GROUND-BASED REMOTE SENSING OF THE BOUNDARY LAYER AND OFFSHORE WIND FARMS

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Instruments:

surface-based (land, buoys, ships, …) scanning instruments

airborne platforms: aircraft, drones

Sites:

atmospheric boundary layers in flat and complex terrain, (coastal) megacities, offshore wind farms

Topics:

internal boundary layers, boundary layer height, air quality, land-sea wind systems, low-level jets, wind resources
Warmer cities influence local and regional climate  
(Clouds over Manhattan on May 28, 2011)
Swedish offshore farm Lillgrund (Öresund) 110.4 MW
48 turbines (2.3 MW)

Coastal farm near Rødby (Denmark)
Erected and planned offshore wind farms in the North Sea

Source: http://www.4coffshore.com/offshorewind/
Measurement techniques

**in situ**
- temperature
- humidity
- wind (speed, direction, turbulence)
- pressure
- radiation (UV, SW, LW, sunshine)
- cloudiness
- precipitation (rain, snow, hail)
- visibility
- atmospheric electricity
- air quality (gases, aerosols)
- radioactivity

**remote sensing**
- temperature
- humidity (?)
- wind (speed, direction, turbulence)
- optical depth
- ceiling, cloud-top temperatures
- precipitation
- optical backscatter intensity
- air quality (gases, aerosols)
- sea surface temperature
- waves (height, speed, direction)
<table>
<thead>
<tr>
<th>Platforms</th>
<th>Characteristics/variables</th>
<th>Types of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>underground</td>
<td>soil temperature, soil moisture, surface properties, surface fluxes, 2 m height, near-surface air properties, near-surface characteristics, some meters above the sea, up to some hundred meters, up to several hundreds of metres, up to several kilometres, up to several hundred meters, floats in a given height, up to 30 km height, flexible flight track, only remote sensing</td>
<td>continuous, in-situ, continuous, in-situ, remote sensing, continuous, in-situ, continuous, in-situ, along route, continuous, in-situ, remote sensing, in-situ along seaways, continuous, in-situ, profile, in-situ along flight path, in situ along flight path, sequential profile measurements, in-situ along flight path, single profile measurement, in-situ+remote along flight path, remote sensing, path-averaged, sounding</td>
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Remote sensing of the atmosphere

LIDAR

RADAR

Wind-profiler

FTIR

MWR

log₁₀ wave number

log₁₀ wave length \( \lambda \)

log₁₀ frequency \( \nu \)

10⁶ cm⁻¹

1 cm⁻¹

10⁻⁶ cm⁻¹

1 nm

1 μm

1 mm

1 m

1 km

electromagnetic

RASS

acoustic

SODAR

clouds

aerosol

precipitation

turbulence

1 THz

1 GHz

1 MHz

1 kHz

1 Hz
SODAR

algorithms for the determination of mixing-layer height

and low-level jet observations
SODAR, acoustic backscatter, Doppler shift analysis $\rightarrow$ wind, turbulence

three antennas

phased-array
Basic principle of a phased-array sodar
monostatic SODAR: measuring principles

<table>
<thead>
<tr>
<th></th>
<th>emit</th>
<th>receive</th>
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<tbody>
<tr>
<td>height</td>
<td></td>
<td></td>
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<tr>
<td>sound travel time</td>
<td>= height</td>
<td></td>
</tr>
<tr>
<td>backscatter intensity</td>
<td>= turbulence</td>
<td></td>
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<tr>
<td>Doppler-shift</td>
<td>= wind speed</td>
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</table>

deduction:
The SODAR equation:

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

- \( P_R \): received power,
- \( P_0 \): emitted power,
- \( \varepsilon \): 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 \( 10^{-11} \text{ m}^{-1} \text{ sr}^{-1} \)),
- \( c_s \): sound speed,
- \( P_{bg} \): background noise.

Emitted power: \( \approx 10^3 \text{ W} \), received (backscattered) power: \( 10^{-15} \text{ W} \)
SODAR sample plot (daytime convective BL)

acoustic backscatter intensity

sigma w

40 – 300 m

2 days, midnight to midnight

22.01.2017
SODAR sample plot (lifted inversion)

acoustic backscatter intensity

sigma w

40 – 400 m

1 day, midnight to midnight

22.01.2017
Algorithms to detect MLH from SODAR data

Criterion 1: upper edge of high turbulence

Criterion 2: surface and lifted inversions

MLH = Min (C1, C2)

Ceilometer algorithms for the determination of mixing-layer height
Ceilometer, optical backscatter, pulsed emission, wave length ~ 0.9 µm

⇒ aerosol profiles
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:

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

- \( r \) 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

negative vertical gradient of optical backscatter intensity

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

CL31 AugsburgFH negative gradient density on 19.05.2007 in $10^{-9} \text{m}^{-1} \text{sr}^{-1}$
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 2\textsuperscript{nd} derivative)
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

LD-40 Augsburg LFU backscatter density on 19.05.2007 in 10^{-9} m^{-1} sr^{-1}

CL31 Augsburg LFU backscatter density on 19.05.2007 in 10^{-9} m^{-1} sr^{-1}
Eyjafjallajökull ash cloud over Southern Germany

RASS

principles of operation

examples
RASS, acoustic, electro-magnetic backscatter, ➔
wind and temperature profiles
RASS: frequencies

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

RASS measuring principle

detection:

- travel time of e/m/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
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)
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

Bragg-RASS

- acoustic frequ.: about 3000 Hz
- radio frequ.: 1290 MHz
- resolution: 50 m
- lowest range gate: ca. 200 m
- vertical range: 1000 m
sample RASS data: summer day potential temperature (left), horizontal wind (right)
sample RASS data: winter day
potential temperature (left), horizontal wind (right)

300 m

10°C

-10°C

-2°C
Doppler windlidar

wind, turbulence, aerosol detection, mixing-layer height, low-level jet
**Wind-LIDAR**, optical backscatter, Doppler shift analysis, wavelength ~ 1.5 µm
→ wind and aerosol profiles

range detection by moving focus

range detection by run time
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
Doppler-beam-swinging (DBS) technique (SODAR)

for the measurement of the three-dimensional wind vector

conical scanning technique (Lidar)

for the measurement of the three-dimensional wind vector
range detection by moving focus

focal range gets longer at larger ranges
The 3-d wind field above the Yatir forest on 10 Sept 2013. The colour indicates the vertical wind component. The black arrows indicate the horizontal wind component: the direction of the arrow shows the wind direction, the length of the arrow shows the wind speed.

During the afternoon hours, there is a 180°-shift in wind direction between surface and boundary-layer top which indicates a stationary circulation. Please note that this picture is not shown in local time, but in UTC (i.e. 12:00 means 14:00 Israel winter time).
valley:

w-component adds to u-component

⇒ SODAR/LIDAR measures too much wind

hill top / pass:

w-component reduces u-component

⇒ SODAR/LIDAR measures too little wind
interesting for complex terrain

three wind lidars ➞ virtual tower
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.
Options for offshore wind farms

buoys, oil rigs, satellites, …
Offshore measurements

In situ: masts

remote sensing: wind lidar on platforms
Offshore measurements

remote sensing: high-resolution wind lidar on ships

Offshore measurements

remote sensing: wind lidar on buoys (Flidar)


Satellite-based remote sensing

TerraSAR-X at a glance:

- **Size:** 4.88 metre
- **Diameter:** 2.4 metre
- **Weight:** 1 230 kilogramme
- **Payload:** ca. 400 kilogramme
- **Radar frequency:** 9.65 GigaHertz
- **Power:** 800 Watt (averaged)
- **Resolution:** 1 metre, 3 metre, 16 metre (abhängig von der Bildgröße)
- **Carrier rocket:** Dnepr 1 (former SS-18)
- **Start:** 15 Juni 2007, 4:14 GMT+2
- **Launch site:** Baikonur, Kasachstan
- **Height:** 514 kilometres
- **Inclination angle against the Equator:** 97.4 degrees (sun synchronised)
- **Life expectancy:** at least 5 years

observations day and night, also through clouds

Satellite-based remote sensing

Sentinel-1 at a glance:

Weight: 2 300 kilogramme

Radar frequency: 5.405 GigaHertz

Power: 5 900 Watt (averaged)

Resolution: 5x5 metre, 5x20 metre, 5x40 metre (depending on image size)

Start: April 2014

Orbit:

Height: 693 kilometres

Inclination angle against the Equator: 98.18 degrees (sun synchronised)

Life expectancy: at least 12 years

https://sentinel.esa.int/web/sentinel/missions/sentinel-1/overview
Satellite-based remote Sensing

Sentinel-1 revisit frequency (two satellites)

https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/revisit-and-coverage
Satellite-based remote sensing

Synthetic Aperture

extensive computer processing of subsequent data allows for an artificial aperture of up to 15 km
Satellite-based remote sensing

SAR images – basic principle of speed measurement

- Smooth sea surface: no return
- Capillary waves on sea surface: best return on Bragg condition

https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/instruments/sar/applications/radar-courses/content-2/-/asset_publisher/qIBc6NYRXfnG/content/radar-course-2-bragg-scattering
Satellite-based remote sensing

wind speed fields at 10 m height in the German Bight from SAR data for three different weather situations

Satellite-based remote sensing

Inversion procedure

SAR data $\rightarrow$ Normalised radar cross-section (NRCS)

$\rightarrow$ Geophysical Model Function (GMF)

$\rightarrow$ $u_{10}$ as function of wind direction, antenna view angle, incident angle

SAR-Bild (TERRA-X) von Horns Rev, 16.2.2012

(c) DLR 2012
TerraSar-X
Alpha Ventus 12. August 2012, 05:51 UTC
North Sea
3 Juni 2015, 17:16 UTC

http://www.ofw-online.de/projekte/nordseekarte.html
Offshore: Wind profile depending on SST – air temperature difference

- Temperature
- Wind speed
- Water temperature
- Wind direction

Winds blowing offshore

Graph showing data from 18:00:00 to 12:00:00 after 26.10.2005, 12 a.m.
offshore: humidity profile contributes to unstable stratification (FINO1 41.5 m data for turb. heat and humidity fluxes)

Source: RAVE-Project TUFFO, Richard Foreman
**Aircraft measurements** Four flight campaigns, two in spring and two in autumn are scheduled in order to assess the extension and characteristics of wind farm wake far fields.

The DO 128 of the Technical University of Braunschweig

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**Far wake flight pattern**

Instrumentation of the nose boom:
- temperature
- humidity
- turbulence (5 hole probe)
Newly started research project WIPAFF (WInd PArk Far Fields)

11.2015 – 02.2019

5 Partners: KIT, Institute of Meteorology and Climate Research
Technical University of Braunschweig
Helmholtz Centre Geesthacht
UL International GmbH (ex: DEWI)
University of Tübingen

Aircraft (Do 128) observations in the wakes
Analysis of satellite SAR data of wakes
Mesoscale wind field modelling with WRF (wave model, park parametrisation)
Adjustment of analytic and industrial wind park models

assessment of impact on regional climate
Impact on regional climate
cloud formation, modification of precipitation patterns
modification of sun shine duration
modification of wind fields
...
airborne measurement system at IMK-IFU: drone (hexacopter)

→ see afternoon lecture
Thank You for your attention