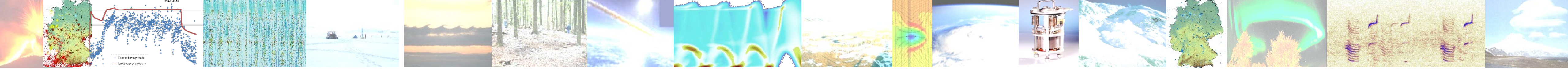


On the infrasound emission generated by wind turbines

Lars Ceranna, Peter Gaebler, Gernot Hartmann, Patrick Hupe,
Christoph Pilger & Andreas Steinberg

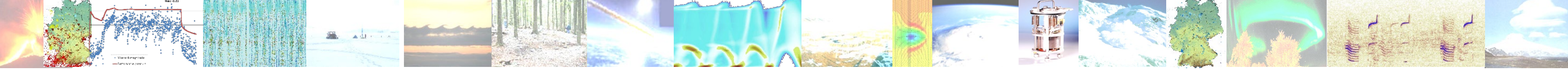
Federal Institute for Geosciences and Natural Resources (BGR)
Hannover, Germany

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

Abstract

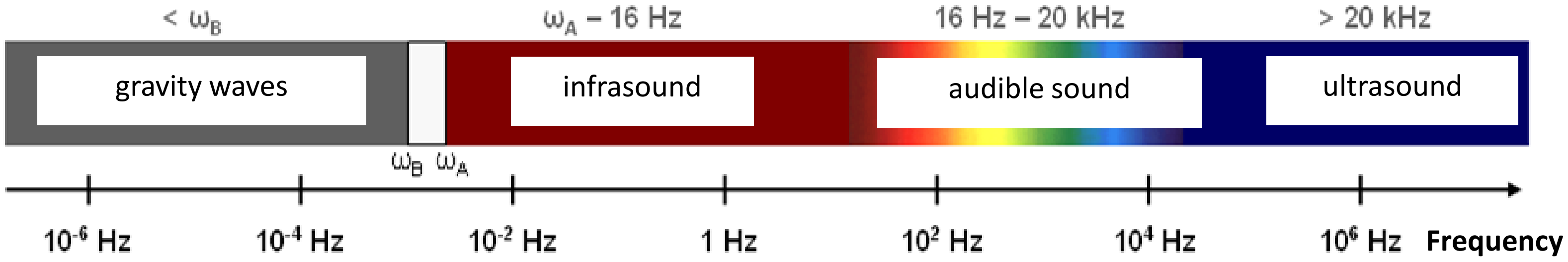
Aerodynamic infrasonic signals generated by wind turbines can be detected by highly sensitive micro-barometers showing spectral peaks at the blade passing harmonics, which are above the background noise level. As infrasound is one of the four verification technologies for the compliances with the Comprehensive Nuclear-Test-Ban Treaty (CTBT), decreases in detection capability for dedicated infrasound arrays have to be avoided. Therefore, preventing such decrease is particularly important for the two German infrasound stations IS26 in the Bavarian Forest and IS27 in Antarctica, which are both part of CTBT's International Monitoring System and have to meet stringent specifications with respect to their infrasonic ambient (natural and anthropogenic) noise levels.

In 2004, micro-pressure variations along a profile starting at a single horizontal-axis wind turbine were measured during a field experiment with mobile micro-barometer stations. As one of the results, a minimum distance to wind turbines for undisturbed recording conditions at infrasound array IS26 was estimated based on numerical modelling, validated with this dataset. Both observations and modelling were in agreement with the literature, where infrasonic signatures of wind turbines are reported at distance ranges up of tens of kilometres. Nevertheless, for broadening the dataset further infrasound measurements at two wind parks with modern large wind turbines have recently been carried out in Lower Saxony and Saxony-Anhalt, respectively. Here various instruments (micro-barometers, microphones, pressure sensors) have been deployed in a comparative manner. We will give an overview of these campaigns, followed by first results of our analysis and interpretation.



Infrasound – the inaudible sound

► **Sound waves** – inaudible for human beings



► **Origins of infrasound** – natural and anthropogenic

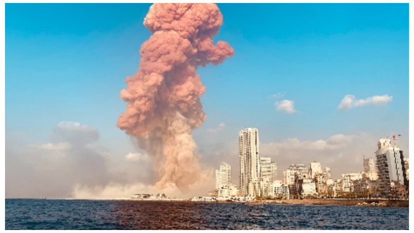


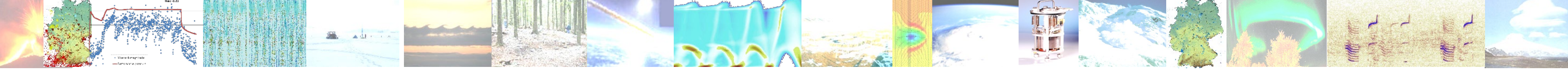










CTBT – Comprehensive Nuclear-Test-Ban Treaty

► **CTBT** – opened for signature by UN's GA in 1996

limiting further development and qualitative improvements of nuclear weapons

putting an end for inventing new nuclear weapon devices

important step towards a world free of nuclear weapons

► **Germany** – signed and ratified the Treaty in 1996 and 1998, respectively

the Treaty, its Protocols and Manuals are binding documents following public international law

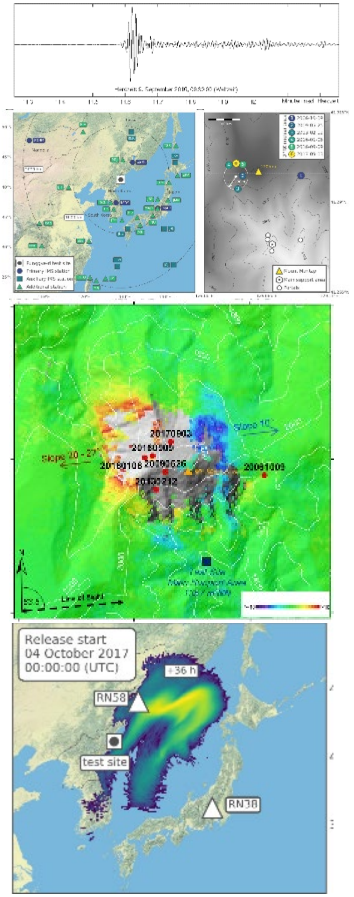
► **BGR** – National Data Centre as well as Station Operator of the CTBT monitoring network

providing technical and scientific expertise to federal government in all issues related to CTBT ***(e.g., DPRK)***

operates two seismological stations: **PS19** in the Bavarian Forest, **AS035** in Antarctica (SANAE research base)

operates two infrasound arrays: **IS26** in the Bavarian Forest, **IS27** in Antarctica (Neumayer III research base)

reference background noise floor has been defined during certification (e.g., 2002 for IS26)



Gaebler et al. 2019, Solid Earth

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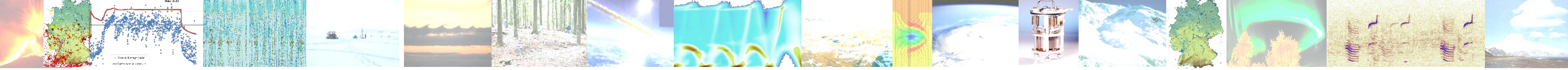


Monitoring the compliance with the CTBT using infrasound

AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL092262

1001 Rocket Launches for Space Missions and Their Infrasonic Signature

Christoph Pilger[1], Patrick Hupe[1], Peter Gaebler[1], and Lars Ceranna[1]

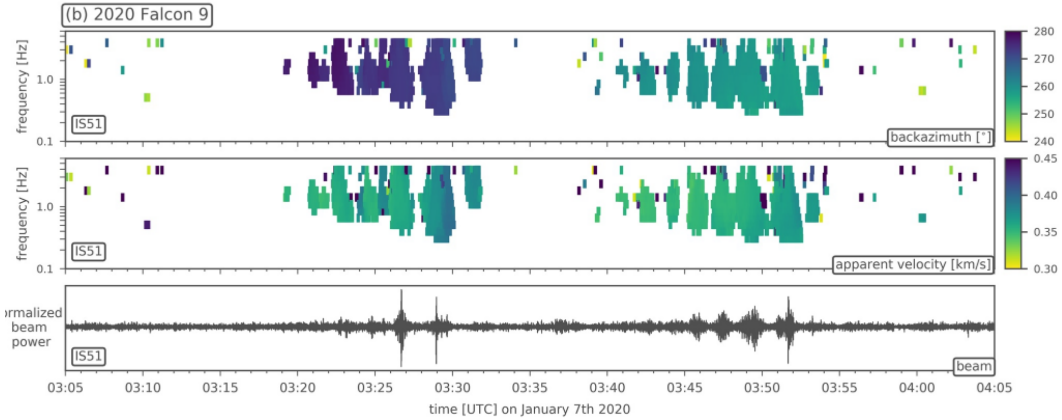
[1]Federal Institute for Geosciences and Natural Resources (BGR), Hanover, Germany

Key Points:
- We analyze 1001 rocket launches since 2009 using International Monitoring System infrasound arrays
- We estimate the global detectability, individual signal characteristics, and an amplitude-energy relation of rocket infrasound
- We provide a ground-truth data set of signal parameters for 7637 infrasound events from 733 launches

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:

Abstract Infrasound array processing is applied to monitor and characterize atmospheric explosions in the context of the Comprehensive Nuclear-Test-Ban Treaty. Anyhow, for many infrasound sources the exact location and time are initially unknown and sometimes difficult to precisely estimate afterward. In contrast, rocket launches are well-defined ground-truth events generating strong infrasonic signatures. During the last decade, the number of rocket launches for sending satellites into Earth's orbit and for reaching space strongly increased. We collected ground-truth information for 1001 rocket launches from 27 global spaceports between 2009 and mid-2020 and were able to identify infrasound signatures from up to 73% of the launches on the International Monitoring System of infrasound stations. We use these unique data to estimate the global detectability of such events, to characterize rocket infrasound, to derive an amplitude-energy relation, and to provide the results for further use as a ground-truth reference in geophysical and atmospheric research.



scientific reports

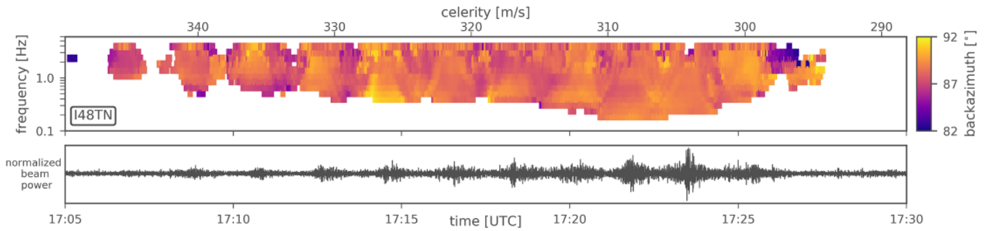
OPEN

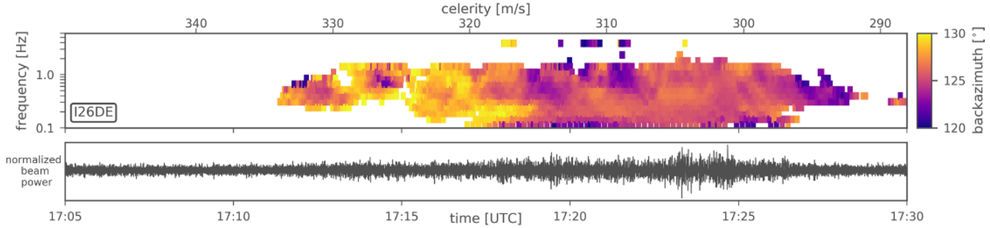
Yield estimation of the 2020 Beirut explosion using open access waveform and remote sensing data

Christoph Pilger[1]✉, Peter Gaebler[1], Patrick Hupe[1], Andre C. Kalia[1], Felix M. Schneider[2], Andreas Steinberg[1], Henriette Sudhaus[3] & Lars Ceranna[1]

We report on a multi-technique analysis using publicly available data for investigating the huge, accidental explosion that struck the city of Beirut, Lebanon, on August 4, 2020. Its devastating shock wave led to thousands of injured with more than two hundred fatalities and caused immense damage to buildings and infrastructure. Our combined analysis of seismological, hydroacoustic, infrasonic and radar remote sensing data allows us to characterize the source as well as to estimate the explosive yield. The latter is determined within 0.13 to 2 kt TNT (kilotons of trinitrotoluene). This range is plausible given the reported 2.75 kt of ammonium nitrate as explosive source. As there are strict limitations for an on-site analysis of this catastrophic explosion, our presented approach based on data from open accessible global station networks and satellite missions is of high scientific and social relevance that furthermore is transferable to other explosions.

Scientific Reports | (2021) 11:14144 | https://doi.org/10.1038/s41598-021-93690-y natureportfolio





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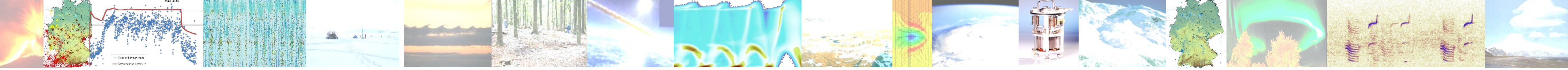
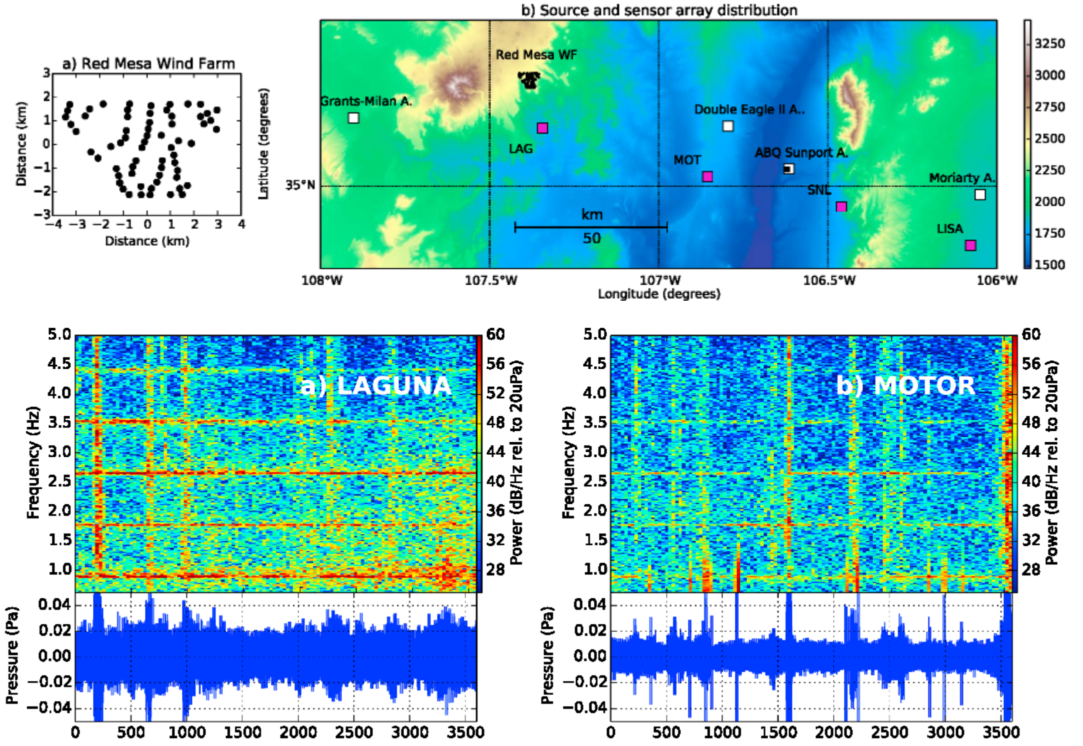


Anthropogenic noise generated by (large) wind turbines

It has been reported in literature that infrasound generated by (large) wind turbines has been measured – made visible as spectral peaks at the blade passing harmonics (BPH) – at large distance ranges:

- ► *Blumendeller et al., 2020, Acoustics*: at 1.45 km indoor
- ► *Dooley K.A. et al., 2014, ASA*: up to 10.8 km distance
- ► *Edwards, 2015, GSC Report*: up to 10 km distance
- ► *Keith et al., 2018, JASA*: up to 10 km distance
- ► *Marcillo et al., 2015, JGR*: at arrays in 13, 54 , and 90 km distance
- ► *Schomer et al., 2015, JASA*: at 3 km distance indoor and outdoor
- ► *Van den Berg, 2004, JSV*: up to 1.5 km distance
- ► *Zajamsek et al., 2016, JSV*: up to 4 km distance indoor and outdoor



Marcillo et al., 2015, JGR

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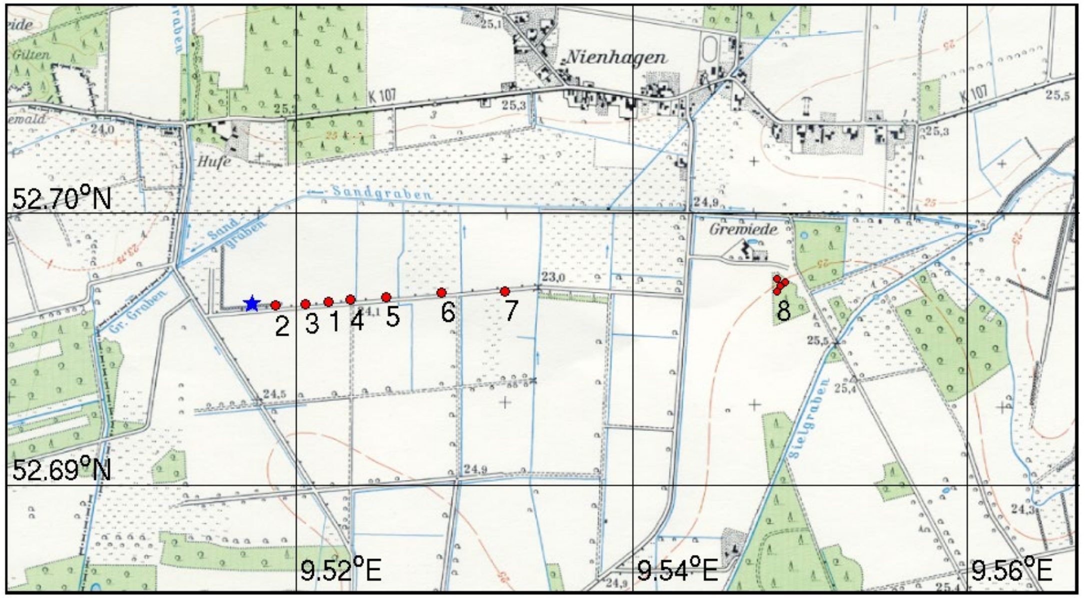
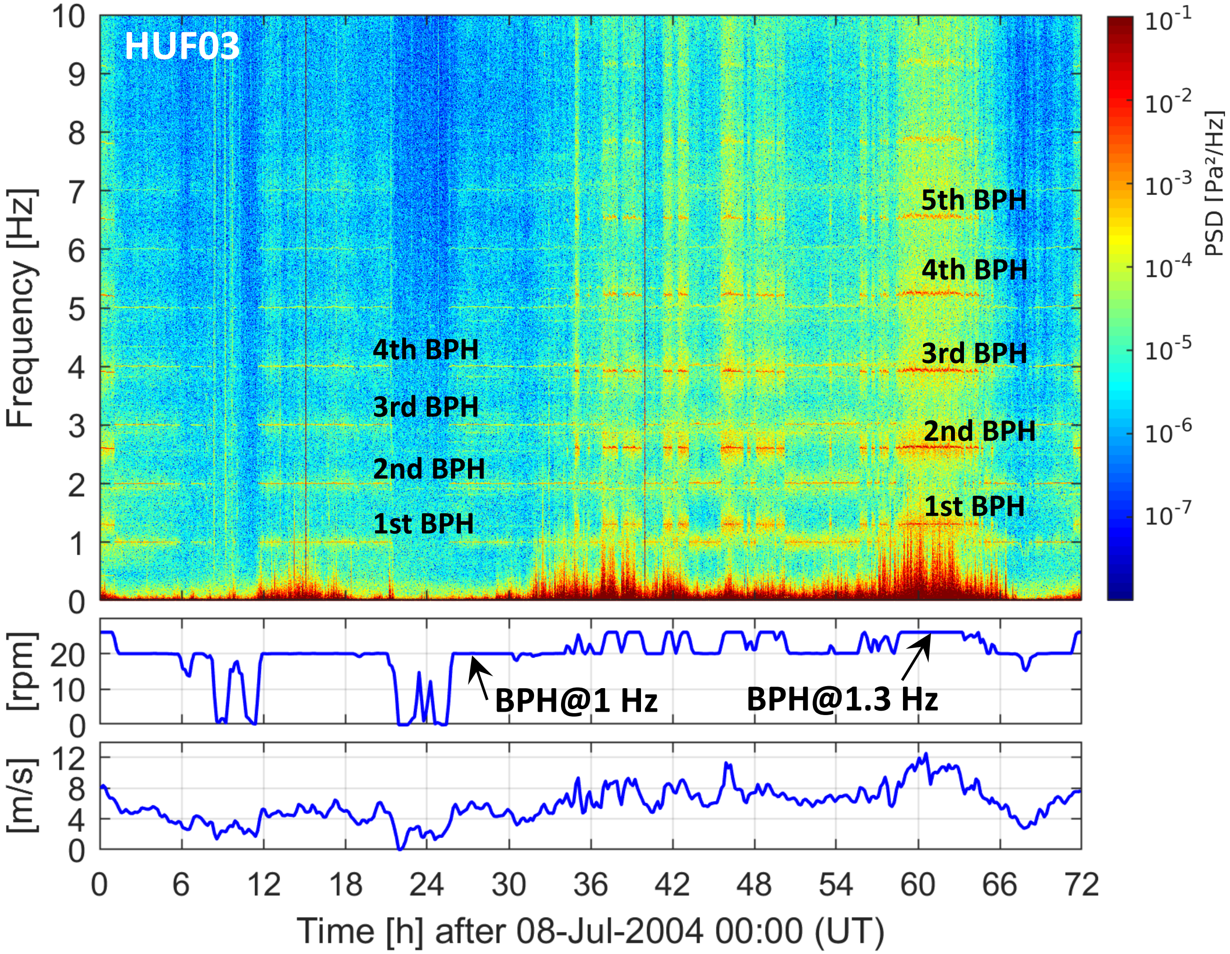
Measuring infrasound at single wind turbine I/II



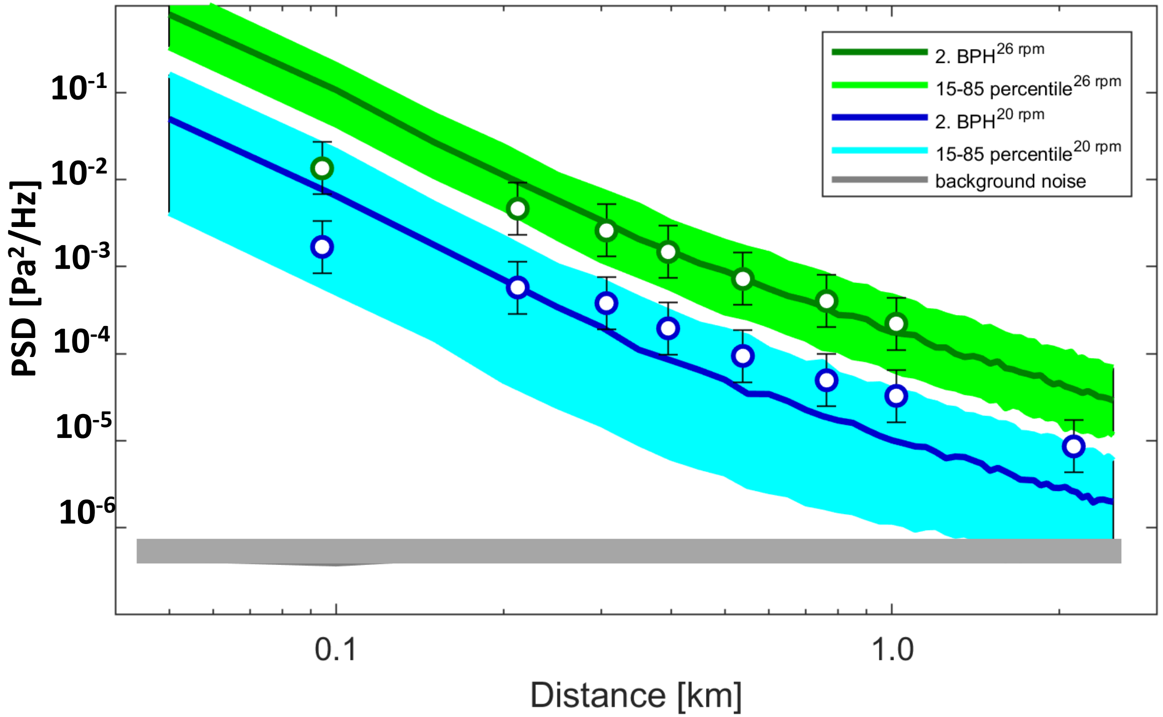
- VESTAS V47, 660 kW
- 48 m diameter, 65 m hub height
- rpm={20 26}
- 8 site (7 single sensors and 1 mini-array), 2 km line
- 07-Jul-2004 – 05-Aug-2004



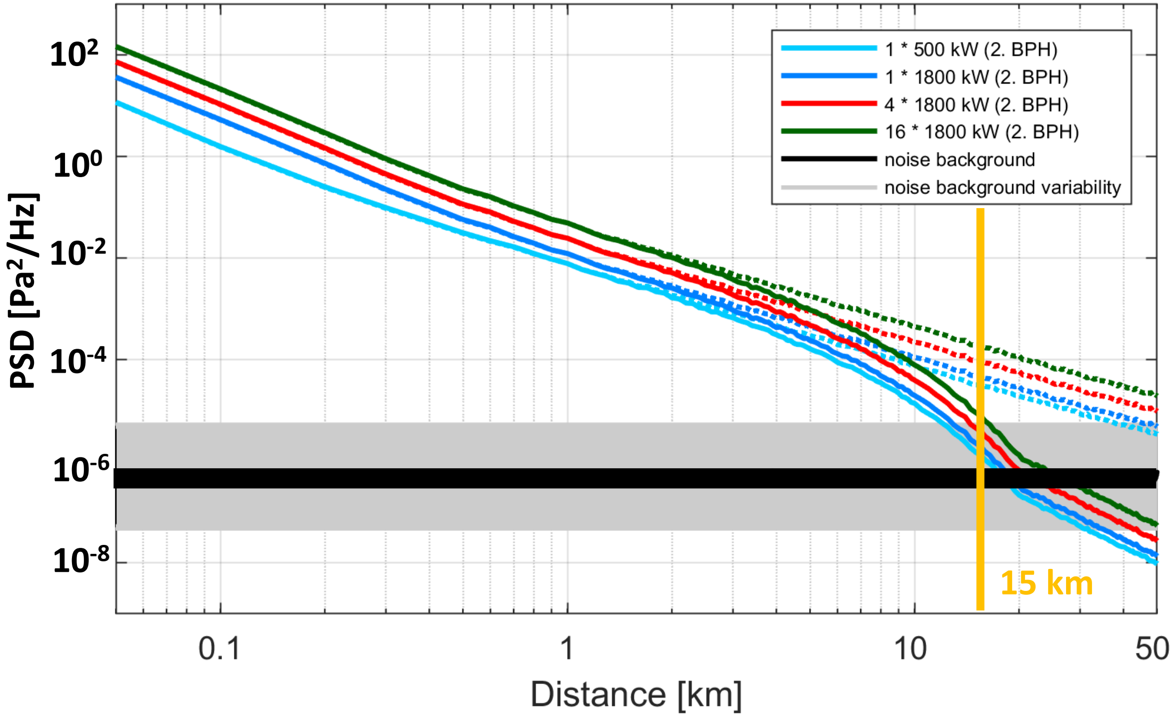
Pilger & Ceranna, 2016, 2021, JSV

Measuring infrasound at single wind turbine II/II – corrected values

Comparing measured data and modelled values



Estimating minimum distance



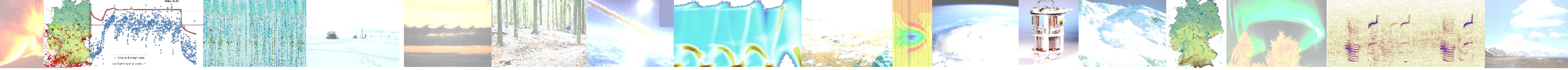
- Computing the RMS sound pressure of the n-th BPH of 3-blade horizontal axis WT using Viterna's (conservative) model:

$$P_n = \frac{k_n\sqrt{2}}{4\pi d}\sum_m \{e^{im(\theta-\pi/2)} J_x(k_n R_e \sin\gamma)\}\cdot\{a_m^T \cos\gamma - \frac{nB-m}{k_n R_e} a_m^Q\}$$

depending on hub height, wind speed, diameter, electric power

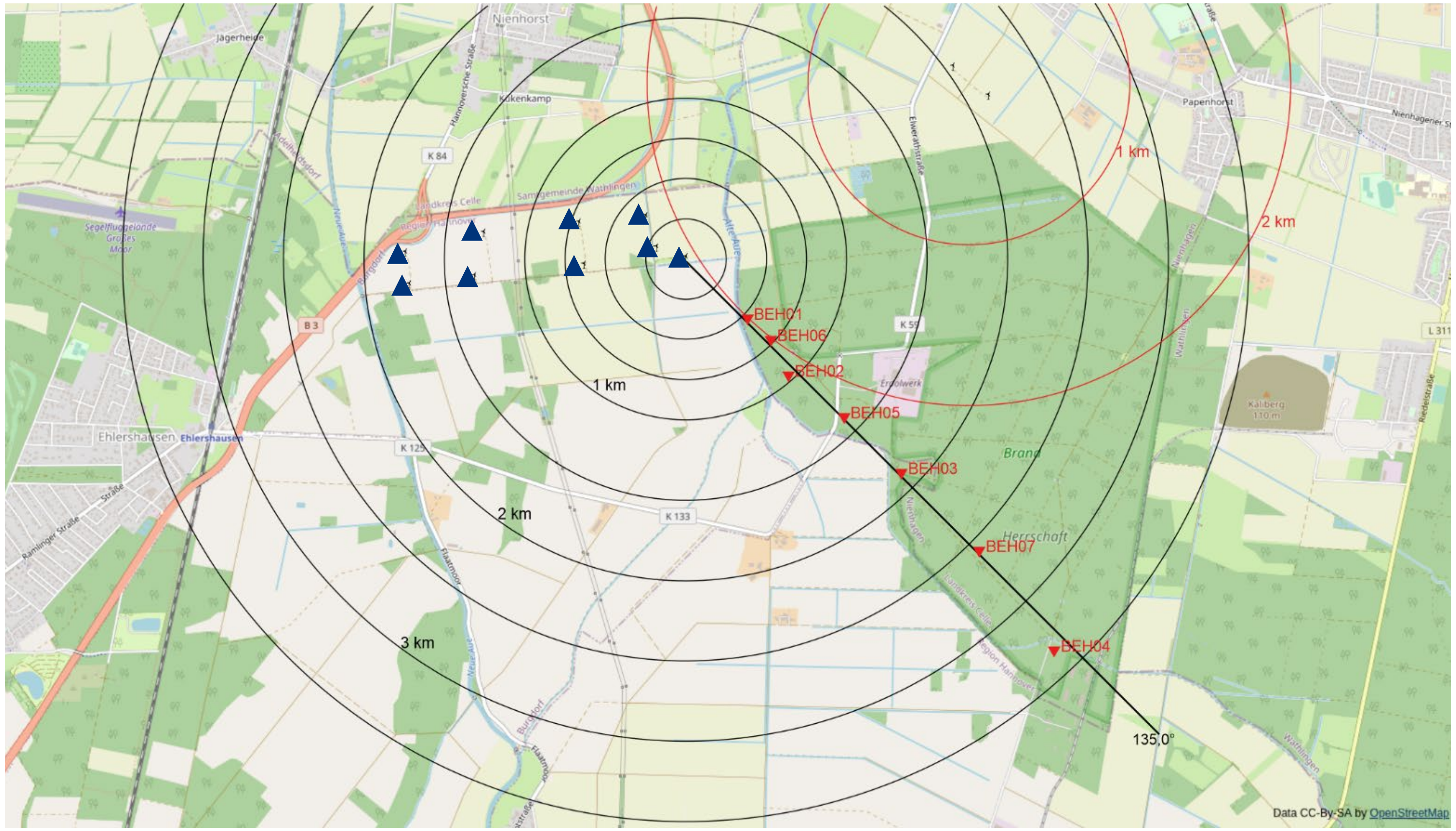
- Recommendation of minimum distance range between IS26 and WT for undisturbed recording conditions

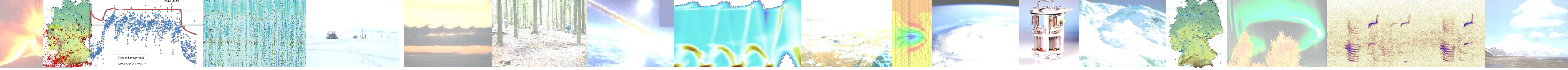
Viterna, 1981, NASA-Report
Klein et al., 2018, WES
Pilger & Ceranna, 2016, 2021, JSV



Measuring infrasound at a windpark near Burgdorf-Ehlershausen, Lower Saxony

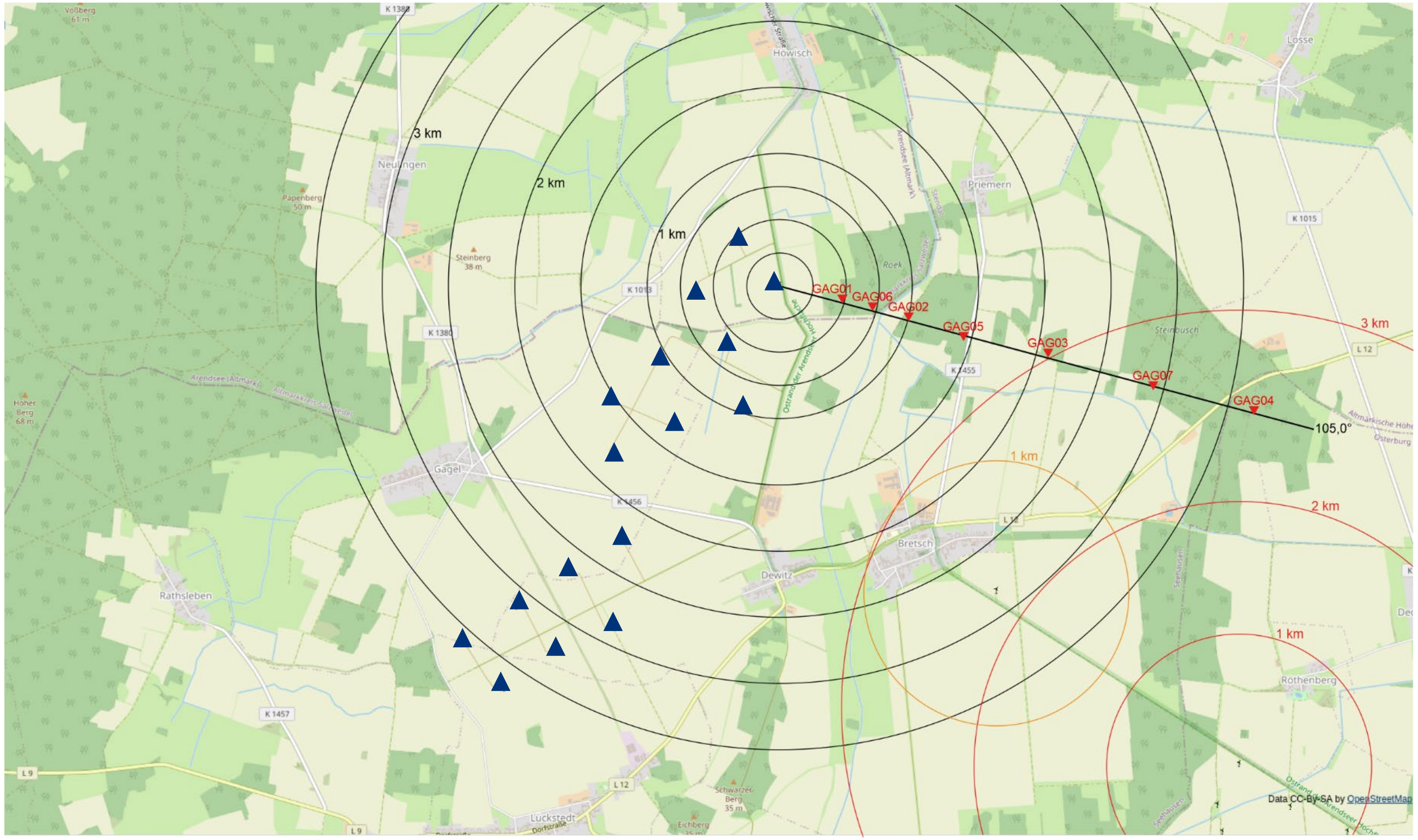
- ▶ wind park Burgwedel-Ehlershausen, Lower Saxony
- ▶ 9 wind turbines, NEG Micon NM52/900 (▲), rpm={22.2 14.8}, 3 blades, horizontal axis
- ▶ 52.2 m diameter, 61.5 m hub height, 900 kW electric power, overall 8.1 MW
- ▶ measuring from 20-May-2021 to 29-Jun-2021
- ▶ 7 sites with single sensors along a 3.5-km line (▼)
- ▶ continuous data, 100 Hz sampling
- ▶ waveform & meta data freely available





Measuring infrasound at a windpark near Gagel, Saxony-Anhalt

- wind park Gagel, Saxony-Anhalt
- 16 wind turbines, Enercon E115-3.0 (▲), rpm {0 to 12.8}, 3 blades, horizontal axis
- 115 m diameter, 146 m hub height, 3000 kW electric power, overall 48 MW
- measuring from 06-Jul-2021 to 23-Aug-2021
- 7 sites with single sensors along a 3.5-km line (▼)
- continuous data, 100 Hz sampling
- waveform and meta data freely available



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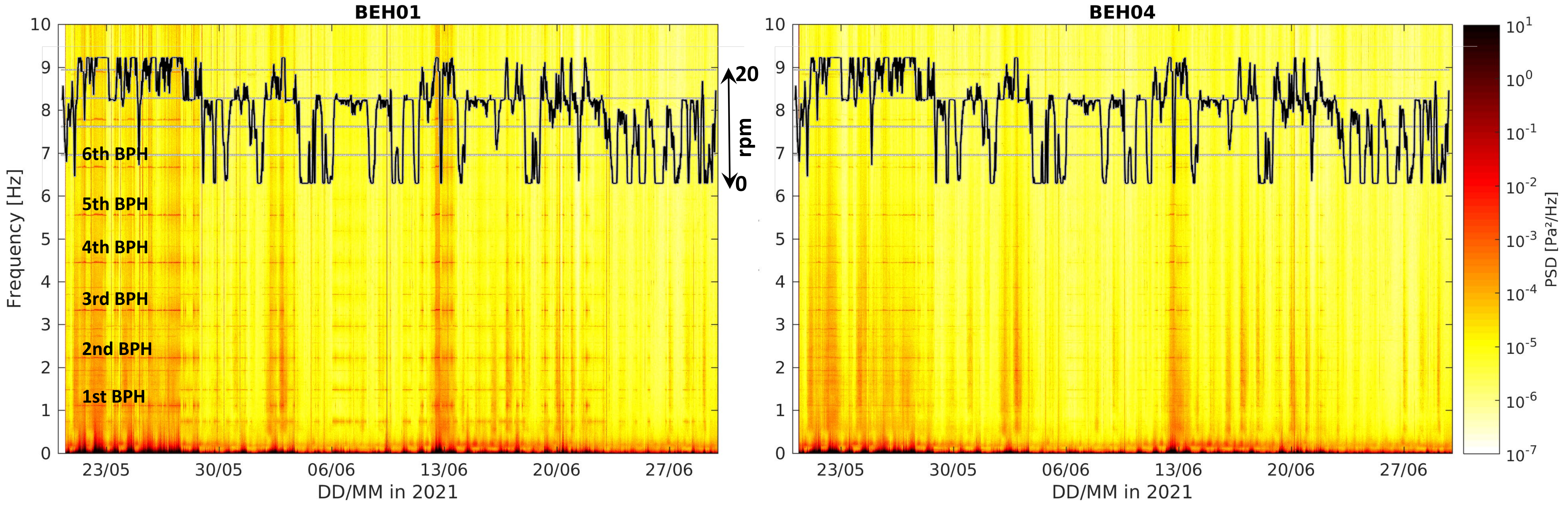
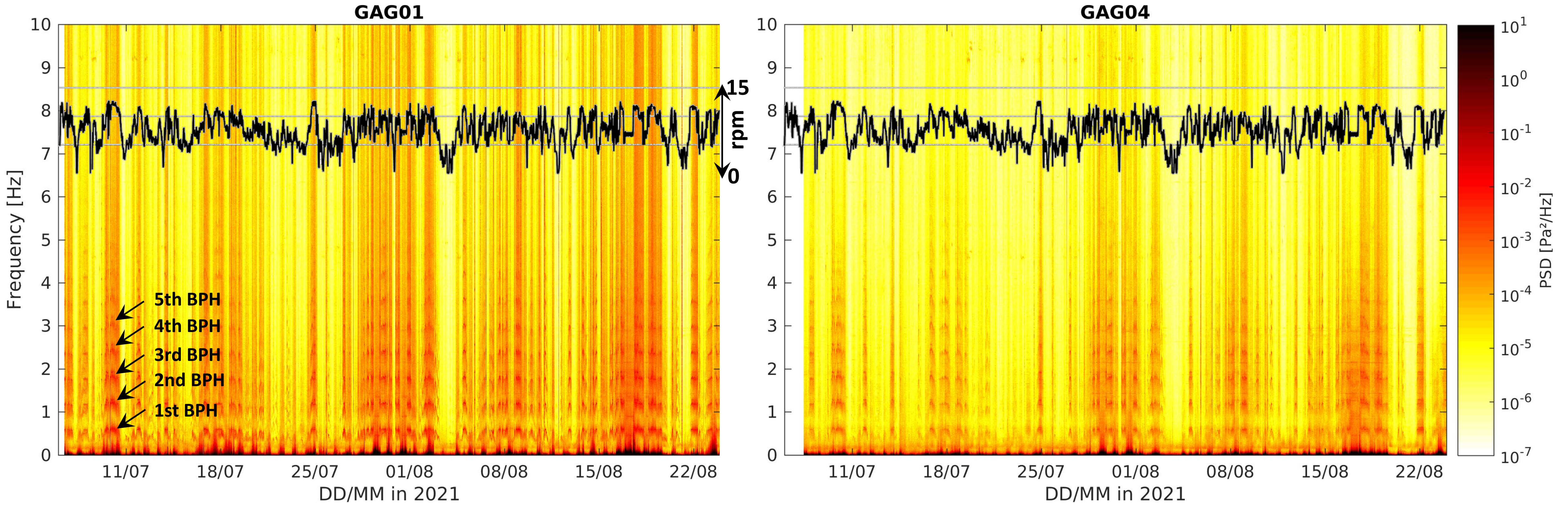
Measuring infrasound at a windpark near Burgdorf-Ehlershausen

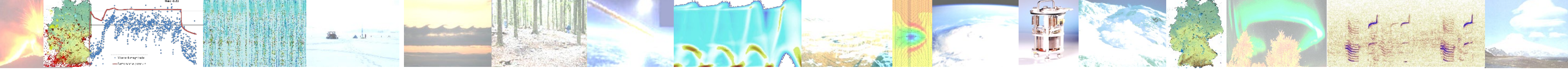


- Power Spectral Density (PSD) at site BEH01 (≥ 0.5 km) and BEH04 (≥ 3.5 km) estimated every 10 minutes (NFFT=8192, 50% overlap)
- dominating horizontal spectral lines at blade passing harmonics depending on prevailing wind speeds
- fundamental BPHs @1.11 Hz and @0.74 Hz (maximum rpm=[22.2, 14.8]) due to active stall control – also spectral lines in between

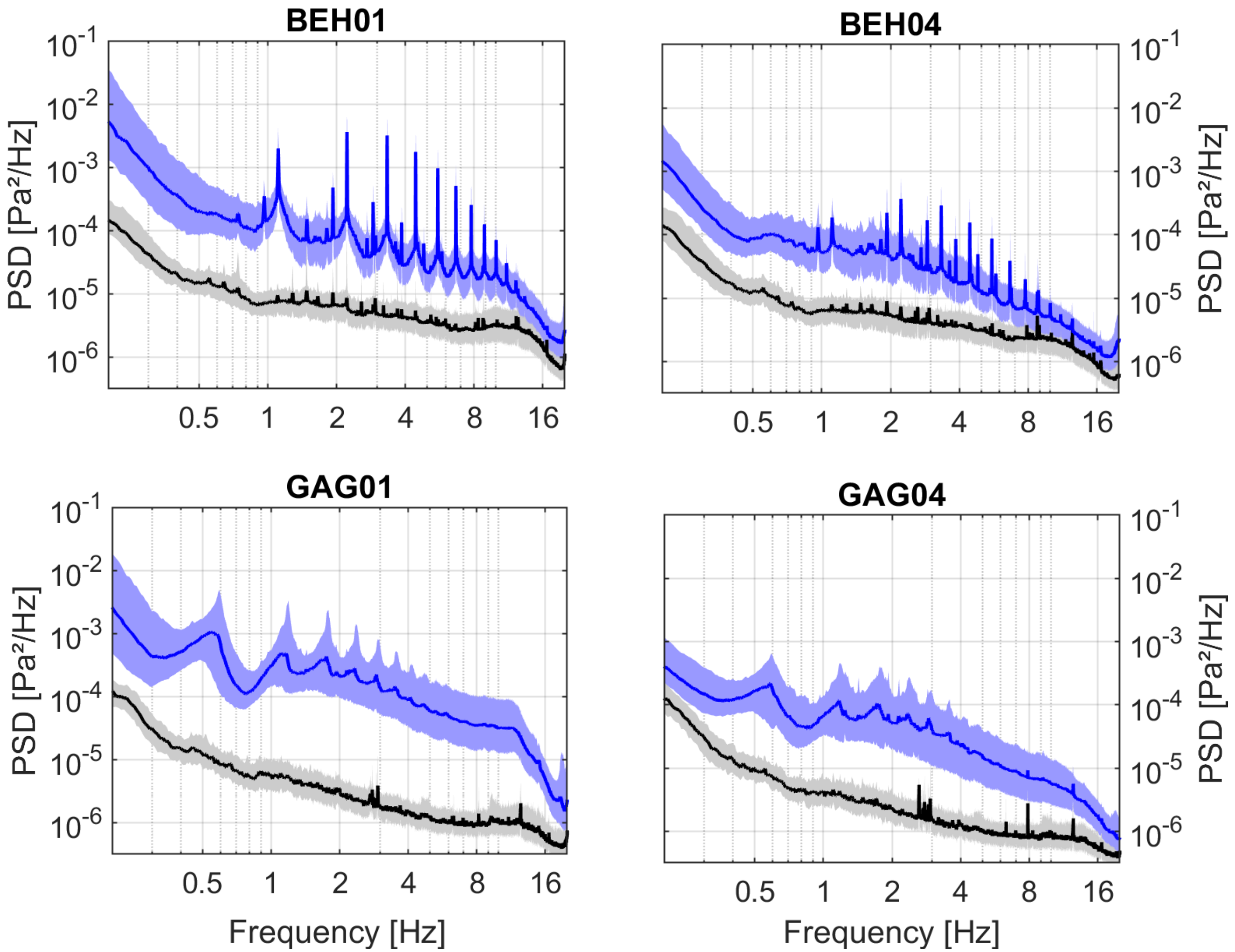
Measuring infrasound at a windpark near Gagel



- Power Spectral Density (PSD) at site GAG01 (≥ 0.5 km) and GAG04 (≥ 3.5 km) estimated every 10 minutes (NFFT=8192, 50% overlap)
- dominating horizontal spectral lines at blade passing harmonics depending on prevailing wind speeds
- fundamental BPH @0.64 Hz (maximum rpm=12.8) – clear variation in spectral peaks due to pitch control

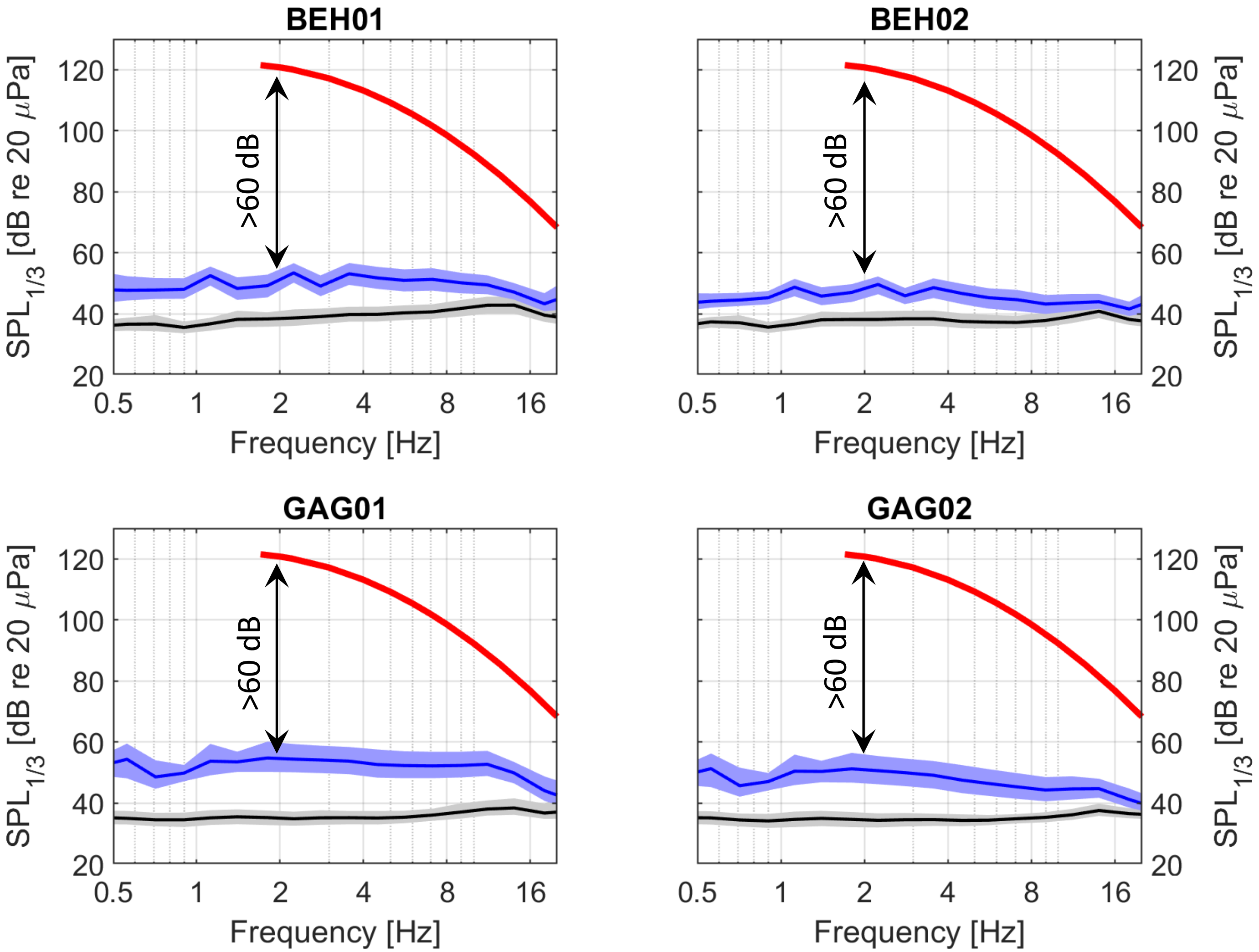


Measuring infrasound at two windpark near Burgdorf-Ehlershause & Gagel



- considering DWD stations 10338 (Airport Hannover) and 10261 (Seehausen) for estimating wind speeds at Burgdorf and Gagel, respectively – 10 min averaged data
- median values shown in blue (> 6 m/s) and black (< 2m/s) for sites BEH01 (> 0.5 km), BEH04 (> 3.5 km), GAG01 (> 0.5 km) and GAG04 (> 3.5 km away from WTs)
- 20- and 80-percentiles marking light coloured areas
- clear differences between high and low wind speeds
- **BEH:** clear spectral speaks at BPHs during periods of high wind speeds, and almost no spectral peaks while low winds are blowing
- **BEH:** „mixed“ status of operation of individual WTs in wind park – operating factors are essential
- **GAG:** spectral peaks much broader compared to BEHxx
- **GAG:** significant broad-band noise level

Infrasound generated by wind turbines & human perception



- estimating SPL-values (Sound Pressure Level) in 1/3-octav bands - following the ISO-EN-DIN 266 - based on PSD-values (Power Spectral Density) computed every 10 minutes at all sites of both field campaigns
- median values shown in **blue** (> 6 m/s) and **black** (< 2m/s) for sites BEH01 (> 0.5 km), BEH02 (> 1.0 km) as well as GAG01 (> 0.5 km), GAG04 (> 1.0 km away from WTs); 20- and 80-percentiles are marked by light coloured areas
- human perception threshold for infrasound (**red line**) based on DIN 45680:2011 for frequencies ≥ 8 Hz and Møller & Pedersen, 2004, Noise and Health below 8 Hz
- **2 Hz:** human perception threshold is more than 60 dB - i.e., factor of ~1000 - above the median SPL-values measured during high wind speeds (operating WTs) at sites in a minimum distance of 0.5 and 1.0 km to a WT
- **10 Hz:** similar picture with a difference in the order of 40 dB (factor of ~100); except for GAG01

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Summary & Conclusions

- ► binding public international law for operating and maintaining infrasound stations of the CTBT network; especially for IS26 in the Bavarian Forest
- ► wind turbines (WT) generate significant infrasound noise for highly sensitive micro-barometers
- ► in 2004, BGR measured infrasound generated by a single WT up to 2 km distance; based on this a minimum distance of 15 km have been recommended for undisturbed recording conditions at IS26
- ► in 2021, BGR has carried another field campaign for measuring infrasound from WT: at all sites (up to 3.5 km away from closest WT) clear infrasonic signatures from wind parks are visible
- ► modern pitch controlled WTs generate infrasonic signatures with broader peaks yielding a stronger impact in micro-pressure recordings, which might be significantly above the natural background noise at IS26 and might therefore be hindering for fulfilling compliance with CTBT

Outlook & Acknowledgements

► comparing / proving Viterna's model with the new data sets; estimating synthetic noise floor considering wind parks with pitch controlled WTs and varying rpm values

► current campaign's data is available to the public (link and how-to on BGR's website www.bgr.bund.de):

BGR - Infraschall - Der Infraschall von Windenergieanlagen (bund.de)

► looking forward to get feedback as a public workshop is planned to present and discuss own results

Finally, we thank our engineers and technicians (TG, MH, and RS) for planning and realisation this field campaign in short time. We thank our colleagues from PTB, Braunschweig, for their support and close cooperation. We also thank the land owners for permitting access to their places for deploying our instruments. We are also grateful to the operator of the two wind parks in Burgdorf-Ehlershausen and Gagel for providing operating factors for each WT during our time of measurement.