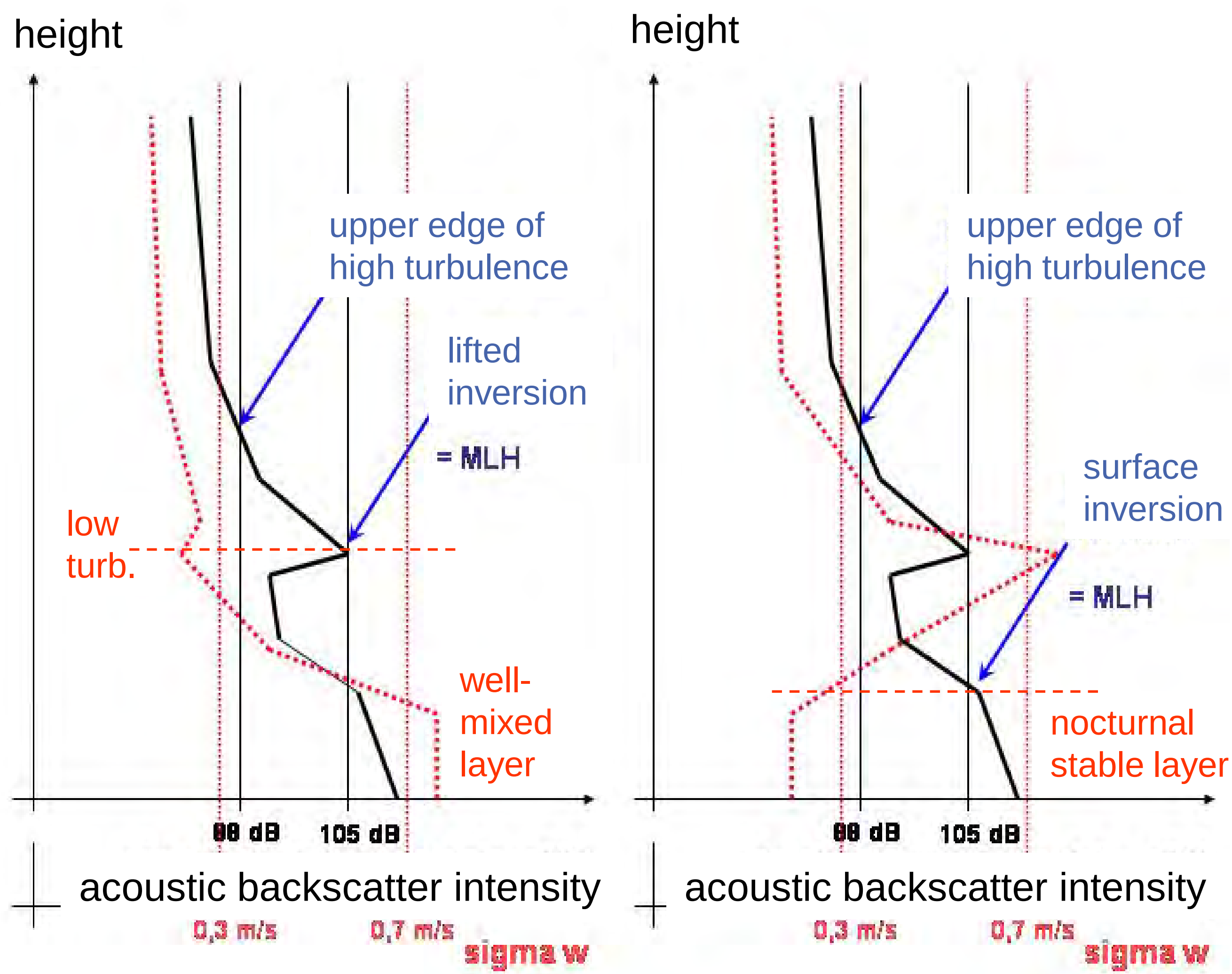
1 day, midnight to midnight

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

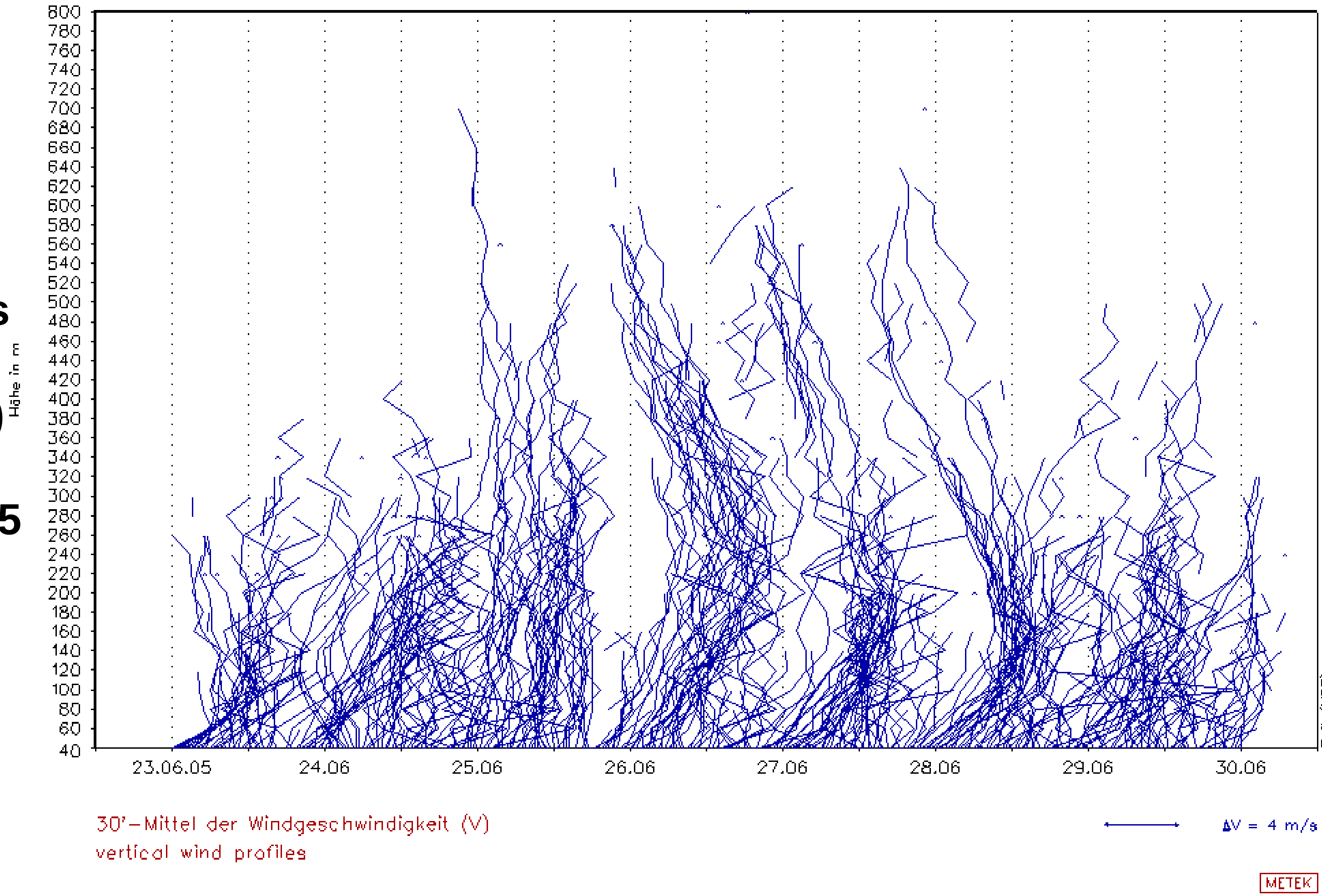
Emeis, S., K. Schäfer, C. Münkel, 2008: Surface-based remote sensing of the mixing-layer height – a review. Meteorol. Z., **17**, 621-630.

examples for low-level jet observations with SODAR

vertical profiles of wind speed (30 min means)

23-30 June 2005

AdP Ch d G

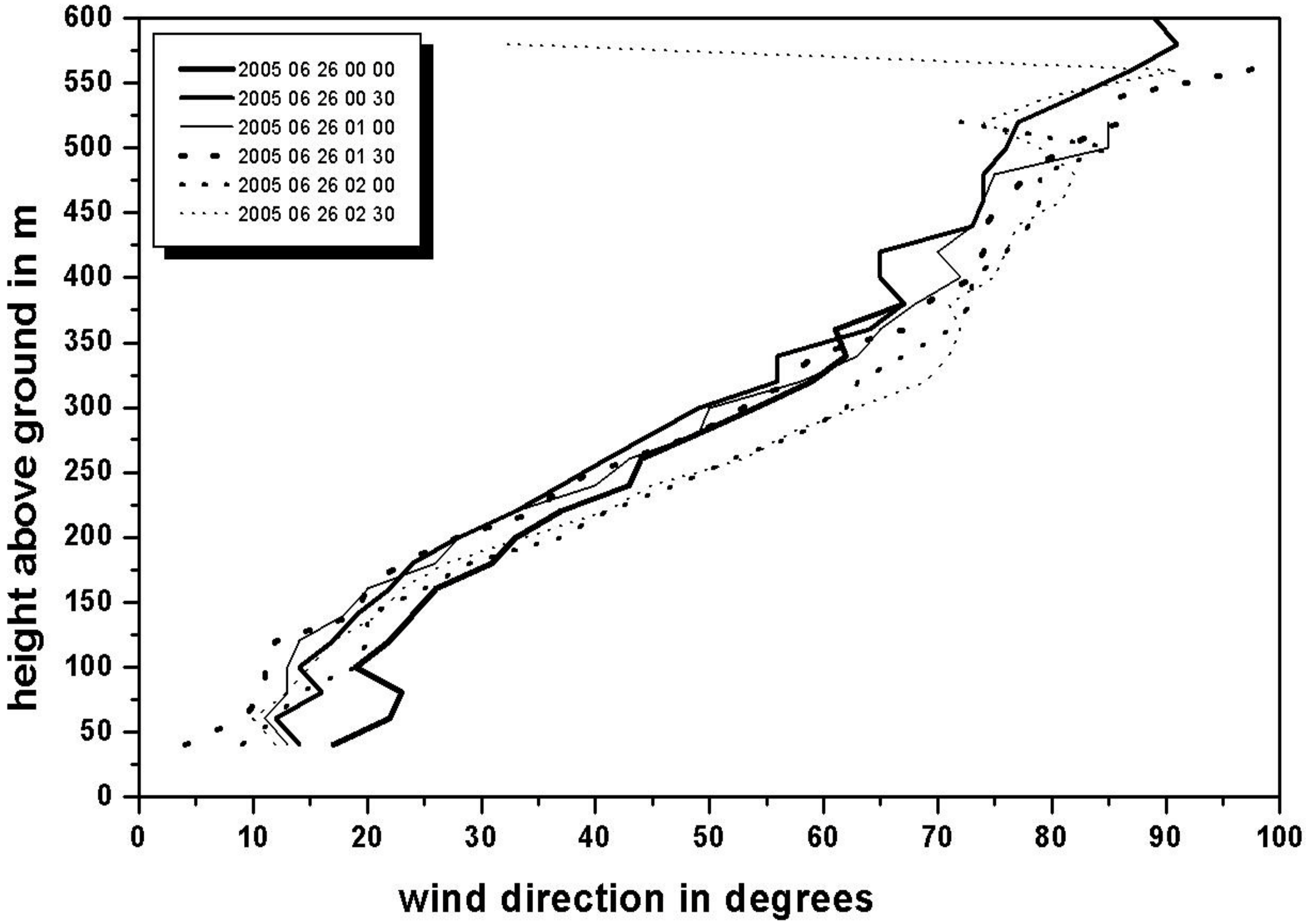


examples for low-level jet observations with SODAR

vertical profiles of wind direction

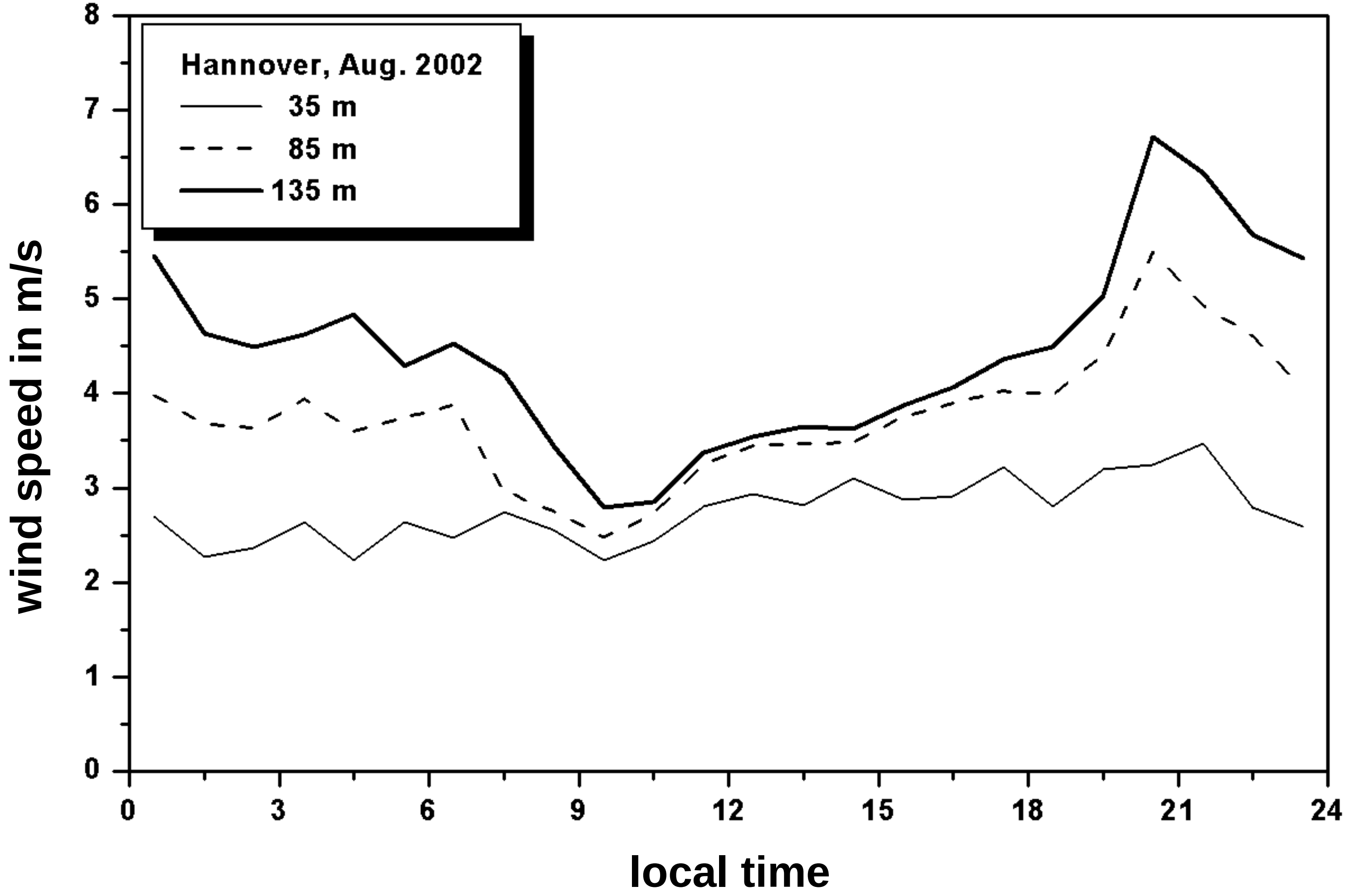
26 June 2005

AdP Ch d G

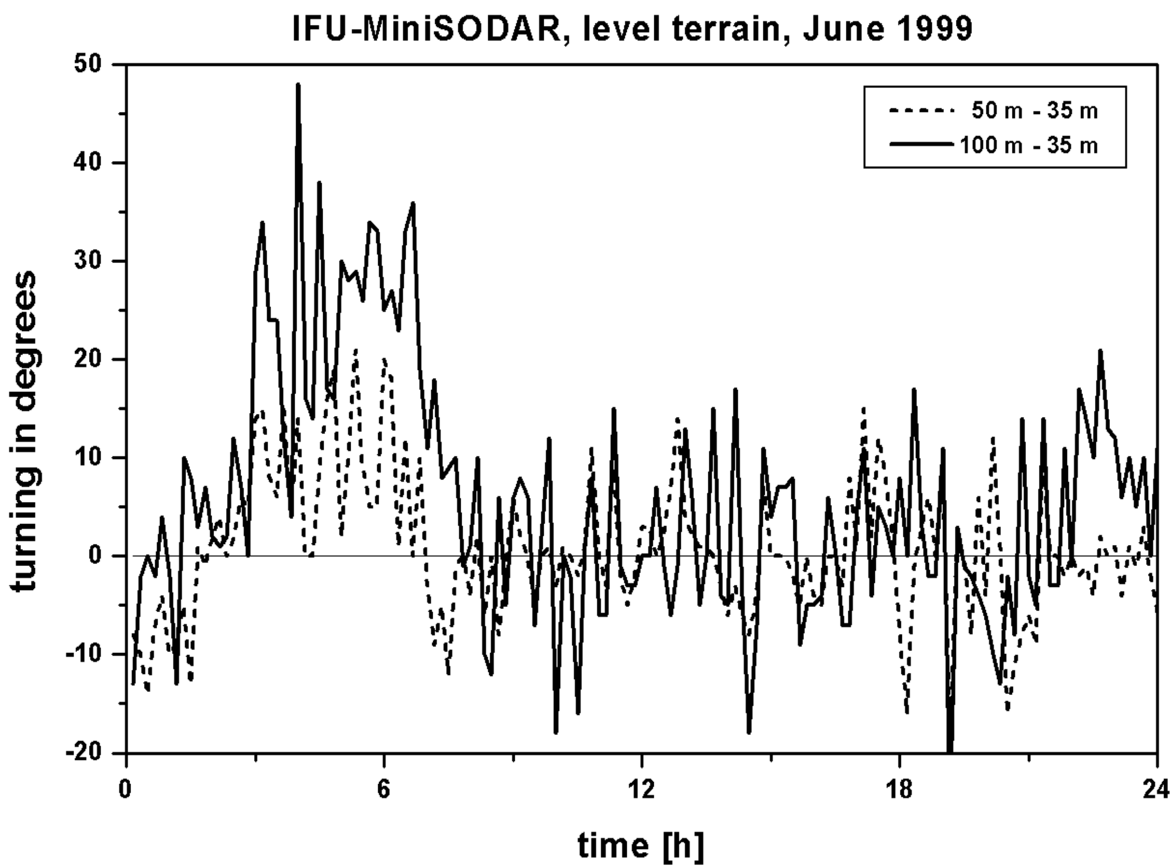


Monthly mean diurnal course of wind speed

August 2002, 17 nights with LLJ



Mean diurnal variation of the turning of wind direction with height



Emeis, S., 2001: Vertical variation of frequency distributions of wind speed in and above the surface layer observed by sodar. Meteorol. Z., **10**, 141-149.

Ceilometer

algorithms for the determination of mixing-layer height

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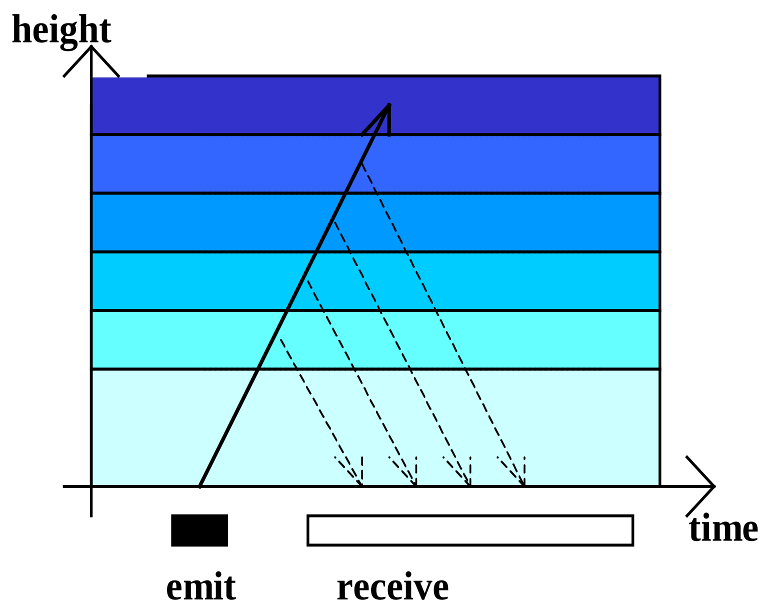
Ceilometer/LIDAR measuring principle

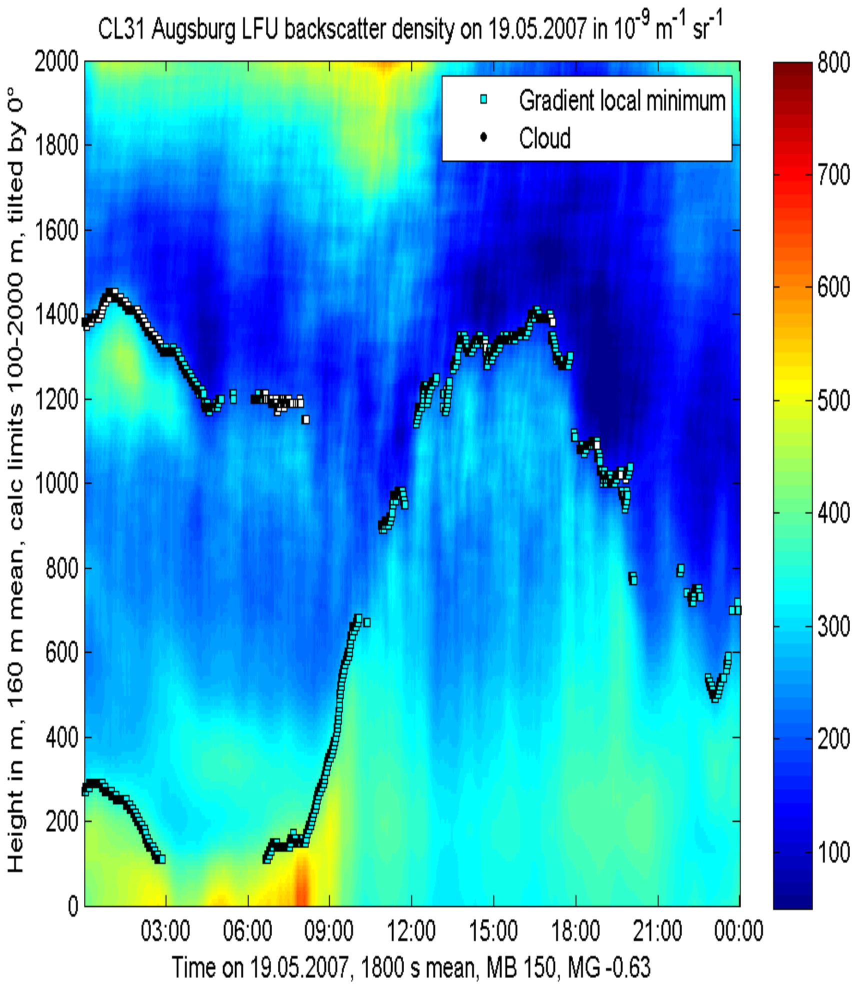


detection:

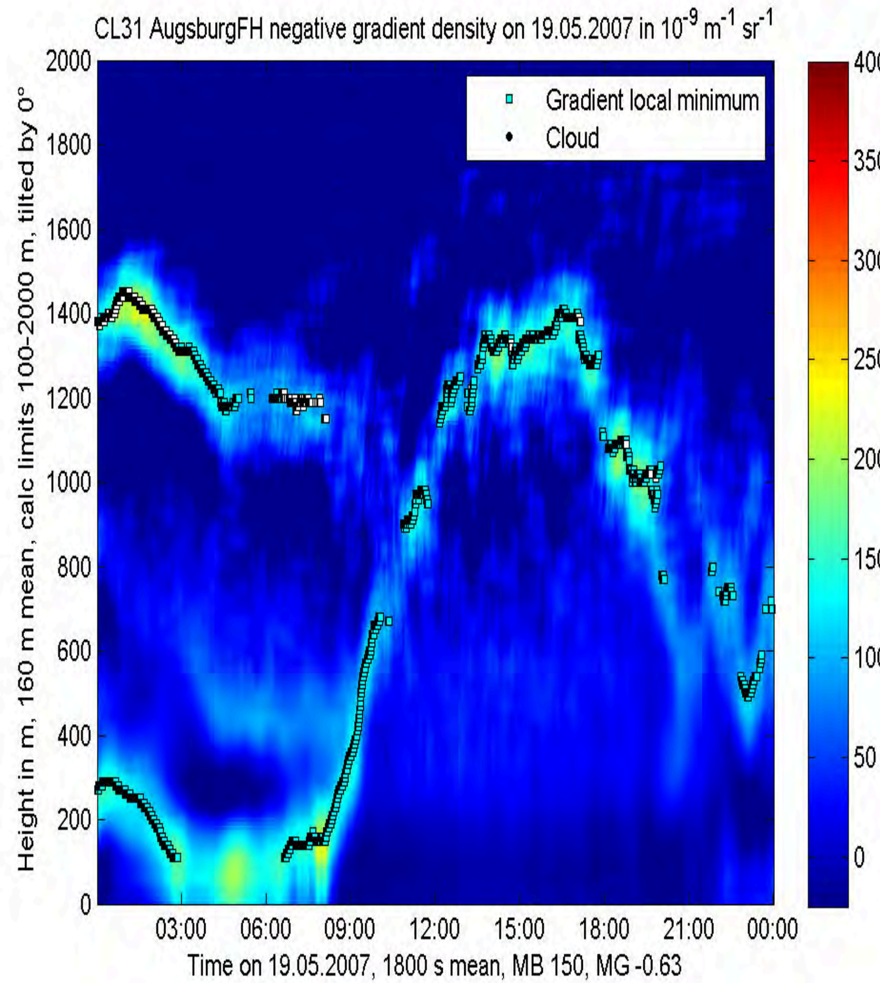
travel time of signal = height
backscatter intensity = particle size and number distribution
Doppler-shift = cannot be analyzed from ceilometer data
(available only from a Wind-LIDAR: velocity component in line of sight)

ceilometer sample plot (daytime convective BL)

optical backscatter intensity



negative vertical gradient of optical backscatter intensity



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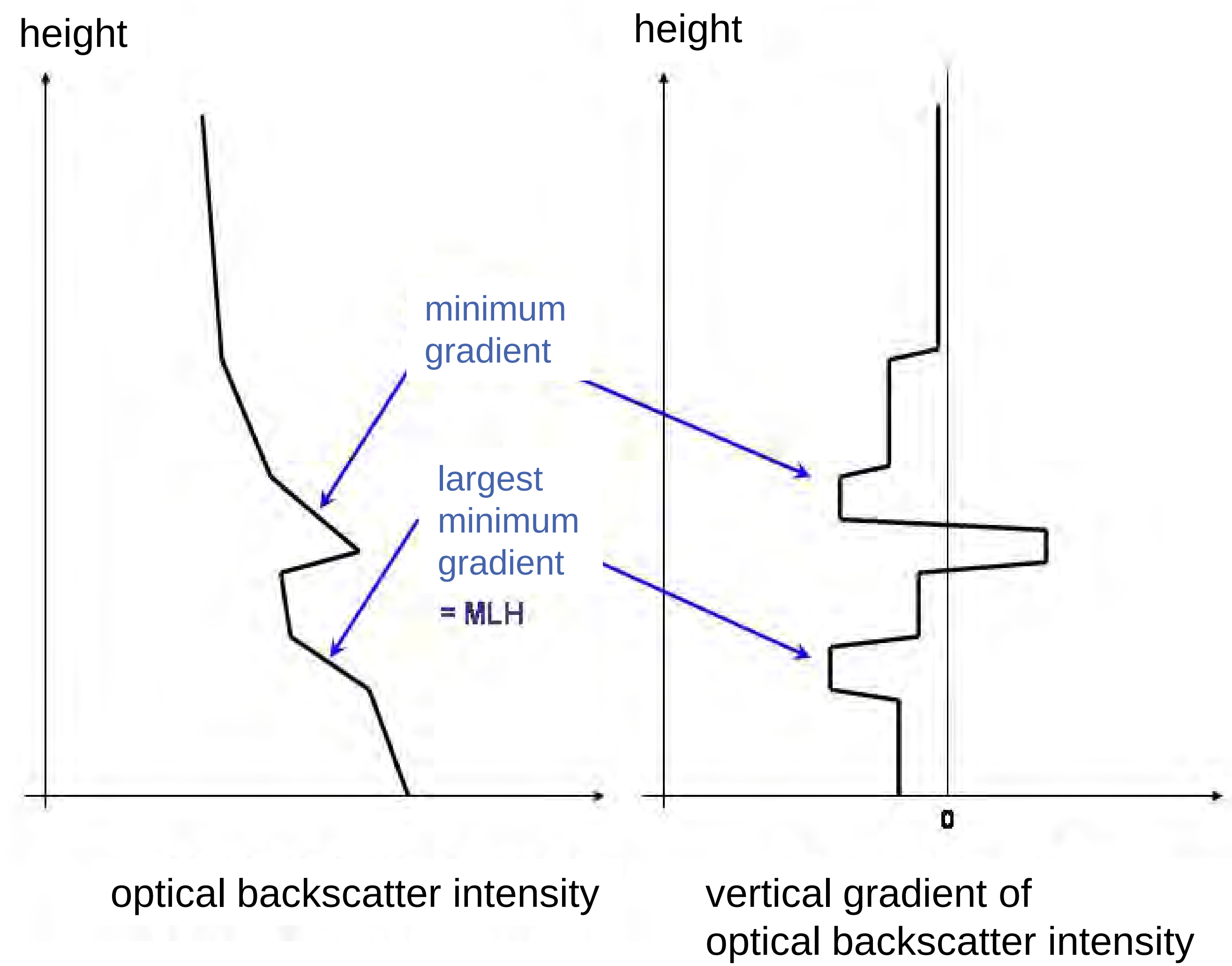
Algorithm to detect MLH from Ceilometer-Daten

Karlsruhe Institute of Technology

criterion

minimal vertical gradient of backscatter intensity (the most negative gradient)



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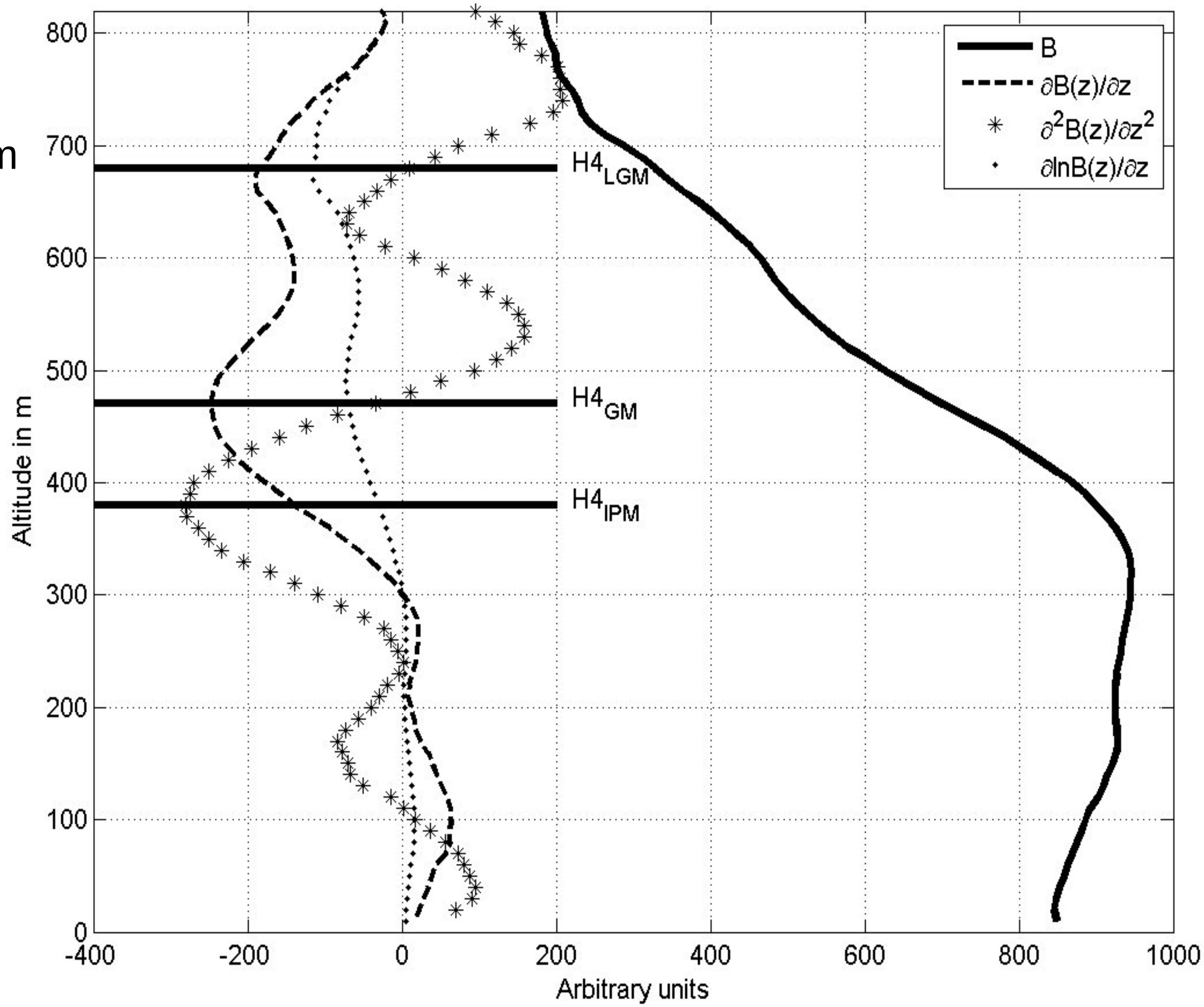
Different gradient methods (see Sicard et al. 2006, BLM 119, 135-157)

logarithmic gradient minimum

gradient minimum

inflection point method
(minimum of 2nd derivative)



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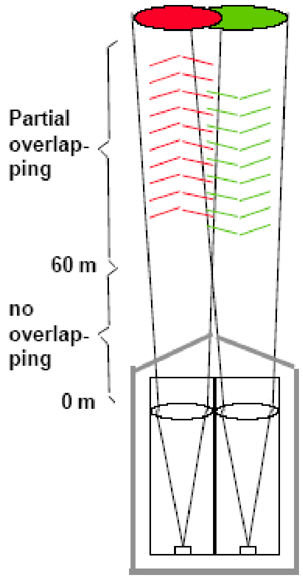
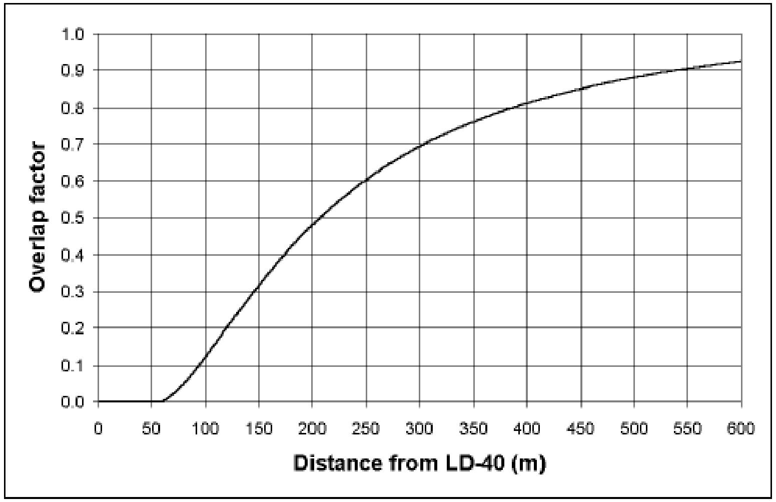
comparison of two different ceilometers

LD40

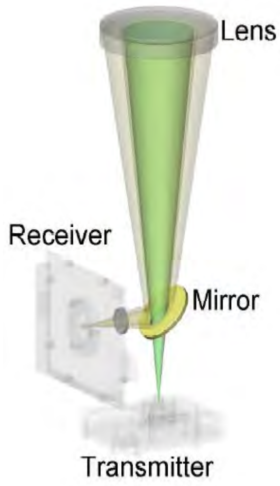
two optical axes
- wave length: 855 nm
- height resolution: 7.5 m
- max. range: 13000 m



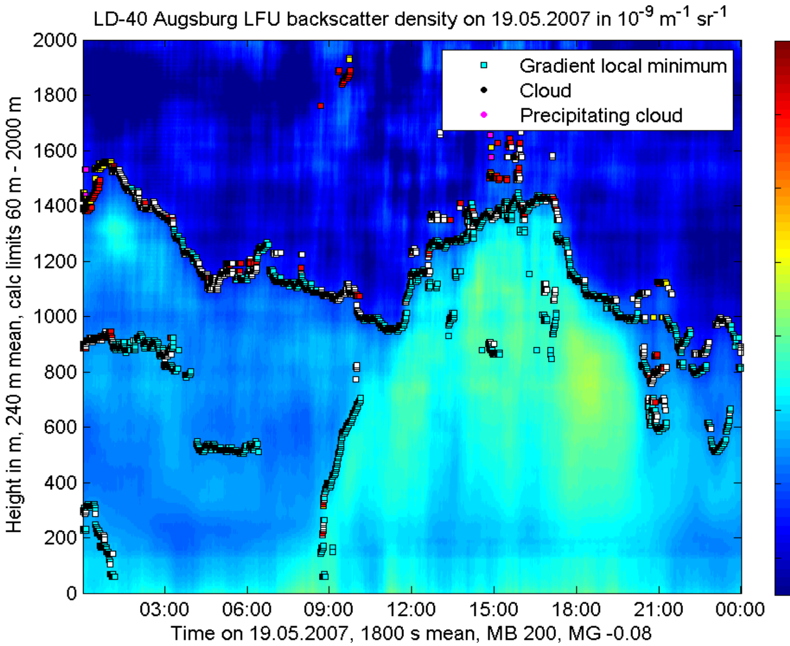


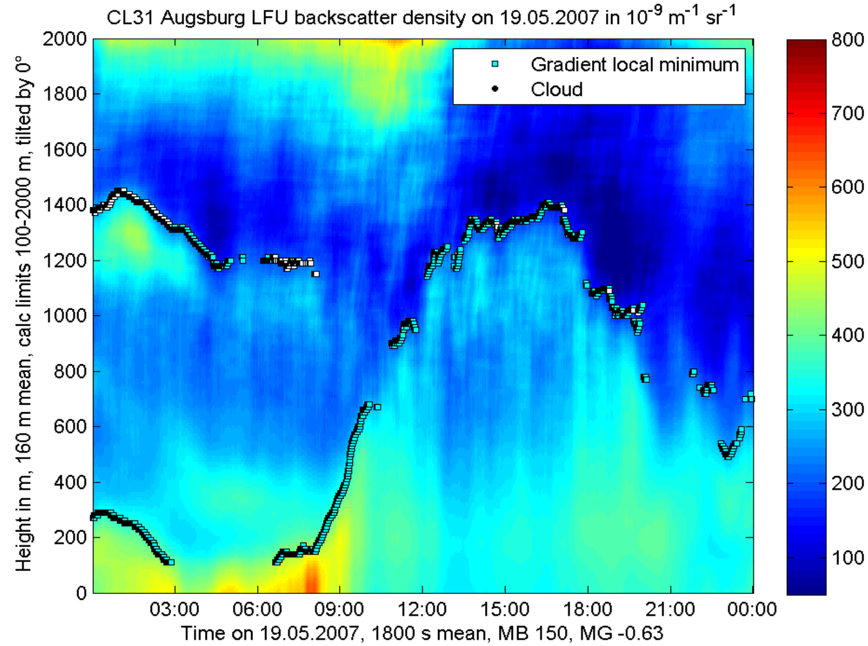
CL31 / CL51

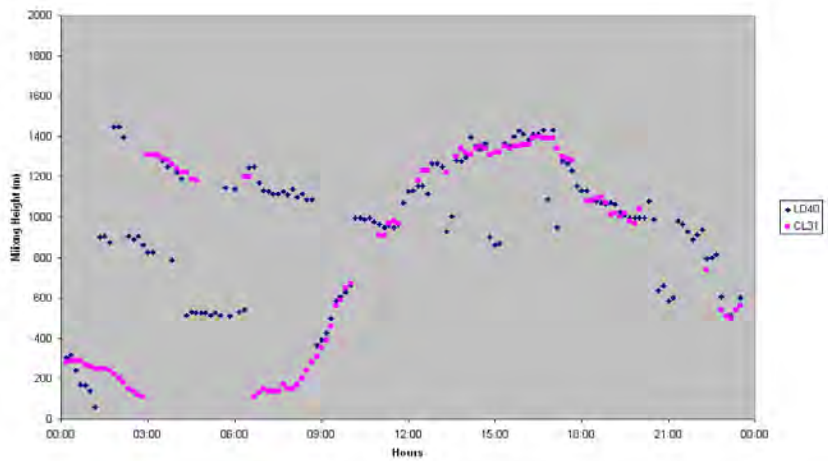
one optical axis
- wave length: 905 nm
- height resolution: 5 m
- max. range: 7500 m



comparison of LD40 and CL31





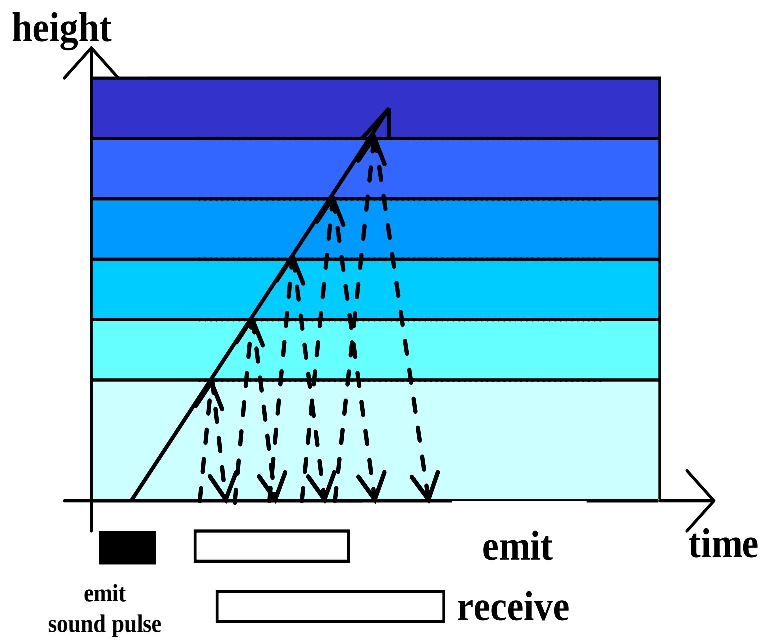


RASS

principles of operation

examples

RASS measuring principle



detection:

travel time of em./ac. signal = height
ac. backscatter intensity = turbulence (identical to SODAR)
ac. Doppler-shift = line-of-sight wind speed (identical to SODAR)
em. Doppler shift = sound speed ➔ temperature

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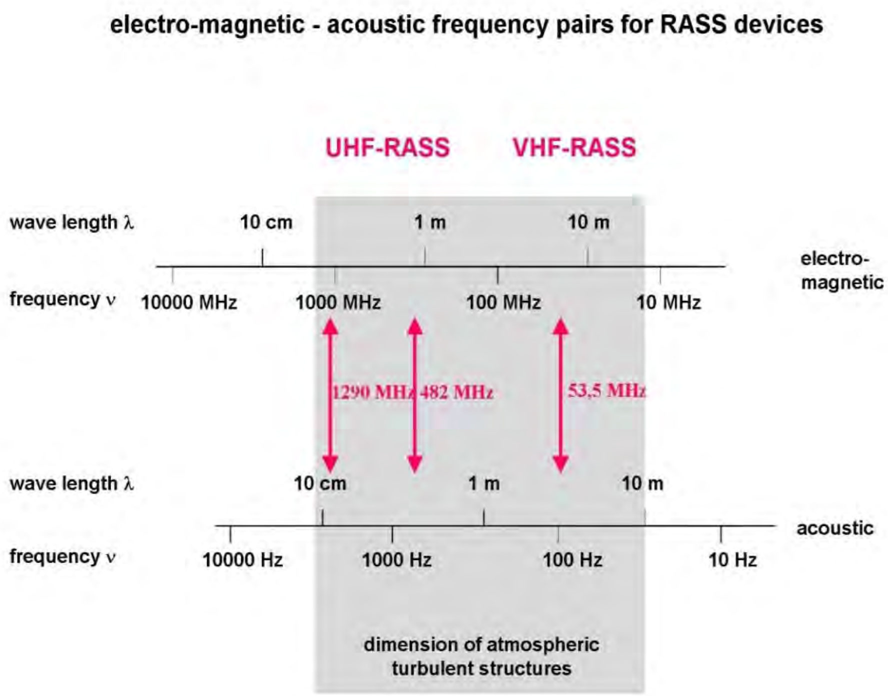
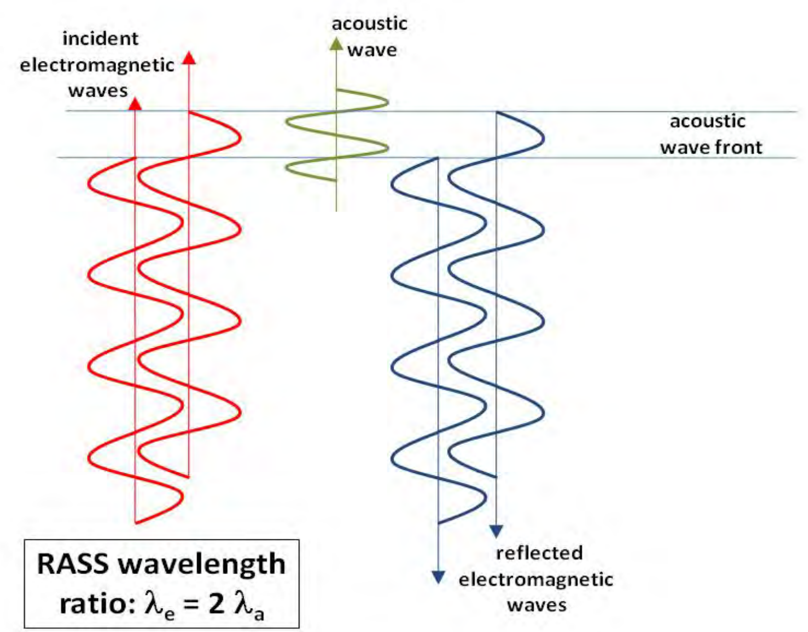
RASS: frequencies

Bragg condition:
acoustic wavelength = ½ electro-magnetic wavelength





Emeis, S., 2010: Measurement Methods in Atmospheric Sciences - In situ and remote. Borntraeger, Stuttgart, 272 pp., 103 figs, 28 tables, ISBN 978-3-443-01066-9.

SODAR-RASS
(Doppler-RASS)

(METEK)

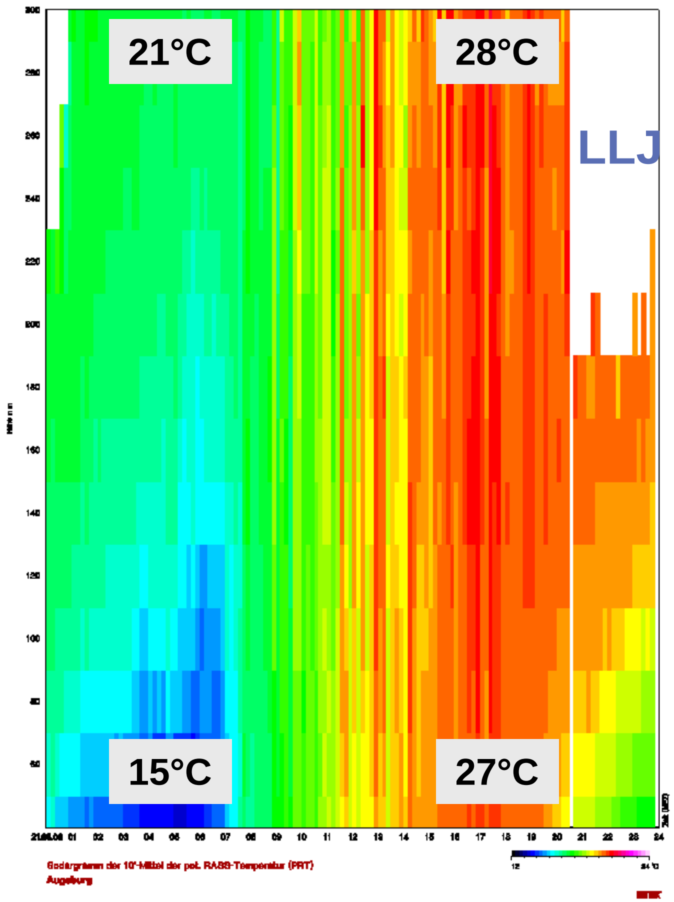
acoustic frequ.: 1077 Hz
radio frequ.: 474 MHz
resolution: 20 m
lowest
range gate: ca. 40 m

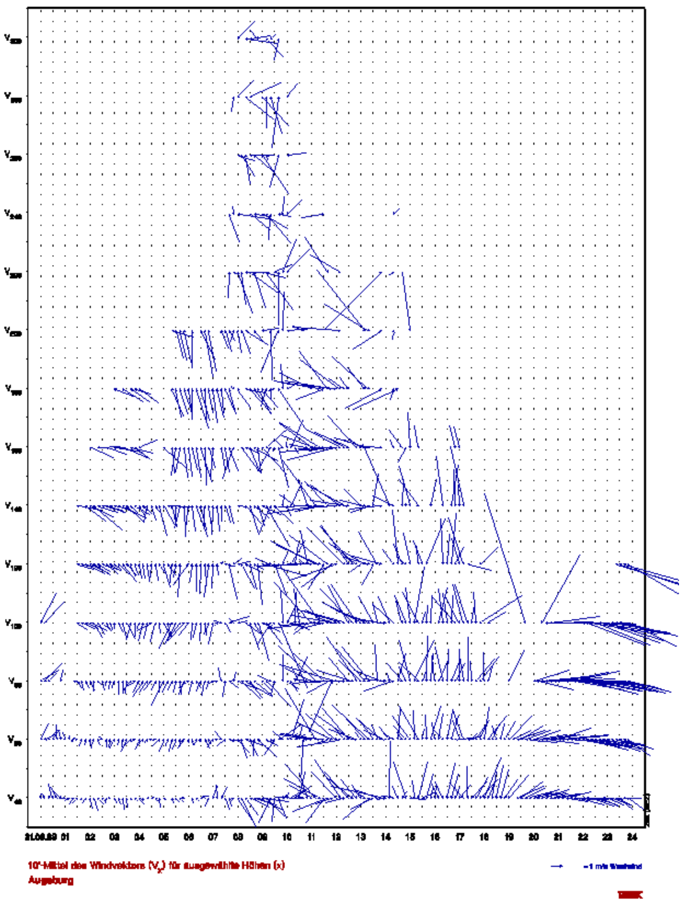
vertical range: 540 m

example RASS data: summer day
potential temperature (left), horizontal wind (right)

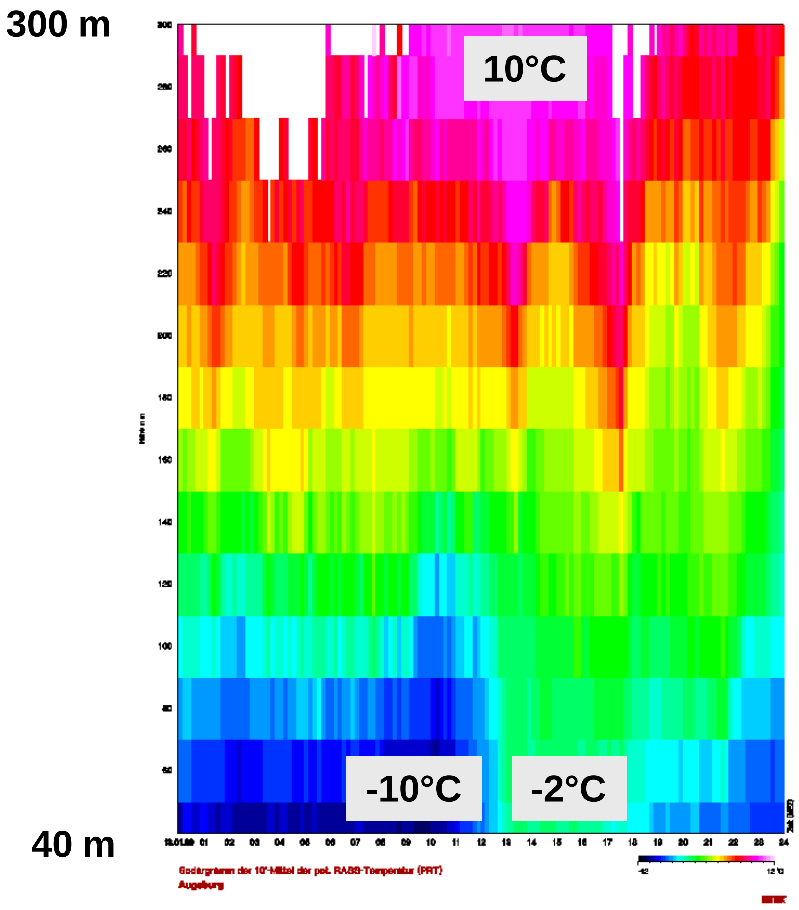
300 m

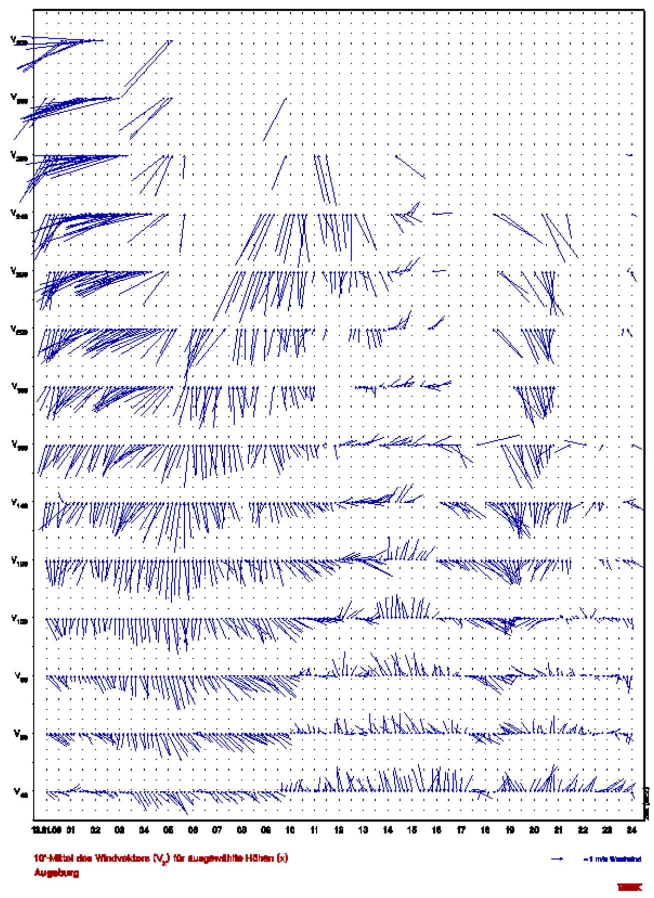
40 m



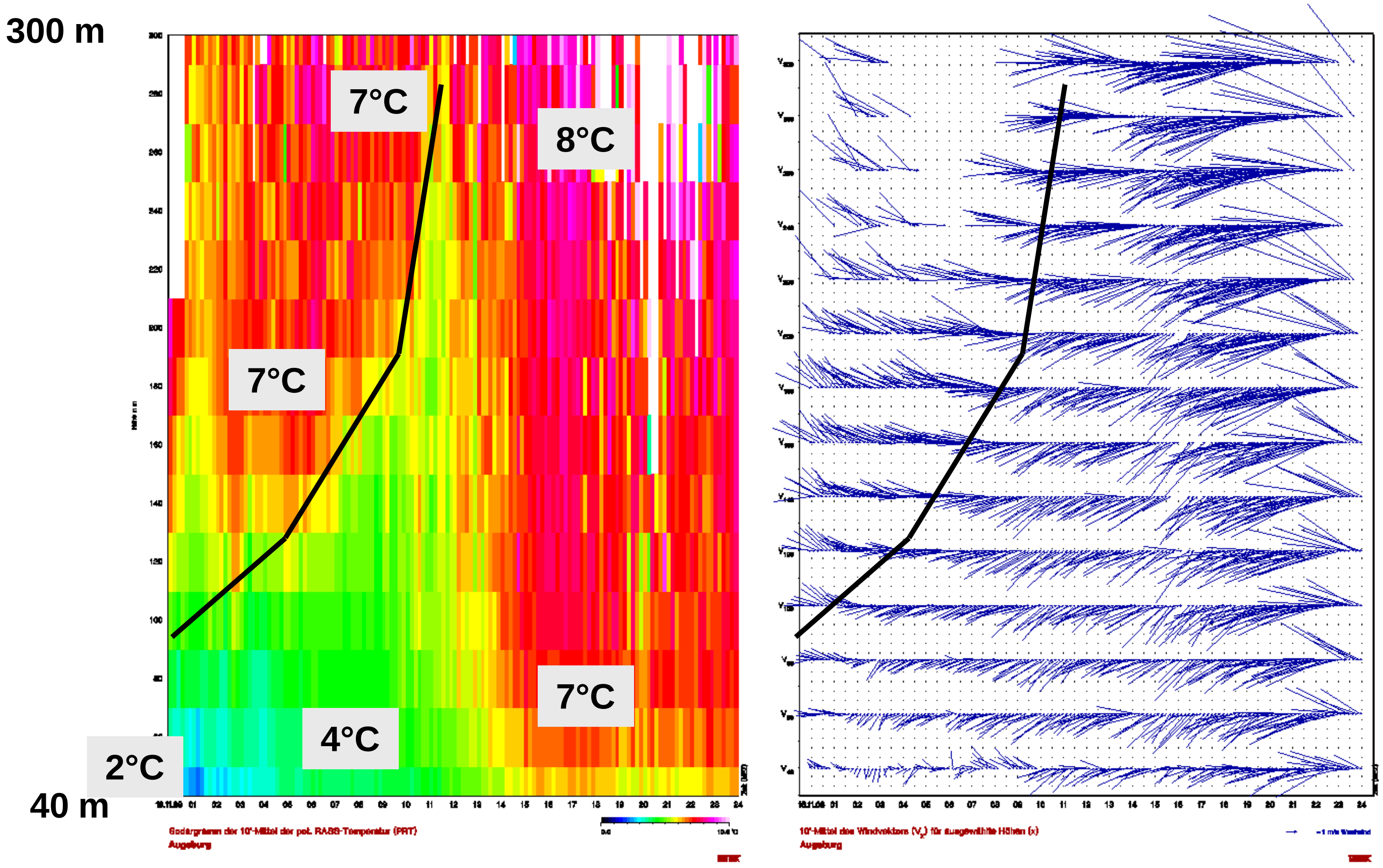


example RASS data: winter day
potential temperature (left), horizontal wind (right)





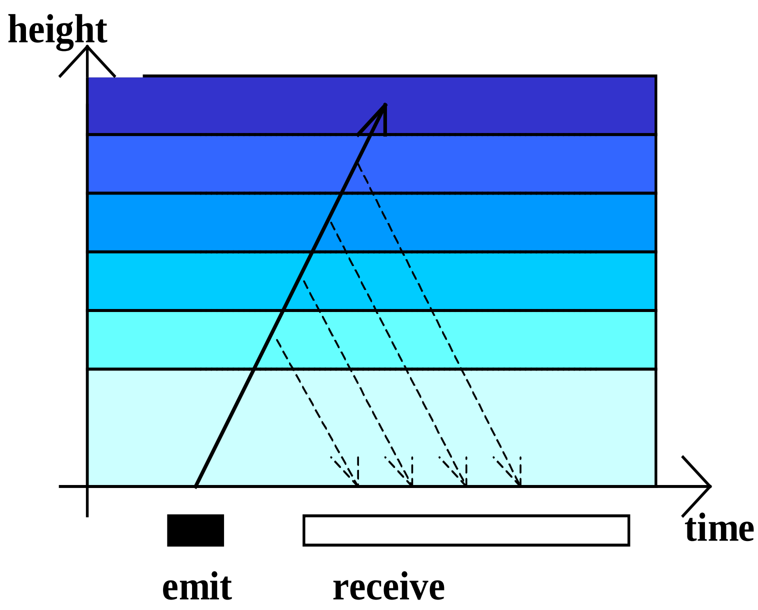
example RASS data: inversion
potential temperature (left), horizontal wind (right)



Doppler windlidar

wind, turbulence, aerosol detection, mixing-layer height, low-level jet

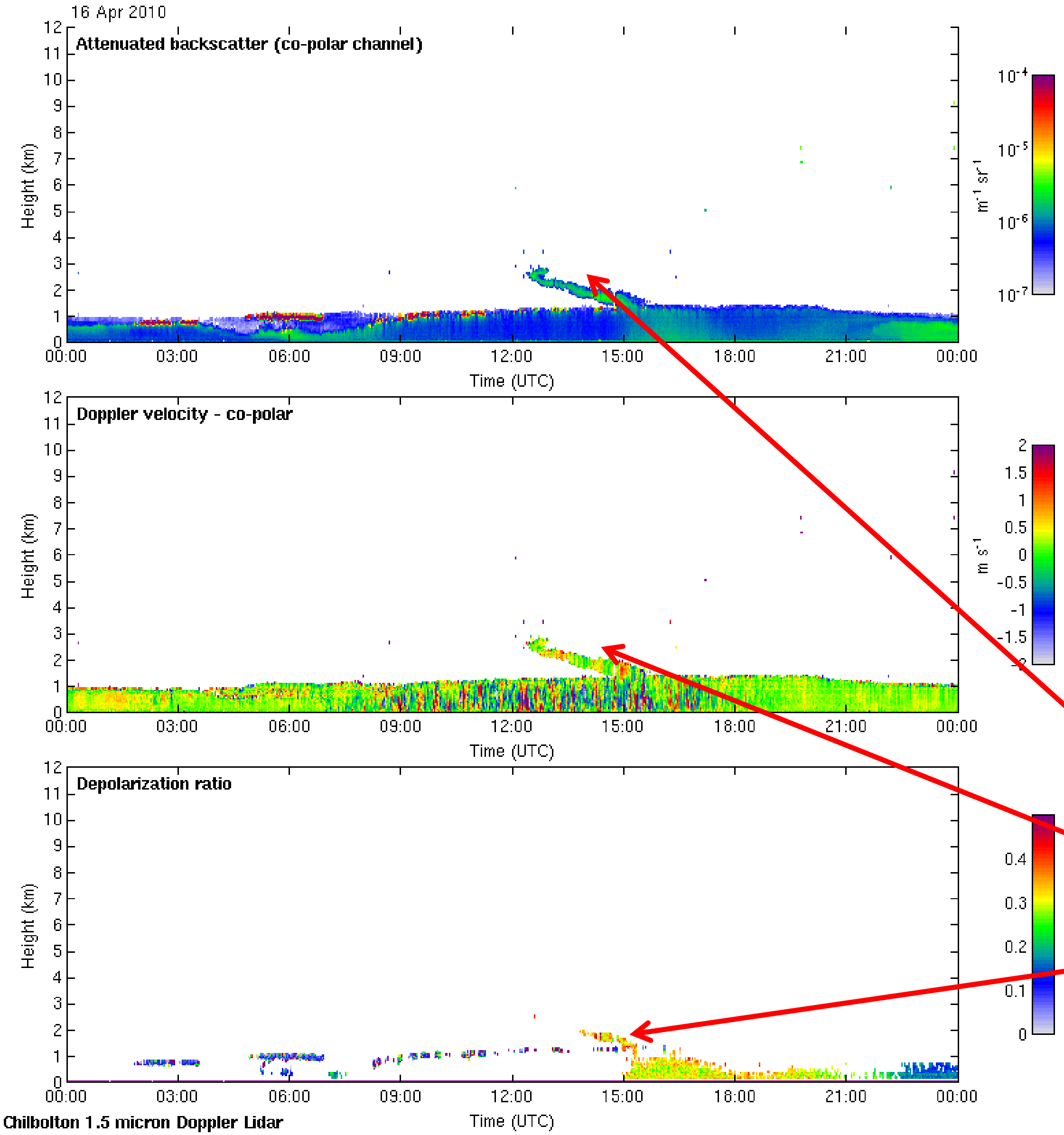
Doppler windlidar measuring principle



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

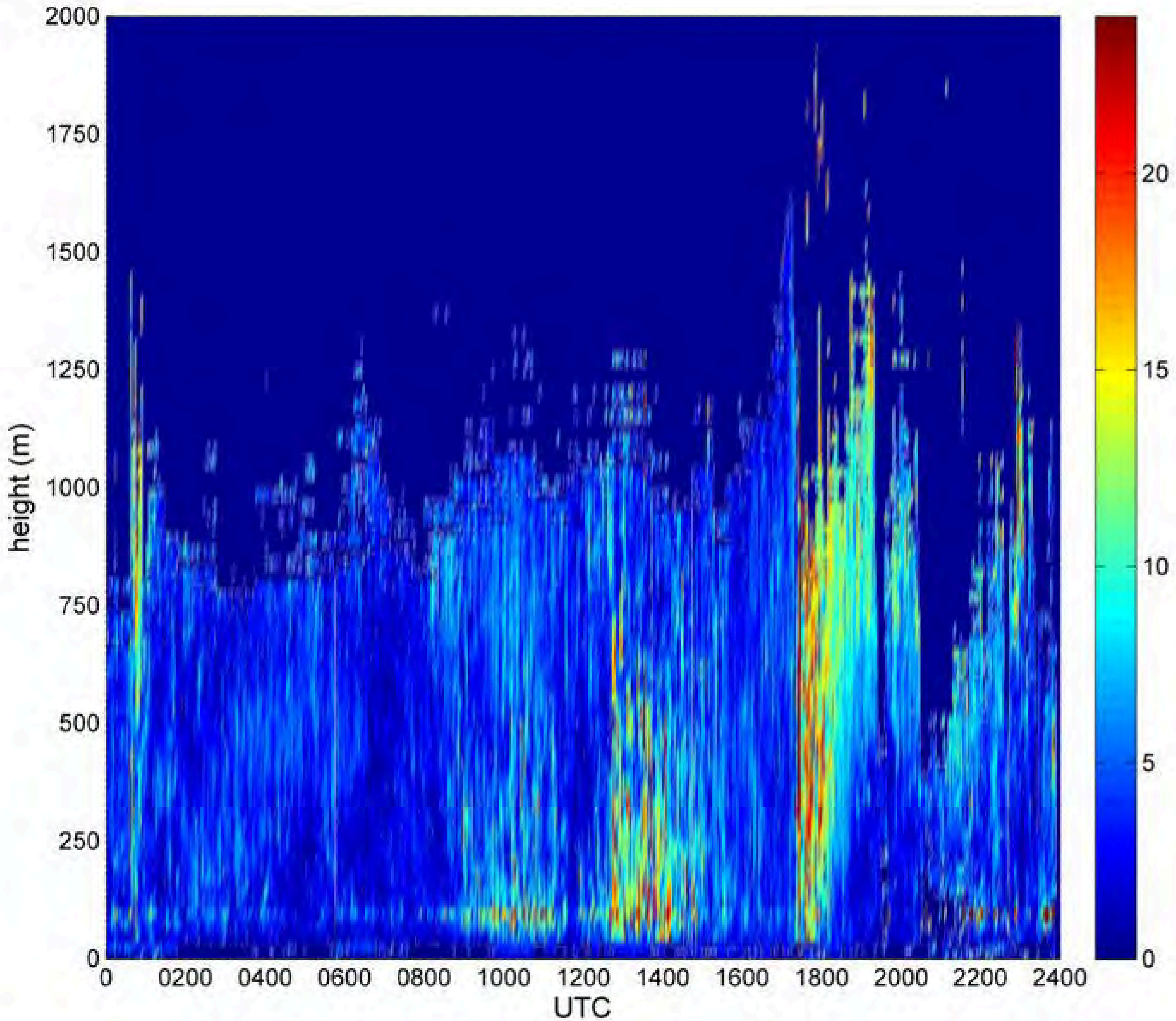
taken at

Chilbolton, UK

http://www.met.reading.ac.uk/radar/realtime/archive/doppler-lidar/20100416_chilbolton_halo-doppler-lidar.png

volcanic ash from Eyjafjallajokull

realtime data: http://www.chilbolton.rl.ac.uk/weather/lidar.htm



sample data from windlidar

wind speeds in m/s (colour bar)

June 22, 2011

by IMK-IFU

taken at

Garmisch-Partenk., Germany

Comparisons between different instruments

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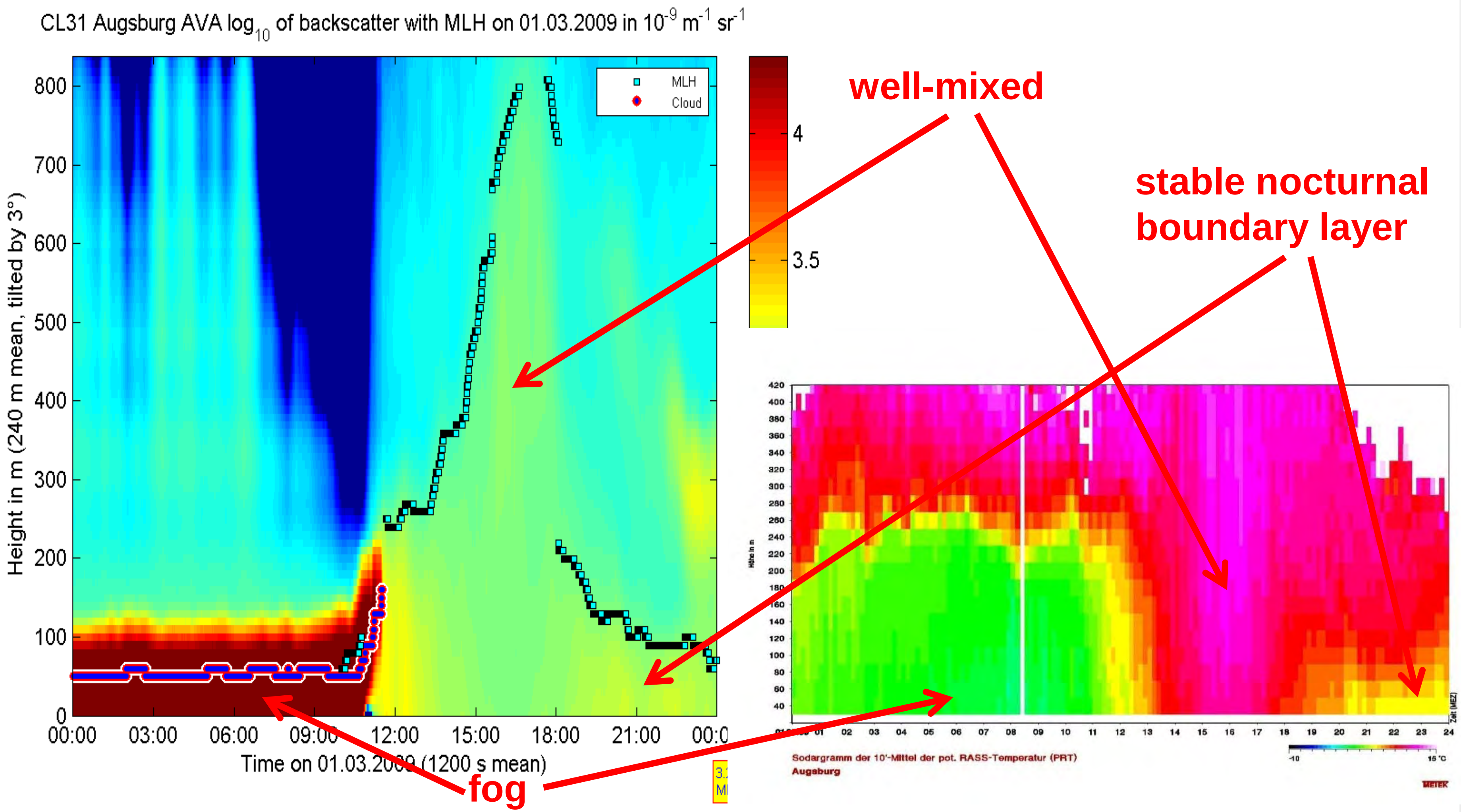
temperature profile and aerosol backscatter

Karlsruhe Institute of Technology

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



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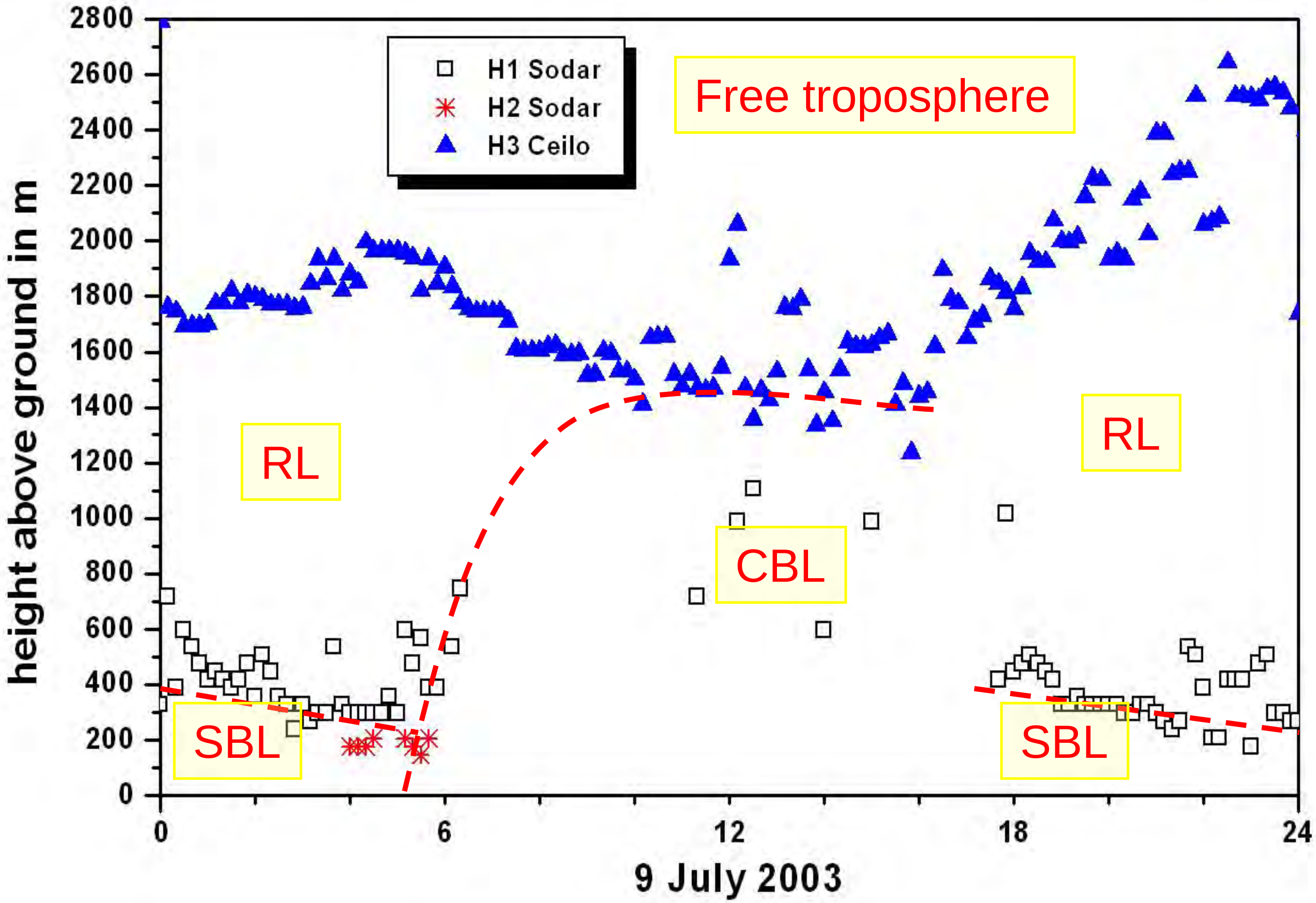
Detection of the diurnal variation of PBL structure from SODAR and Ceilometer data taken in Budapest

KIT Karlsruhe Institute of Technology



SBL:

stable boundary layer (usually at night and in winter)

CBL:

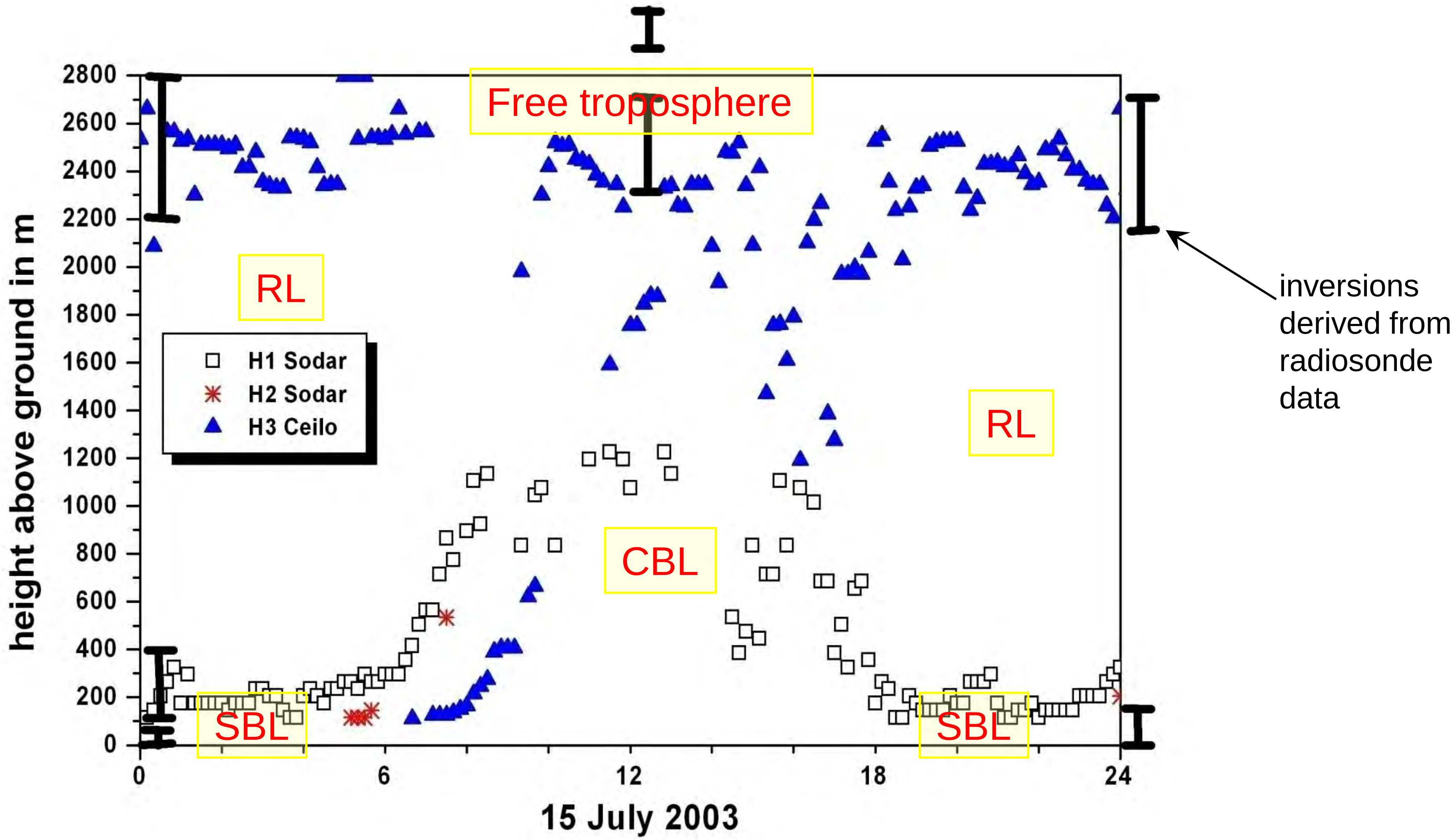
convective boundary layer (usually at daytime due to strong insolation)

RL:

residual layer (usually at night-time)

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,

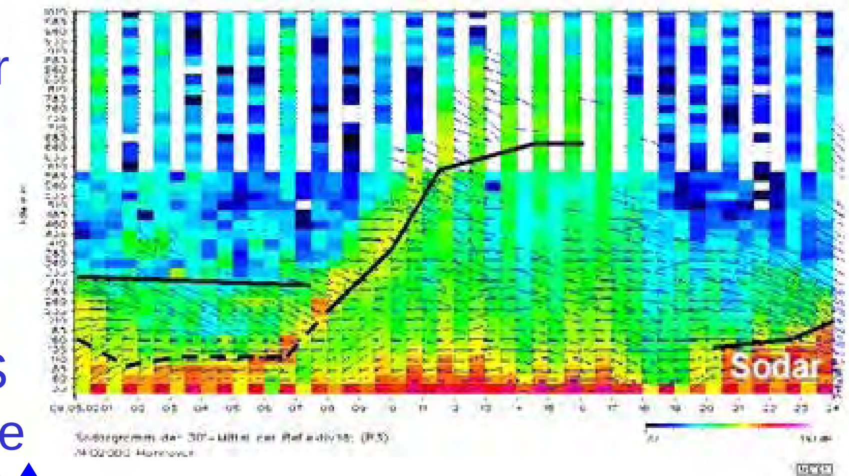
Differences in MLH detection from SODAR and Ceilometer data taken in Budapest



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,

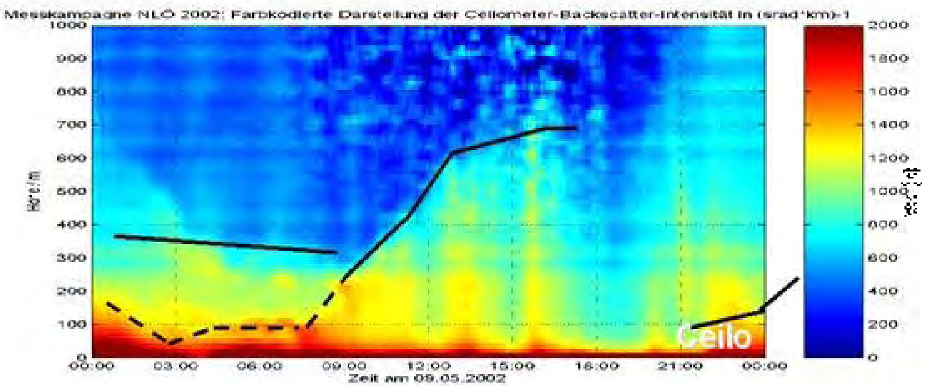
Comparison of MLH retrievals with three different remote sensing techniques

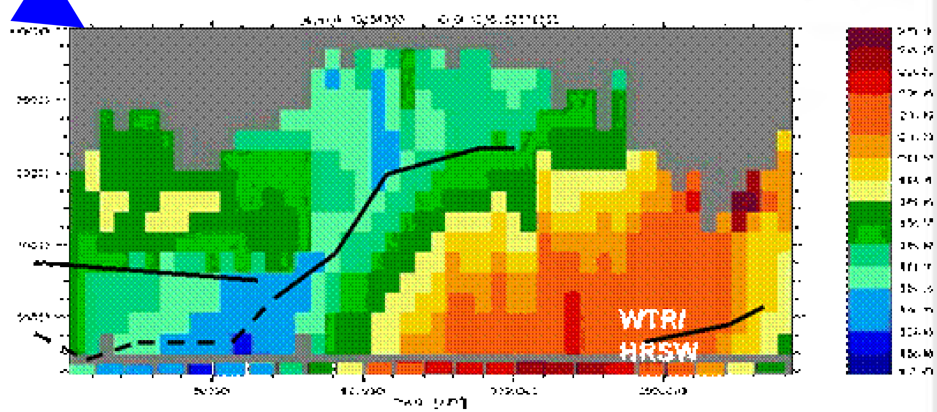
SODAR
acoustic backscatter



ceilometer
optical backscatter

RASS
temperature





Emeis, S., Chr. Münkel, S. Vogt, W.J. Müller, K. Schäfer, 2004: Atmospheric boundary-layer structure from simultaneous SODAR, RASS, and ceilometer measurements. Atmos. Environ., 38, 273-286.

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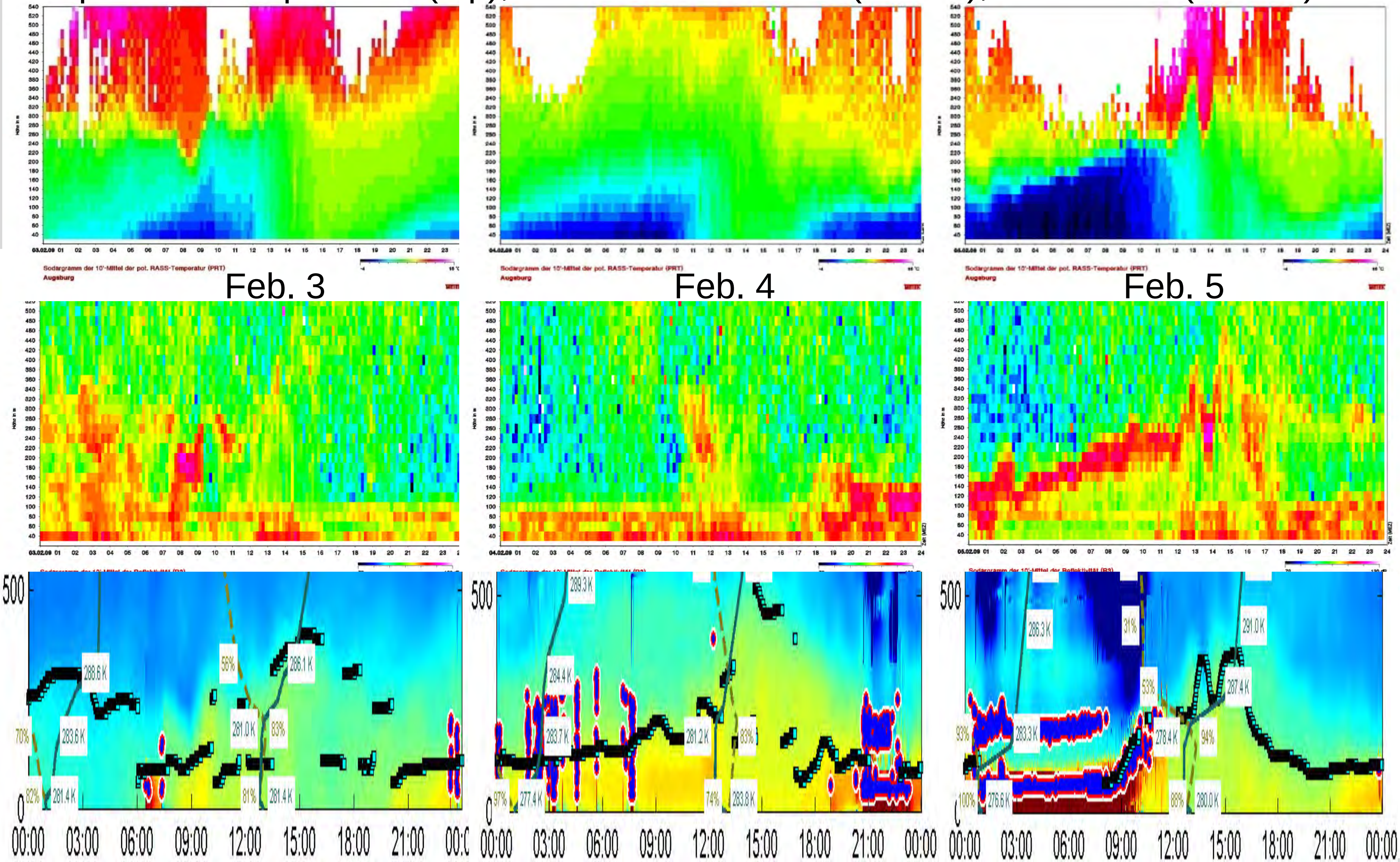
RASS data Augsburg February 2009

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



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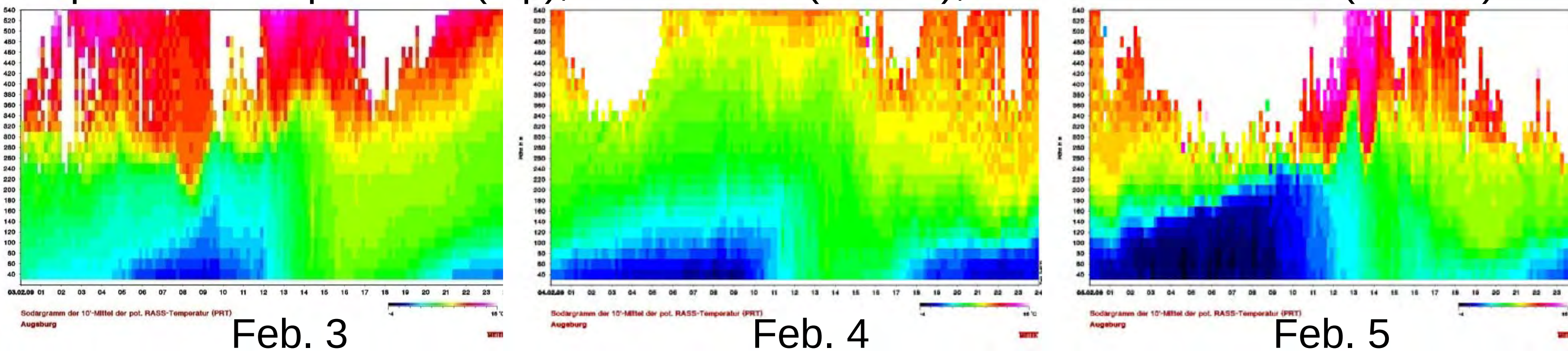
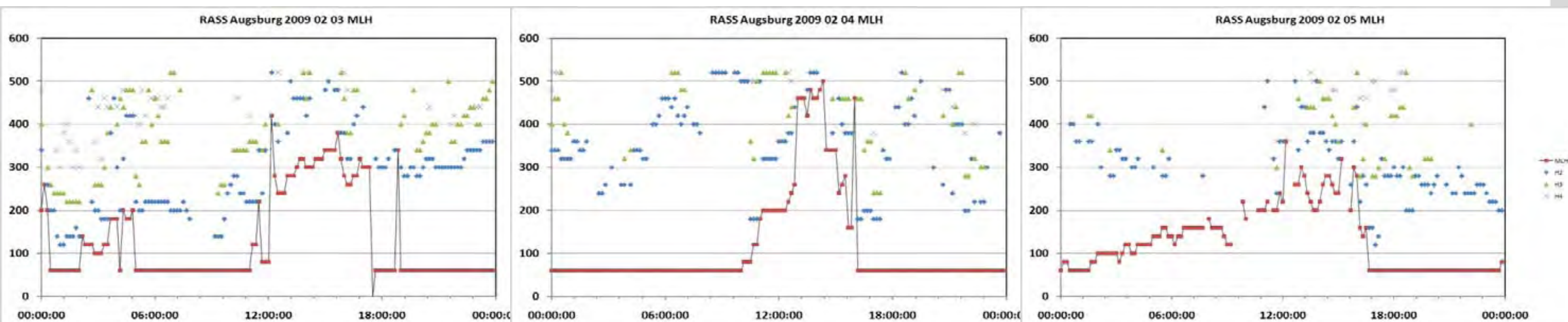
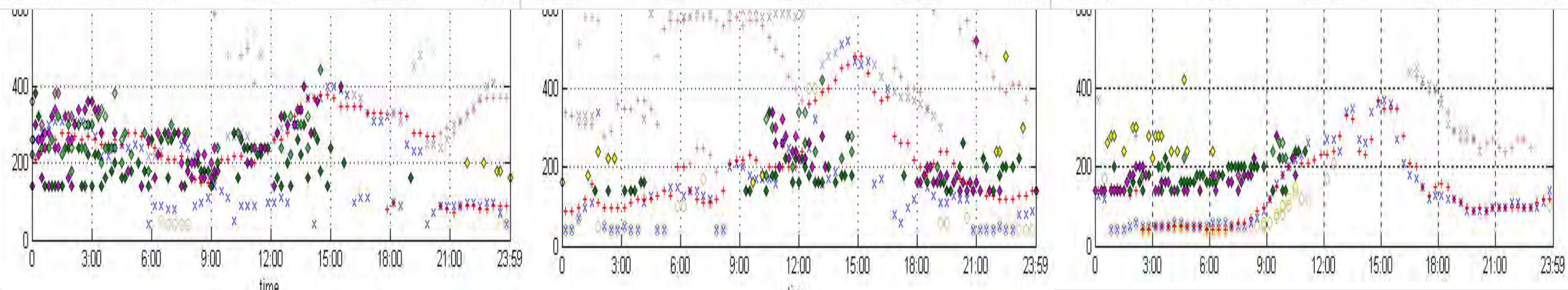
RASS data Augsburg February 2009

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







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Application of MLH information for regional emission flux estimates

Determination of regional surface emission fluxes of a substance e

Assumptions:

- horizontal homogeneity
- no fluxes through the upper boundary (inversion)
- no sources and sinks within the volume of interest

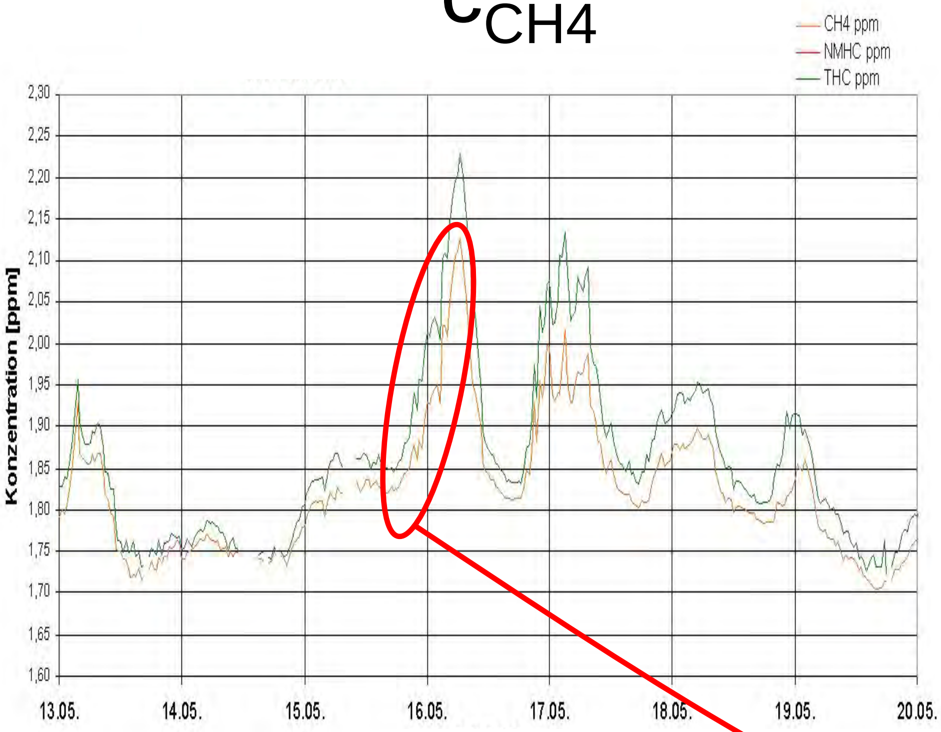
$$\int_{S_{surf}} \overline{e'w'} \cdot dS = \int_V \frac{de}{dt} dV$$

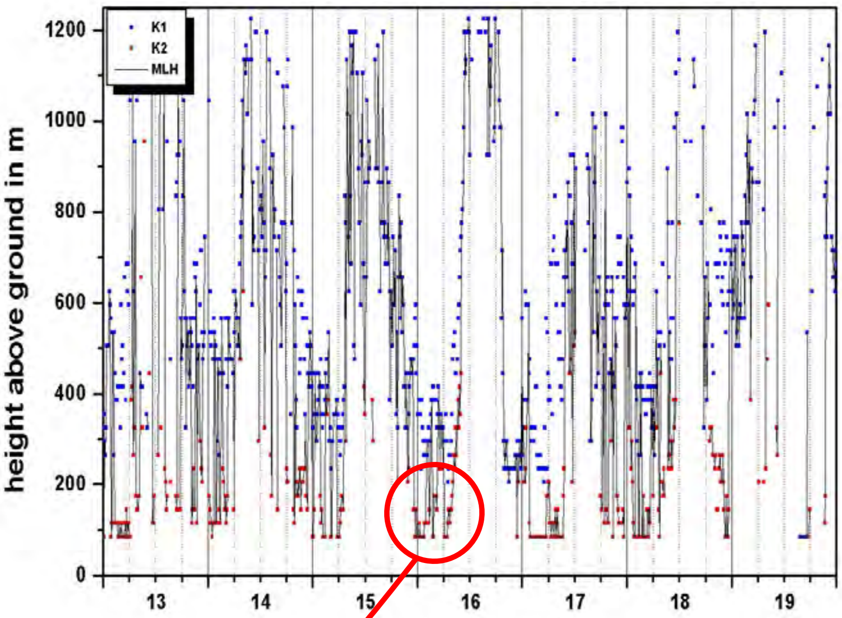
simultaneous measurement of concentration and MLH

(inverse method)

c_{CH4}

MLH



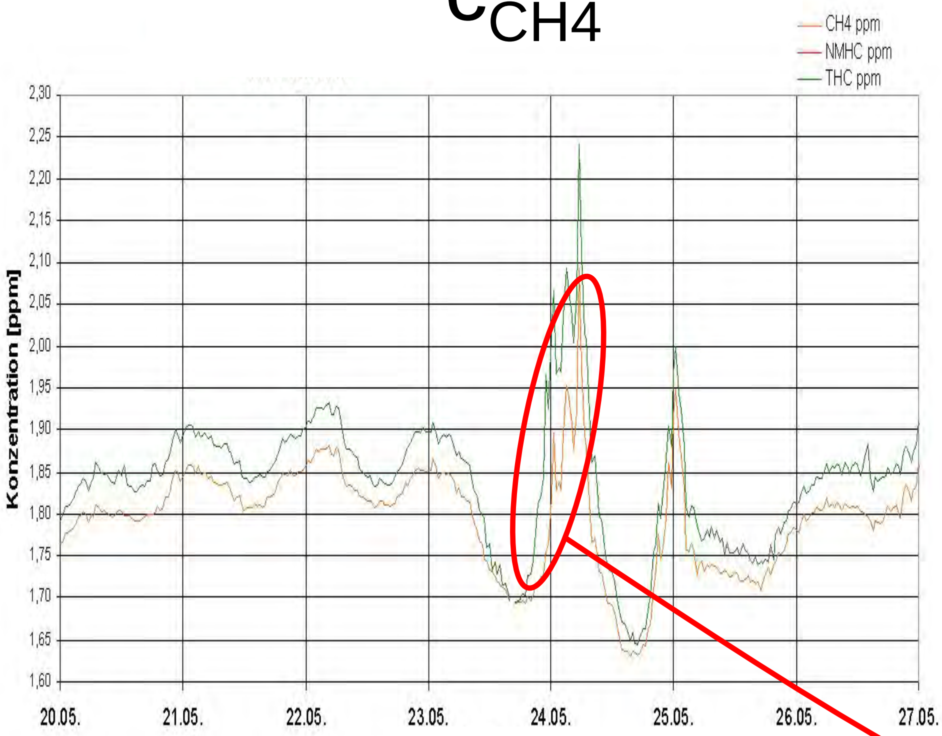


13.-19.05.2003

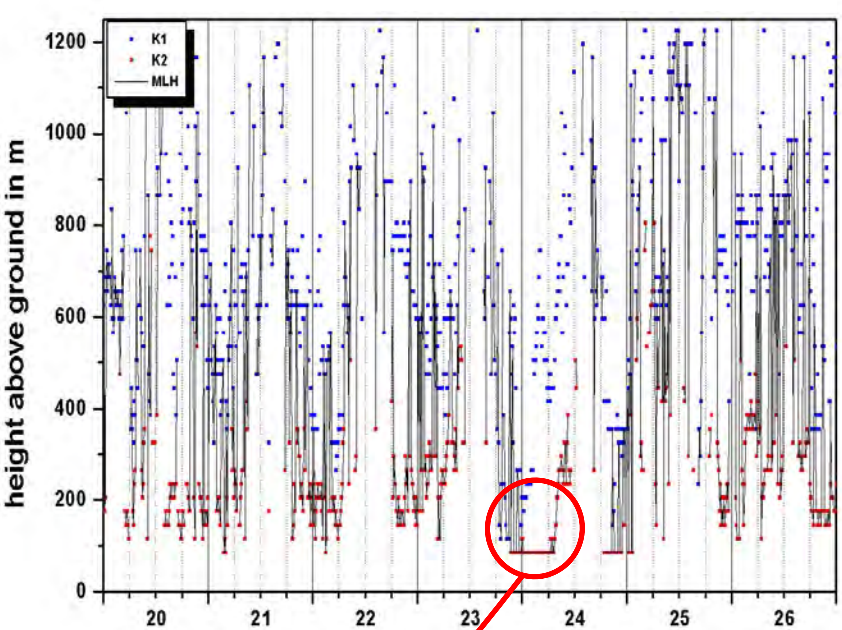
simultaneous measurement of concentration and MLH

(inverse method)

c_{CH4}

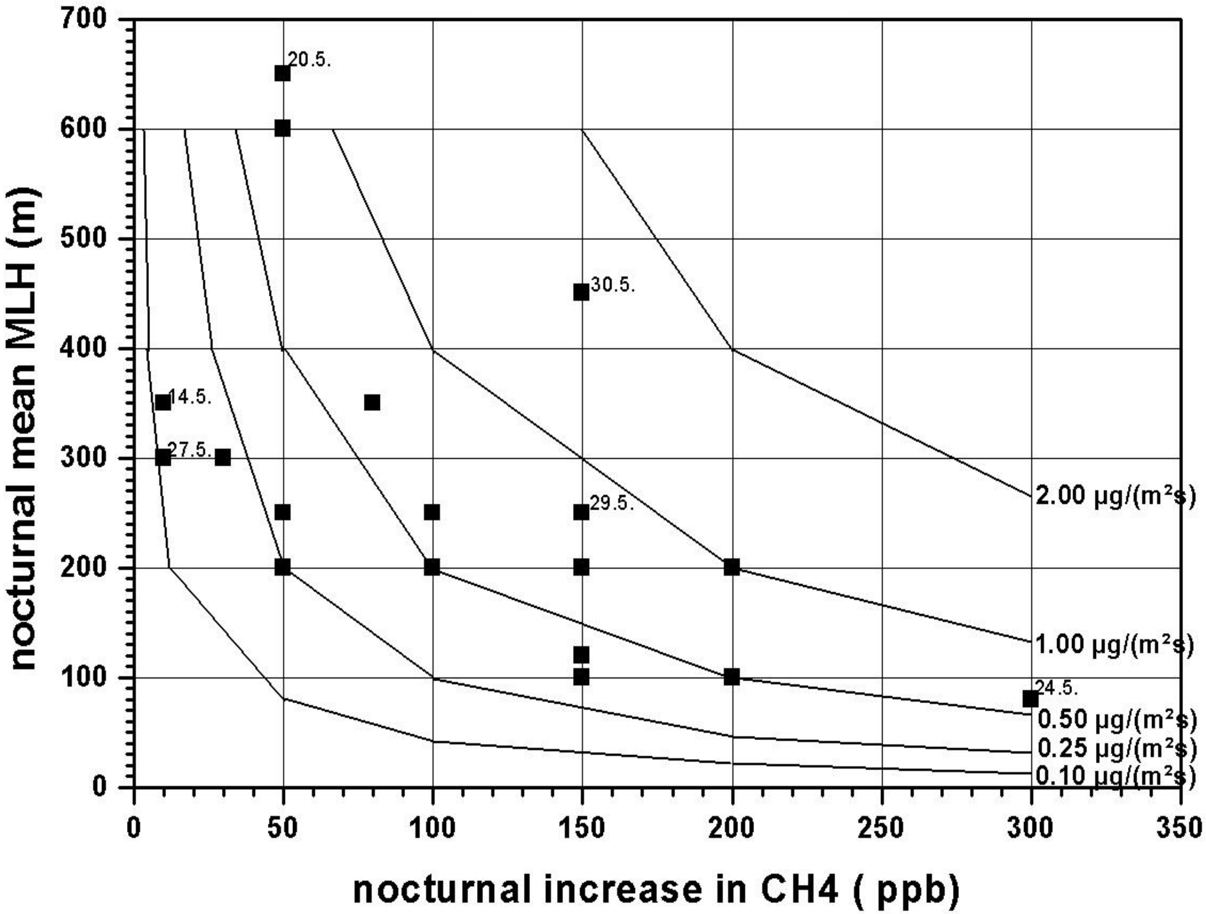


MLH



20.-26.05.2003

determination of regional $[C_{CH4}{}'w']_{surf}$ (curves) from concentration changes (x-axis) and MLH (y-axis)



determination of regional $[C_{CH4}'w']_{surf}$ (curves) from concentration changes and remotely sensed MLH

methane emissions:

typical values obtained here:

span:	0.10 to 2.00 µg/(m² s)
mean value:	0.50 µg/(m² s)

average values from national reporting (Kyoto protocol):

for entire Germany:	0.20 µg/(m² s)
among this from agriculture:	0.13 µg/(m² s)

Summary

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☺☺☺💣 **RASS** delivers temperature profiles, wind profiles are additionally available.
MLH directly from temperature profiles. LLJ from wind profiles.
Does not work properly under high wind speeds. Restricted range.

☺☺☺💣 **wind lidar** detects wind profiles, aerosol distribution and water droplets. It has to be assumed that the aerosol follows the thermal structure of the atmosphere and the wind.
MLH from aerosol backscatter, wind speed variance, LLJ from wind profiles.
Does not work properly in extreme clear (aerosol-free) air and during precipitation events and fog.

☺☺💣💣 **Ceilometer** detects aerosol distribution and water droplets. It has to be assumed that the aerosol follows the thermal structure of the atmosphere.
MLH indirectly from aerosol backscatter using a MLH algorithm.
Does not work properly in extreme clear (aerosol-free) air and during precipitation events and fog.

☺💣💣💣 **SODAR** detects wind profiles, temperature fluctuations and gradients, but no absolute temperature.
MLH indirectly from acoustic backscatter (MLH algorithm). LLJ from wind profiles.
Does not work properly under perfectly neutral stratification, with very high wind speeds, and during stronger precipitation events. Restricted range.

Literature

SODAR:

Asimakopoulos, D.N., C.G. Helmis, J. Michopoulos, 2004: Evaluation of SODAR methods for the determination of the atmospheric boundary layer mixing height. - Meteor. Atmos. Phys. 85, 85–92.

Beyrich, F., 1997: Mixing height estimation from sodar data – a critical discussion. - Atmos. Environ. 31, 3941–3953.

Ceilometer:

Schäfer, K., S.M. Emeis, A. Rauch, C. Münkel, S. Vogt, 2004: Determination of mixing-layer heights from ceilometer data. In: Remote Sensing of Clouds and the Atmosphere IX. Schäfer, K., A. Comeron, M. Carleer, R.H. Picard, N. Sifakis (Eds.), Proc. SPIE, Bellingham, WA, USA, Vol. 5571, 248–259.

Sicard, M., C. Pérez, F. Rocadenbosch, J.M. Baldasano, D. García-Vizcaino, 2006: Mixed-Layer Depth Determination in the Barcelona Coastal Area From Regular Lidar Measurements: Methods, Results and Limitations. - Bound.-Lay. Meteor. 119, 135–157.

RASS:

Engelbart, D.A.M., J. Bange, 2002: Determination of boundary-layer parameters using wind profiler/RASS and sodar/RASS in the frame of the LITFASS project. Theor. Appl. Climatol. 73, 53–65.

Emeis, S., K. Schäfer, C. Münkel, 2009: Observation of the structure of the urban boundary layer with different ceilometers and validation by RASS data. Meteorol. Z., 18, 149-154. (Open access, freely available from http://dx.doi.org/10.1127/0941-2948/2009/0365)

Emeis, S., K. Schäfer, C. Münkel, R. Friedl, P. Suppan, 2011: Evaluation of the interpretation of ceilometer data with RASS and radiosonde data. Bound.-Lay. Meteorol., online April 5, 2011. DOI: 10.1007/s10546-011-9604-6

Windlidar:

Emeis, S., M. Harris, R.M. Banta, 2007: Boundary-layer anemometry by optical remote sensing for wind energy applications. - Meteorol. Z., 16, 337-347.

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Reginal budget studies:

Emeis, S., 2008: Examples for the determination of turbulent (sub-synoptic) fluxes with inverse methods. Meteorol. Z., 17, 3-11. DOI: 10.1127/0941-2948/2008/0265

Reviews:

Emeis, S., K. Schäfer, C. Münkel, 2008: Surface-based remote sensing of the mixing-layer height – a review. - Meteorol. Z., 17, 621-630. (Open access, freely available from http://dx.doi.org/10.1127/0941-2948/2008/0312)

Books:

boundary-layer remote sensing with application examples:

Emeis, S., 2011: Surface-Based Remote Sensing of the Atmospheric Boundary Layer. Series: Atmospheric and Oceanographic Sciences Library, Vol. 40. Springer Heidelberg etc., X+174 pp. 114 illus., 57 in color., H/C. ISBN: 978-90-481-9339-4, DOI: 10.1007/978-90-481-9340-0

overview on the entire range of meteorological measurement methods:

Emeis, S., 2010: Measurement Methods in Atmospheric Sciences. In situ and remote. Series: Quantifying the Environment Vol. 1. Borntraeger Stuttgart. XIV+257 pp., 103 Figs, 28 Tab. ISBN 978-3-443-01066-9.


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Thank you very much for your attention