Workshop 2: Study of structural and foundation systems of Wind Turbines

Acoustic and seismic measurements of low frequency emissions of onshore wind turbines

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Patras, Greece – 01.10.2021

Wind farm Wilstedt, Germany

1) Motivation

The expansion of renewable energy usage is one of the major social tasks in Europe and therefore requires acceptance and support from the population.

Source:
Mark Ellis/flickr

Is this acceptable?

1) Motivation – Tremor & Acoustics (TremAc)

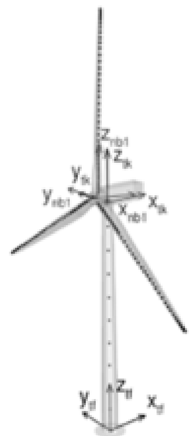
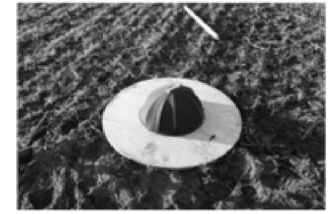
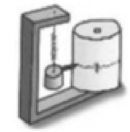


Abb.: [1]

Development of models for the simulation of emissions, acoustic noise propagation and vibrations

Validation of models through seismic and acoustic measurements





Objective criteria for seismic and acoustic emissions of onshore wind turbines

Environmental health and psychological interviews

Focus on low-frequency signals (< 150 Hz), especially infrasonic range (< 20 Hz)

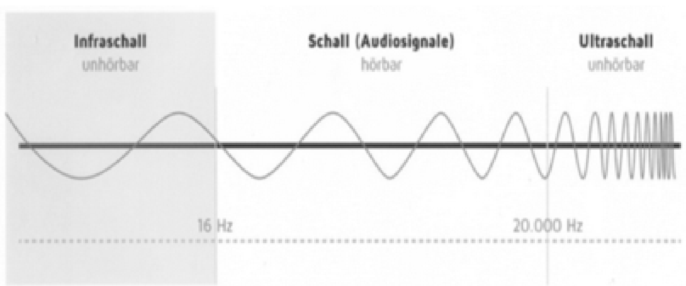


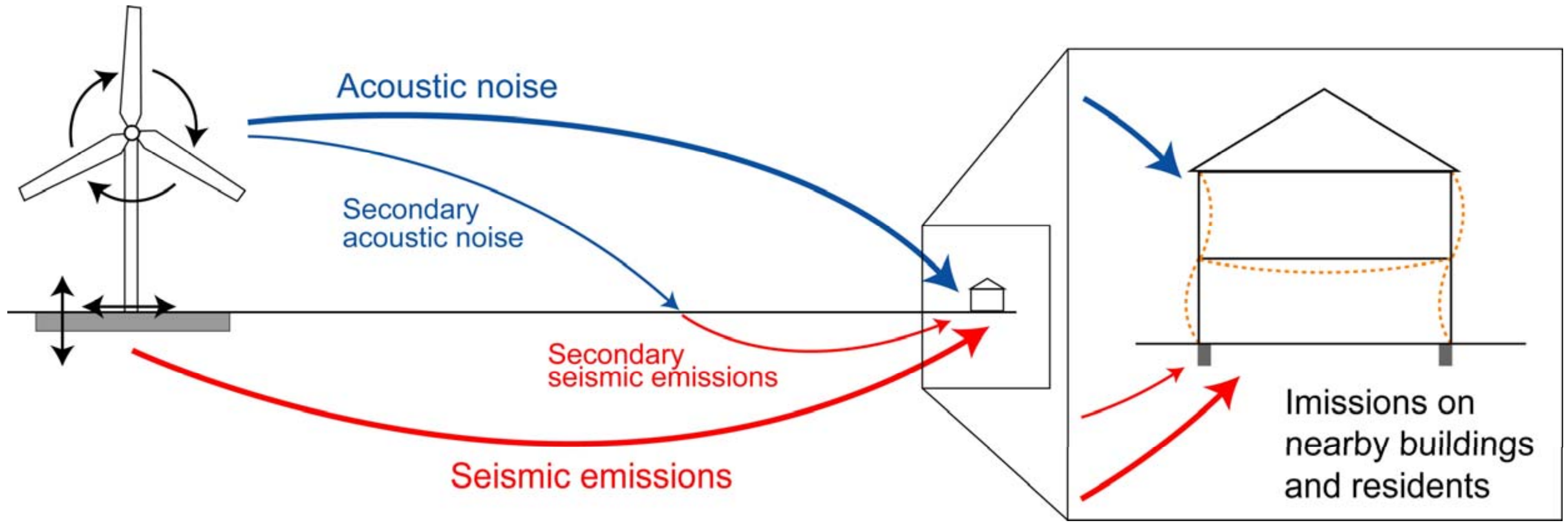
Abb.: https://www.alarm4you.de/infraschall/

1) Motivation - Measurement part of the project

- **What is to be investigated?**
  Transmission of vibrations from wind turbines to buildings, transmission paths soil and air as well as their interaction.

- **How?**
  Long-term measurements with measuring points in the vicinity of nearby buildings.

- **Why long-term measurements?**
  Wind conditions are subjected to strong fluctuations, depending on weather and time of day. Recording of representative data through a longer measurement period is required. Disturbances due to vibrations from the environment (traffic, machines, etc.).



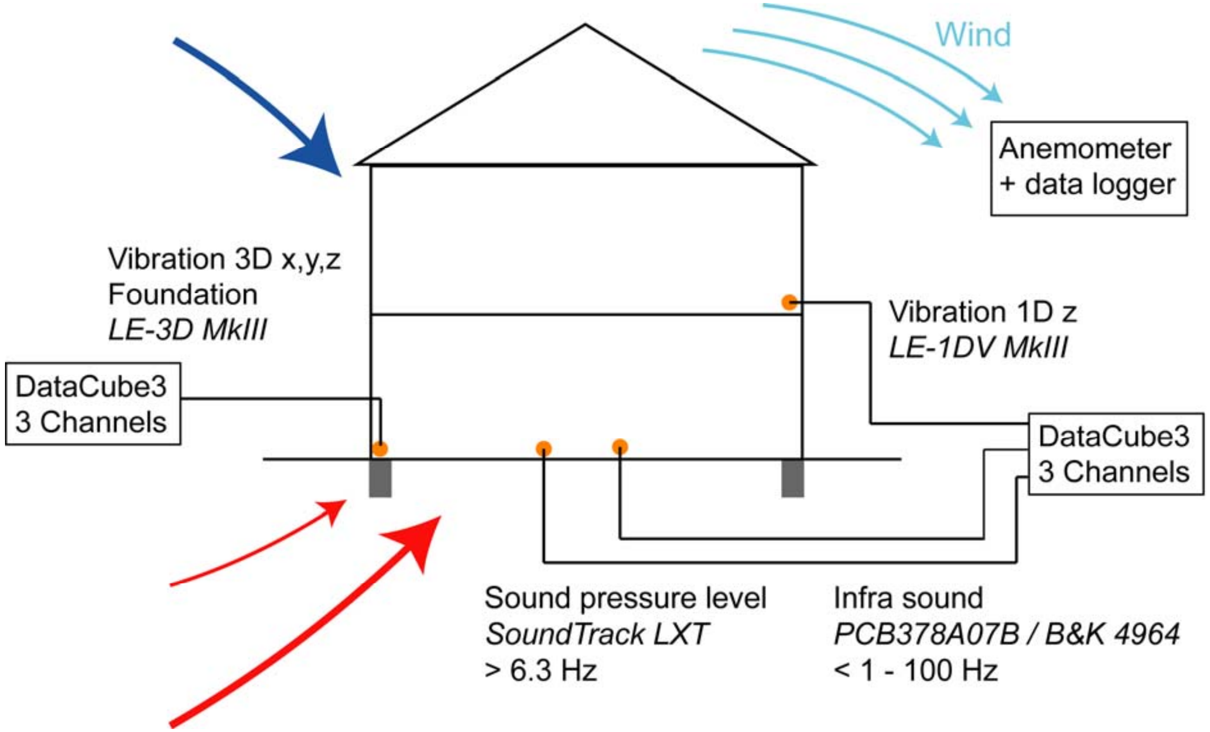
- **What is measured?**
  Time series of vibrations and low-frequency airborne sound (< 1 - 100 Hz) as well as unweighted third-octave SPL curve over time.

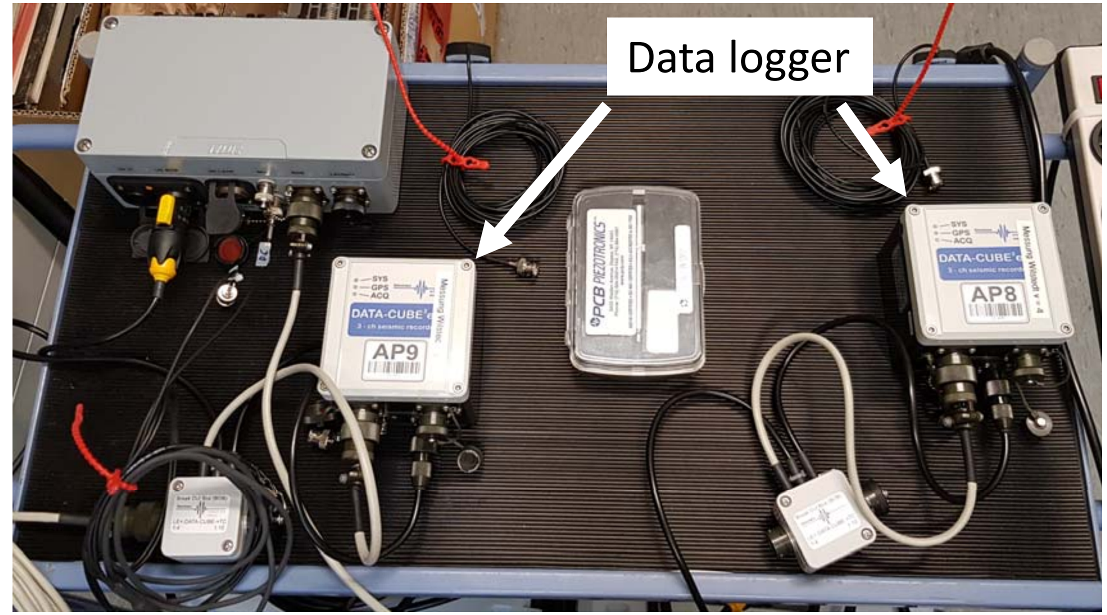
- **What infrastructure is needed?**
  Free view for GPS, continuous access for check-ups, power supply for measuring instruments.

Content

- ~~1) Motivation~~
- 2) Measurement technology and measurement setup
- 3) Execution of measurements
- 4) Evaluation of measurement results
- 5) Summary

2) Measuring concept





Acoustic sensors

Seismic sensors

2) Measurement technology

- **Infrasound microphones**

  PCB 378A07: Sensitivity: 5.8 mV/Pa
  Frequency Range (± 1 dB): 0.25 to 10 kHz

  Brüel & Kjær 4964: Sensitivity: 50.0 mV/Pa
  Frequency Range (± 1 dB): 0.04 to 10 kHz

- **Sound level meter**

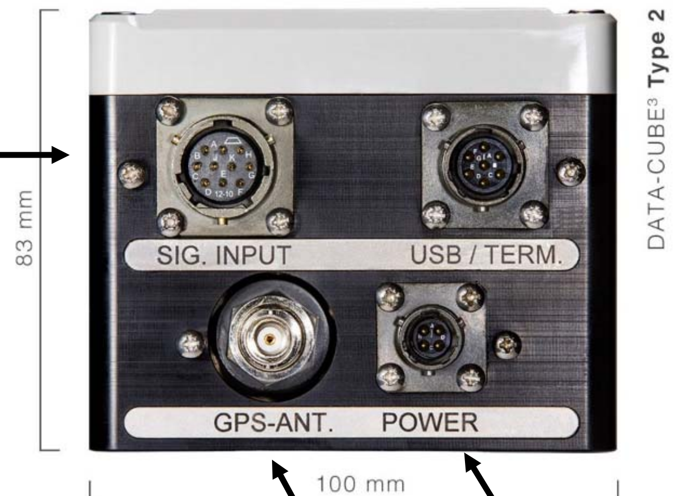
  Larson Davis SoundTrack LxT: Open Circuit Sensitivity: 50 mV/Pa
  Frequency Range (± 1 dB): 5 to 10 kHz

- **Seismometer**

  Lennartz LE-1DV MkIII: Eigenperiod: 1 s
  Upper limiting frequency: 100 Hz
  Transmission factor: 800 V/(m/s)

  Lennartz LE-3Dlite MkIII: As above

2) Data acquisition



Break-Out-Box (BOB)
Voltage divider
(1/4, 1/10)

GPS antenna

PSU

DATASHEET 02-17

DATA-CUBE³

SEISMIC DATA RECORDER – DEVELOPED FOR REAL FIELD APPLICATIONS

TECHNICAL SPECIFICATION

A/D converter	
Type	Delta-Sigma 24 Bit
ADC resolution	24 bit per channel
ADC channels	3
ADC dynamic range	125dB @100sps (128dB @50sps)
Effective resolution	22.4bit @100sps @ gain 1 (typical)
ADC sample rates	50, 100, 200 or 400sps in 3 channel mode 800sps in 1 channel mode
ADC gain selection	1, 2, 4, 8, 16, 32, 64
ADC noise level	10µV/√HZ
Full scale input	4,096Vpp @ gain 1
Input impedance	100kOhm
Signal input voltage	Adjusted by customized breakout box according to sensor specification

Time base	
Type	GPS synchronized free running internal quartz
GPS	GPS receiver built-in
GPS accuracy	1µs
GPS antenna	Internal or external GPS antenna versions available External version is delivered with 3-5m GPS antenna cable
Free running accuracy	<10ms for 20 days without processing <0.01ms with processing (resampling)

Data storage	
Storage type	SDHC memory card (internal)
Capacity	Up to 32GB (ca. 280 days @100sps)
Recording type	Continuous recording
Recording format	Raw (miniSEED & SEG-Y offline converter software included)

Local user interfaces	
Serial port	Monitoring, additional sensor modules
USB 2.0	Configuration, setup, data download (16MB/s)
LEDs	Indicating status of system, acquisition, GPS timing and data storage

Connectors	
Sensor	MIL-C-2684 A12-10S
Power/Communication	MIL-C-2684 A10-07P
Power	Type 2: MIL-C-2684 A08-04P
GPS antenna	Type 1 e/a: SMA (female) or BNC (female) Type 2: BNC (female)

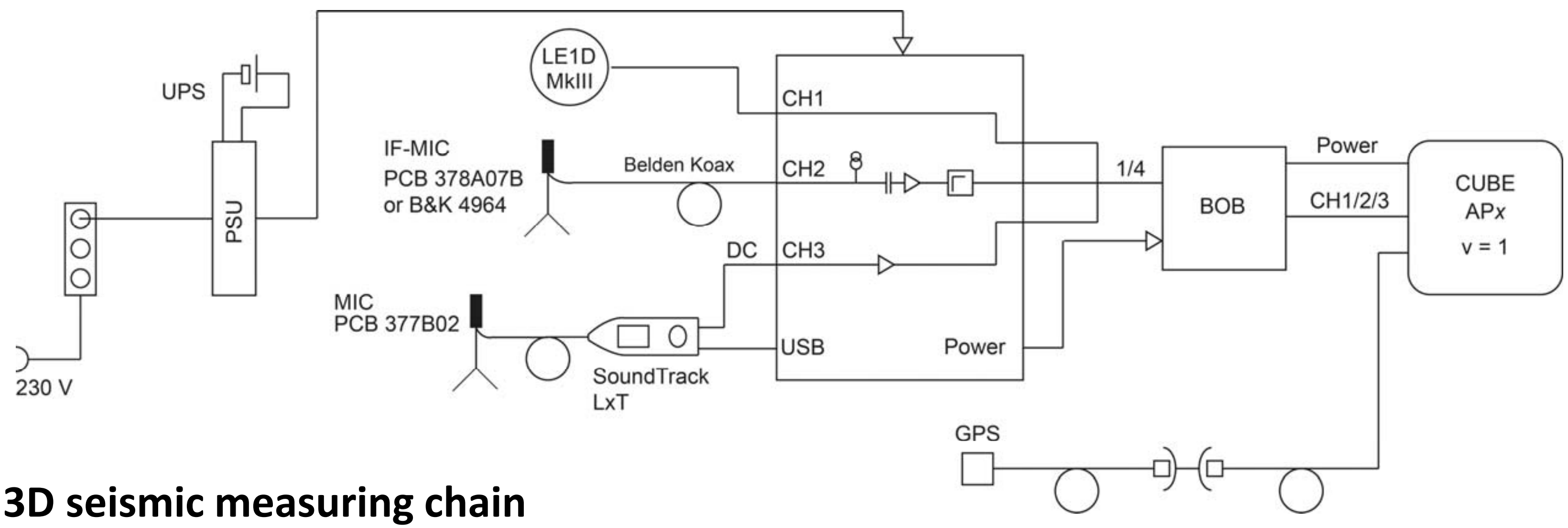
Power supply	
Input voltage	5-24V DC
Battery	Type 1: internal & external Type 2: external only
Power consumption	120mW with internal GPS antenna 197mW with external GPS antenna for vault installations (rated for 100sps & GPS active 5min per 30min)

Physical	
Size	100 x 100 x 83mm (830ml)
Weight	890g with internal GPS antenna 850g with external GPS antenna
Operating outdoor temperature	-20 - 70°C Lower temperature versions available
Housing	Reinforced plastic
Shock resilience	5g (sinus)
Waterproof	IP67 (1m water depth for 48h)
Transportation	Optional: Rugged aluminium transport box for up to 12 DATA-CUBEs for easy handling & deployment in the field.

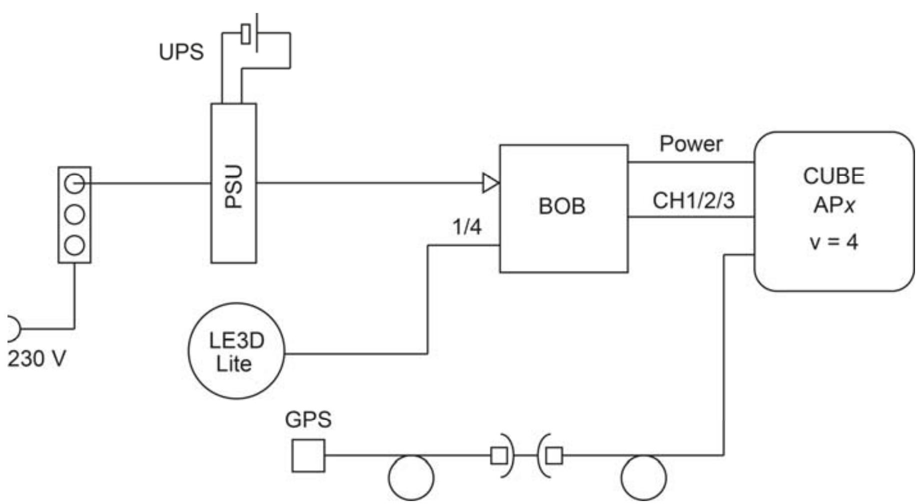
Specifications are subject to change without notice.

2) Measurement setup

- **Combined acoustic and seismic measuring chain**

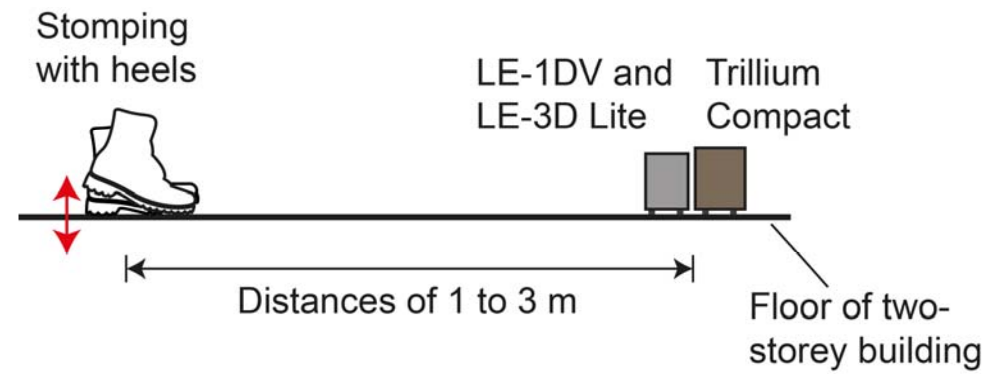


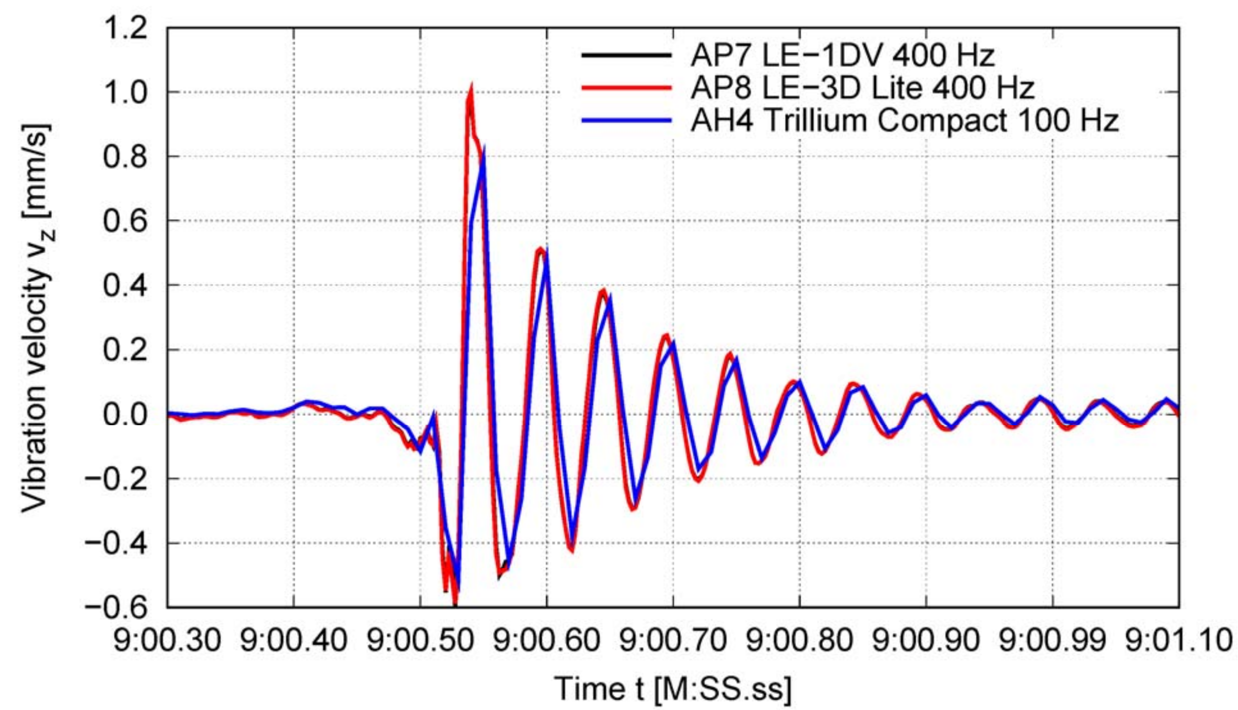
- **3D seismic measuring chain**



2) Conduction of pretests

- Different tests in- and outside of buildings were performed together with our project partners of Geophysical Institute of KIT (GPI) to prove the measured magnitude of vibration velocity and time synchronization
- The results show good accordance of the vibration signals in vertical and horizontal direction, taken into account the different seismometers and slower sampling rate of GPI





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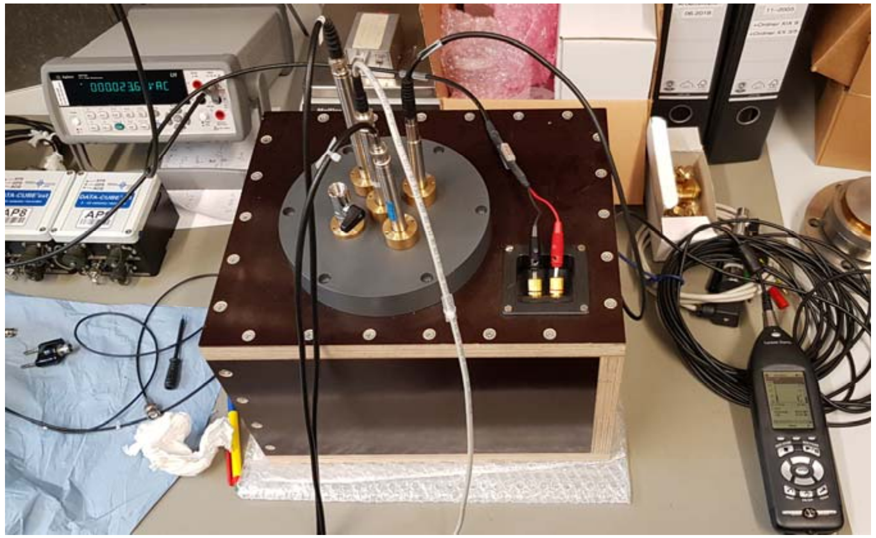
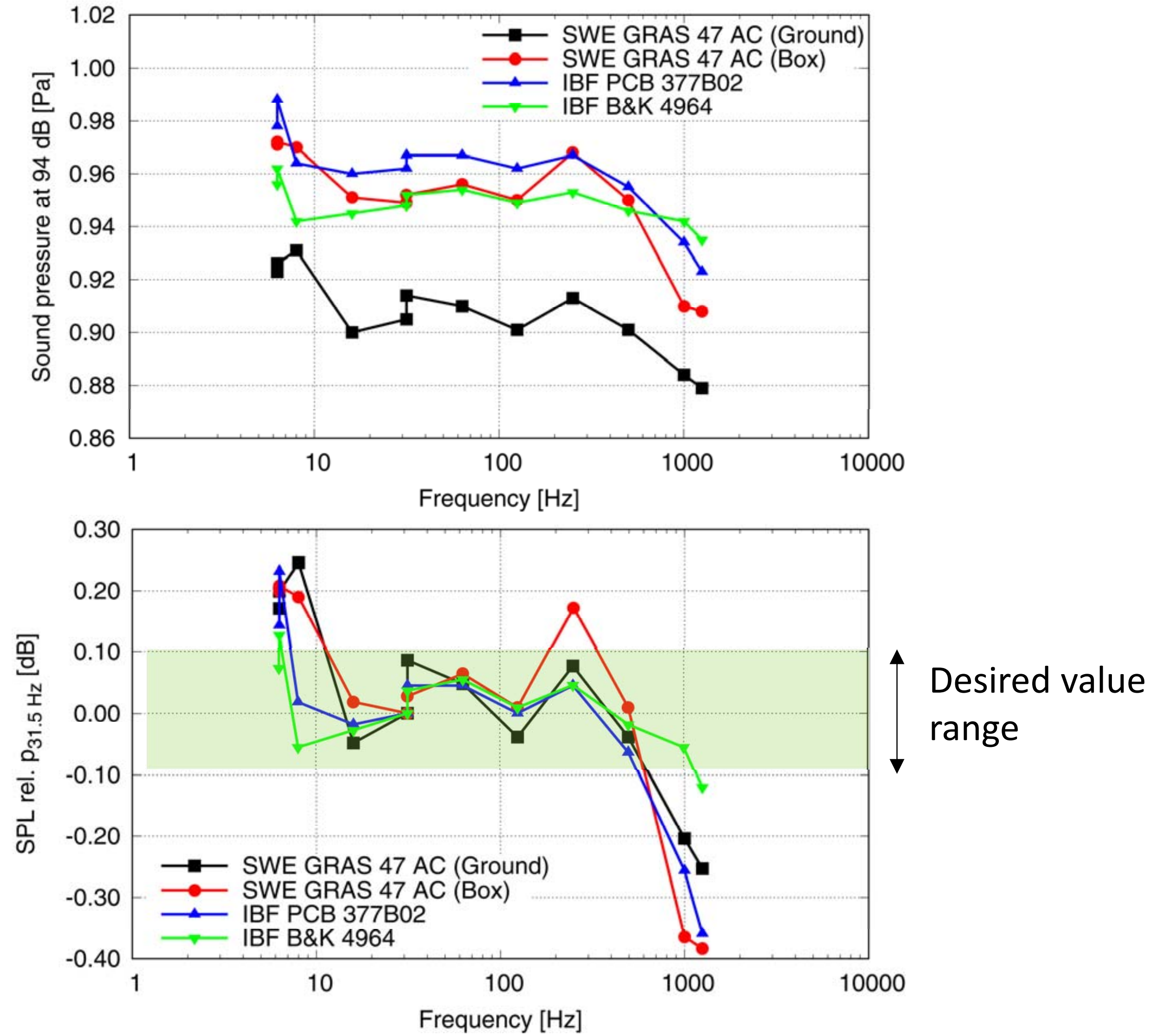
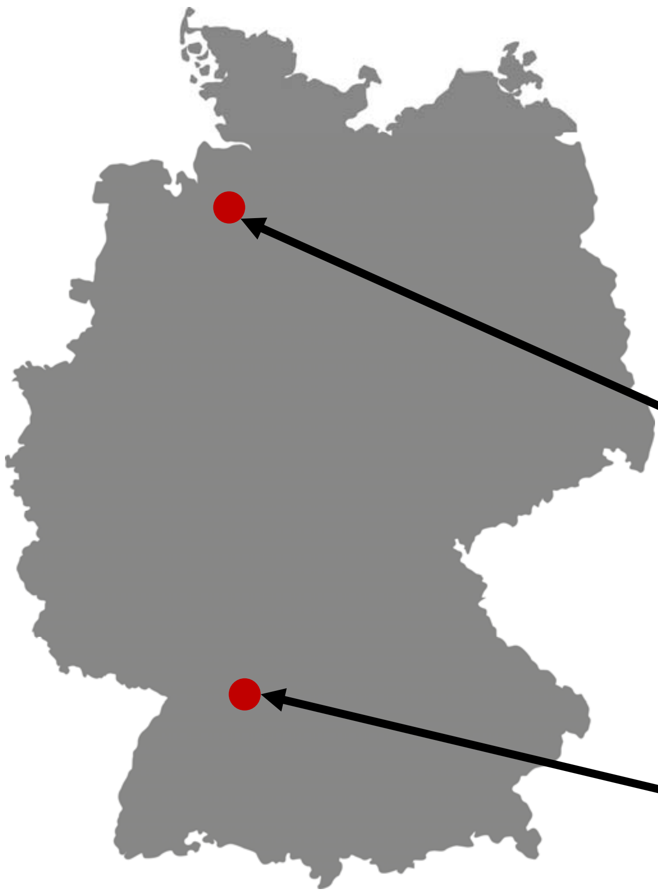




- In-house calibration of infrasound microphones (used by IBF and SWE) using a self-built calibration box. Sound pressure meter (SoundTrack LxT) at 94 dB as reference between 6.3 Hz and 1250 Hz.

3) Measurement locations

- Two possible areas of investigation were chosen during the beginning phase of TremAc project
- Residents of the villages were asked to participate in the measuring part of the project by making available space for the measurement setup inside their buildings



Wilstedt

- Flat topology
- Loosely bedded sands, partly peat soil
- Wind farm consisting of 9 WT

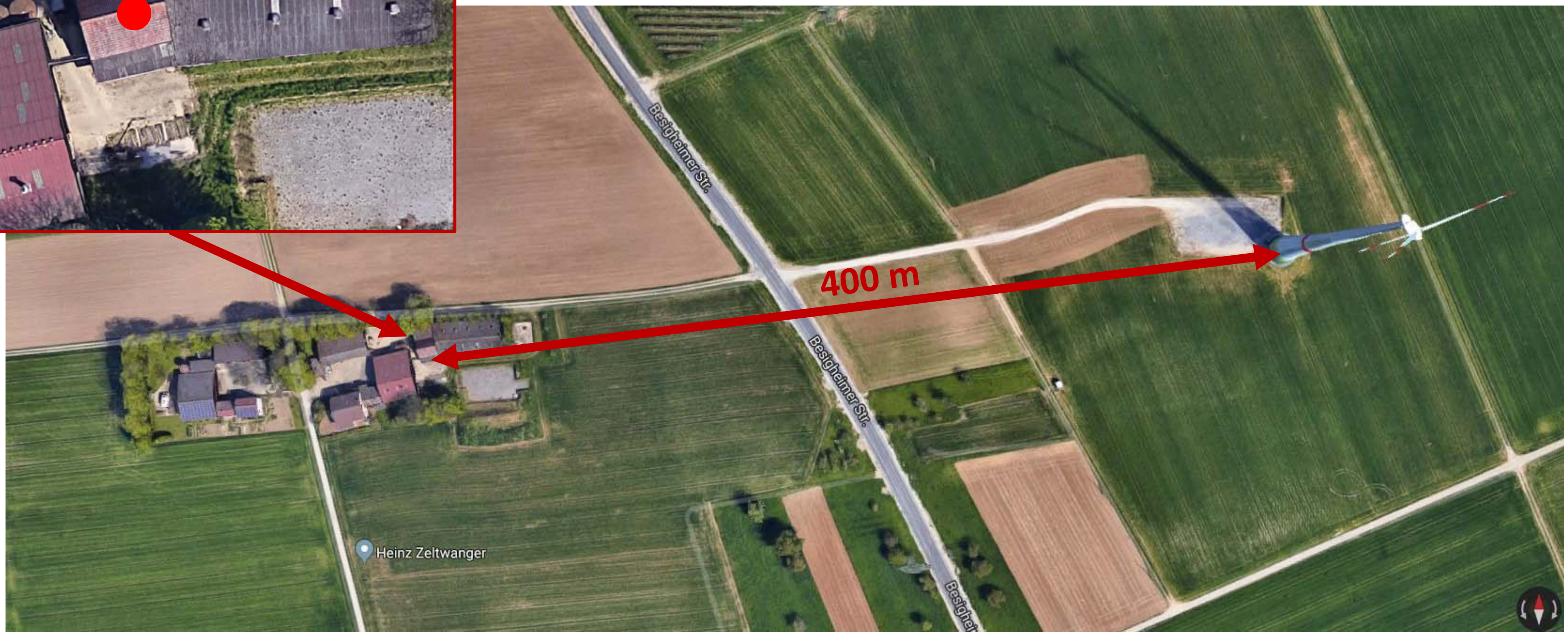
Ingersheim

- Hilly topology
- Thin soil layer on limestone
- Only one WT

3) Measurement locations near WT Ingersheim

3) Measurement locations near WT Ingersheim

An unused barn (9 m x 7.6 m, height approx. 8 m) in wooden construction method was available as an installation site in Ingersheim.



3) Measurement locations near WT Ingersheim

- Measurement setup is weather-protected in the barn and low-frequency sound can be registered nearly unhindered by the open construction method.

3) Measurement locations near wind farm Wilstedt

- **Location 1:**
  Single-family house in solid construction, two-storey, partly with basement. Combined acoustic/ seismic measurement in the entrance area of the building as well as seismic measurement in the basement.
- **Location 2:**
  Former horse stable in wooden construction with paved ground

3) Measurement locations near wind farm Wilstedt

Location 2

- **Setup:**
  Arrangement of B&K infrasound microphone and LxT sound level meter near the ground (sound pressure tends to be highest) and LE-1DV seismometer between.
  LE-3D Lite seismometer near the foundation at the edge

3) Measurement periods

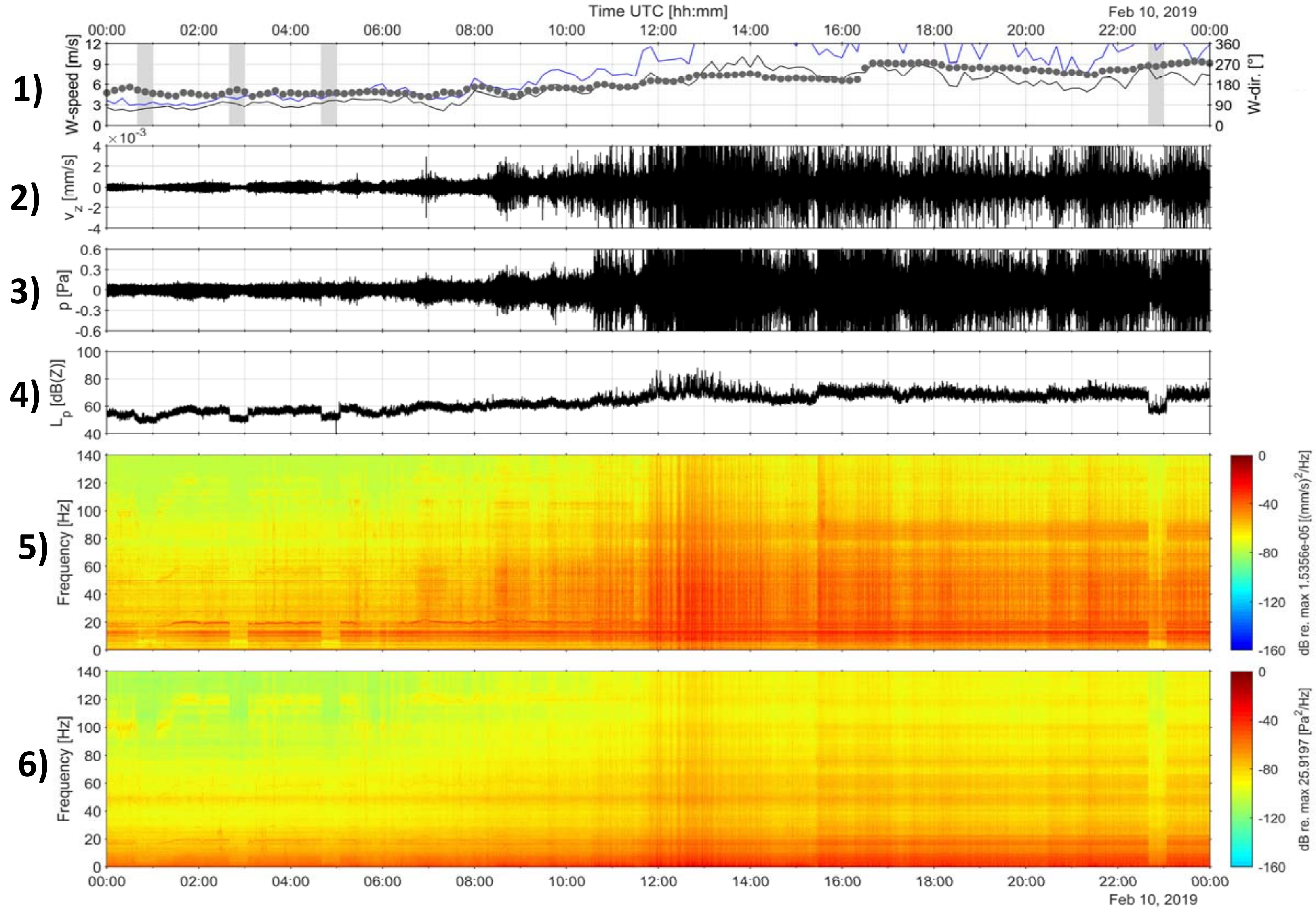
Area	Location	Setup	Time period
WT Ingersheim	Location 1	LE-1DV, PCB 378A07, CUBE AP7	13.08.2018 – 31.08.2018
		LE-3D Lite, CUBE AP9	13.08.2018 – 31.08.2018
		LE-1DV, B&K 4764, CUBE AP9	09.02.2019 – 11.03.2019
		LE-3D Lite, CUBE AP8	09.02.2019 – 11.03.2019
	Location 2	LE-3D Lite, CUBE AP8	13.08.2018 – 31.08.2018
		LE-1DV, PCB 378A07, CUBE AP7	07.09.2018 – 19.09.2018
		LE-3D Lite, CUBE AP7	10.02.2019 – 19.02.2019
		LE-3D Lite (CH1), PCB 378A07, CUBE AP7	20.02.2019 – 11.03.2019
Wind farm Wilstedt	Location 1	LE-1DV, B&K 4764, CUBE AP9	27.11.2018 – 05.12.2018
		LE-3D Lite, CUBE AP8	27.11.2018 – 05.12.2018
	Location 2	LE-1DV, B&K 4764, CUBE AP9	07.12.2018 – 30.12.2018
		LE-3D Lite, CUBE AP8	07.12.2018 – 30.12.2018

- **Evaluation:**
  Large amounts of measurement data had to be evaluated. Events with high acoustic or seismic noise level were picked based on time series and time-variant spectra.
- **WT standstill:**
  Fixed time periods with standstill of the WT during day- and nighttime were essential for the direct association of acoustic and seismic emissions with WT operation

4) Evaluation of results – WT Ingersheim

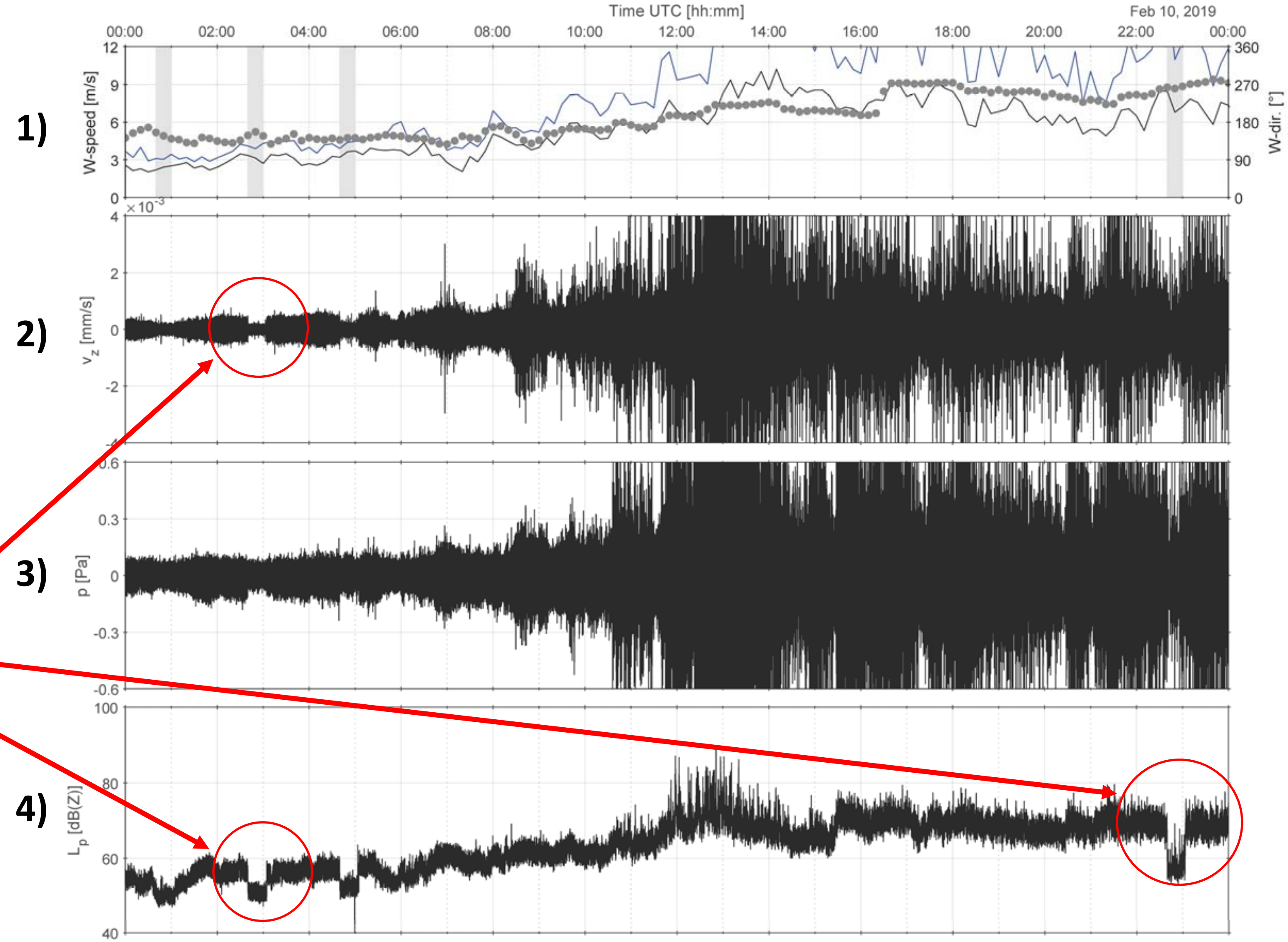
- **1)** Wind speed (max/mean) and wind direction of nearby agricultural weather station; Grey bands mark WT standstill periods
- **2-4)** Time series of vertical vibration velocity (LE-1DV), sound pressure (B&K 4964) and SPL (SoundTrack LxT)
- **5-6)** Time variant Power-Spectral-Density (PSD) of vibration velocity and sound pressure

  dt = 1/400 s, F = 200 Hz, T = 10 s,
  N = T/dt = 4000; Hanning-Window
  Recording per day
  (24 x 60 x 60 / 10 = 8640 spectra/day;
  No overlap, no averaging
  Shown log. intensity relative to max. value



4) Evaluation of results – WT Ingersheim

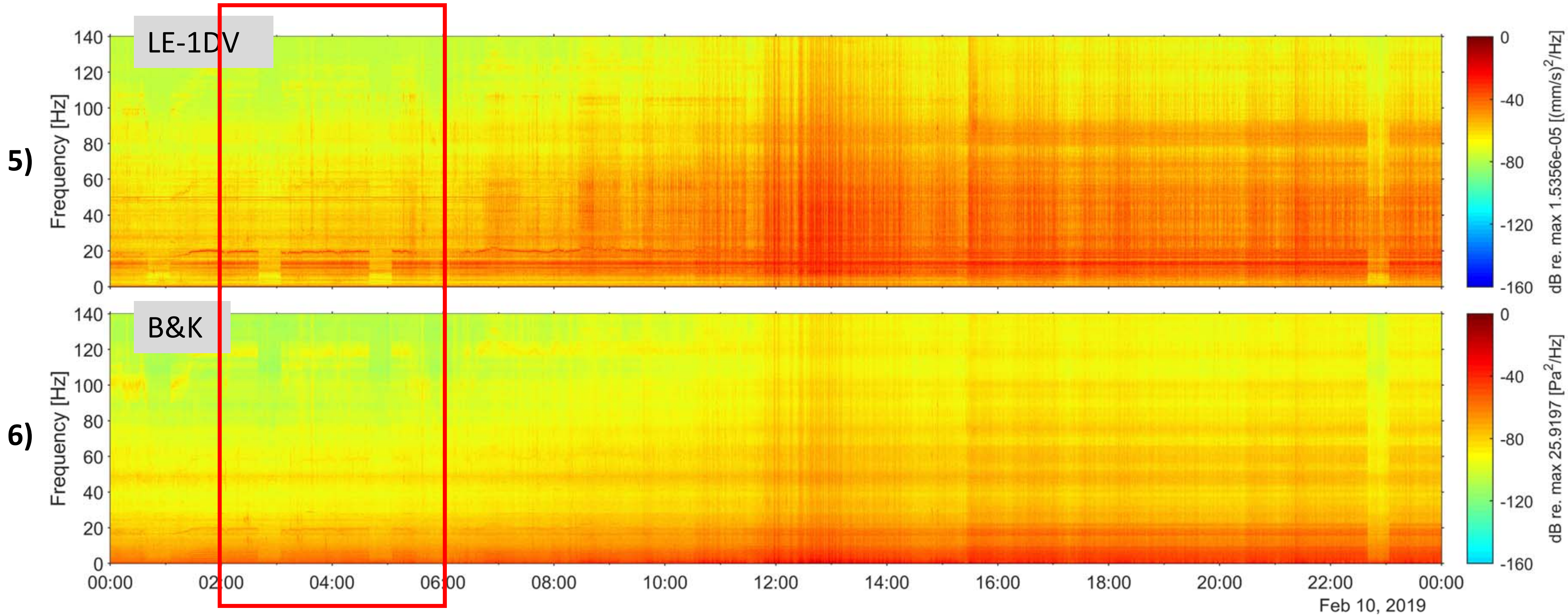
- Switch-off times with LE-1D, LE-3D and SoundTrack LxT well recognizable
- Tendencies of reduced sound pressures recognizable with B&K infrasound microphone during WT standstill
- Due to surrounding noise sources no clear association with WT operation possible during daytime



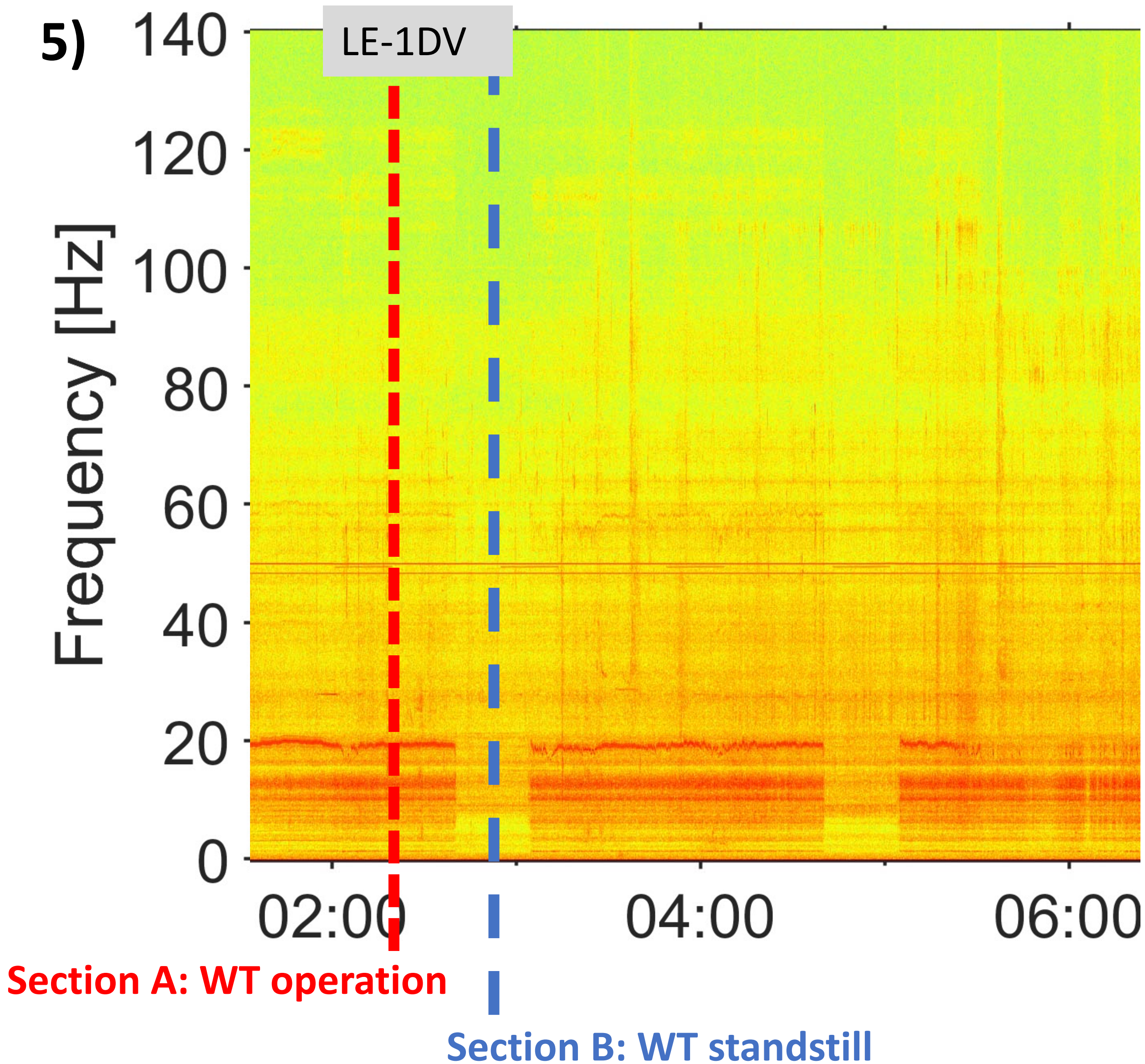
Reduction of magnitude

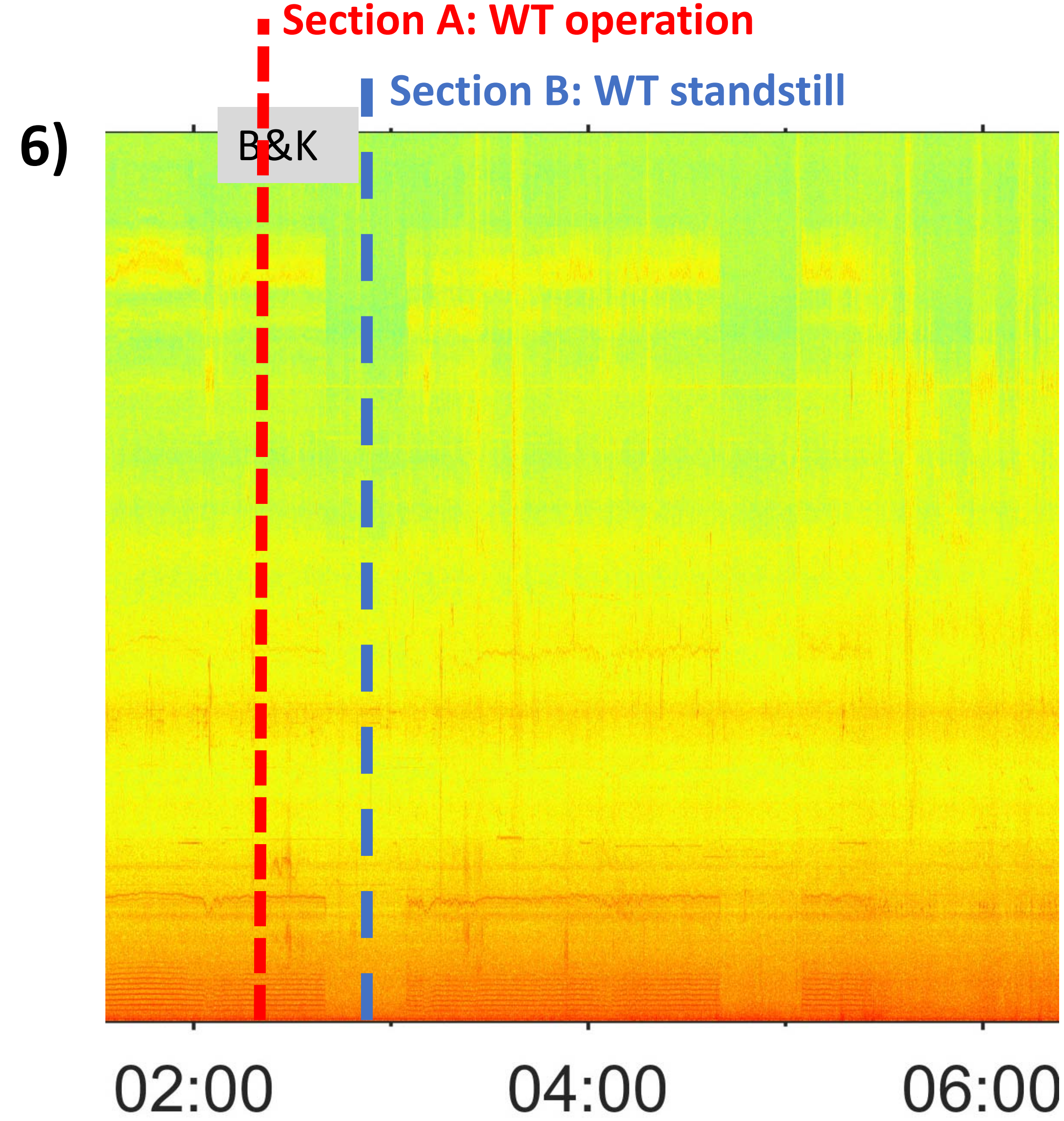
4) Evaluation of results – WT Ingersheim

- Noticeable pattern can be identified with spectrograms in seismic and acoustic signals



4) Evaluation of results – WT Ingersheim





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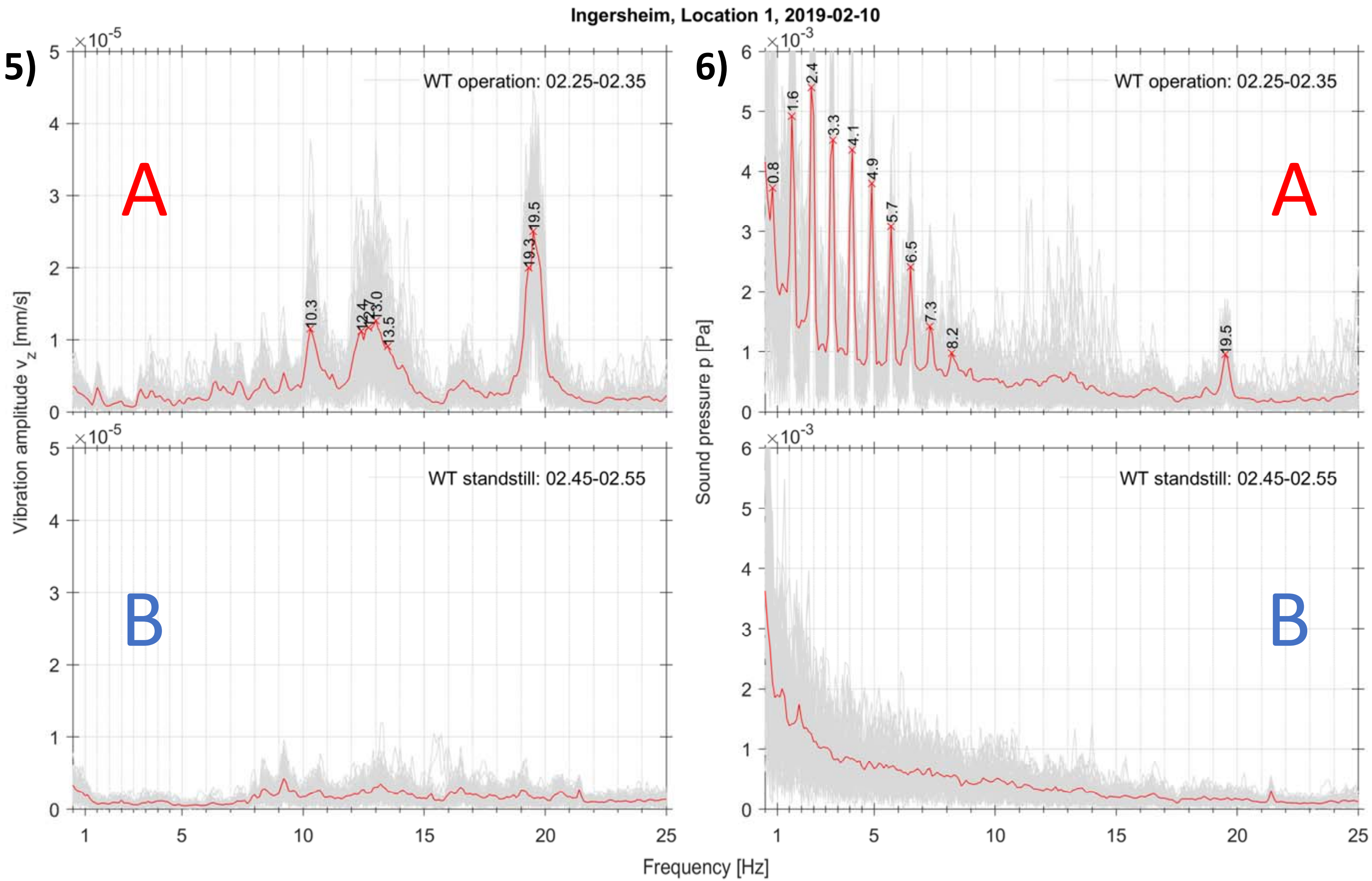
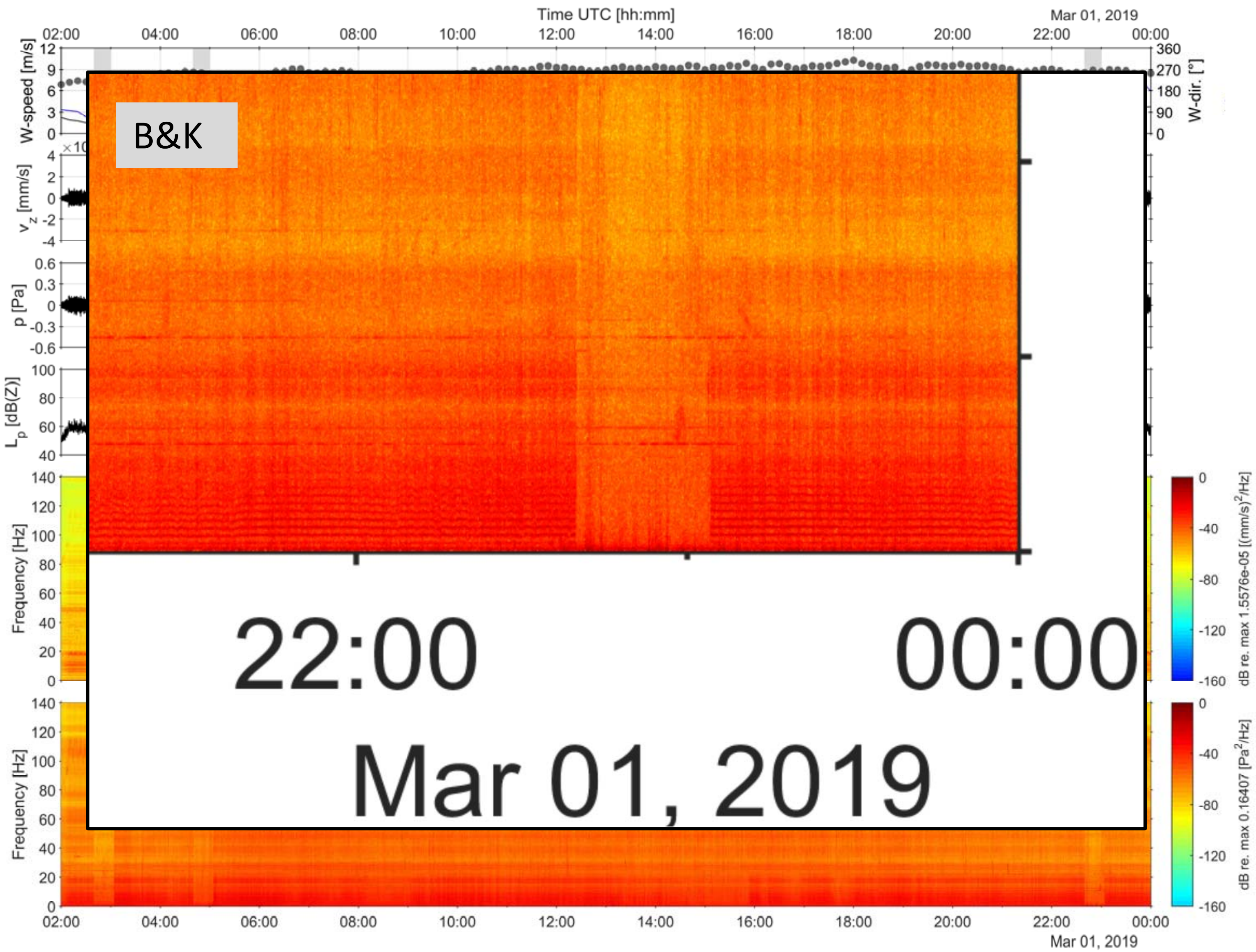


→ Mean values of time variant 10 s spectra over 10 min period during operation and standstill of WT

- Seismic signals with highest intensity at f = 19.5 Hz; further peaks at 10.3, 13.0 Hz and between 1.0 and 10 Hz (low intensity)
- Sharp peaks in the acoustic signal for Blade-Passing-Frequency (BPF): f = 0.8 Hz and its multiples 1.6, 2.4, 3.3, 4.1, 4.9 Hz etc. Also components with 19.5 Hz
- **Amplitude spectra show characteristic low-frequency components of seismic and acoustic noise by WT**

4) Evaluation of results – WT Ingersheim

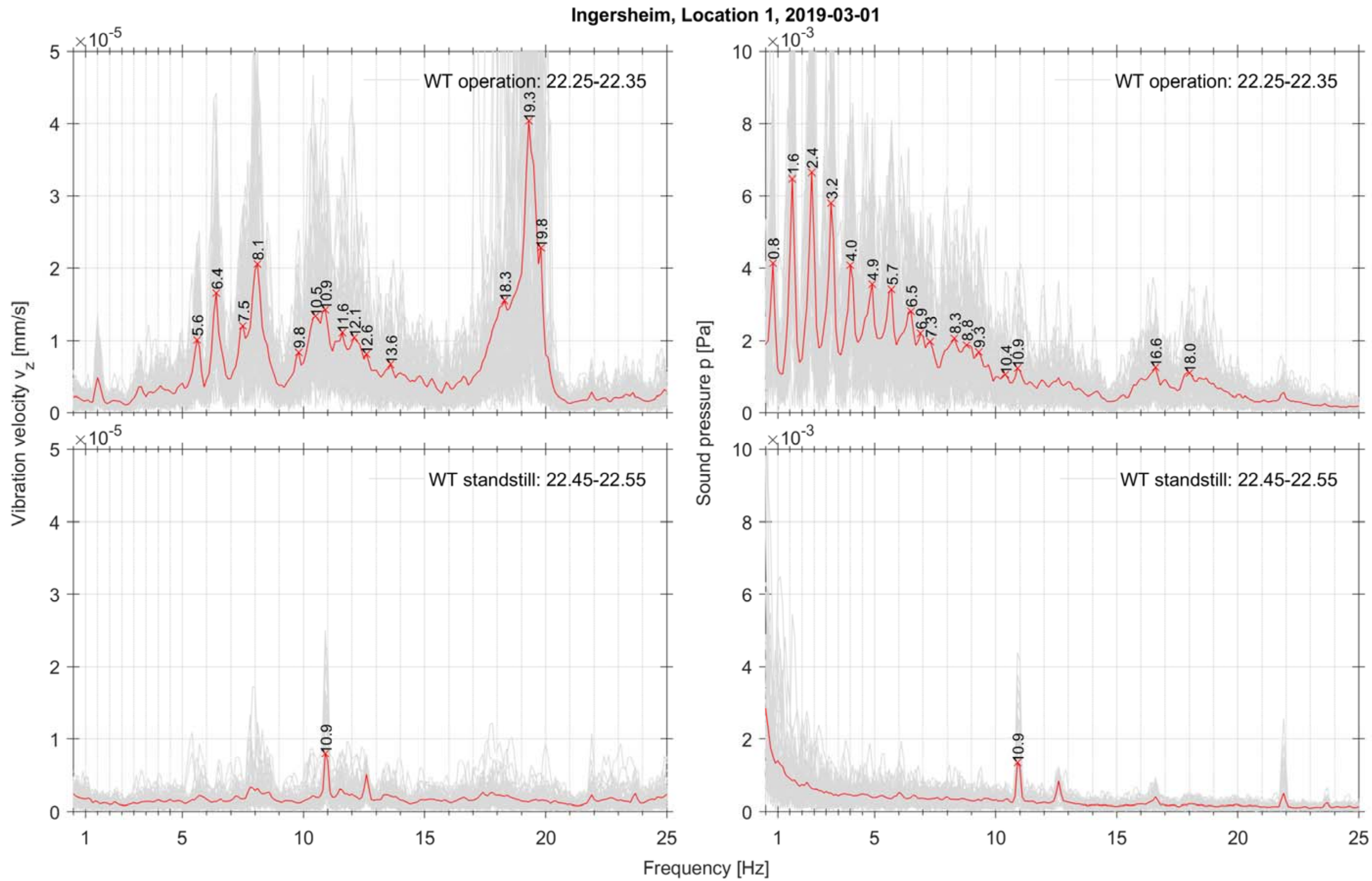


→ Location 1 in Ingersheim, 0.4 km distance to WT

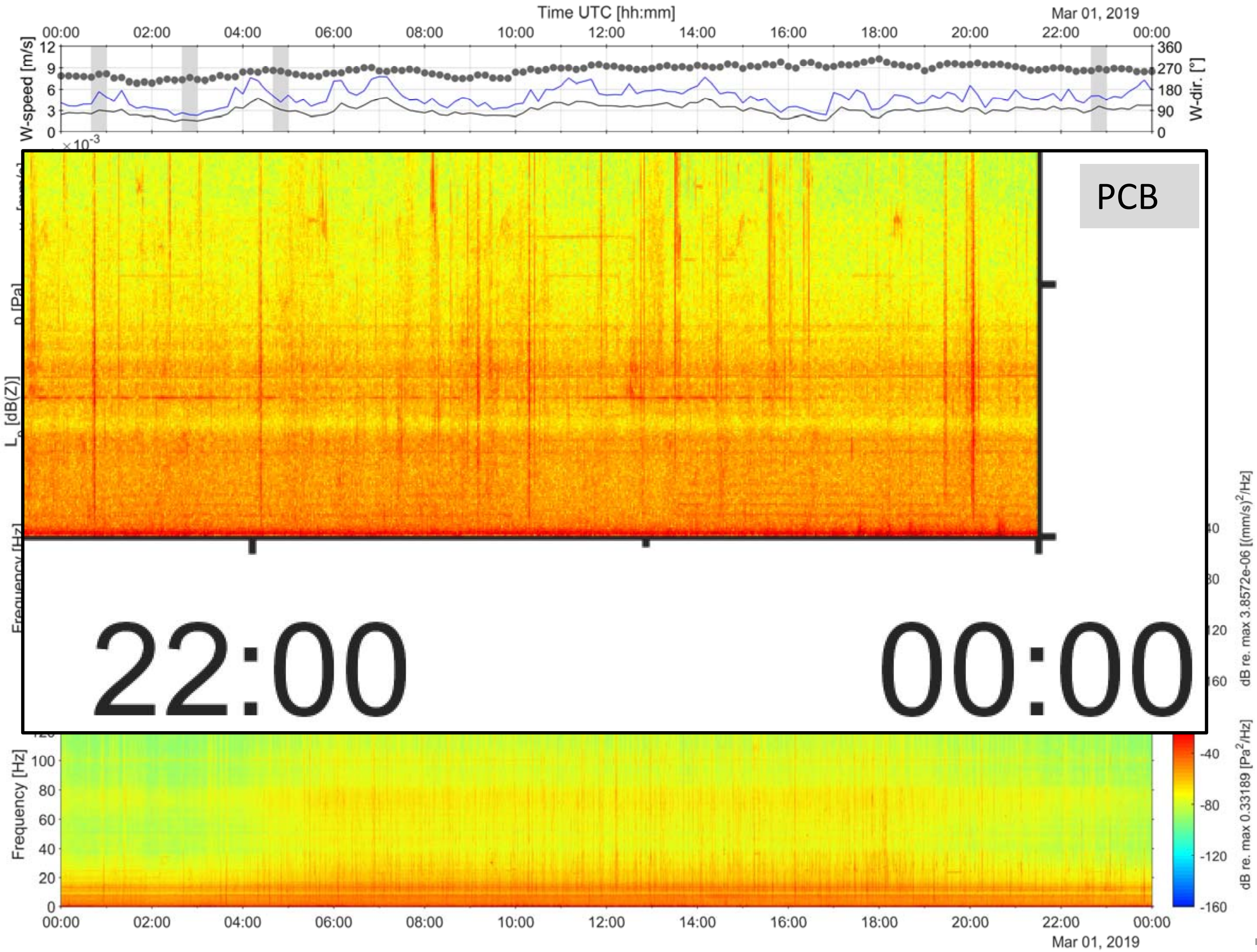
- Switch-off times are clearly visible in time domain and PSD spectra of acoustic or seismic signals
- Characteristic thin lines are observed in the PSD plot of B&K infrasound microphone

4) Evaluation of results – WT Ingersheim

- As expected, high intensity of seismic emissions with around 19.3 Hz, upper harmonic frequencies of BPF (5.6, 6.4 Hz) are also significant
- Beside the emissions caused by the blade passing of the tower there are several other sources for emissions (i.e. power train noise)
- Differentiation between secondary and primary acoustic/seismic noise is not possible without further investigations



4) Evaluation of results – WT Ingersheim

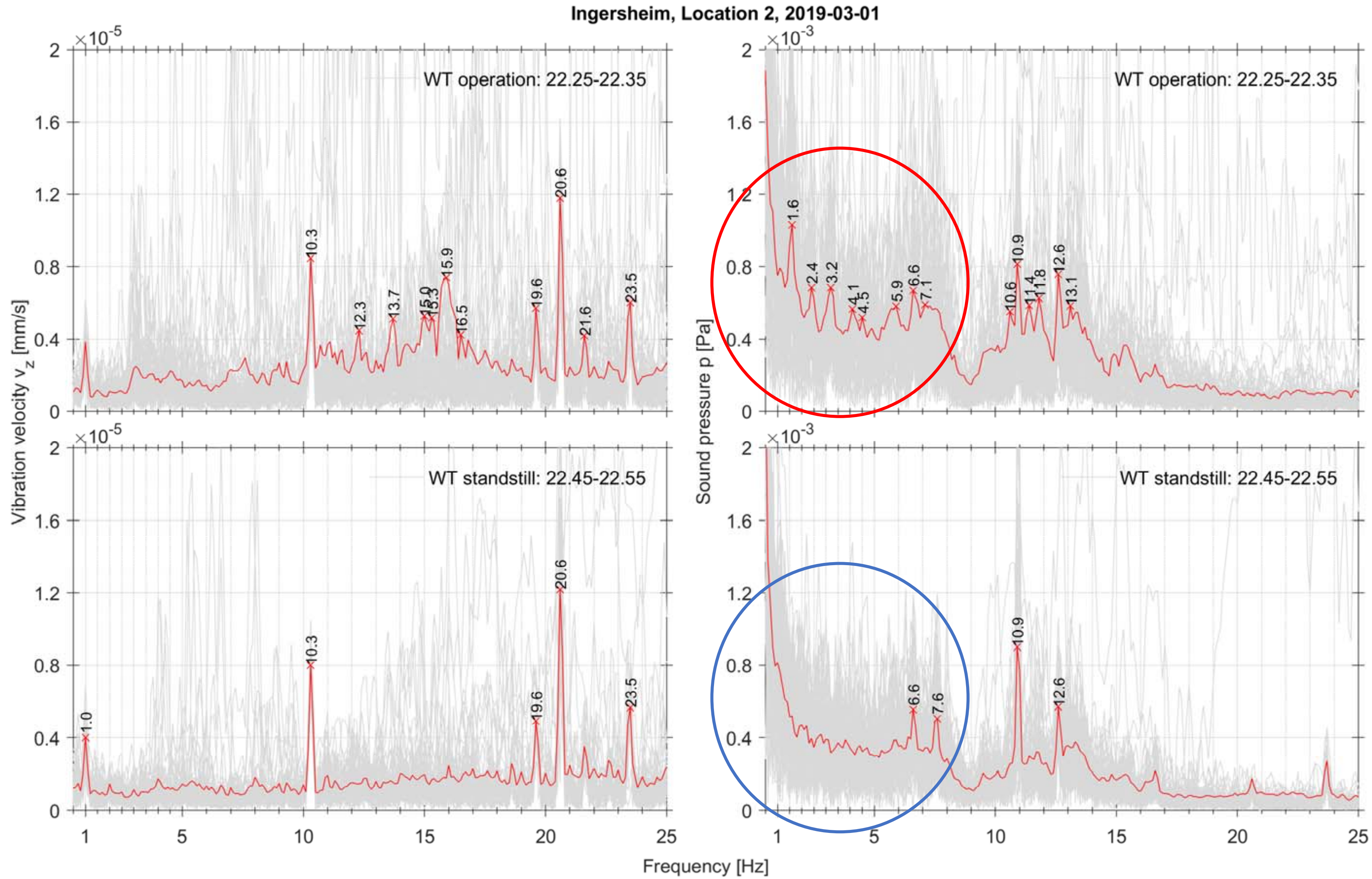


→ Location 2 in Ingersheim, 2.4 km distance to WT, forest in between

- Switch-off times are not visible in time domain or PSD spectra (at first glance) of acoustic or seismic signals
- Seismic signals overlapped by not yet identified disturbances (10.3 Hz plus multiples)
- Characteristic thin lines are observed in the PSD plot of PCB infrasound microphone, but only for small time periods

4) Evaluation of results – WT Ingersheim

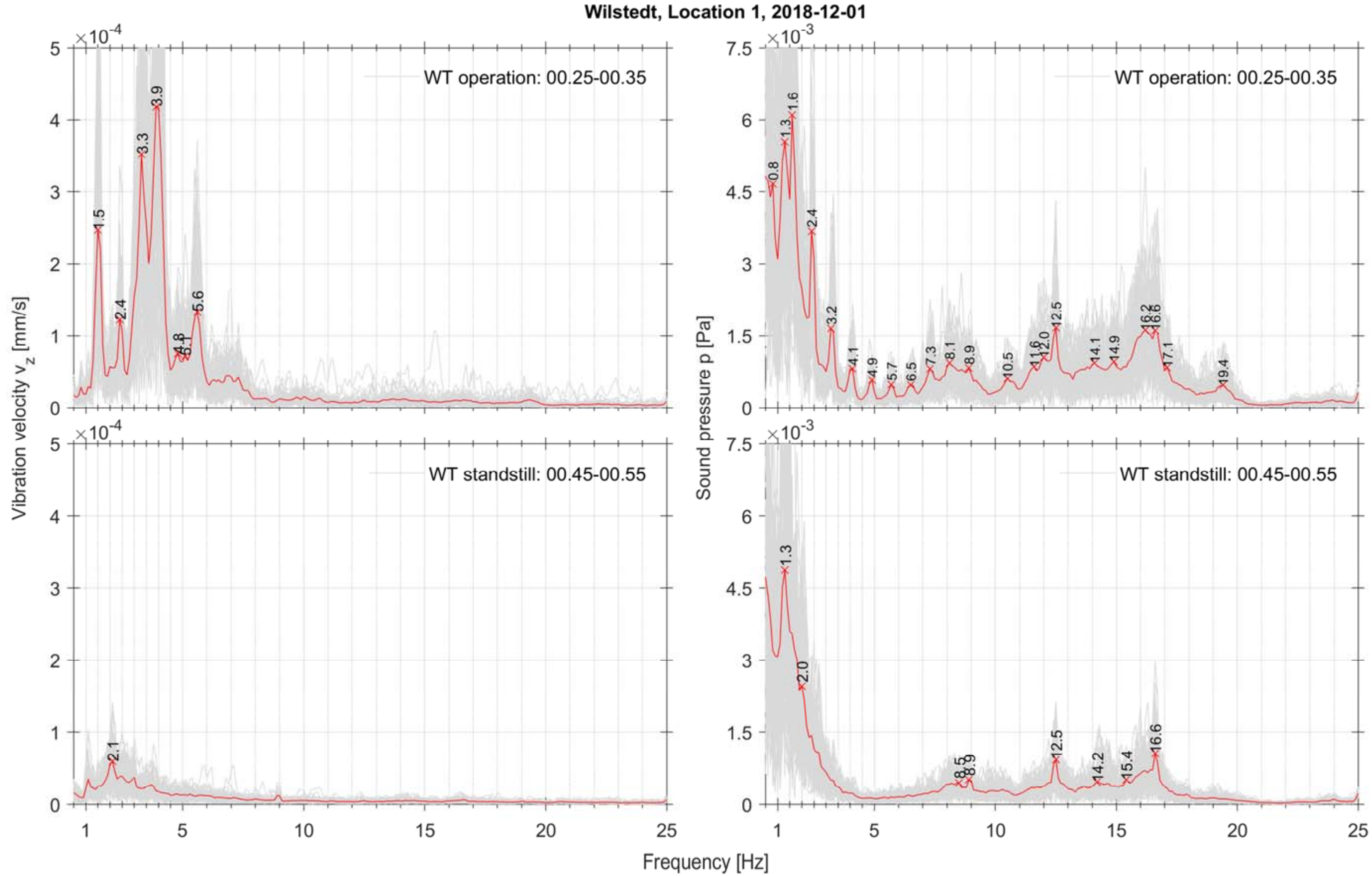
- Peaks at harmonic frequencies of BPF (1.6, 2.4, 3.2 Hz, etc.) are visible in the acoustic spectrum for WT operation; Compared to Location 1 the intensity is low (factor 5)
- Seismic signals with frequencies between around 12.3 and 16.5 Hz are missing during WT stillstand; Though the signal is overlapped by disturbances
- Out of the measurement results it is not clear why the residents of Location 2 near Ingersheim feel heavily annoyed by assumpted "WT noise"



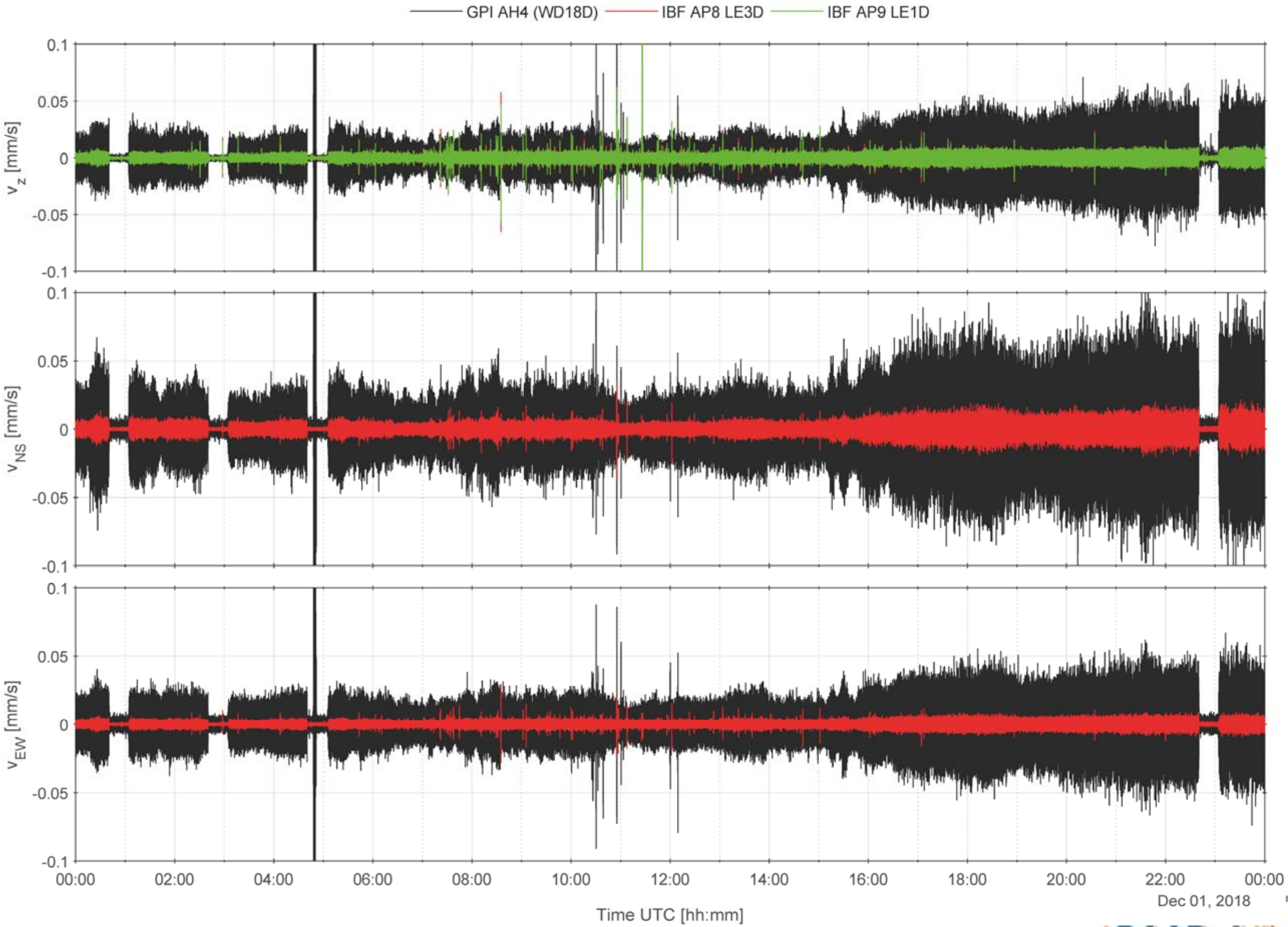
4) Evaluation of results – Wind farm Wilstedt

→ Now measurements in larger distance, more WT, different soil

- Seismic emissions with higher frequencies (> 10 Hz) nearly completely damped; Harmonic frequencies of BPF dominant
- Overall intensity of seismic signals: $5 \cdot 10^{-4}$ mm/s compared to $5 \cdot 10^{-5}$ mm/s in Ingersheim; Sound pressures are alike
- Emissions of other WT (not included in the wind farm) as well as nearby biogas plants overlap the signals

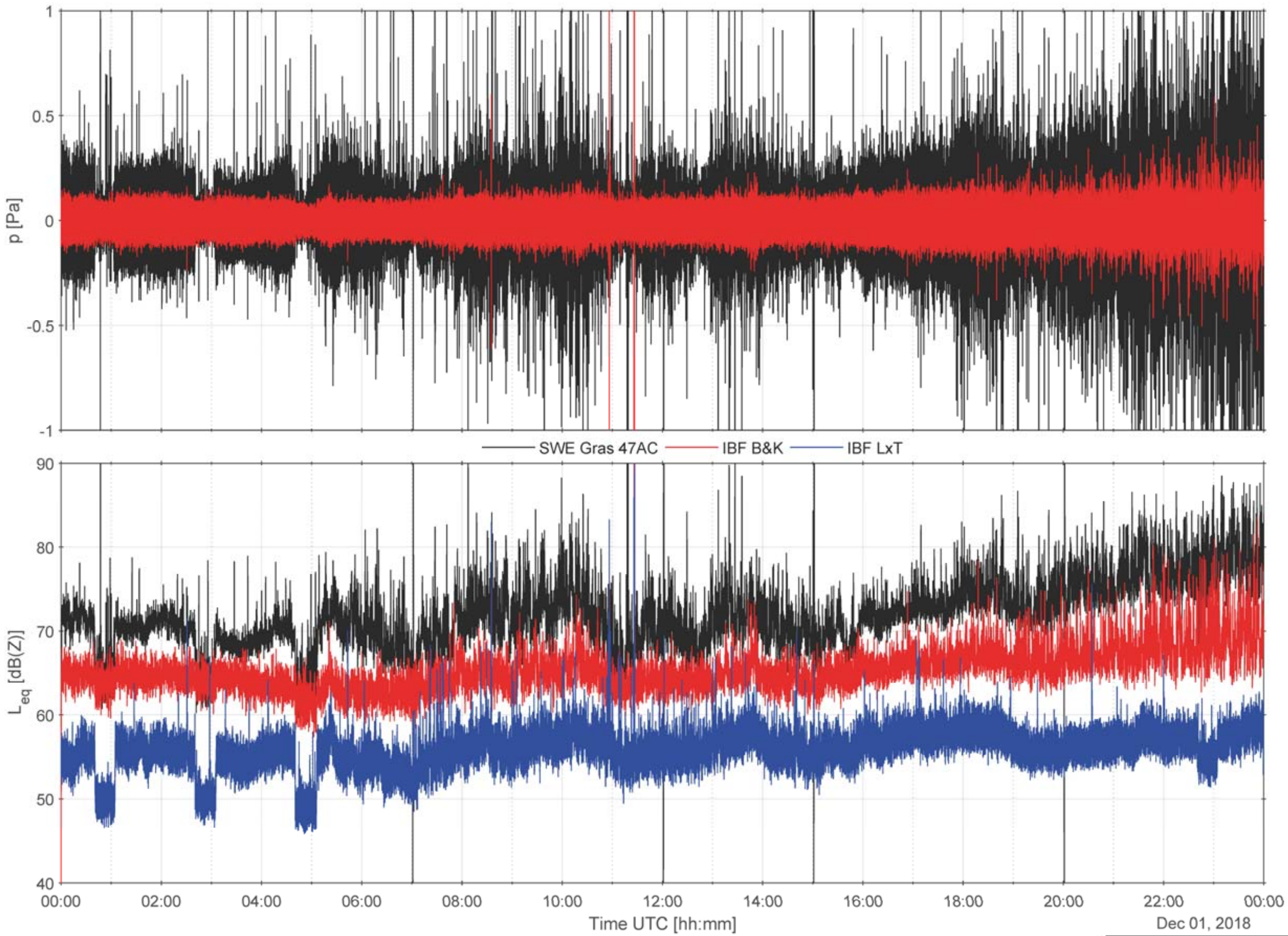


4) Evaluation of results – Wind farm Wilstedt



- Comparison of seismic signals measured by IBF (inside building, 1.5 km) and GPI (field, < 0.5 km):
  - Good accordance; Switch-off times clearly visible
- Horizontal components of vibration velocity partly with higher intensity than vertical component

4) Evaluation of results – Wind farm Wilstedt



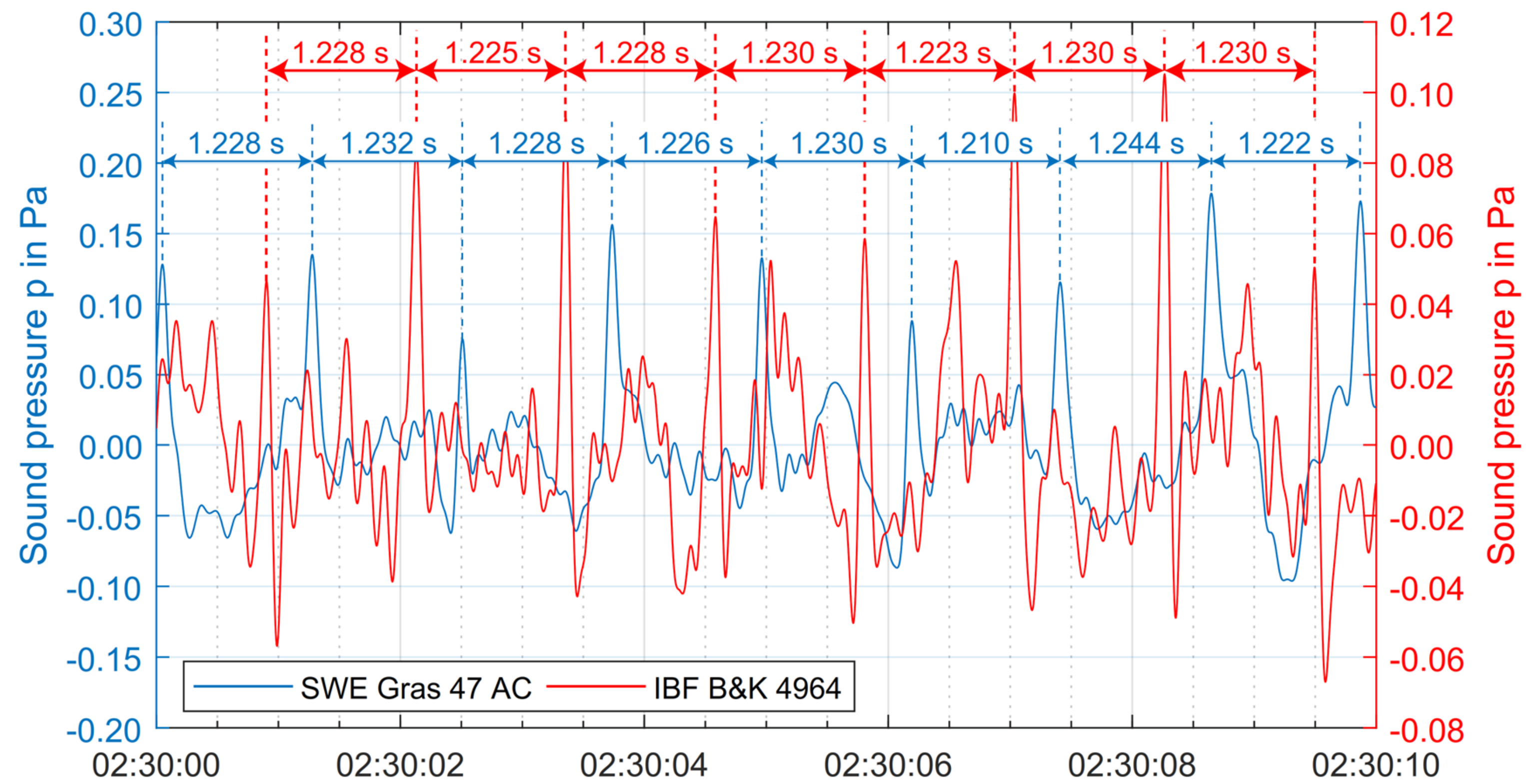
- Comparison of acoustic signals measured by IBF (inside building, 1.5 km) and GPI (field, < 0.5 km):
  - Switch-off times only visible during nighttime and lower wind speeds in the time series of sound pressure
  - SoundTrack LxT sound level meter (f > 6.3 Hz) seems to be a reliable tool for the measurement of acoustic (low-frequency) emissions even in greater distances

4) Evaluation of results – Impulsiveness

Blumendeller et al., 2020

- The impulsiveness of noise is often seen as critical because it favors the perceptibility of such acoustic emissions
- Each blade passage is clearly visible as a sharp peak of sound pressure both for measured data of SWE (emission) as well as IBF (immission).

  Time difference about Δt ≈ 1.23 s, which results in a blade passing frequency of BPF = 1/Δt = 0.81 Hz, corresponding to a rotational speed of 16 rpm.



4) Evaluation of results – Atmospheric conditions

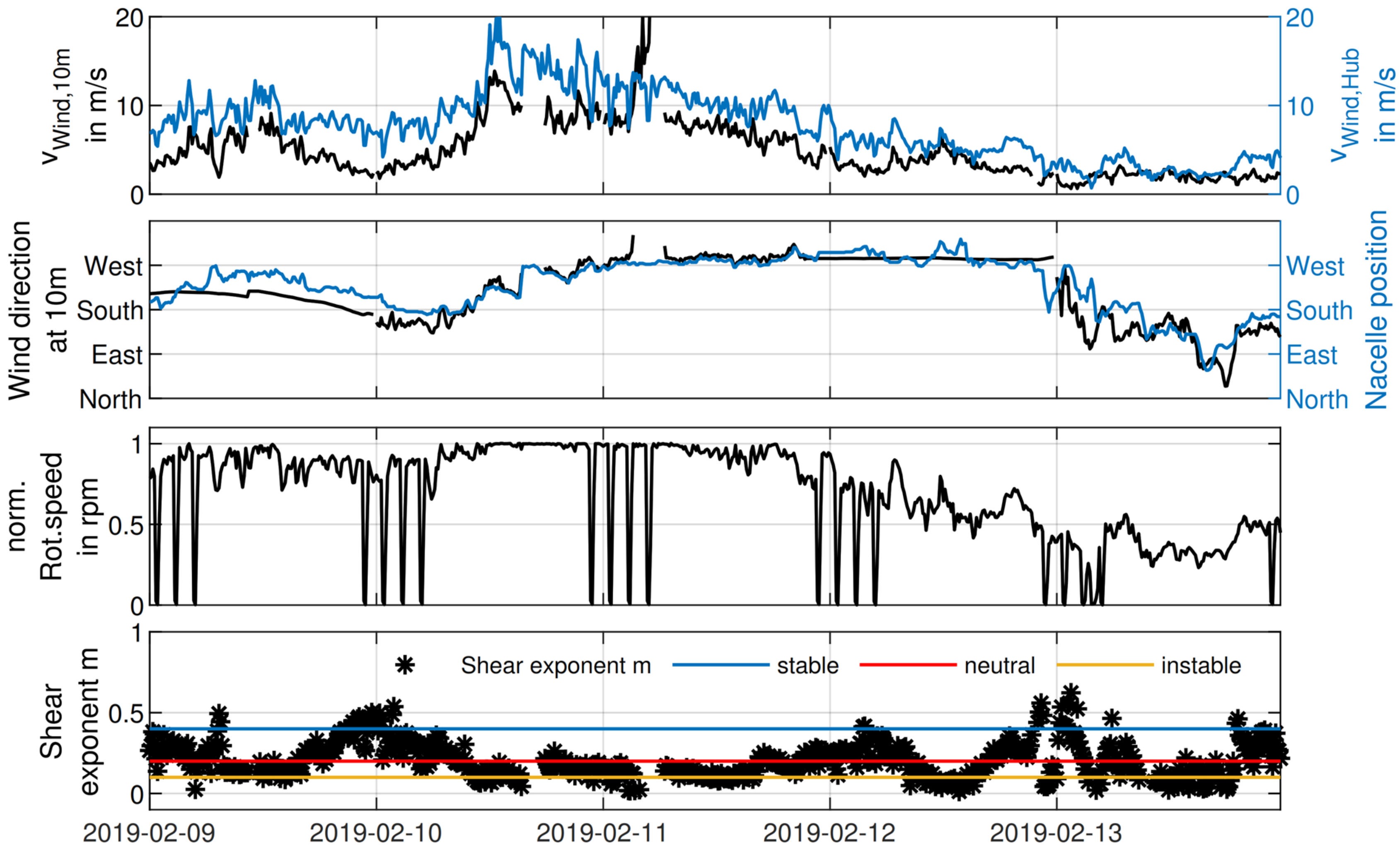
- Wind conditions and atmospheric conditions affect measurement results
- Method for the evaluation of atmospheric conditions presented by van den Berg, 2004:
  Calculation of an athmospheric stability expressed by logarithmic shear exponent m:

$$m = \frac{\ln(v_h / v_{\mathrm{ref}})}{\ln(h/h_{\mathrm{ref}})}$$

v_h: Wind speed at hub height h
v_{ref}: Wind speed at reference height $h_{\mathrm{ref}} = 10\ \mathrm{m}$

Atmospheric Stability	Shear Exponent
very-slightly unstable	$m \leq 0.1$
neutral	$0.1 < m < 0.2$
slightly stable	$0.2 < m < 0.4$
moderately-very stable	$0.4 \leq m$

4) Evaluation of results – Atmospheric conditions

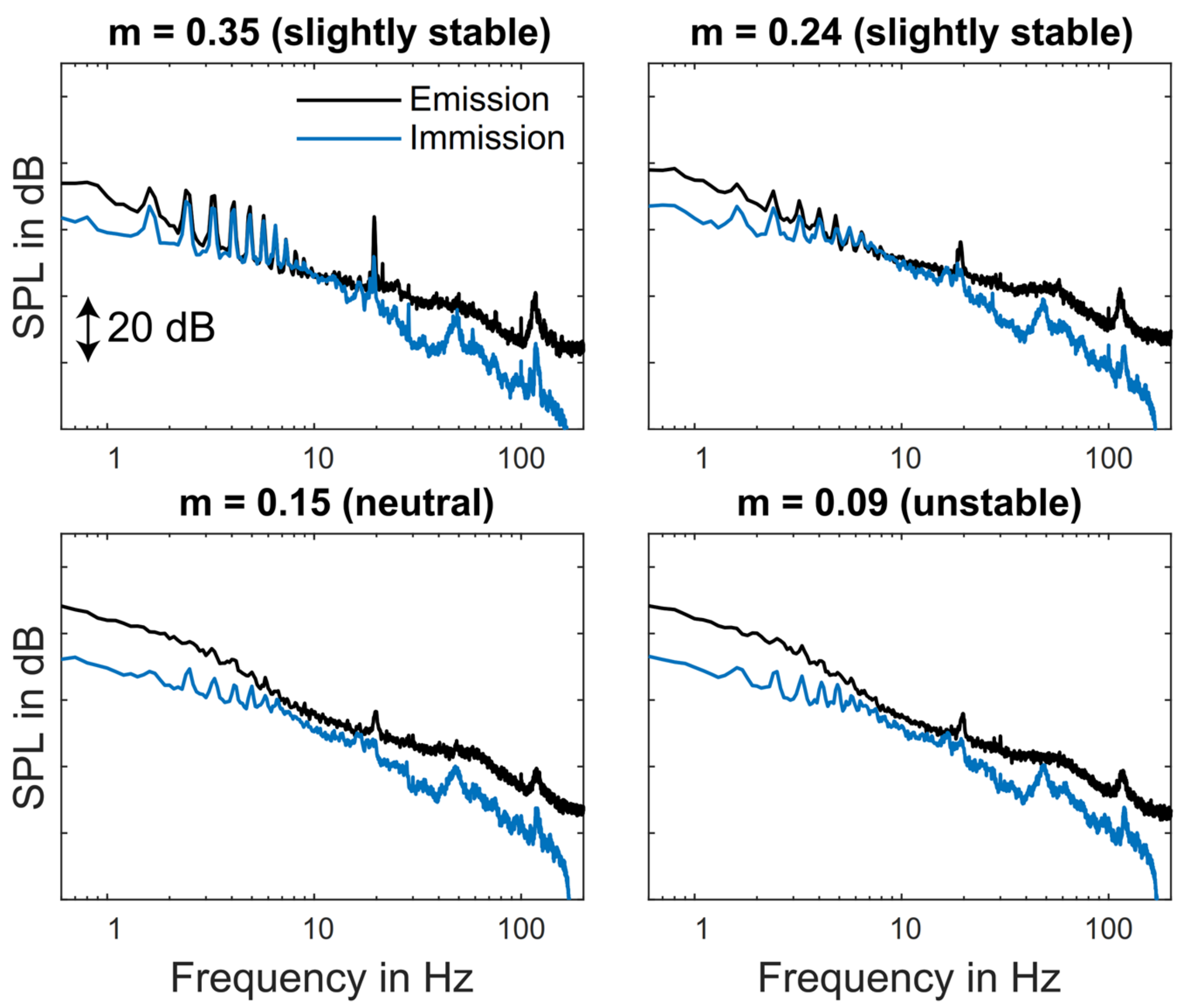


Blumendeller et al., 2020

→ Location 1 in Ingersheim, 0.4 km distance to WT

- From the bottom plot, it is evident that stable atmospheric conditions mainly occurred during the nighttime
- During time periods with high wind speeds at both considered heights (e.g., 11 February 2019 and 12 February 2019), mixed air layers led to an instable or neutral atmosphere, which was more likely during the daytime.
- Same applies to time periods with low wind speeds at both heights (e.g., 13 February 2019).

4) Evaluation of results – Atmospheric conditions

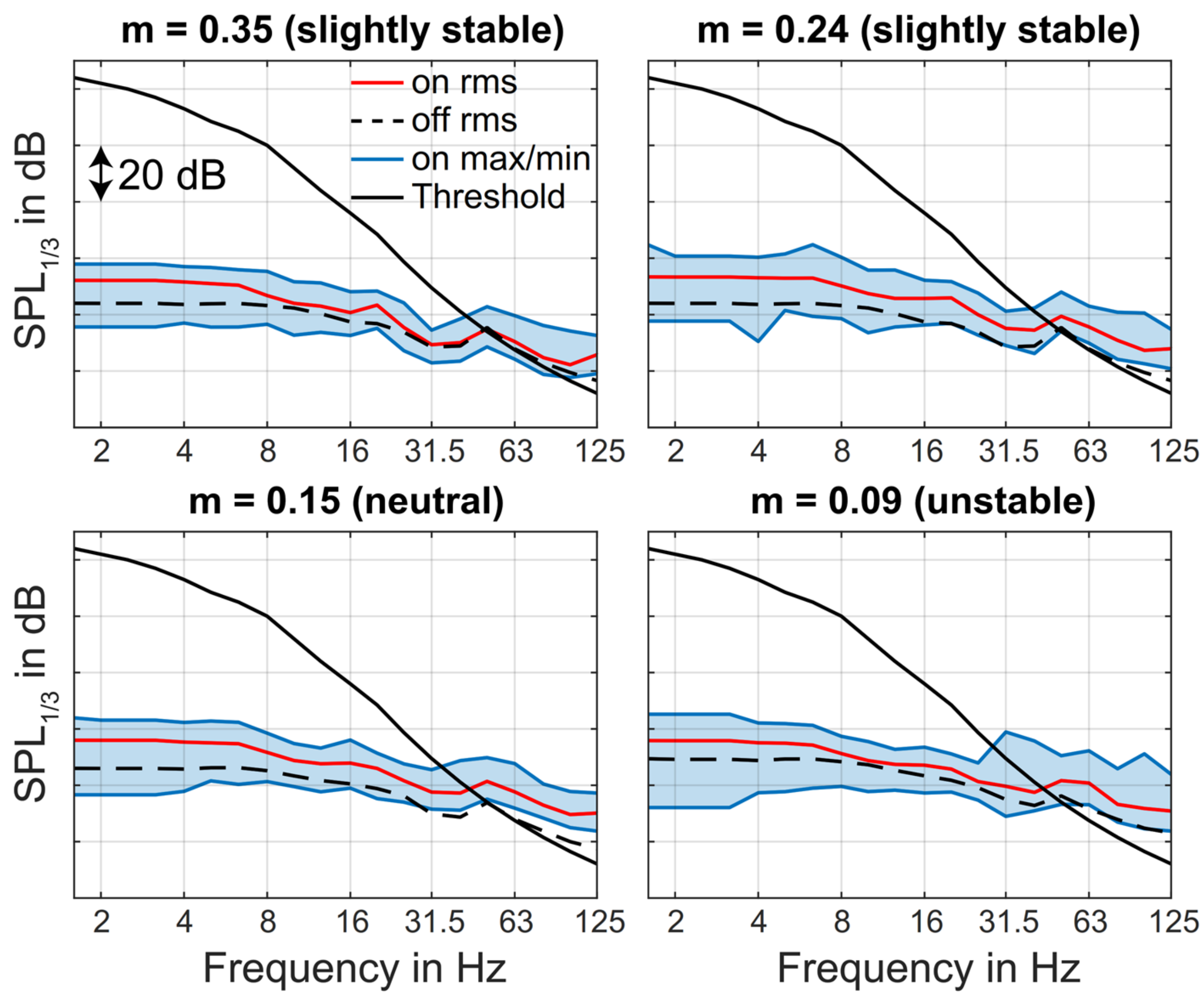


→ Measurements in Ingersheim, Between 0.24 and 0.4 km distance to WT outside (emission) and inside (immission)

- Influence of atmospheric conditions visible. More dominant outside.
- BPF tones still recognizable inside during unstable conditions

Blumendeller et al., 2020

4) Evaluation of results – Atmospheric conditions



→ Measurements in Ingersheim, Between 0.24 and 0.4 km distance to WT outside (emission) and inside (immission)

- Classification of sound pressure levels: minimum, maximum and mean value of one-third octave level ($SPL_{1/3}$) during operation and standstill in comparison with a popular hearing threshold
- Hearing threshold not reached for infrasonic sound below 30 Hz. Above 40 Hz to 50 Hz the hearing threshold can be reached depending on wind conditions

Blumendeller et al., 2020

5) Summary

Shutdowns of WT are recognizable in measurements

Vibrations caused by WT operation are broadband in the low-frequency range up to 25 Hz and can be identified up to frequencies of 120 Hz

Spectrogram of sound pressure shows clear, thin lines with sharp peaks between 0.8 and 8 Hz, also signals above. Low-frequency components are partly masked by wind noise

Spectral amplitudes of the seismic signals of wind farm (9 WT) significantly higher (approx. factor 10) than single WT

Seismic signals of WT far below noticeability limit for humans

Atmospheric conditions influence acoustic emissions and immissions

Passage of rotor blades in front of the tower causes impulsive behavior which could favor the perceptibility

Hearing threshold not reached in infrasonic range below 30 Hz. Could be reached around 50 Hz.


DAAD Workshop 2: Study of structural and foundation systems of Wind Turbines
University of Patras, Greece & Karlsruhe Institute of Technology, Germany
Research with a view…