LUBW

Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg

Low-frequency noise incl. infrasound from wind turbines and other sources

Report on results of the measurement project 2013-2015

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Naturschutz Baden-Württemberg

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1 Background and introduction

There are currently (as of 31.12.2015) 445 wind turbines in operation in Baden-Wuerttemberg and 100 more under construction [1]. In the coming years many more will be added to that number. When it comes to the expansion of wind energy, the effects on humans and the environment need to be taken into account. Wind turbines make noise. In addition to the usual audible sound, they also generate low-frequency sounds or infrasound, i.e. extremely low tones.

Infrasound is described as the frequency range below 20 hertz (for explanations of important technical terms, please refer to Appendix A3). From a physical point of view, these noises are generated particularly through aerodynamic and mechanical processes, e.g. the flow around rotor blades, machine noise or the vibration of equipment components. Our hearing is very insensitive to low-frequency noise components. The wind energy decree of Baden-Wuerttemberg [1] includes, among other things, regulations and statements to protect the population against low-frequency noise and infrasound. However, within the scope of wind energy development, fears are commonly expressed that this infrasound may affect people or jeopardize their health.

In September 2012, the LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Wuerttemberg presented the concept for a measuring project, with which current data on low-frequency noise incl. infrasound from wind turbines and other sources was to be collected. As a result, the LUBW was entrusted with the implementation of the project by the Ministry of Environment, Climate and Energy Baden-Wuerttemberg. The company Wölfel Engineering GmbH + Co. KG was taken on board as a supporting measuring institute. The detailed planning and work was thus begun together at the beginning of 2013.

Within the project, numerous measurements near wind turbines and other sources as well as the associated analyses and evaluations were carried out. The results obtained are summarized in this measurement report. The LUBW wishes to use it as a contribution towards providing objectivity to the discussion. The report is aimed at the interested public as well as administrative bodies and professionals.

At this point we would like to thank all participants for enabling the measurements as well as the friendly support during the implementation, in particular the operators of wind turbines, the involved administrative authorities in Baden-Wuerttemberg and Rhineland-Palatinate, the State Museum of Natural History Karlsruhe and the Education Authority of Karlsruhe. The Bavarian State Office for the Environment and the State Office for the Environment, Nature Conservation and Geology Mecklenburg-Western Pomerania were kind enough to provide a number of pictures.

1) The terms "wind power plant" and "wind turbine" are synonymous. For our measurement project we have used the term "wind turbine" in the title. The German term is embedded in immissions law (fourth regulation on the implementation of the Federal Immission Control Act – Regulation on licensing requirements Appendices – 4. BImSchV, Appendix 1 no. 1.6.1 [2] [3]). In the text of this report the common term "wind power plant" may also be used.

2 Summary

In cooperation with Wölfel Engineering GmbH + Co. KG, the LUBW carried out the measurement project "Low-frequency noise incl. infrasound from wind turbines and other sources", which began in 2013. This report provides information on the results of the measurement project.

The aim of the project is to collect current data on the occurrence of infrasound (from 1 Hz) and low-frequency noise in the area of wind turbines and other sources. For this purpose, measurements were taken up to the end of 2015 in the areas around six wind turbines by different manufacturers and with different sizes, covering a power range from 1.8 to 3.2 megawatts (MW). Depending on local conditions, the distances to the wind turbines were approx. 150 m, 300 m and 700 m. The results of the measurements at the wind turbines are described and illustrated by means of graphs in Chapter 4. In addition to the acoustical analyses, vibration measurements were performed in the vicinity of a wind power plant in order to determine possible vibration emissions of the power plant on the environment. The procedure and the difficulties encountered are explained accordingly.

Since road traffic is also considered to be a source of infrasound and low-frequency noise, it stood to reason to extend the measurement project to cover that too. Chapter 5 provides results of measurements at an urban road, which took place both outside as well as inside a residential building. In addition, the data from the LUBW measurement stations for road traffic noise in Karlsruhe and Reutlingen were analysed and illustrated with respect to low-frequency noise and infrasound. Furthermore, results of own measurements at a motorway are also illustrated. This is supplemented by data from sound level measurements inside a moving car.

Measurements without reference sources during the day and at night took place in the centre of Karlsruhe on the Friedrichsplatz. At the same time, measurements were also taken on the roof of the natural history museum and in an interior room of the education authority (Chapter 6). Typical noise occurring in residential buildings through widespread technical equipment, such as washing machines, refrigerators or heating equipment, was also recorded and is presented in Chapter 7. In order to enable statements about natural sources of infrasound, measurements were taken on an open field, near a forest and in a forest. The measurement of low-frequency sound through sea surf is also introduced based on literature (Chapter 8). In Chapter 9, considerations are made for a monitoring station for the continuous monitoring of low-frequency noise incl. infrasound. Such an independently operating permanent measuring station could possibly be used when it comes to complaint cases.

***Figure 2-1**: Wind turbines – how much infrasound do they emit? Photo: Wölfel company*

The report at hand extends the previous interim report through further findings and contains a multiplicity of measurement results. It is aimed at both professionals as well as the interested general public. Great interest for our analyses was shown by the public and administrative bodies during the entire duration of the project. SWR TV even aired a report about the measurements. The LUBW will continue to pursue the issue in the future.

In addition to general information about infrasound, the appendices provide extensive explanations of technical terms and the technology used, as well as information on the sources.

***Figure 2-2**: Impressions of the measurements during the execution of the measurement project. a) Construction of a wind measuring mast (top left) and b) of a measurement point (top right) during measurement at a wind turbine. c) and d) Setup of measurement points in the city centre of Karlsruhe (bottom). Photos: LUBW*

RESULTS

In summary, the measurements lead to the following findings:

- The infrasound being emanated from the wind turbines can generally be measured well in the direct vicinity. Discrete lines occur below 8 Hz in the frequency spectrum, which are attributed to the uniform movement of the individual rotor blades.

- For the measurements carried out even at close range, the infrasound level in the vicinity of wind turbines is – at distances between 120 m and 300 m – well below the threshold of what humans perceive in accordance with DIN 45680 (2013 Draft) [5] or ***Table A3-1***.

- At a distance of 700 m from the wind turbines, it was observed by means of measurements that when the turbine is switched on, the measured infrasound level did not increase or only increase to a limited extent. The infrasound was generated mainly by the wind and not by the turbines.

- The determined G-weighted levels [2)] at distances between 120 m and 190 m were between 55 dB(G) and 80 dB(G) with the turbine switched on, and between 50 dB(G) and 75 dB(G) with the turbine switched off. At distances of 650 m and 700 m, the G-levels were between 50 dB(G) and 75 dB(G) for both turbines switched

2) The G-level – expressed as dB(G) – represents a frequency-weighted single value of the noise in the low-frequency and infrasound range. The human ear is insensitive to any influences in this frequency range (for definition and measurement curve see Appendix A3).

on as well as off, see ***Table 2-1***. The large fluctuations are caused, among other things, by the strongly varying noise components due to the wind, as well as various different surrounding conditions.

- The infrasound and low-frequency noise measured in the vicinity of operating wind turbines consists of a proportion that is generated by the wind turbine, a proportion that occurs by itself in the vicinity due to the wind, and a proportion that is induced by the wind at the microphone. In this case the wind itself is thus always an "interference factor" when determining the wind turbine noise. The measured values are therefore subject to a wide spread.

- The vibrations caused by the wind turbine being examined were already minimal at a distance of less than 300 m. At distances provided for residential areas alone due to noise protection issues, no relevant effects are to be expected for residential buildings.

- It was possible to carry out the measurements for the low-frequency noise incl. infrasound resulting from road traffic during times without interfering wind noise. Contrary to the case with wind turbines, the measured levels also occur directly in areas with adjacent residential buildings. As expected, it was observed that the infrasound and low-frequency noise levels fell at night. Clear correlations with the amount of traffic were also ascertained. The higher the amount of traffic, the higher the low-frequency noise and infrasound levels.

- The infrasound noise levels of road traffic in the area of residential buildings in the vicinity in the individual third octave bands were a maximum of approx. 70 dB (unweighted), while the G-weighted level was in the range between 55 dB(G) and 80 dB(G).

- When it comes to the immission measurements of road traffic noise, increased levels in the area between approx. 30 Hz and 80 Hz were ascertained in the frequency spectra. The low-frequency noise in this area lies well above the perception threshold according to ***Table A3-1*** and is therefore more relevant with regards to its effect

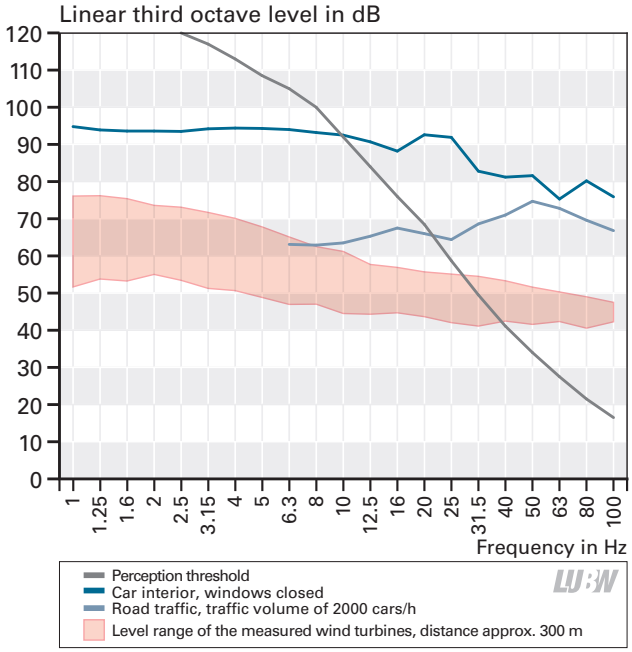
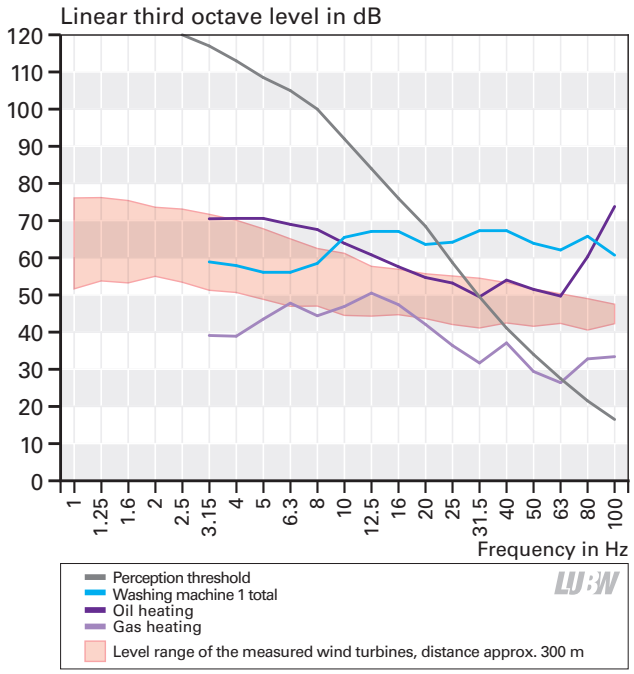


Figure 2-3*: Comparison of road noise inside and outside of motor vehicles with the level range of wind turbines at a distance of approx. 300 m as well as the perception threshold according to Table A3-1 regarding infrasound and low-frequency noise. For measuring corrections, see Section 4.1.*

than the subliminal infrasound levels below 20 Hz. The levels of low-frequency noise in the observed situations of road traffic are significantly higher than in the vicinity of wind turbines (***Table 2-1***).

- The measurements in the city centre of Karlsruhe (Friedrichsplatz) showed that the G-weighted levels dropped from 65 dB(G) during the day to levels of around 50 dB(G) at night. Wind noise played no role for these measurements. Relatively high third octave levels up to 60 dB (unweighted) could be observed between 25 Hz and 80 Hz, probably deriving from traffic noise, even though the Friedrichsplatz is not located directly on a busy road.

- The highest levels in the context of the measurement project were measured in the interior of a mid-range car travelling at 130 km/h. Even though these are not immission levels that occur in a free environment, they are an everyday situation that many people are frequently subjected to for a longer period of time. The measured values for both the infrasound as well as the other



***Firgure 2-4**: Comparison of noise of technical appliances in residential buildings with the level range of wind turbines at a distance of approx. 300 m as well as the perception threshold according to Table A3-1 regarding infrasound and low-frequency noise. For measuring corrections, see Section 4.1.*

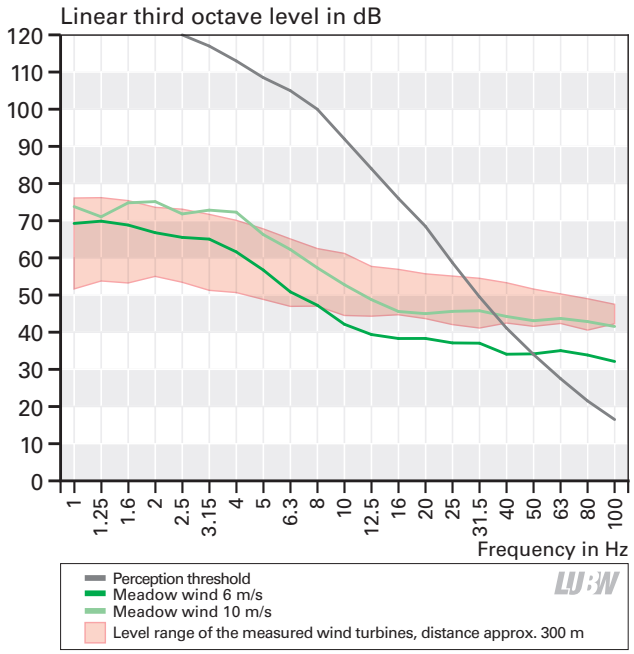


***Figure 2-5**: Comparison of noise situation in an open field (without source reference) with the level range of wind turbines at a distance of approx. 300 m as well as the perception threshold according to Table A3-1 regarding infrasound and low-frequency noise. For measuring corrections for wind turbines, see section 4.1.*

low-frequency areas are higher by several orders of magnitude than the values measured in road traffic or at the wind turbines.

- The measurement of appliances in a residential building showed the highest infrasound levels during the spin cycle of washing machines. In individual third octaves the levels reached the perception threshold according to ***Table A3-1***. As expected, it turned out that building components deaden higher-frequency noise significantly better than the low frequencies below 20 Hz.

- In a rural area, the spectral distribution of noise on an open field, the edge of a forest, in a forest with wind is in principle similar to in the vicinity of a wind turbine (***Figure 2-5***). For open fields, linear levels that are up to 30 dB higher than in a forest can be seen in the narrow-band spectrum. Above 16 Hz, the differences are no longer as pronounced. Higher levels occur for A-weighted audible sound in the forest, which is attributable to the rustling of leaves.

CONCLUSION

Infrasound is caused by a large number of different natural and technical sources. It is an everyday part of our environment that can be found everywhere. Wind turbines make no considerable contribution to it. The infrasound levels generated by them lie clearly below the limits of human perception. There is no scientifically proven evidence of adverse effects in this level range.

The measurement results of wind turbines also show no acoustic abnormalities for the frequency range of audible sound. Wind turbines can thus be assessed like other installations according to the specifications of the TA Lärm (noise prevention regulations). It can be concluded that, given the respective compliance with legal and professional technical requirements for planning and approval, harmful effects of noise from wind turbines cannot be deduced.

***Table 2-1**: Comparative overview of results. The readings were often subject to considerable fluctuations. Here they were rounded to the nearest 5 dB, some are based on different averaging times. More information can be found in the relevant sections of the report. To enable a comparison of the results (measurements with/without reverberant plate) a correction was carried out; for more information see Section 4.1.*

Source/situation	Section	G-weighted level in dB(G)	Infrasound third octave level ≤ 20 Hz in dB [1]	Low-frequency third octave levels 25-80 Hz in dB [1]
Wind turbines [2]		**WT on / off**	**WT on**	**WT off**
– WT 1	4.2	700 m: 55-75 / 50-75 150 m: 65-75 / 50-70	– 150 m: 55-70	– 150 m: 50-55
– WT 2	4.3	240 m: 60-75 / 60-75 120 m: 60-80 / 60-75	– 120 m: 60-75	– 120 m: 50-55
– WT 3	4.4	300 m: 55-80 / 50-75 180 m: 55-75 / 50-75	– 180 m: 50-70	– 180 m: 45-50
– WT 4	4.5	650 m: 50-65 / 50-65 180 m: 55-65 / 50-65	– 180 m: 45-55	– 180 m: 40-45
– WT 5	4.6	650 m: 60-70 / 55-65 185 m: 60-70 / 55-65	– 185 m: 50-65	– 185 m: 45-50
– WT 6	4.7	705 m: 55-65 / 55-60 192 m: 60-75 / 55-65	– 192 m: 55-65	– 192 m: 45-50
Road traffic				
– Würzburg inner city, balcony [3] – Würzburg inner city, living quarter [3]	5.1	50-75 40-65	35-65 20-55	55-75 35-55
– Karlsruhe, noise measurement station [3]	5.2	65-75	45-65	55-70
– Reutlingen, noise measurement station [3]	5.2	70-80	50-70	55-75
– Motorway A5 near Malsch, 80 m [4] – Motorway A5 near Malsch, 260 m [4]	5.3	75 70	55-60 55-60	60-70 55-60
– Interior noise in passenger car 130 km/h [4] – interior noise in minibus at 130 km/h [4]	5.4	105 100	90-95 85-90	75-95 80-90
Urban background, Karlsruhe [3] – roof of natural history museum – Friedrichsplatz – Interior	6	50-65 50-65 45-60	35-55 35-50 20-45	up to 60 up to 60 up to 55
Noise sources in residential buildings [5]				
– Washing machine (all operating modes)	7.1	50-85	25-75	10-75
– Heating (oil and gas, full load)	7.2	60-70	40-70	25-60
– Refrigerator (full load)	7.2	60	30-50	15-35
Rural environment [6]		**Wind 6 / 10 m/s**	**Wind 6 / 10 m/s**	**Wind 6 / 10 m/s**
– open field, 130 m from forest	8.1	50-65 / 55-65	40-70 / 45-75	35-40 / 40-45
– Edge of forest	8.1	50-60 / 50-60	35-50 / 45-75	35-40 / 40-45
– Forest	8.1	50-60 / 50-60	35-40 / 40-45	35-50 / 35-40
Sea surf				
– Beach, 25 m away	8.2	75	55-70	not reported
– Rock cliff, 250 m away	8.2	70	55-65	not reported

1) Linear third octave level (unweighted)
2) For wind turbines: From 10-second values (see illustrations of the G-level depending on the wind speed)
3) For road traffic (Würzburg) and urban background (Karlsruhe): From averaging levels over an hour
4) For federal motorway and car interior level: From averaging over several minutes
5) For noise sources in residential building: From averaging levels of typical operating cycles
6) The wind measurement was always carried out at the measurement point MP1 (open field).

3 Scope of analysis

The scope of analysis includes the following measurements and examinations:

- Measurement of low-frequency noise, including infrasound, from 1 Hz at a total of six different wind turbines at a distance of approx. 150 m, 300 m and 700 m respectively (if possible). In the process, the turbines were each turned on and off. The distances roughly correspond to the set reference intervals for emission measurements at close range (approx. 150 m), a roughly double distance in the immediate vicinity (approx. 300 m) and a distance that can occur for real noise immissions (700 m, see also planning information in the wind energy statute of Baden Wuerttemberg [1]).

- Comparative measurement of the noise immission in the sphere of influence of a road both outside as well as inside a residential building.

- Determination of low-frequency effects from 6.3 Hz of road traffic on the permanent monitoring stations in Karlsruhe and Reutlingen as well as at the A5 motorway near Malsch at different distances.

- Measuring of the infrasound levels within a passenger car travelling at 130 km/h.

- Determination of the urban background through a comparative measurement of the noise situation in Karlsruhe (Friedrichsplatz) without specific source reference both outside as well as inside a building.

- Comparative measurement of the noise situation in a rural area without a concrete source reference.

- Measurement of oscillations (vibrations) in the ground in the vicinity of a wind turbine.

- Elaboration of a feasibility concept for the conception of a self-sufficient permanent measuring station for low frequency noise incl. infrasound, in order to possibly measure the effects over a longer period of time (e.g. several weeks).

The following planned steps of the project have not yet been completed:

- Measurement of the direction dependency in the low-frequency frequency range based on four measurement points around a wind turbine. – This is where technical problems occurred during the measurement. They therefore have to be repeated.

- Measurement of low-frequency noise, including infrasound, from 1 Hz at a wind farm, incl. indoor measurement in a residential building at a distance of approx. 700 m to the nearest turbine. The wind turbines are switched on and off in the process. – The necessary meteorological conditions did not occur at the planned measuring location since commissioning in August 2014. It was therefore not possible to carry out a standard-compliant measurement. The measurement is to be carried out at a later date.

4 Wind turbines

The results of the six measurements that took place in the context of this project at wind turbines in Baden-Wuerttemberg, Rhineland-Palatinate and Bavaria are presented in the following (***Table 4-1***). The measurements were carried out by Wölfel Engineering GmbH + Co. KG, Höchberg, on behalf of the LUBW. The graphical representations of the emissions and immissions in the low-frequency range, both with the turbines switched on and off, are an integral part. The third octave levels enable a comparison with the human perception threshold. The A and G-weighted sound pressure levels are represented depending on the wind velocity for three different distances from the turbine. The A-weighted sound level – specified as dB(A) – simulates the human hearing sensitivity. The G-level – specified as dB(G) – represents a singular value, which rates only infrasound and parts of the low-frequency frequency range. The human ear is very insensitive to these frequency ranges (for more info please refer to ***Figure A3-1*** in Appendix A3). Additionally recorded narrow band spectra, all specified with a resolution of 0.1 Hz, are able to depict more clearly specific features of the noise characteristics of wind turbines. The level values in a spectrum depend on the selected resolution. Therefore, narrow band levels cannot be compared with third octave levels. Only third octave levels are suitable for comparisons with the hearing threshold, as it also corresponds to third octave levels.

All the following results of measurements on operating wind turbines also include the noise caused by the wind itself in the vicinity. In addition, in the case of strong wind, noise will inevitably be induced at the microphones despite the use of double wind screens. Therefore, the results of a measurement cannot be attributed to the respective wind turbine alone. The differences shown by the comparison of situations with the turbine switched on and off are therefore all the more important. When it comes to the noise measurements at roads (Chapter 5) and in the city centre (Chapter 6), the effects related to the wind are irrelevant. Thus, the measuring results for wind turbines and roads designate different situations, which cannot be directly compared with one another.

The selection of the wind turbines that were to be measured proved to be rather difficult. The initial contacts with operators were kindly set up by the Baden-Wuerttemberg approval authorities (district offices) after the LUBW had carried out a corresponding query. The participation of the turbine operators was on a voluntary basis. Some operators had concerns about participating in the project.

First, the locations were qualified from an acoustic perspective. Sites near busy roads, or other disruptive noise sources – including forests – were deemed unsuitable and thus rejected. Regarding more powerful turbines, the site search had to be extended by the LUBW to include Rhineland-Palatinate. In this case constructive support was also provided several times by the authorities. Not only weather-related restrictions had to be coped with (matching wind directions and wind speeds; strong winds resulting in termination of measuring due to automatic shutdown; snowfall in the vicinity) during the project. One wind power plant broke down shortly before the measurement and was

Table 4-1*: Overview of the wind power plants where measurements were carried out in the context of this project. The individual power plants and the associated results are described in more detail in Sections 4.2 to 4.7.*

Wind turbine (WT)	WT 1	WT 2	WT 3	WT 4	WT 5	WT 6
Manufacturer **Model**	REpower* MM92	Enercon E-66	Enercon E-82	REpower* 3.2M114	Nordex N117/2400	Enercon E-101
Nominal capacity	2.0 MW	1.8 MW	2.0 MW	3.2 MW	2.4 MW	3.05 MW
Rotor diameter	92 m	70 m	82 m	114 m	117 m	101 m
Hub height	100 m	86 m	138 m	143 m	140.6 m	135.4 m

* Senvion since 2014

inoperable for a longer period of time. One operator withdrew his consent to the measurement as the proposed turbine had difficulties with the acceptance inspection. A construction site was set up in the vicinity of another wind turbine, which caused background noise and thus made the measurement of the turbine noise impossible. This is just to show some of the challenges that had to be overcome during the project. The delays that were thus incurred were not foreseeable from the start.

***Figure 4-1**: Model type WT 1, REpower MM92*

***Figure 4-2**: Model type WT 2, Enercon E-66*

***Figure 4-3**: Model type WT 3, Enercon E-82*

***Figure 4-4**: Model type WT 4,* REpower 3.2M114

***Figure 4-5**: Model type WT 5,* Nordex N117/2400

***Figure 4-6**: Model type WT 6,* Enercon E-101

These images convey an impression of the examined wind power plants, covering the common power range between 1.8 MW and 3.2 MW. The hub height varies between 86 m and 143 m, the rotor diameter varies between 70 m and 117 m. Photos: batcam.de (left column), LUBW (Fig. 4-2 and 4-4), Lucas Bauer wind-turbine-models.com (Fig. 4-6)

4.1 Measurements and evaluations

The noise measurements were carried out according to DIN EN 61400-11 [6] and the technical guidelines for wind turbines [7] respectively. Furthermore, the noise immissions in the frequency range from 1 Hz were measured and further guidelines [8] [9] used if necessary.

These regulations describe noise measurement methods for determining the sound emissions of a wind turbine. They establish the procedures for the measurement, analysis and presentation of results of noise emitted by wind turbines. Likewise, requirements for the measuring devices and calibration are provided in order to ensure the accuracy and consistency of the acoustic and other measurements. This is where special microphones that can be applied from levels of 1 Hz onwards were used. The non-acoustic measurements that are necessary in order to determine the atmospheric conditions that are relevant for the determination of the noise emission are also described in more detail. All the parameters that are to be measured and illustrated, as well as the necessary data processing to determine these parameters are defined. For more details on measurement techniques, please refer to Appendix A4.

Based on the measurements, which – if possible – should be made at distances of approx. 150 m, 300 m and 700 m from the turbine (it was not always possible to observe these distances exactly), statements about emissions and immissions of the turbines can be made. The wind turbines that were to be measured were each operated in open operating mode, where the system is geared towards performance optimization. Experience has shown that the highest noise levels can be expected in this mode.

Over the entire measurement time, both third octave as well as octave bandwidths in the frequency range of 6.3 Hz to 10 Hz were formed and stored with the sound level meters used (see Appendix A4). From the recorded audio files, third octave and octave spectra were formed in the range of 1 Hz to 10 kHz as well as narrowband spectra in the range of 0.8 Hz to 10 kHz by means of digital filters. Times with extraneous noise were marked during the measurements and not used for the evaluations. The microphones were each mounted on a reverberant floor plate and provided with a primary and secondary wind screen (see ***Firgure 4.3-1***), in order to reduce or even avoid wind noise induced at the microphone. The use of a reverberant plate results in a doubling of sound pressure at the microphone, resulting in higher readings. When determining the sound power level, a correction of -6 dB therefore has to be undertaken afterwards. The correction was carried out in this report for the presentation of measured values only in the case of a comparison of results that emerged through different measuring arrangements (see ***Firgures 2-3 to 2-5*** as well as ***Table 2-1***) or comparisons with the perception threshold, e.g. in ***Figure 4.2-5***.

For some representations of the measuring results, the human perception threshold was inserted into the graphics as a comparison. This is where we used the values of DIN 45680 (2013 draft) [5]. These values are somewhat lower than those of the currently valid DIN 45680 (1997) [4] that are to be applied in accordance with the TA Lärm [10]. Below 8 Hz, the values of the standard work were supplemented by data from literature [11], see ***Table A3-1***. Further information is listed in Appendix A1 for the difficulties regarding the hearing and perception threshold. Graphical comparisons of the hearing and perception threshold are also presented there (***Figure A1-2***).

In addition to the sound level measurements, vibration measurements were also carried out at the foundation of wind turbine 5, and at distances of 32 m, 64 m and 285 m (see Section 4.8).

4.2 Noise at wind turbine 1: REpower MM92 – 2.0 MW

BASIC CONDITIONS

The wind turbine 1 (WT 1) is a power plant made by the company Repower, model MM92/100 (***Figure 4-1***) with a nominal generator capacity of 2.05 MW at a wind speed of 12.5 m/s at hub height. The rotor diameter is 92 m, the hub height above ground is 100 m. The immediate vicinity of the wind turbine is defined by agricultural land with individual trees scattered around. Adjacent to it are areas with conifer tree culitvation and forest. Further wind power plants are located in the wider vicinity of the wind turbine

***Figure 4.2-1**: Wind measurement mast with view in direction of the wind power plant being measured. Photo: Wölfel company*

being measured. These were switched off during the measurement period. A path in close proximity is allowed to be used only by agricultural traffic and is used only seldom. The measurements were carried out on 11.04.2013 between 8:00 a.m. and 4:00 p.m. The position of the microphone at the measurement point MP1 was at a distance of 150 m to the power plant in a downwind direction. This was in order to take into account the worst case scenario (support of sound propagation through the wind). Further measurement points MP2 and MP3 were located at intervals of 300 and 700 m in a downwind direction. ***Figure 4.2-1*** provides an impression. The measurement was carried out in a wind speed range of 5 to 14 m/s, a temperature range of 10 to 12 °C and an atmospheric pressure range of 946 to 951 hPa. The entire power range of the power plant was covered up to the nominal power. The turbulence intensity, which is basically a measure of the gustiness of the wind (see Appendix A3), was 18 %.

RESULTS: NARROW BAND LEVEL

Figure 4.2-2 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 150 m with a resolution of 0.1 Hz. The wind speed was 6.5 m/s. With the power plant switched on, six discrete maxima can be clearly seen in the infrasound range between 1 Hz and 5.5 Hz. This concerns infrasound generated by the rotor due to its motion. The measured frequencies correspond to the passage frequency of a rotor blade of approximately 0.75 Hz, which corresponds with a frequency of the rotor of 15 rpm and the harmonic overtones at 1.5 Hz, 2.2 Hz, 3.0 Hz, 3.7 Hz, 4.5 Hz and 5.2 Hz (***Figure 4.2-2***). Further maxima were measured at 25 Hz and

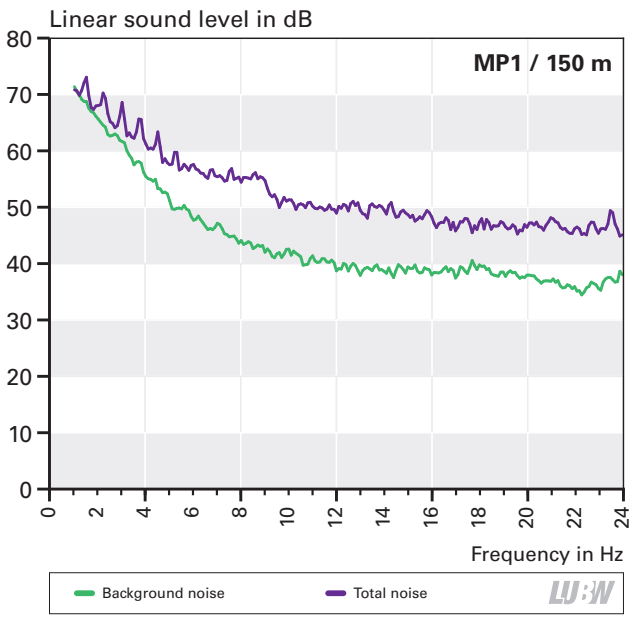


***Figure 4.2-2**: Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 1 for the frequency range of infrasound*

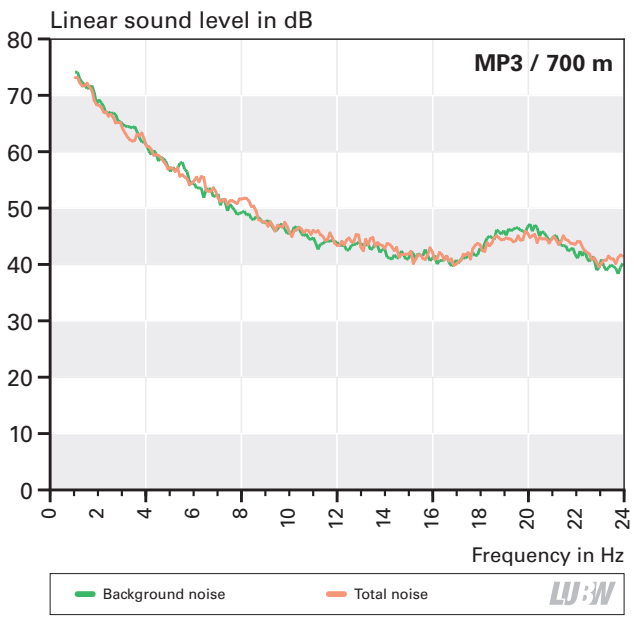


***Figure 4.2-3**: Narrow band spectra of background noise and total noise at a far range from the wind turbine WT 1 for the frequency range of infrasound*

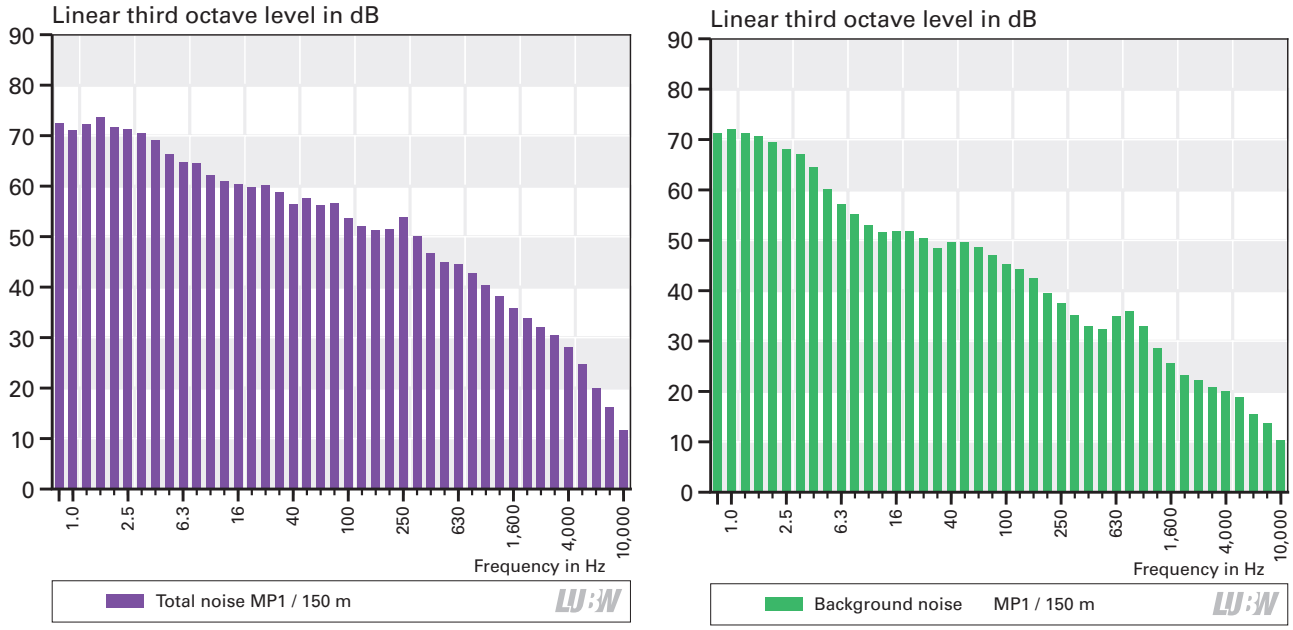


***Figure 4.2-4**: Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 1*

50 Hz, These are at a much lower level, and are attributable to the operation of the generator. The peaks disappear when the power plant is switched off.

Figure 4.2-3 shows the narrow band spectra of background noise and overall noise at the measurement point MP3 at a distance of 700 m. At this distance, no discrete infrasound maxima can be distinguished anymore when the power plant is on. There were no measurable differences in infrasound between the conditions "turbine on" and "turbine off" for this measurement at a distance of 700 m. This was apparently caused by the noise of wind and the surroundings. Here too, the wind speed was 6.5 m/s.

RESULTS: THIRD OCTAVE LEVEL

Figure 4.2-4 shows the third octave spectra of background noise and overall noise at the measurement point MP1 (150 m) for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 6.5 m/s. The level reduction due to the shutdown of the power plant is visible here in a considerably broader spectral range.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.2-5 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP3 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was

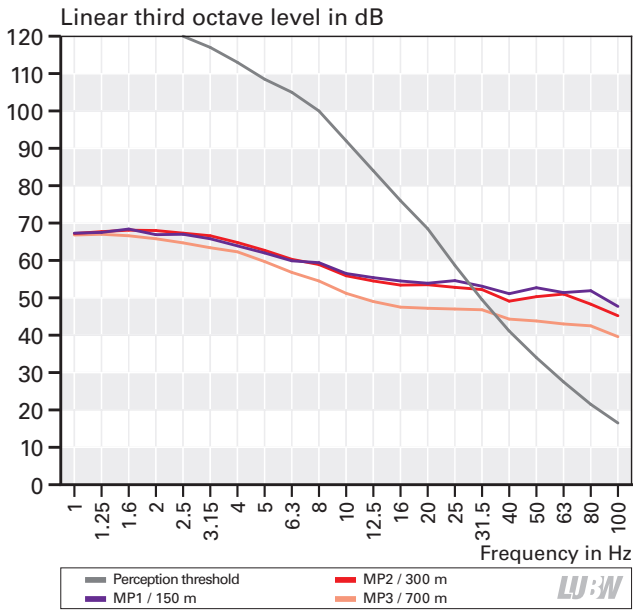


***Figure 4.2-5**: Third octave spectra of total noise at the measurement points MP1 (150 m), MP2 (300 m) and MP3 (700 m) of WT 1, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

6.8 m/s. It must be kept in mind that the background noise of wind and vegetation are also included. These may vary at the respective measurement point. It is apparent that from about 6-8 Hz the overall noise becomes less with increasing distance to the power plant. The differences become clearer with increasing frequency. In terms of audible sound, this constitutes an audible effect. At the measure-

ment point located at a distance of 700 m, the turbine is no longer constantly and at most only slightly noticeable; the curve is almost the same as for the background noise. In the infrasound range, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

The above charts reflect a concrete individual situation at a given wind speed (6.5 or 6.8 m/s respectively) as an example. However, the results were presented at different frequencies. Of course this is where the question arises as to what the relationships are like at different wind speeds. These were also measured, and the results are shown in ***Figure 4.2-6***. This figure is not easy to understand straight away and should therefore be explained step by step.

The three graphs represent the relationships at the respective measurement points at a distance of 150 m (upper figure), 300 m (middle figure) and 700 m (lower figure). The wind speed of 4.5 to 10.5 m/s is placed on the bottom, horizontal axis. The vertical axis represents the sound level values. Each point corresponds to a single measurement sequence of 10 seconds at a given wind speed. Violet dots, which depict the lower value area, represent audible sound with the turbine on, expressed in dB(A). It is easy to see at distances of 150 and 300 m that the audible sound increases slightly at wind speeds of 4.5 m/s up to just above 5.5 m/s, but then remains constant at higher wind speeds. How does this behave with low-frequency sound or infrasound respectively? In order to find out, the dependency of the G-weighted sound level, specified as dB(G), was examined.

The red dots represent the G-weighted sound level when the turbine is switched on, the green dots when the turbine is switched off. In the vicinity of the power plant, at a distance of 150 m (upper image), you can see clearly that the sound level is similarly dependent on the wind speed also in the low-frequency range (incl. infrasound) as is the case for audible sound when a power plant is switched on. Furthermore, it is also visible that there is a clear difference between the turbine being on and the turbine being off. The G levels are significantly higher when the turbine is on (red dots) than when it is switched off (green dots). At a distance of 300 m (middle image) this difference is already less pronounced, and at 700 m it is no longer recognizable. There is virtually no difference anymore between the red cluster of dots (turbine on) and the green cluster of dots (turbine off), regardless of the wind speed.

These readings also show clearly that the background noise through wind and vegetation, measured when the turbine is switched off (green dot cluster), is subject to strong scattering, i.e. particularly noticeable natural fluctuations. The values span a range of up to 20 dB(G). The measured sequences of the turbine noise, on the other hand, scatter significantly less, at least in the near-field.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.2-7 shows the A and G-weighted level curves between 11:00 a.m. and 3:00 p.m. at a distance of 150 m and 700 m. In addition, the operating conditions of the wind turbine (green = turbine on, light blue = turbine off) as well as periods of time with external noise (violet) are depicted. For the two level developments of measurement point MP1, the operational phase "turbine off" is easily recognisable through the considerably declining level developments. At the measurement point MP3, a drop in the level with the turbine turned off is barely distinguishable due to the fluctuating background noise – only the minima of the A level development are slightly lower than when the turbine is on. The G level development, however, covers nearly the same range of values as when the turbine is switched off.

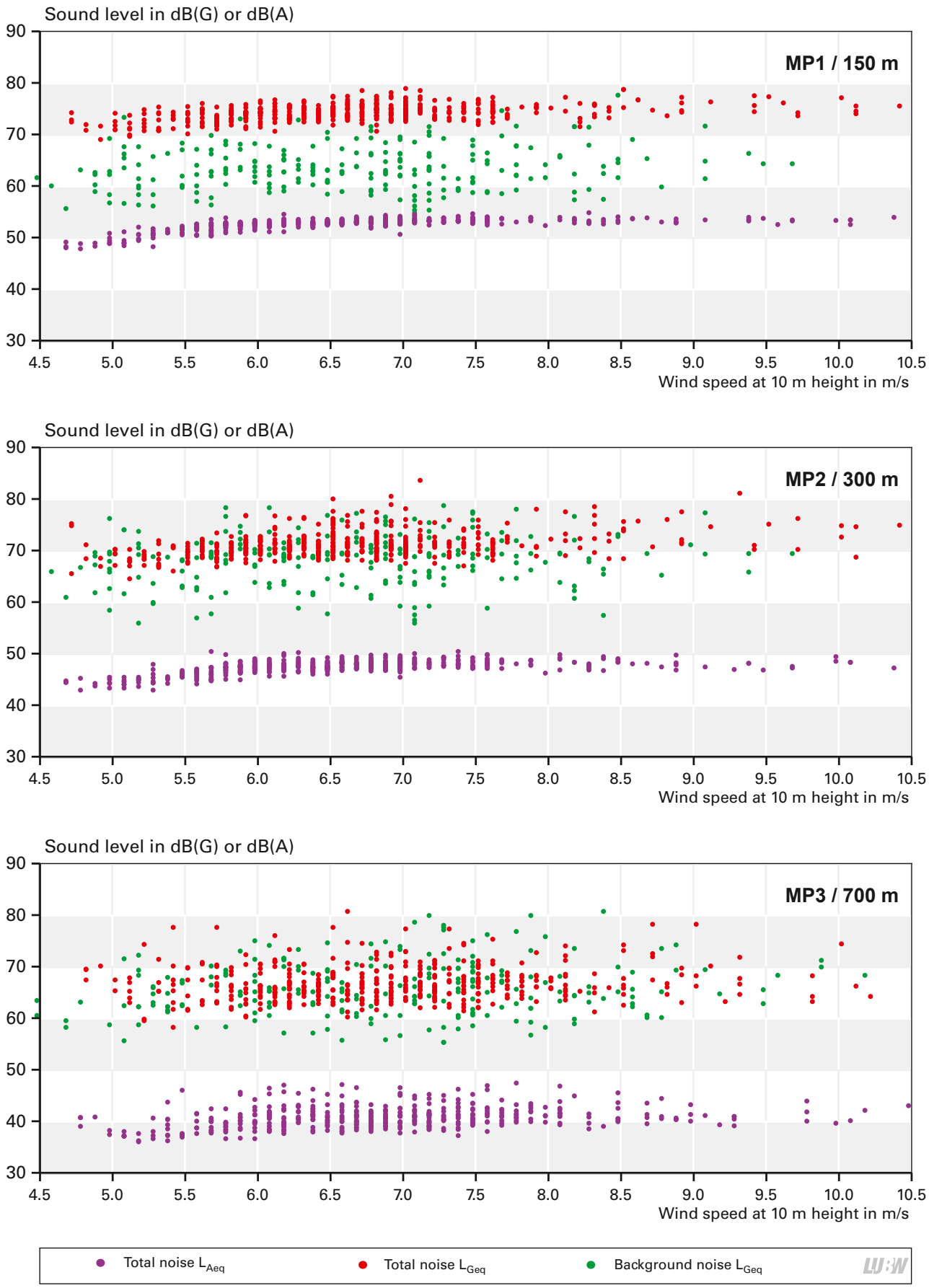


***Figure 4.2-6**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 1. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

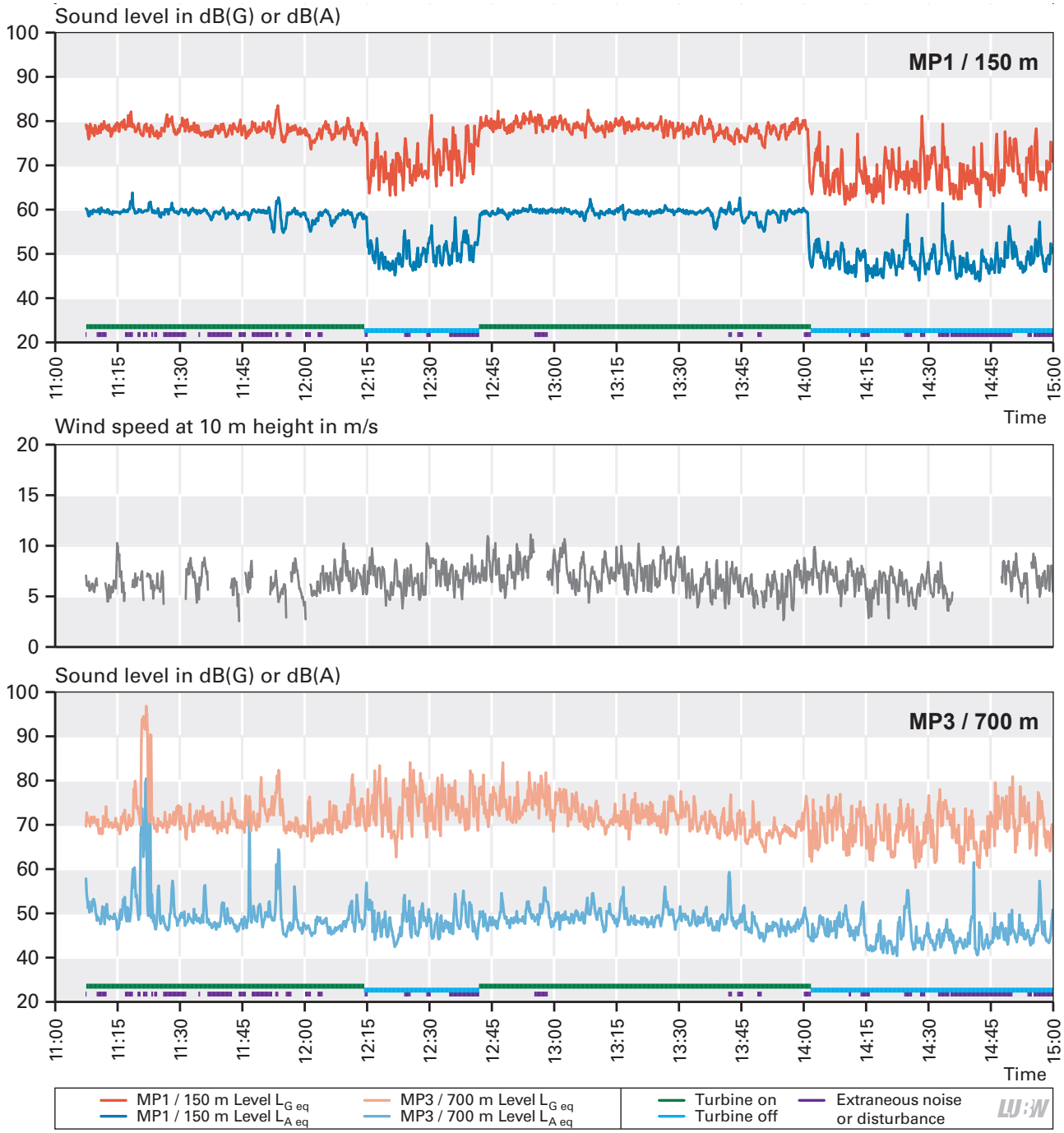


***Figure 4.2-7**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 1*

4.3 Noise at wind turbine 2: Enercon E-66 – 1.8 MW

BASIC CONDITIONS

The wind turbine 2 (WT 2) is a gearless unit by the company Enercon, Model E-66 18/70 (***Figure 4-2***) with a nominal generator capacity of 1.8 MW. The rotor diameter is 70 m, the hub height above ground is 86 m. The immediate vicinity of the turbine consists of agricultural land, with forest partly adjacent to it. Further wind turbines are located in the vicinity. These were completely turned off during the measurement period in order to prevent extraneous noise. A further wind power plant is located at a distance of about 1.5 km; this was in operation during the measurement period. A path in close proximity is allowed to be used only by agricultural traffic and is used very seldom. The measurements were carried out on 02.11.2013 between 10:00 a.m. and 6:00 p.m. The position of the microphone at the measurement point MP1 was at a distance of 120 m from the power plant, measurement point MP2 at a distance of 240 m, both in a downwind direction (in order to take into account the propagation of sound through the wind). The microphone at the measurement point MP3 was positioned at a distance of 300 m from the tower axis and deviated by 30° from the prevailing wind direction. A measurement point at a distance of 700 meters was not possible at this site. ***Figure 4.3-1*** provides an impression.

The measurement was performed in a wind speed range of 5 to 15 m/s (measured at 10 m height), a temperature range of 11 to 12.5 °C, an air pressure range of 926 to 927 hPa and in a power range of 0 to 1,800 kW. The turbulence intensity (see Appendix A3) during the measurement was 28 % and thus relatively high.

RESULTS: NARROW BAND LEVEL

Figure 4.3-2 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 120 m with a resolution of 0.1 Hz. The wind speed was 9 m/s. With the turbine turned on, several discrete maxima can be observed in the infrasound range below 8 Hz. This concerns infrasound generated by the rotor due to its motion. The measured frequencies are in accordance with the passage frequency of a rotor blade and its harmonic overtones. At 22.5 rpm, the speed at which the turbine was running, one can mathematically determine the peaks at 2.2 Hz, 3.4 Hz, 4.5 Hz, 5.6 Hz, 6.8 Hz and 7.9 Hz with good conformance. They disappear when the turbine is turned off; at a distance of 300 m they occur

Figure 4.3-1*: Measurement point MP1 with microphone, reverberant plate and dual wind screen. In the background: wind turbine WT 2 at a distance of 120 m. Photo: Wölfel company.*

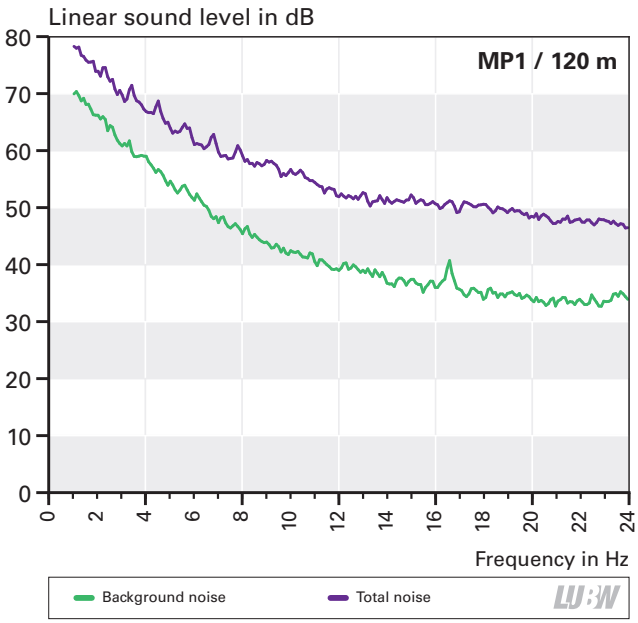


Figure 4.3-2 *Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 2 for the frequency range of infrasound*

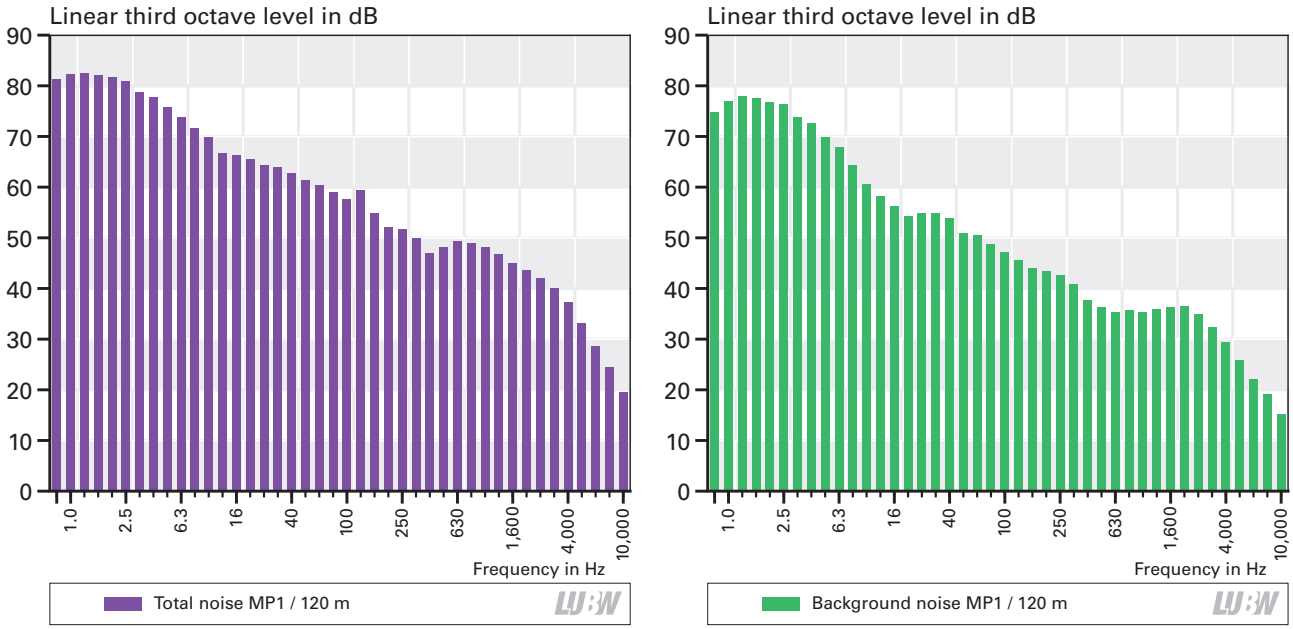


***Figure 4.3-3**: Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 2*

only faintly (not shown). The level peak at approx. 17 Hz that is clearly visible in the background is probably due to extraneous noise.

RESULTS: THIRD OCTAVE LEVEL

Figure 4.3-3 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 120 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 9 m/s. The level reduction through switching off the turbine is recognizable in a much broader spectral range here.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.3-4 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP3 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 9 m/s. The background noise of wind and vegetation are also included. These may vary at the respective measurement point. The measurement points MP2 and MP3 are further away from the turbine than measurement point MP1 (240 m and 300 m compared to 120 m). This is where somewhat lower values are also measured, which becomes more apparent with increasing frequency. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were taken and are depicted in ***Figure 4.3-5***. The three charts represent the conditions at distances of 120 m (MP1, upper figure), 240 m (MP2, middle figure) and 300 m with a lateral displacement by 30° to the wind direction (MP3, lower figure). The violet dots in the lower range of values represent audible sound, expressed in dB(A). In the upper image it

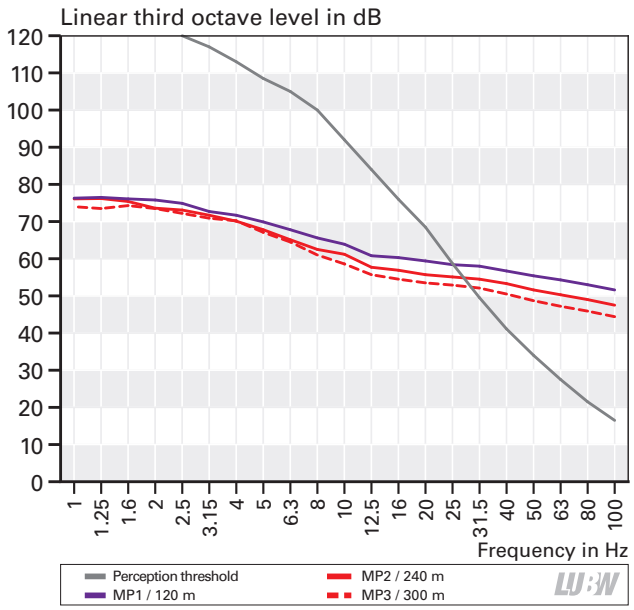


***Figure 4.3-4**: Third octave spectra of total noise at the measurement points MP1 (120 m), MP2 (240 m) and MP3 (300 m) of WT 2, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

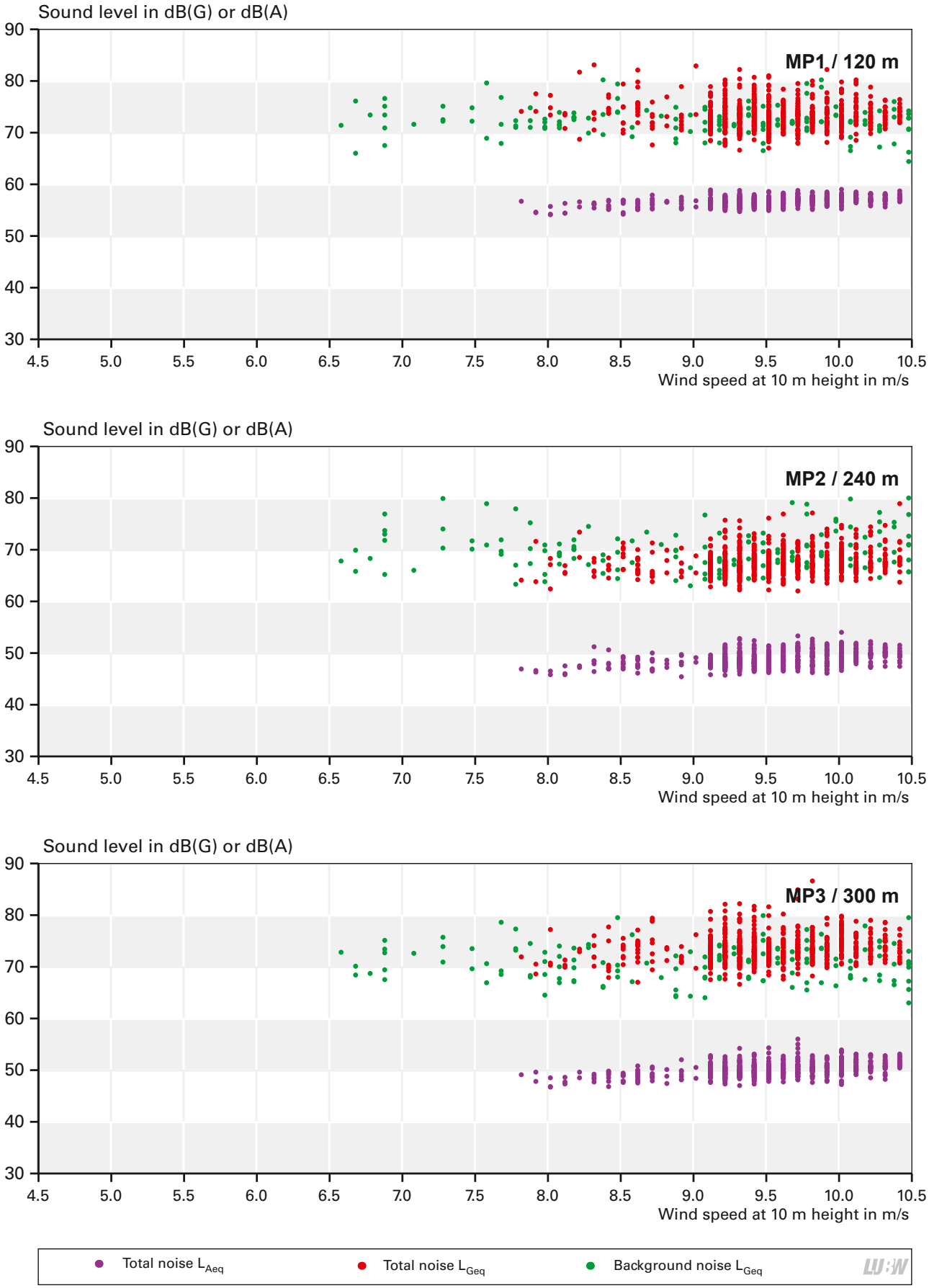


***Figure 4.3-5**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 2. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

can be seen clearly that the measured A levels are higher at a distance of 120 m than at the measurement points at a distance of 240 m and 300 m from the power plant. The turbine was perceived to be louder at a distance of 120 m than at a distance of 240 m.

The red dots represent the G-weighted sound level when the turbine is switched on, the green dots when the turbine is switched off. The upper image shows that at the measurement point MP1, i.e. in the near field at a distance of 120 m from the power plant, the G-weighted sound pressure level during operation of the wind power plant is approximately constant and minimally higher than that of the background noise when the turbine is not running. A similar situation is given at the measurement points MP2 and MP3. Hardly any differences can be seen between the measured values, as the red and green dot clusters pretty-much overlap each other.

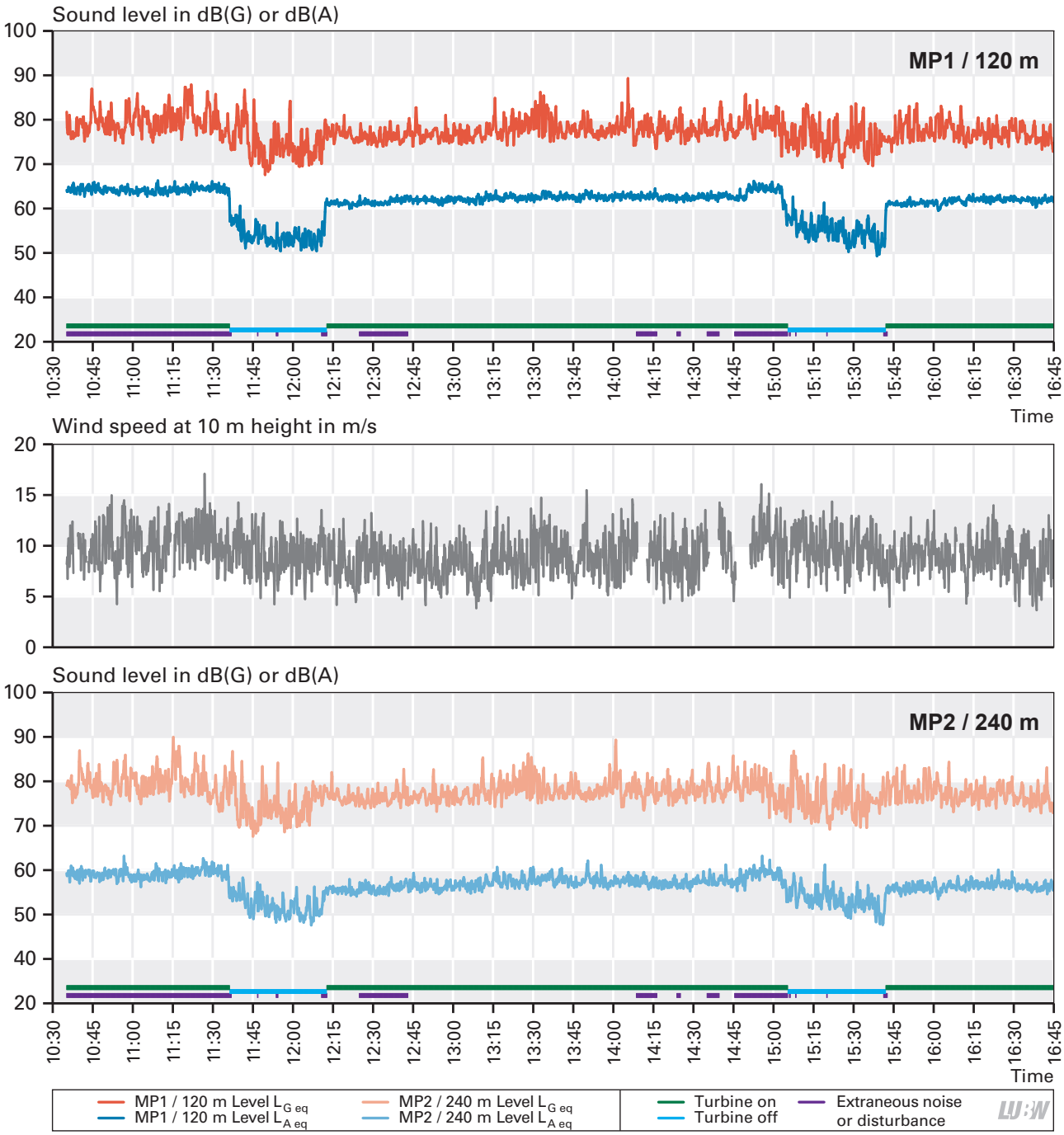


***Figure 4.3-6**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements at the wind turbine WT 2*

The relatively large scattering of the measured values for when the turbine is running and when it is not running, and the relatively high G-weighted sound pressure level – even when the turbine is off – are in this case probably due to the high wind speeds prevailing throughout. The measurements with the turbine in operation were taken in the range of 8 to 11.5 m/s (10 m height). In this case, part of the effect is potentially also attributable to wind-induced noise at the microphones.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.3-6 shows the A and G-weighted level curves between 10:30 a.m. and 5:00 p.m. at a distance of 120 m and 240 m. In addition, the operating conditions of the wind turbine (green = turbine on, light blue = turbine off) as well as periods of time with external noise (violet) are depicted. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. At measurement point MP2, the level drop is less pronounced when the turbine is off, but still clearly recognizable.

Figure 4.4-1*: Wind turbine WT 3 in surroundings used for agricultural purposes. The measurement point with reverberant plate and dual wind screen can be seen in the foreground. Photo: Wölfel company*

4.4 Noise at wind turbine 3: Enercon E-82 – 2.0 MW

BASIC CONDITIONS

The wind turbine 3 (WT 3) is a gearless unit by the company Enercon, Model E-82 E2 (***Figure 4-3***) with a nominal generator capacity of 2.0 MW. The rotor diameter is 82 m, the hub height above ground is 138 m. As can be seen in ***Figure 4.4-1***, agriculturally used areas are located in the closer vicinity. An adjacent wooded area is located at a distance of about 400 meters. A dirt road is located in the immediate vicinity of the power plant, which is used only seldom by agricultural and forestry vehicles. A road is located at a distance of approx. 450 m from the power plant. During the measurement, no traffic noise was noticeable. Further wind turbines from other operators are located at a distance of 1,500 meters. These power plants located further away were in operation during the measurement period. The immissions were not subjectively noticeable during the background noise measurements. The nearest residential building is more than 1,000 meters away. The measurement was carried out on 15.10.2013 between 10:30 a.m. and 3 p.m. The microphone at the measurement point MP1 was located at a distance of 180 meters in a downwind direction from the tower axis, at the measurement point MP2 it was 300 m in a downwind direction. The microphone at the measurement point MP3 was also positioned at a distance of 300 meters, however at an angle of 90° to the downwind direction. A measurement point at a distance of 700 meters was not feasible due to the local conditions.

The measurement was performed in a wind speed range of 2 to 12 m/s (measured at 10 m height), a temperature range of 9 to 13 °C, an air pressure range of 931 to 934 hPa and in a power range of 0 to 2,070 kW. The turbulence intensity (see Appendix A3) during the measurement was 25 % and thus relatively high.

RESULTS: NARROW BAND LEVEL

Figure 4.4-2 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m with a resolution of 0.1 Hz. With the turbine turned on, several discrete maxima can be clearly observed in the infrasound range below 8 Hz. This con-

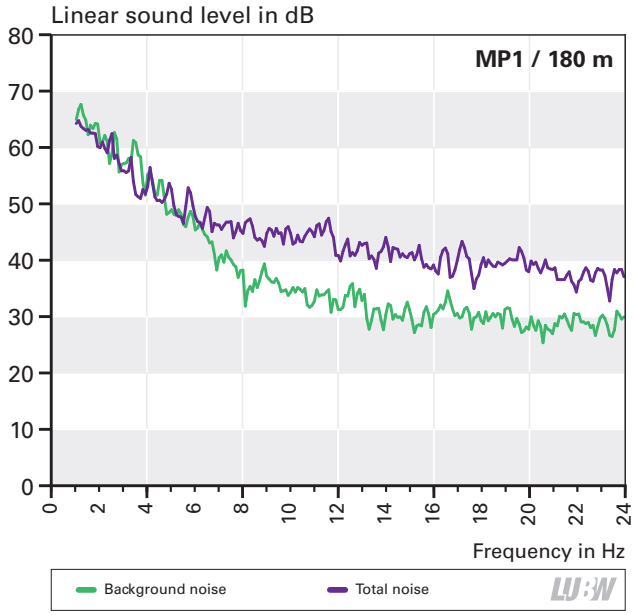


***Figure 4.4-2**: Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 3 for the frequency range of infrasound*

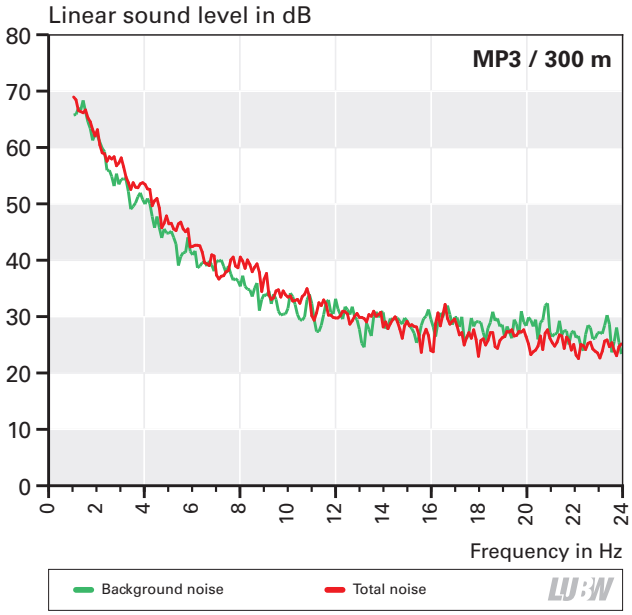
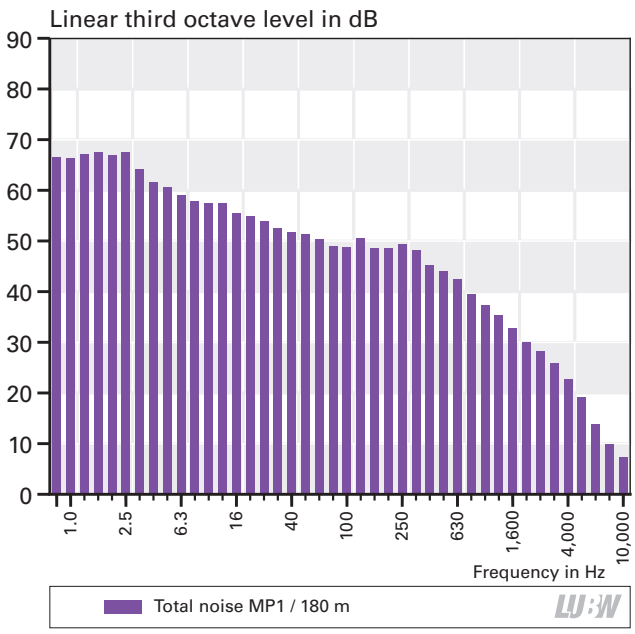


***Figure 4.4-3**: Narrow band spectra of background noise and total noise in the far range of the wind turbine WT 3 for the frequency range of infrasound*

cerns infrasound generated by the rotor due to its motion. The measured frequencies correspond to the passage frequency of a rotor blade (here about 0.83 Hz) and the associated harmonic overtones (2.5 Hz, 3.3 Hz, 4.1 Hz, 5 Hz, 5.8 Hz). The peaks disappear when the power plant is switched off, and occur only slightly at a distance of 300 m (***Figure 4.4-3***). The wind speed was 6 m/s during both measurements.

RESULTS: THIRD OCTAVE LEVEL

Figure 4.4-4 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 6 m/s. Here the level reduction through switching off the turbine is recognizable in a much broader spectral range.



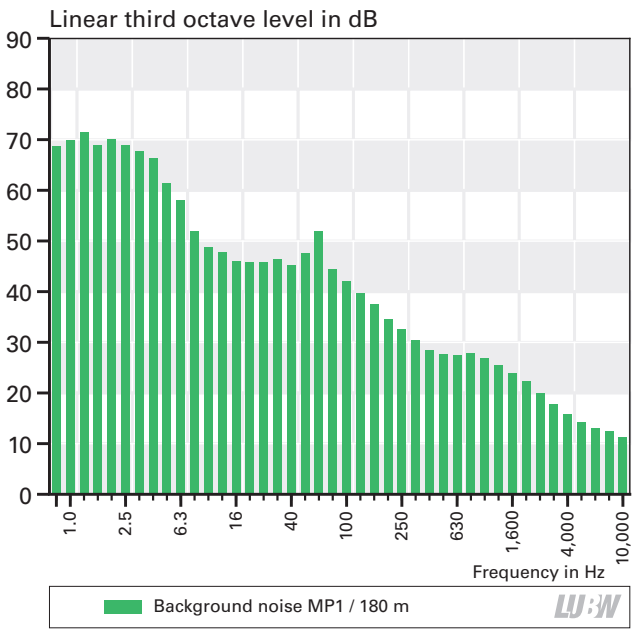


***Figure 4.4-4**: Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 3*

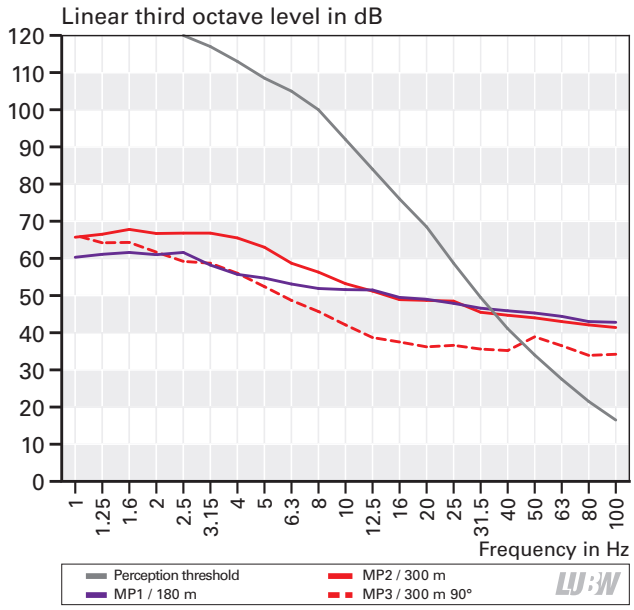


***Figure 4.4-5**: Third octave spectra of the total noise at the measurement points MP1 (180 m), MP2 (300 m) and MP3 (300 m, offset by 90 °) of wind turbine 3, perception threshold according to Table A3-1 for comparison. The measured values were corrected according to Section 4.1.*

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.4-5 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP3 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 9 m/s. It must be kept in mind that the background noise of wind and vegetation are also included. These may vary at the respective measurement point. The measurement points MP2 and MP3 are further away from the power plant than measurement point MP1 (300 m compared to 180 m). Measurement point MP3 is offset to the downwind direction by 90°. Lower values are thus measured there than at measurement point MP2, which is equally far away. The measurement point MP2 is also closer to an existing nearby road than the measurement points MP1 and MP3, which could also be a reason for the slightly higher values. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.4-6***. The three charts represent the relationships at the respective measurement points at the distances 180 m (top), 300 m (centre) and 300 m with lateral offset by 90° to the downwind direction (bottom). Violet dots, which depict the lower curve, represent audible sound, expressed in dB(A). It can be clearly seen that at a distance of 180 m (top image) the measured A levels are higher than at the measurement points at a distance of 300 m from the turbine. The turbine was thus also clearly more perceptible at a distance of 180 m than at a distance of 300 m. The A level first rises with increasingly higher wind speed.

The red dots represent the G-weighted sound level when the wind power plant is switched on, the green dots when the power plant is switched off. Similarly to the A level, it can also be seen for the G level that – despite higher scattering – it increases somewhat with increasing wind speed, and then remains constant.

The top image shows that at MP1, i.e. in the near field at a distance of 180 m from the turbine, the G-weighted sound pressure level during operation of wind turbine 3 is significantly higher than the background noise when the turbine is off. This is far less pronounced at a distance of 300 meters (centre image) and barely detectable at a distance of 300 meters with 90° offset to the downwind direction (bottom image). The red and green dot clusters then overlap each other in many areas.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.4-7 shows the A and G-weighted level development between 10:15 a.m. and 2:45 p.m. for distances of 180 m and 300 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. At measurement point MP2, the recognisable level drop is significantly weaker with the turbine switched off due to the fluctuating background noise.

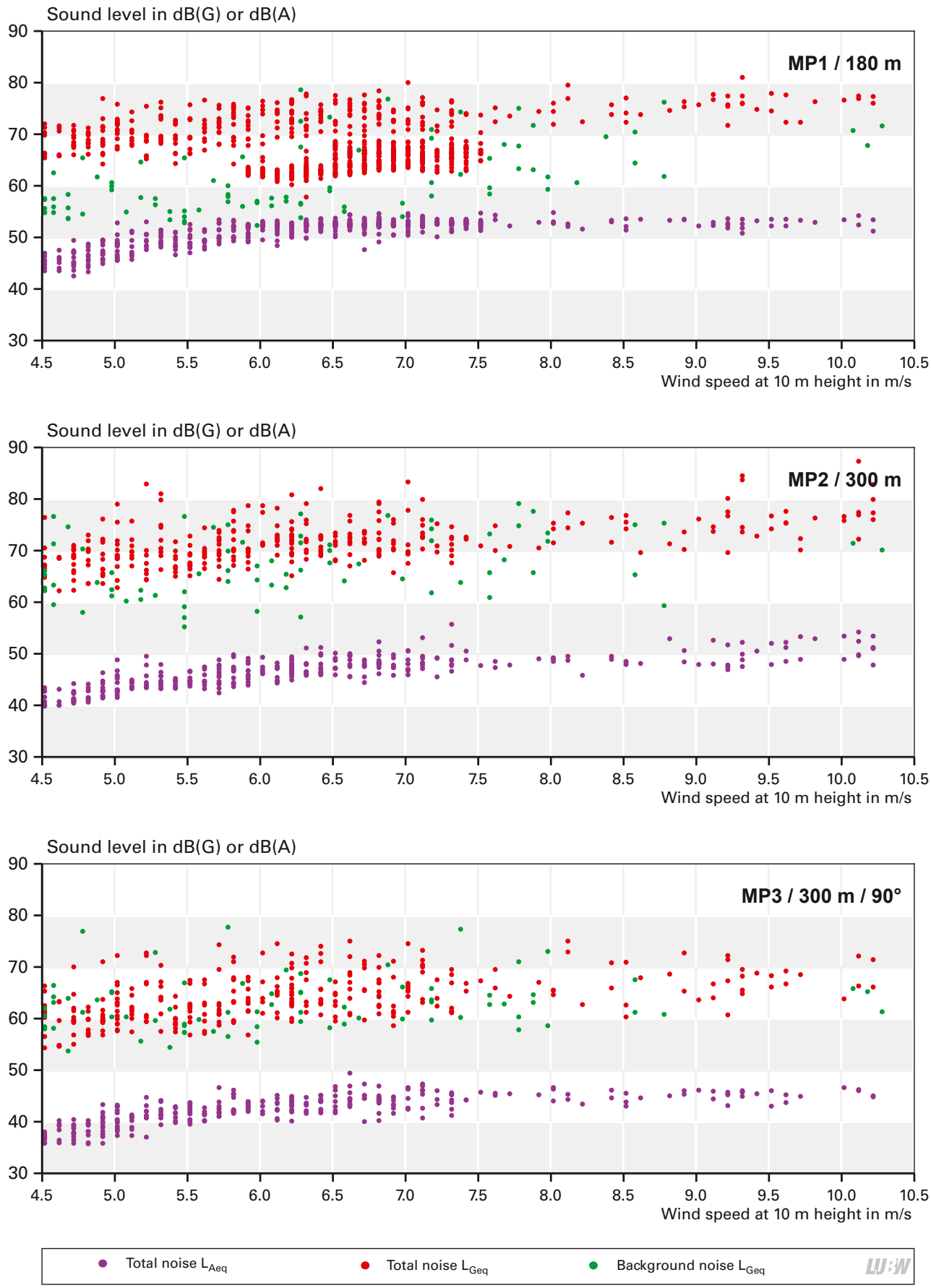


***Figure 4.4-6**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 3. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

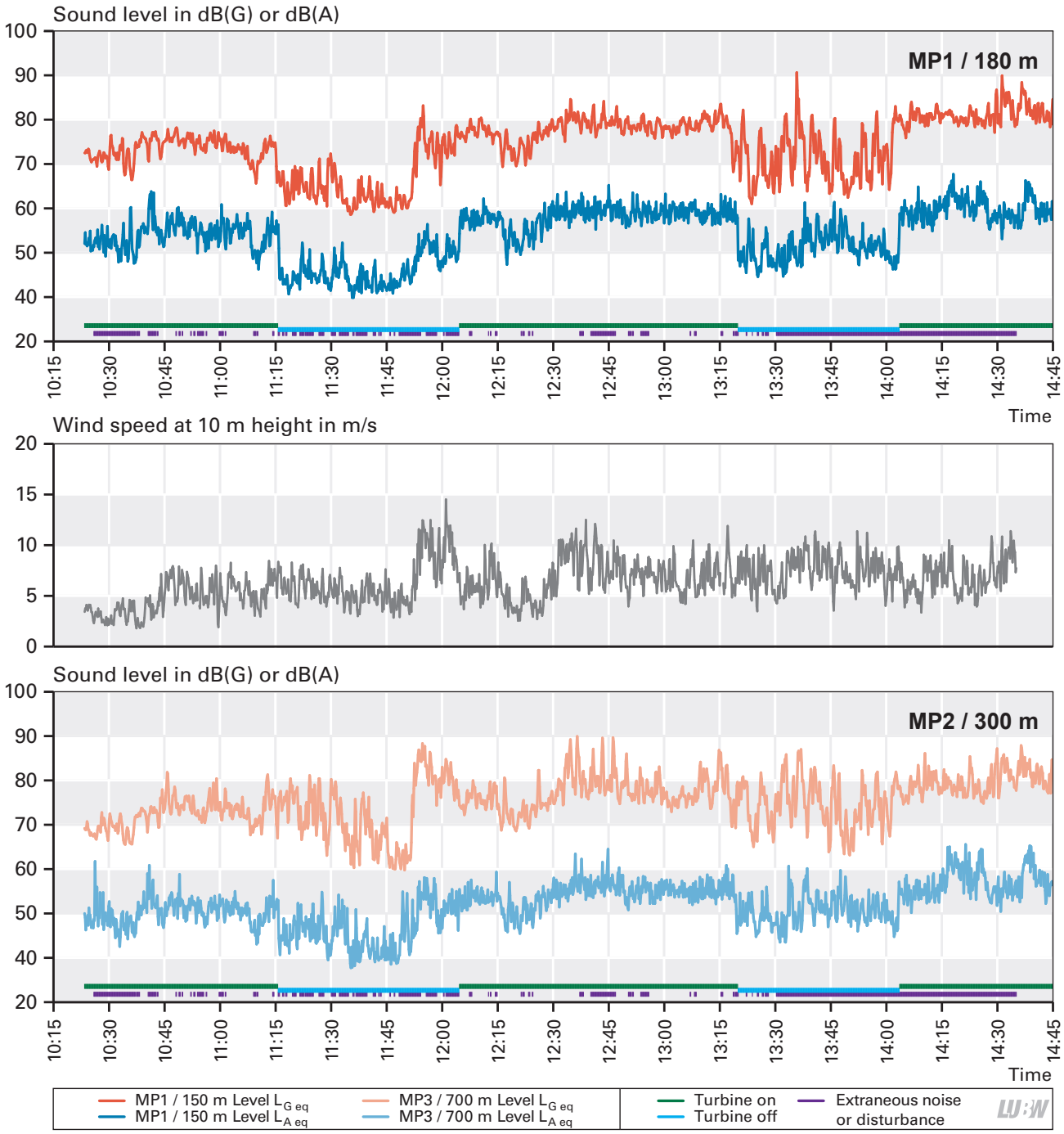


***Figure 4.4-7**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 3*

4.5 Noise at wind turbine 4: REpower 3.2M114 – 3.2 MW

BASIC CONDITIONS

The wind turbine 4 (WT 4) is a unit by the company REpower, type 3.2M114 (***Figure 4-4***) with a nominal generator capacity of 3.2 MW. The rotor diameter is 114 m, the hub height 143 m.

The measured wind turbine is part of a wind farm with several other wind turbines. The adjacent turbines were completely turned off during the measurement period in order to prevent extraneous noise. The vicinity of the turbine consists of agricultural land. A dirt road in the immediate vicinity of the measured turbine is rarely used by agricultural traffic. A forest is located further away. Further wind turbines were in operation at distances of 0.7 km and 2 km, in the opposite direction to the measurement points. Their noise could not be subjectively perceived at any time. The measurements were carried out on 20.03.2014 between 10:00 a.m. and 9:30 p.m. The position of the microphone at the measurement point MP1 was at a distance of 180 m from the turbine, measurement point MP2 and MP3 at a distance of 300 m and measurement point MP4 at a distance of 650 m, in a downwind direction respectively, in order to take into account the most adverse case (promotion of sound propagation through the wind). The measurement point MP2, located directly next to measurement point MP3, served as a comparative measurement point. Its microphone was provided with a primary wind screen and placed into an approx. 50 cm deep hole that was dug especially for that purpose. A secondary wind screen covered the hole flush. The parallel measurements were taken at the measurement points MP2 and MP3 in order to enable a comparison of the measurement values and enable conclusions to be made regarding wind-induced sound components arising at the microphone. The two measurement points MP2 and MP3, as well as the measured turbine, can be seen in ***Figure 4.5-1***. ***Figures 4.5-2 to 4.5-5*** provide an impression of the conditions on site and the measurement technology used.

The measurement was performed in a wind speed range of 3 to 7 m/s (measured at 10 m height), a temperature range

Figure 4.5-1 *(right): Measurement points MP2 and MP3 at a distance of 300 m from the tower axis. Reverberant plate and double wind screen (left), spanned hole in the ground (right). Photo: Wölfel company*

Figure 4.5-2*: View inside the power plant with 143 m hub height. Photo: LUBW*

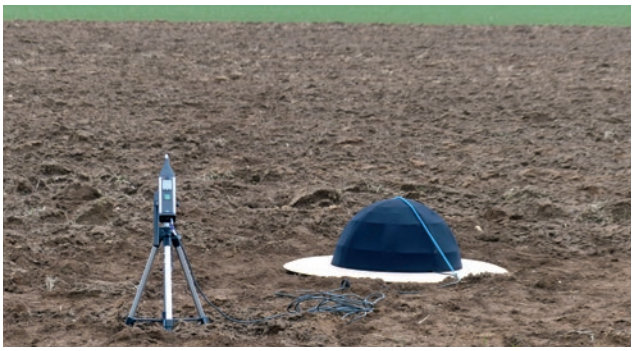


Figure 4.5-3*: Reverberant plate with mounted microphone and dual wind screen. The type DUO measurement device is mounted on a tripod next to it and is connected to the microphone via a measuring cable. Photo: LUBW*

***Figure 4.5-4**: Anemometer mast for measuring wind speed and wind direction, air pressure, humidity and temperature. The mast is extended to 10 m (not yet extended in the image). Photo: LUBW*

***Figure 4.5-5**: Data is constantly collected inside the system during the measurement and transmitted by radio (left). Photo: LUBW*

of 15 to 19 °C, an air pressure range of 979 to 981 hPa and in a power range of 0 to 3,170 kW. The turbulence intensity (see Appendix A3) during the measurement was 15 %.

RESULTS: NARROW BAND LEVEL

Figure 4.5-6 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m with a resolution of 0.1 Hz. With the turbine turned on, clearly visible maxima can be seen in the infrasound range. The measured frequencies correspond to the passage frequency of a rotor blade (here approximately 0.6 Hz) and its harmonic overtones at 1.2 Hz, 1.8 Hz, 2.4 Hz, 3 Hz, etc. This concerns infrasound generated by the rotor due to its motion. The peaks disappear when the turbine is switched off. ***Figure 4.5-7*** shows the narrowband spectra of background noise and total noise at the measurement point MP4 at a distance of 650 m. At this location the discrete infrasound maxima (see measurement point MP1) are still detectable with the wind power plant turned on. The recognizable slightly higher levels at measurement point MP4, with frequencies lower than 5 Hz, cannot be attributed to turbine operation. The cause for

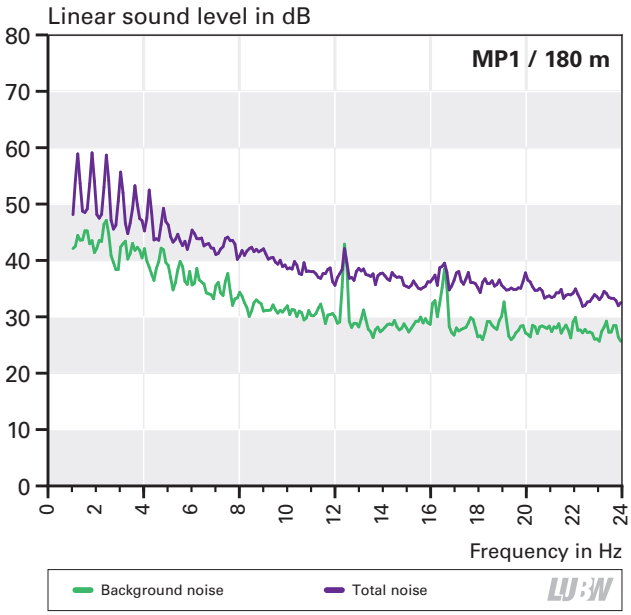


***Figure 4.5-6**: Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 4 for the frequency range of infrasound*

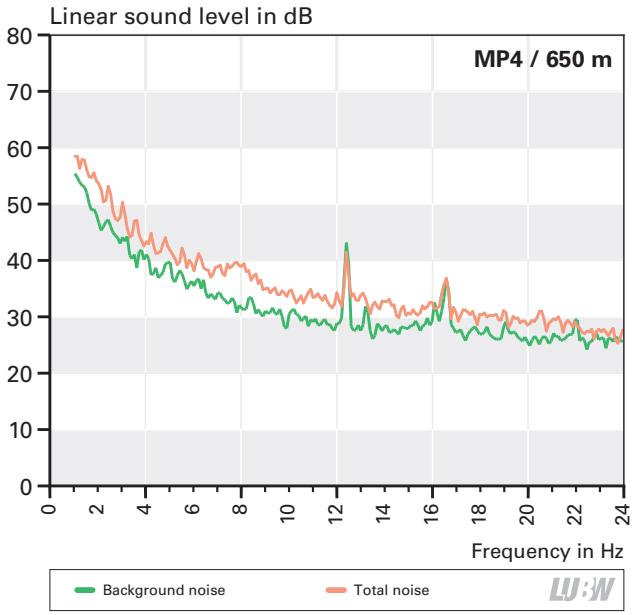


***Figure 4.5-7**: Narrow band spectra of background noise and total noise in the far range of the wind turbine WT 4 for the frequency range of infrasound*

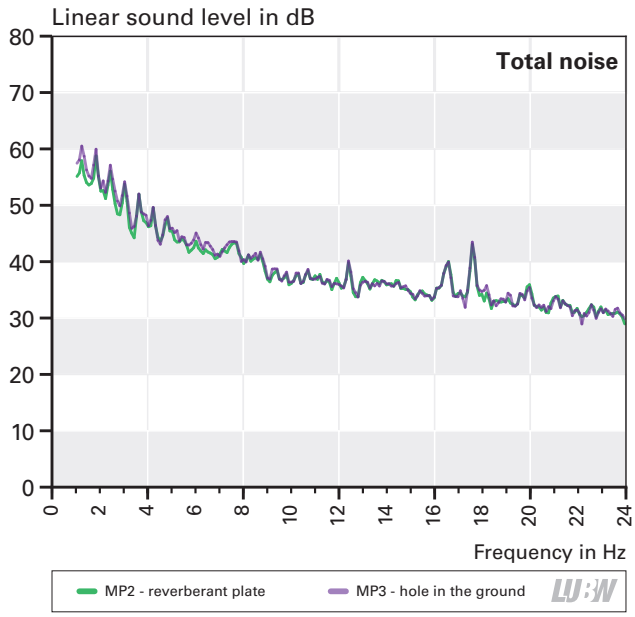


***Figure 4.5-8**: Narrowband spectra of the total noise at the measurement points MP2 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 4 for the range of infrasound. The distance from the turbine was 300 m*

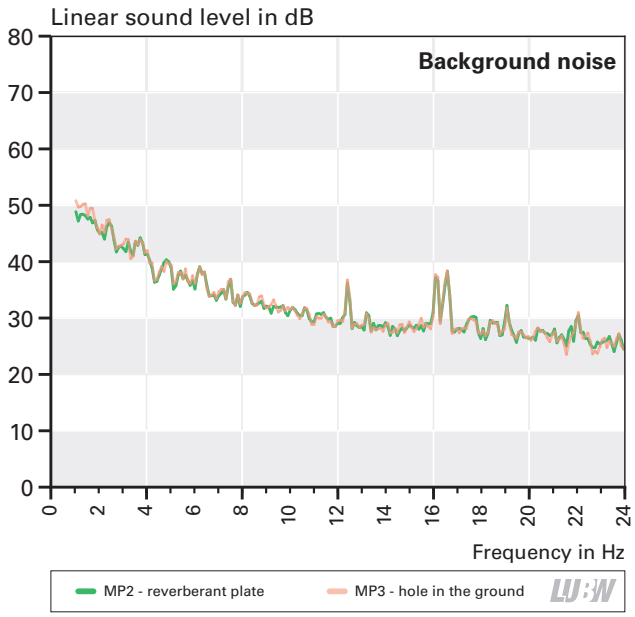


***Figure 4.5-9**: Narrowband spectra of the background noise at the measurement points MP2 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 4 for the range of infrasound. The distance from the turbine was 300 m.*

the up to 10 dB higher values is another background noise at the measurement point MP4 compared to the measurement point MP1. The wind speed was 5.5 m/s for both measurements.

The comparison of narrowband spectra for the two measurement points MP2 and MP3 in ***Figures 4.5-8 to 4.5-9*** shows that there is no significant difference between the two measurement points for the range of infrasound. The wind speed was 5.5 m/s respectively. It can therefore be assumed that below 20 Hz neither the absorption of the secondary wind screen nor the ground influences play a role. The increase in level towards lower frequencies was present in this measurement to an equal extent both with and without a hole in the ground. The expected reduction in the wind-induced background noise in the infrasound range cannot be observed in a direct comparison between the two measurement points. Further investigations regarding the issue of noise at the microphone induced by the wind were thus not deemed necessary.

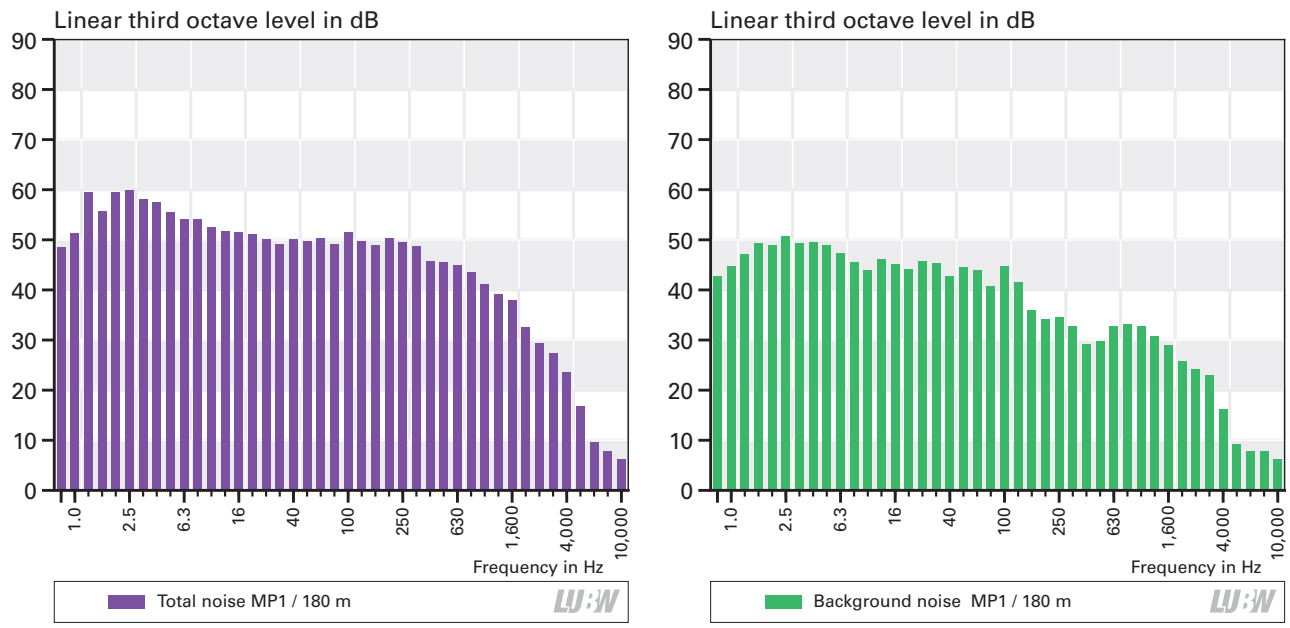


***Figure 4.5-10**: Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 4*

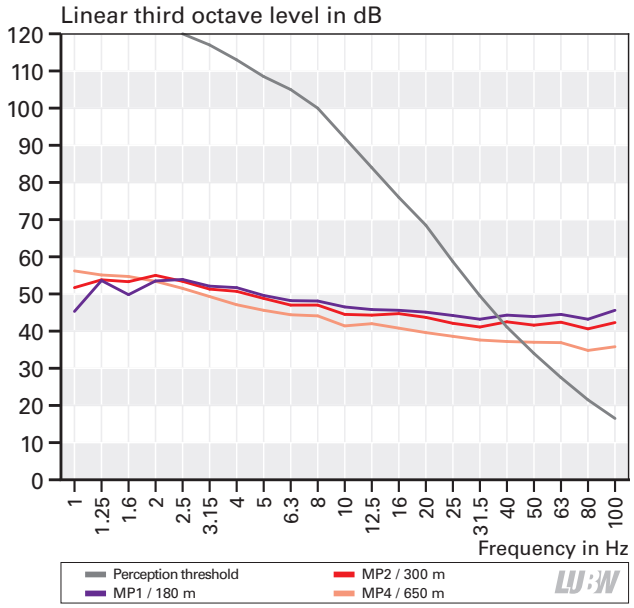


***Figure 4.5-11**: Third octave spectra of total noise at the measurement points MP1 (180 m), MP2 (300 m) and MP4 (650 m) of WT 4, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

RESULTS: THIRD OCTAVE LEVEL

Figure 4.5-10 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 5.5 m/s. Here the level reduction through switching off the turbine is recognizable in a much broader spectral range.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.5-11 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP4 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 5.5 m/s. It must be kept in mind that the background noise of wind and vegetation are also included. These may vary at the respective measurement point. The measurement points MP2 and MP4 are further away from the turbine than MP1 (300 m and 650 m compared to 180 m). This is where somewhat lower values are also measured, which becomes more apparent with increasing frequency. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.5-12***. The three charts represent the relationships at the respective measurement points at the distances 180 m (top), 300 m (centre) and 650 m (bottom). Violet dots, which depict the lower value area, represent audible sound, expressed in dB(A). It can be seen clearly that the measured A levels are higher at a distance of 180 m (upper image) than at the measurement points at a distance of 300 m and 650 m from the turbine.

The red dots represent the G-weighted sound level when the wind turbine is switched on, the green dots when the turbine is switched off. The data shows that the G-weighted sound pressure level of the tested measurement points increases slightly during operation of the wind turbine with increasing wind speed. For the G-weighted sound pressure level of the background noise, no connection can be ascertained with the wind speed for the main part of the measuring period. However, the readings are also in a similar order with the turbine switched off due to strongly fluctuating wind conditions (gusts, turbulence). Lower levels were observed for the background noise merely for a late, roughly 30-minute measurement period from 8:50 p.m. onwards. During this period, the mean normalized wind speed was relatively constant at 5.5 m/s.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.5-13 shows the A and G-weighted level development between 4:00 p.m. and 9.00 p.m. for the distances of 180 m and 650 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. A level drop is also evident with the turbine switched off at measurement point MP3.

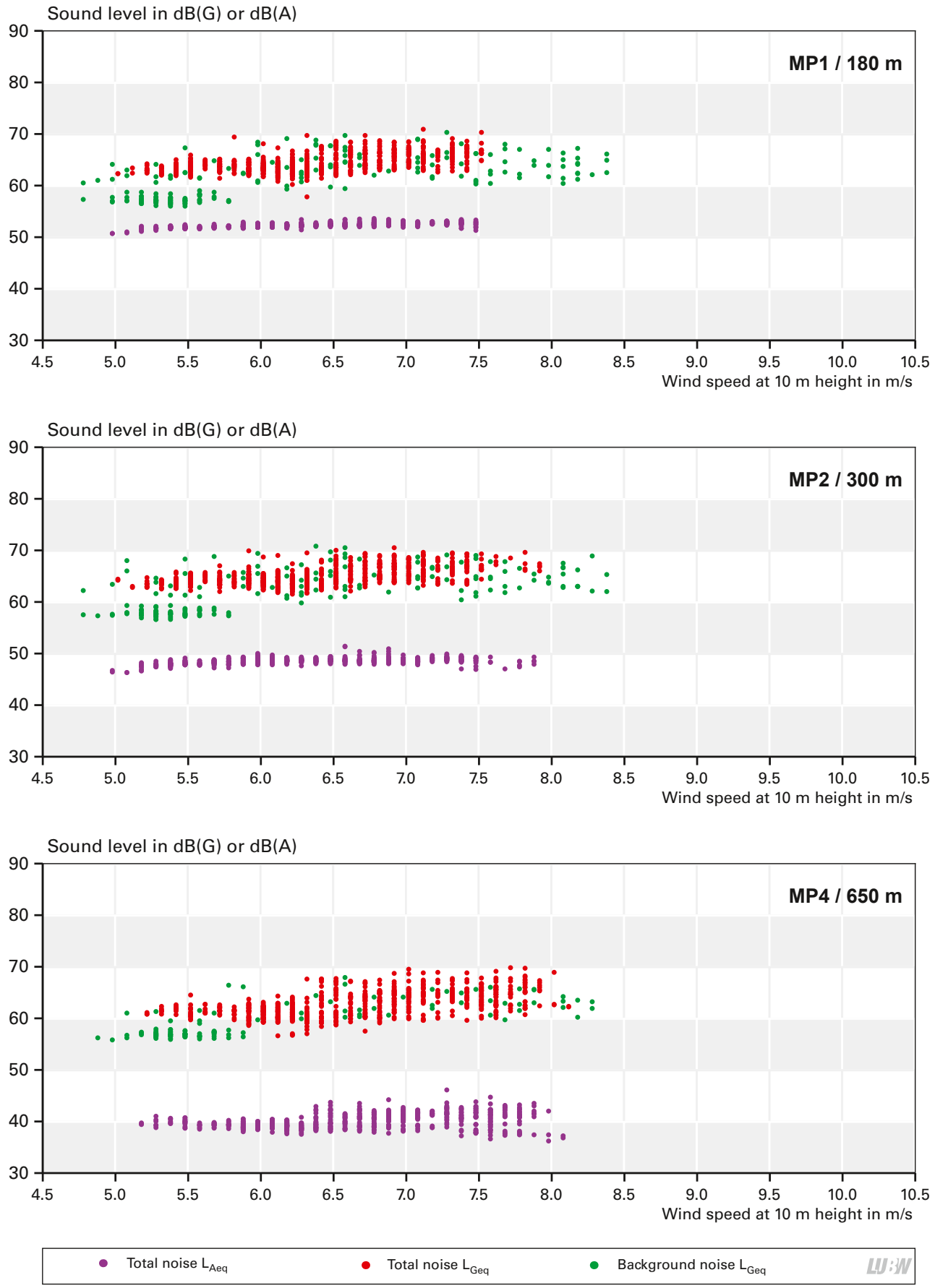


***Figure 4.5-12**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 4. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

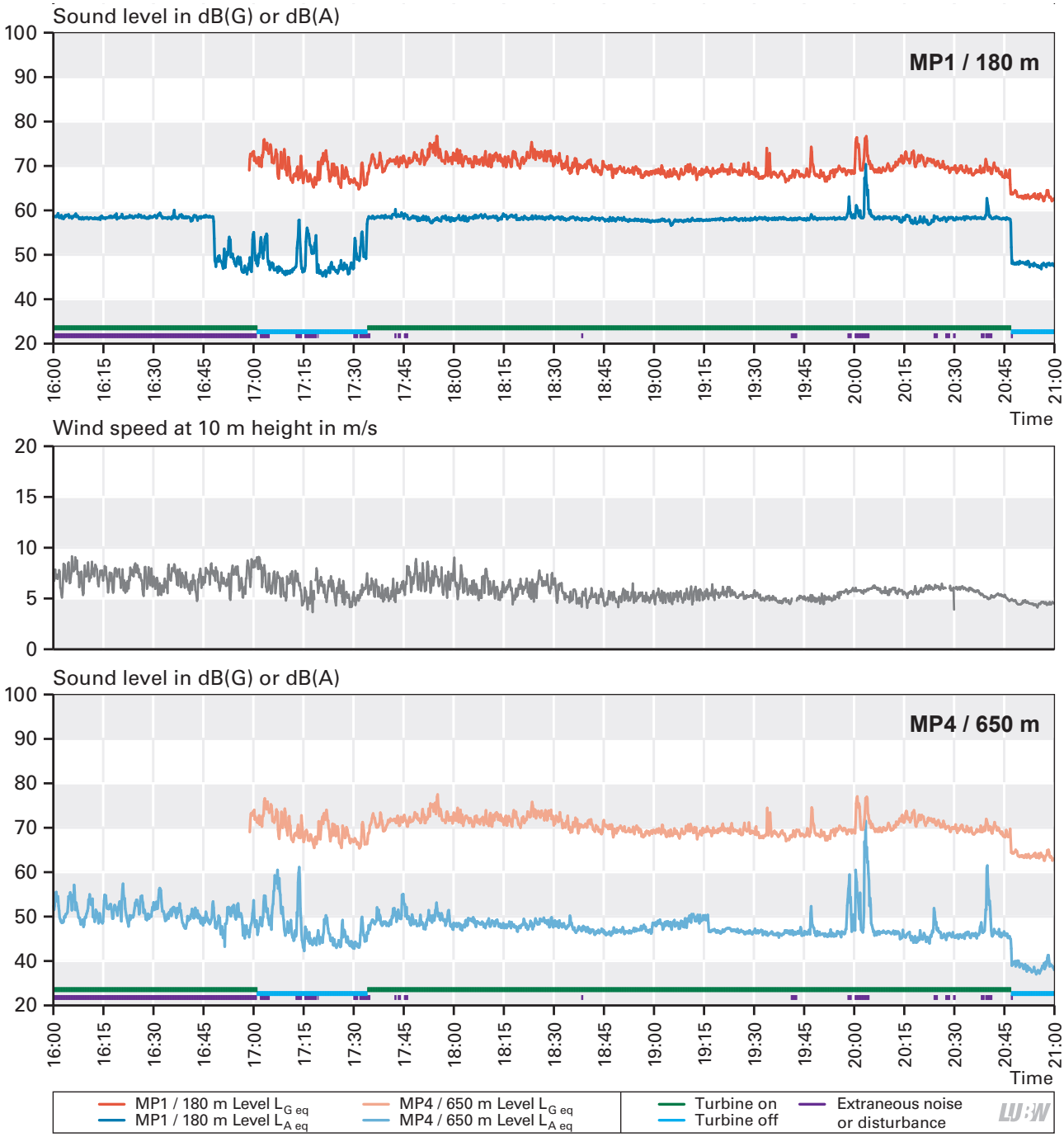


***Figure 4.5-13**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements at wind turbine WT 4*

4.6 Noise at wind turbine 5: Nordex N117 – 2.4 MW

BASIC CONDITIONS

The wind turbine 5 (WT 5) is a unit by the company Nordex, type N117/2400, with a nominal generator capacity of 2.4 MW (***Figure 4-3 and 4.6-1***). The rotor diameter is 117 m, the hub height above ground is 140.6 m.

The measured turbine is part of a wind farm with several wind turbines. The adjacent turbines were completely turned off during the measurement period in order to prevent extraneous noise. The vicinity of the turbine consists of agricultural land. A dirt road is located in the immediate vicinity of the turbine, which is used only very seldom by agricultural and forestry vehicles. A district road is located about 400 meters south of the investigated wind power plant, and another road roughly 1,000 m east. During the measurement, no traffic noise was subjectively perceptible. A forest is located further away. The measurements were carried out on 13.01.2015 between 11:00 a.m. and 4:00 p.m. The microphone position of the measurement point MP1 was 185 meters from the turbine, the measurement point MP2 300 m and the measurement points MP3 and MP4 each 650 m from the turbine. All measurement points were located in a downwind direction in order to take into account a generally unfavourable situation (promotion of sound propagation through the wind). The measurement points MP3 and MP4 were immediately next to one another and served as a comparison. The microphone MP3 was provided with a primary wind screen and placed into an approx. 50 cm deep hole that was dug especially for that purpose. A secondary wind screen covered the hole flush. The parallel measurements were taken at the measurement points MP3 and MP4 in order to enable a comparison of the levels and allow conclusions to be made regarding wind-induced sound components arising at the microphone.

Figure 4.6-1: *Wind turbine WT 5 in surroundings used for agricultural purposes. In the foreground you can see the 10 m high wind measurement mast. Photo: Wölfel company*

The measurement was performed in a wind speed range of 5 to 12 m/s (measured at 10 m height), a temperature range of 10 to 13 °C, an air pressure range of 975 to 979 hPa and in a power range of 0 to 2,400 kW. The turbulence intensity (see Appendix A3) during the measurement was 13 %.

RESULTS: NARROW BAND LEVEL

Figures 4.6-2 to 4.6-5 show narrow band spectra of background noise and total noise for different measurement locations with a resolution of 0.1 Hz. The wind speed was 7.6 m/s during the measurement of the total noise and 6.9 m/s during the measurement of the background noise.

Figure 4.6-2 shows the results of measurement point MP1 at a distance of 185 m. With the turbine turned on, several discrete maxima can be seen in the infrasound range below 6 Hz. This concerns infrasound generated by the rotor due to its motion. The measured frequencies correspond to the passage frequency of a rotor blade of about 0.6 Hz and its harmonized overtones at 1.2 Hz, 1.7 Hz, 2.3 Hz, 2.9 Hz, 3.5 Hz, 3.9 Hz, etc. The peaks disappear when the turbine is switched off.

Figure 4.6-3 shows the narrow band spectra of background noise and overall noise at the measurement point MP4 at a distance of 650 m. At this distance, the infrasound maxima

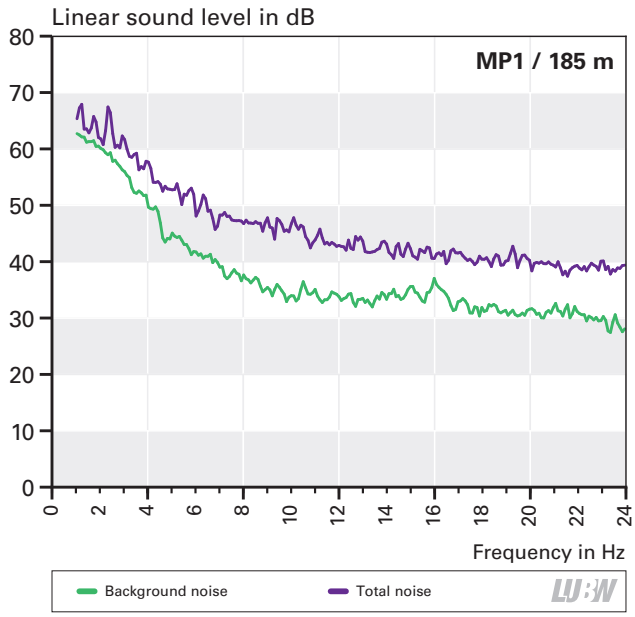


***Figure 4.6-2**: Narrow band spectra of background noise and total noise in the vicinity of wind turbine WT 5 for the frequency range of infrasound*

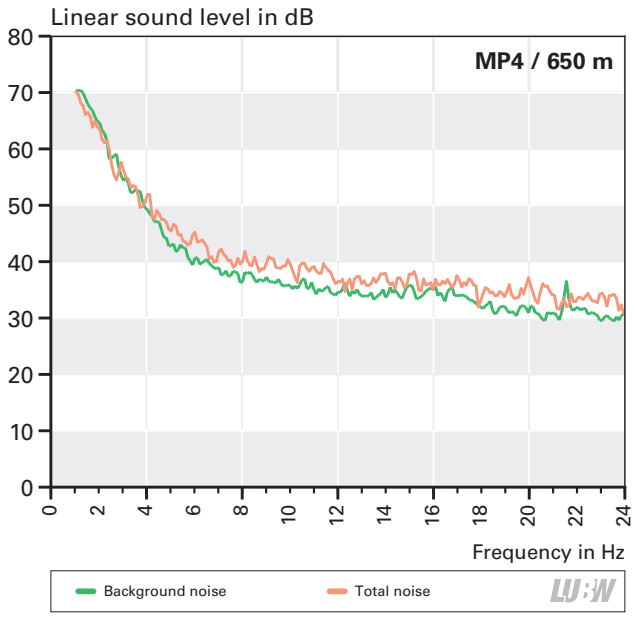


***Figure 4.6-3**: Narrow band spectra of background noise and total noise in the far range of wind turbine WT 5 for the frequency range of infrasound*

of measurement point MP1 with the wind turbine switched on can no longer be distinguished. Between the states "turbine on" and "turbine off" there were only minor differences in infrasound for this measurement at a distance of 650 m. The infrasound here was primarily due to the sounds of wind and from the surroundings. The comparison of the narrowband spectra for the two measurement points MP3 (hole in the ground) and MP4 (reverberant plate) at a distance of 650 meters in ***Figures 4.6-4 to 4.6-5*** illustrates that in the infrasound range there is generally no significant difference between the two measurement points. Only at frequencies between 2 Hz and 8 Hz did the measurements in the hole in the ground show slightly higher levels. Neither the absorption of the secondary wind screen nor the ground influence appear to be of significance below 20 Hz. The increase in level towards lower

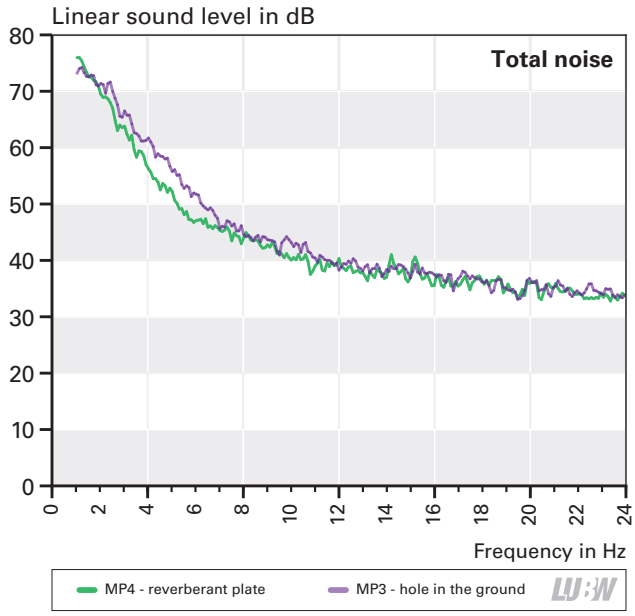


***Figure 4.6-4**: Narrowband spectra of the total noise at the measurement points MP4 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 5 for the range of infrasound. The distance from the turbine was 650 m.*

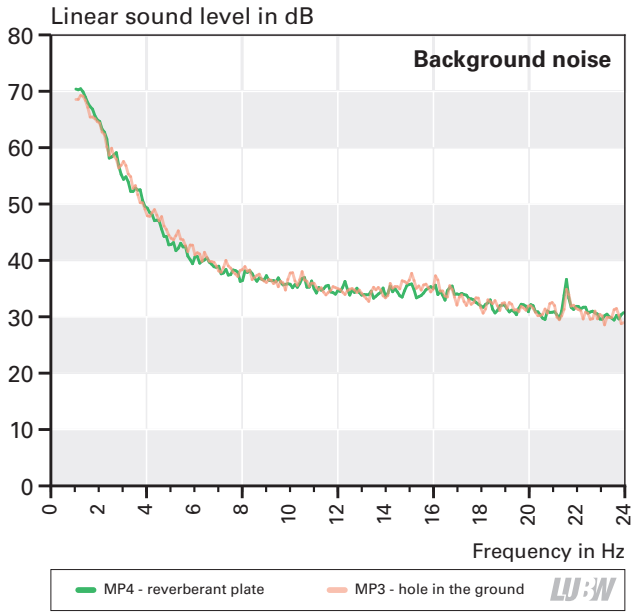


***Figure 4.6-5**: Narrowband spectra of the background noise at the measurement points MP4 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 5 for the range of infrasound. The distance from the turbine was 650 m.*

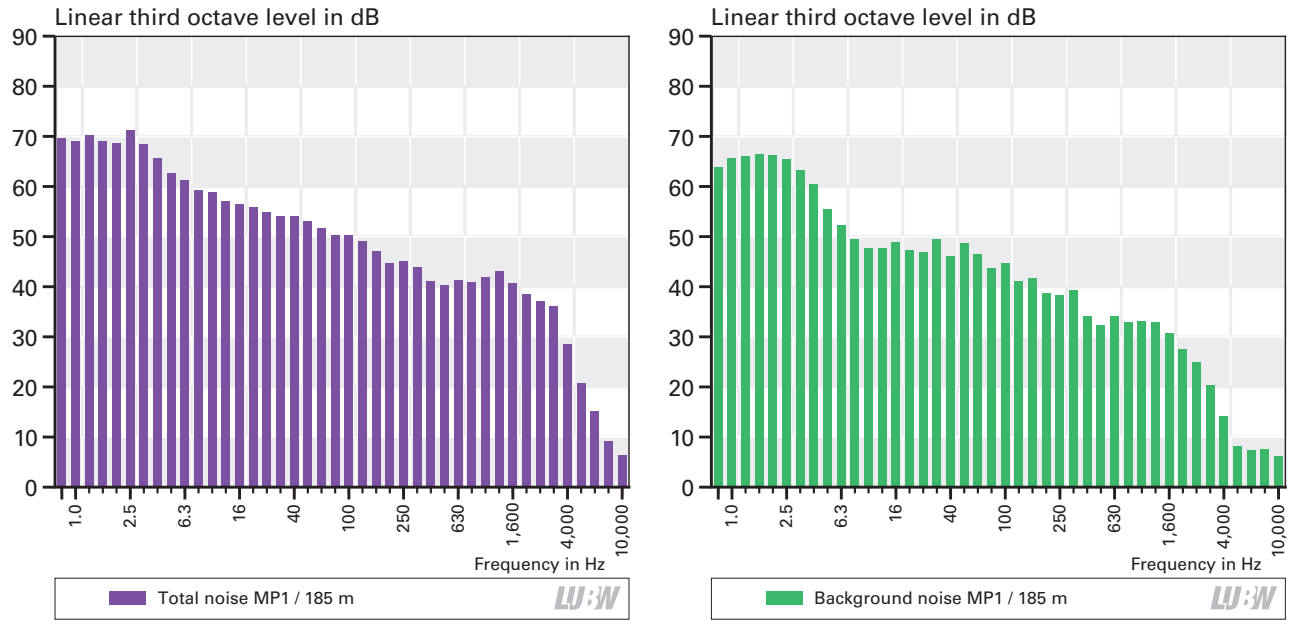


***Figure 4.6-6**: Third octave spectra of total noise and background noise in the vicinity of wind turbine WT 5*

frequencies was present during this measurement with and without the hole in the ground. The expected reduction in the wind-induced background noise in the infrasound range cannot be observed in a direct comparison between the two measurement points (see also Section 4.5).

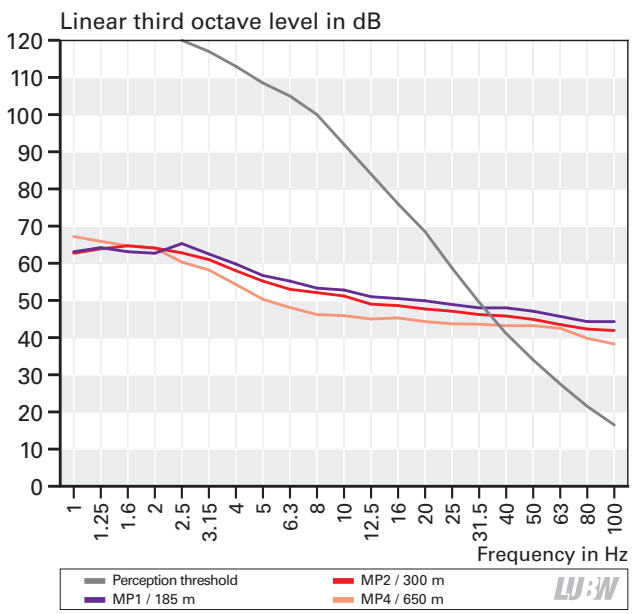


***Figure 4.6-7**: Third octave spectra of total noise at the measurement points MP1 (185 m), MP2 (300 m) and MP4 (650 m) of WT 5, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

RESULTS: THIRD OCTAVE LEVEL

Figure 4.6-6 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 185 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 5.5 m/s. The influence of the turbine in a much broader spectral range can be recognised here.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.6-7 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP4 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 7 m/s. It must be kept in mind that the background noise (wind, vegetation) is also included. This may vary at the respective measurement points. The measurement points MP2 and MP4 were further away from the turbine than measurement point MP1 (300 m and 650 m compared to 185 m). As expected, somewhat lower values were measured there, which becomes more apparent with increasing frequency. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.6-8***. The three

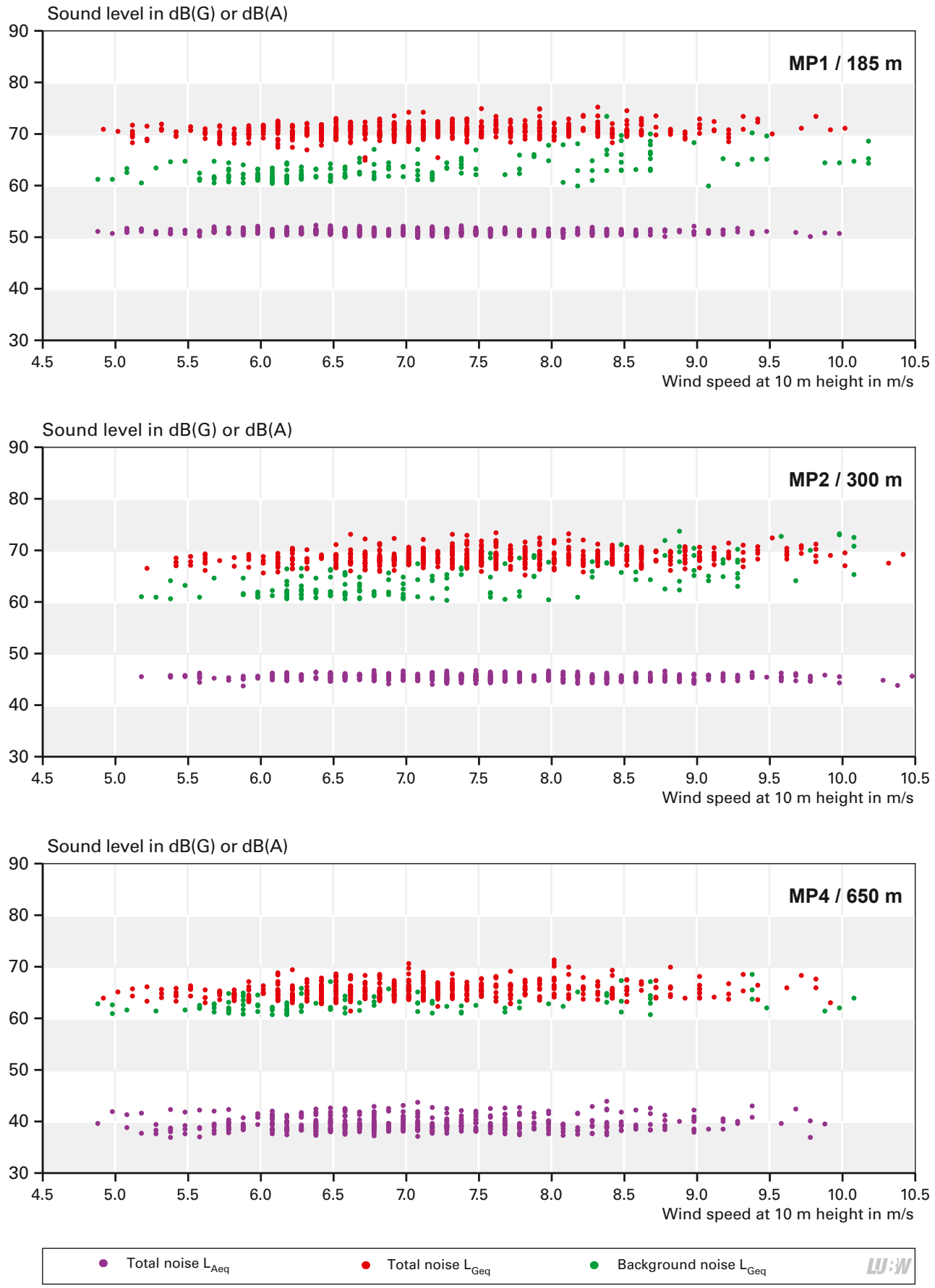


***Figure 4.6-8**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 5. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

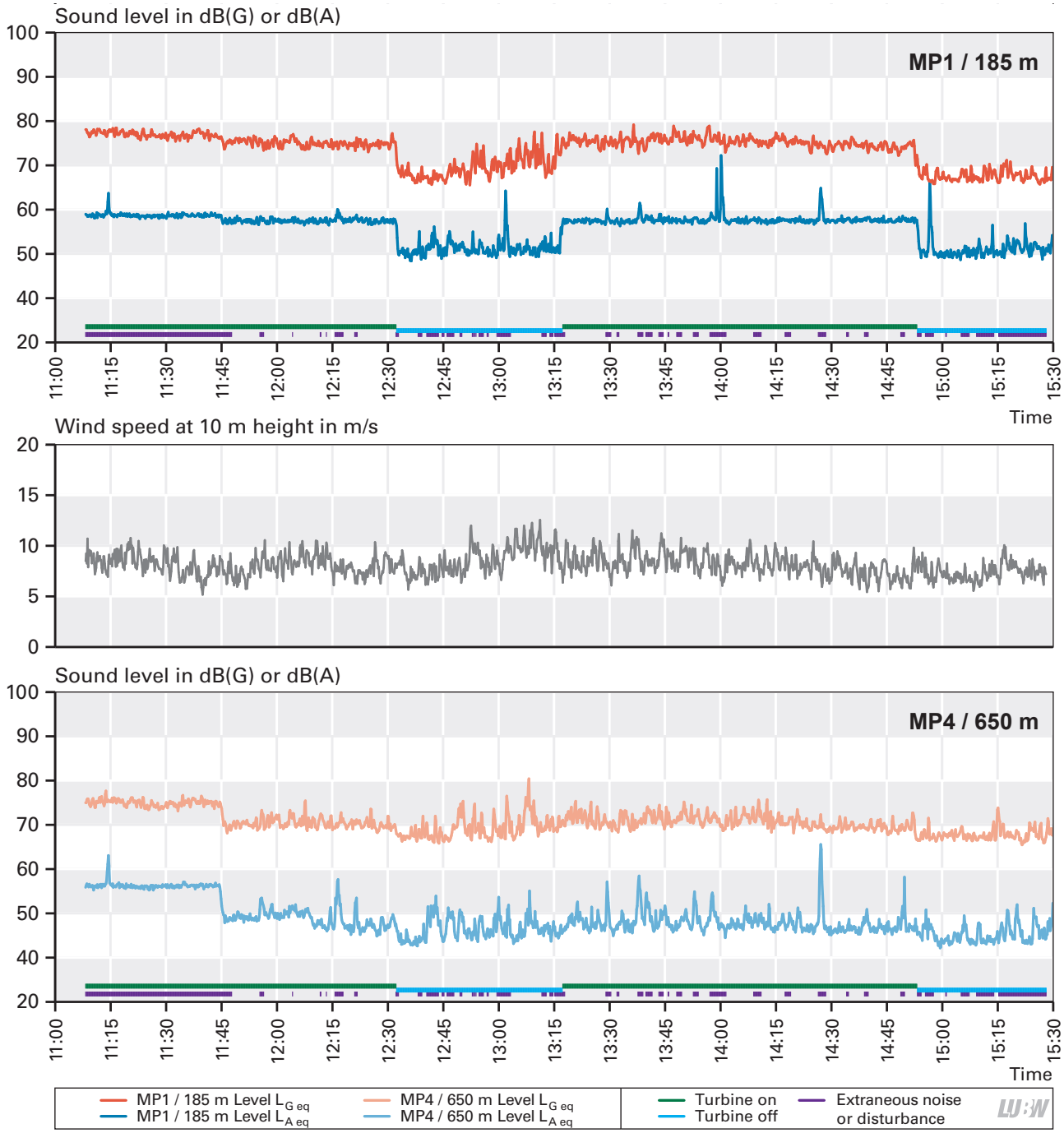


***Figure 4.6-9**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 5*

charts represent the relationships at the measurement points MP1 (185 m), MP2 (300 m) and MP4 (650 m).

The violet dots represent audible sound, expressed in dB(A). It is clearly visible that the measured A levels are higher close to the turbine than at the measurement points that are further away. The red dots represent the G-weighted sound level when the turbine is switched on, the green dots when the turbine is switched off. The figure shows that the G-weighted sound pressure levels at the measurement points examined during operation and standstill of the WT have no significant connection with the increase in wind speed. This fairly constant level curve can also be seen in the A-weighted level development. At measurement point MP1, a significantly increased mean G level can be seen during operation of the wind turbine compared to turbine standstill. As expected, the level difference between the states "turbine on" and "turbine off" decreases

***Figure 4.7-1**: Wind turbine WT 6 in surroundings used for agricultural purposes. The measurement point MP1 with reverberant plate and dual wind screen can be seen in the foreground. Photo: Wölfel company*

with increasing distance. The A level also drops from values greater than 50 dB(A) at measurement point MP1 to values of around 40 dB(A) at measurement point MP4.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.6-9 shows the A and G-weighted level developments between 11:00 a.m. and 5:30 p.m. for distances of 185 m and 650 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. At measurement point MP4, a level drop with the turbine switched off due to the fluctuating background noise is only slightly recognisable.

4.7 Noise at wind turbine 6: Enercon E-101 – 3.05 MW

BASIC CONDITIONS

The wind turbine 6 (WT 6) is a unit by the company Enercon, type E-101 (***Figure 4-6***) with a nominal generator capacity of 3.05 MW. The rotor diameter is 101 m, the hub height above ground is 135.4 m.

The measured turbine is part of a wind farm with several wind turbines. The adjacent turbines were completely turned off during the measurement period in order to prevent extraneous noise. The nearest other turbine that was in operation during the measurement period was located at a distance of approx. 850 m and was subjectively not perceptible over the entire measuring period. The vicinity of the turbine consists primarily of agricultural land. A dirt road is located in the immediate vicinity of the turbine, which is used only very seldom by agricultural and forestry vehicles. A state road is located at a distance of approx. 480 m eastward of the examined wind power plant. During the measurement, only occasionally traffic noise was perceptible. The measurements were carried out on 15.01.2015 between 12:00 p.m. and 3:00 p.m. The position of the microphone at the measurement point MP1 was located at a distance of 192 m from the turbine; the measurement point MP2 at a distance of 305 m and the measurement point MP3 at a distance of 705 m. The measurement points were each in a downwind direction in order to take into account the generally most unfavourable situation (promotion of sound propagation through the wind). The measurement point MP1 and the measured turbine can be seen in ***Figure 4.7-1***.

The measurement was performed in a wind speed range of 2.8 mm/s to 9.9 m/s (measured at 10 m height), a temperature range of 6 °C to 7 °C, an air pressure range of 954 hPa to 956 hPa and in a power range of 0 to 3,050 kW. The turbulence intensity (see Appendix A3) during the measurement was 14 %.

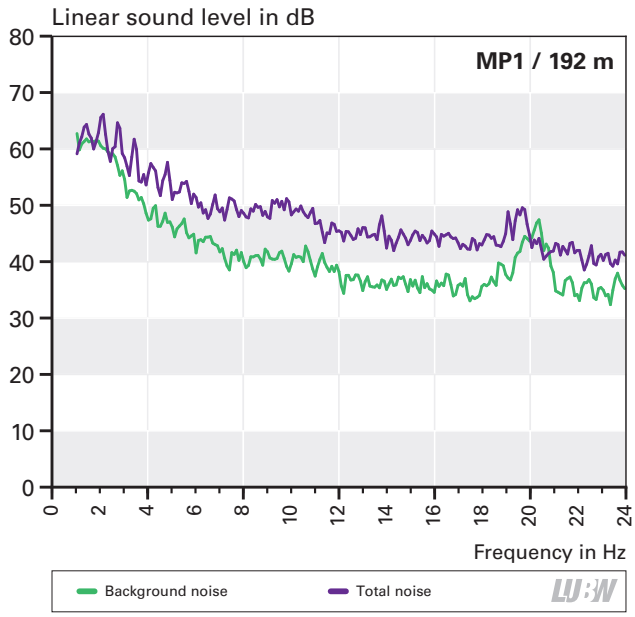


***Figure 4.7-2**: Narrow band spectra of background noise and total noise in the vicinity of wind turbine WT 6 for the frequency range of infrasound*

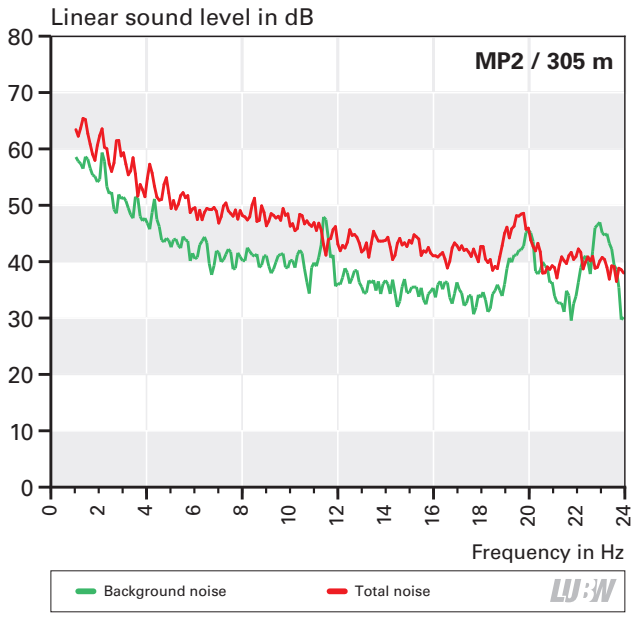


***Figure 4.7-3**: Narrow band spectra of background noise and total noise in the far range of wind turbine WT 6 for the frequency range of infrasound*

RESULTS: NARROW BAND LEVEL

Figures 4.7-2 to 4.7-3 show the established narrow band spectra for the operation of WT 6 with a mean wind speed of approximately 5.6 m/s at a height of 10 m. Clearly visible maxima can be seen at the measurement points MP1 and MP2. The measured frequencies correspond to the passage frequency of a rotor blade (here approx. 0.7 Hz) and the harmonic overtones at 1.4 Hz, 2.1 Hz und 2.8 Hz. This concerns infrasound generated by the rotor due to its motion. The peaks disappear when the turbine is switched off. At the measurement point MP3 at a distance of 705 m (not pictured), the mentioned maxima no longer occur so clearly. The level maximum at approx. 20 Hz is striking, which is clearly visible at all measurement points. However, it is highly likely that this is not attributable to the wind turbine, as it is also evident in the background noise.

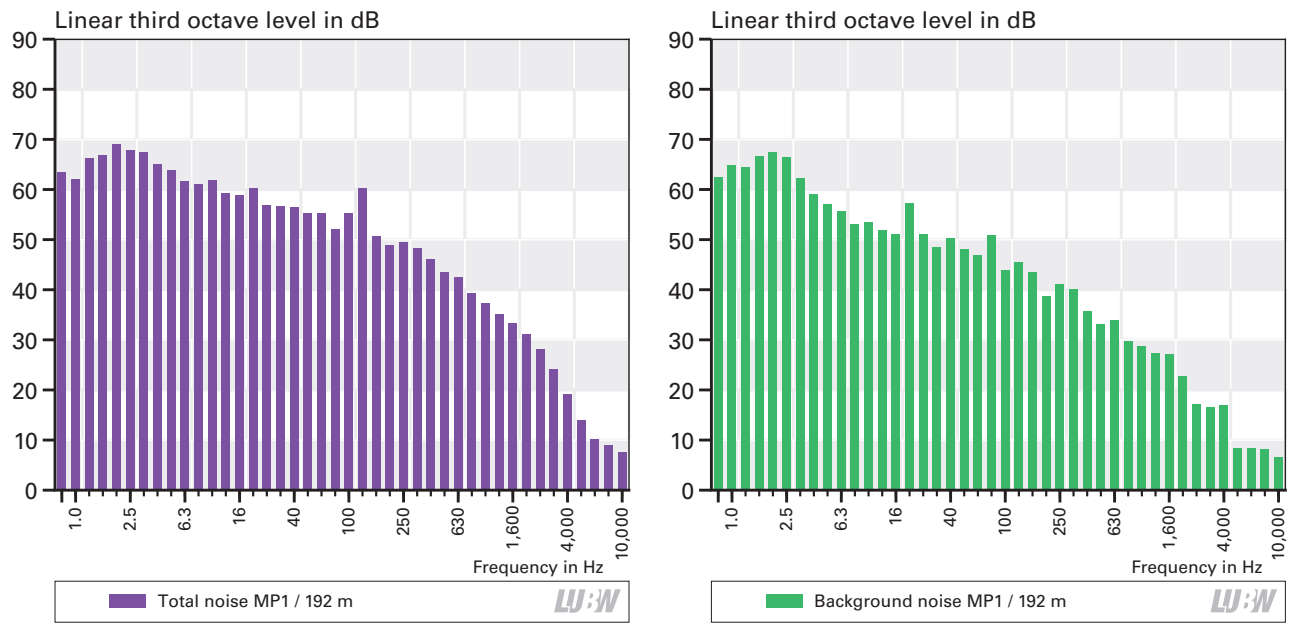


***Figure 4.7-4**: Third octave spectra of total noise and background noise in the vicinity of wind turbine WT 6*

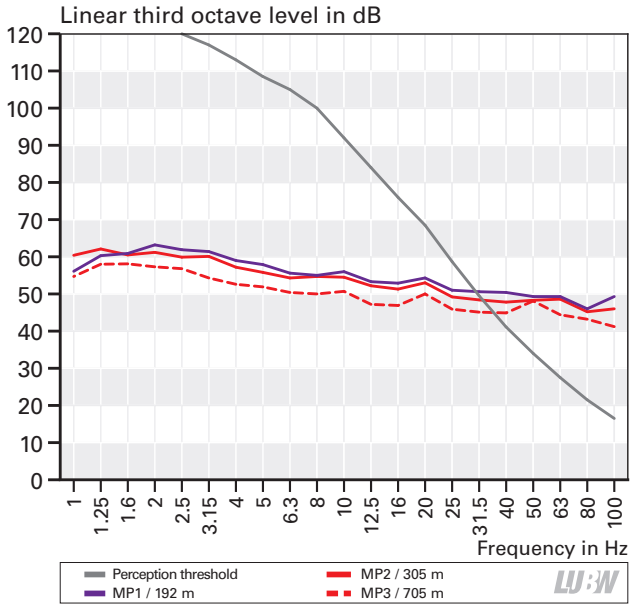


***Figure 4.7-5**: Third octave spectra of total noise at the measurement points MP1 (192 m), MP2 (305 m) and MP3 (705 m) of WT 6, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

RESULTS: THIRD OCTAVE LEVEL

Figure 4.7-4 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 192 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 5.6 m/s. The level reduction through switching off the turbine in a clearly broader spectral range can be seen.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.7-5 shows a comparison of the three measurement points for the low-frequency range from 1 Hz to 100 Hz. It must be noted that the background noise (wind, vegetation) is also included. This may vary at the respective measurement point. The wind speed at 10 m height during the averaging period was on average 5.6 m/s. At all measurement points, the ascertained levels were below the perception threshold at frequencies lower than 30 Hz. The levels in the area of infrasound fell clearly below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.7-6***. The three charts represent the relationships at the measurement points at the distances 192 m, 305 m and 705 m.

The violet dots, which depict the lower value area, represent audible sound, expressed in dB(A). It can be seen clearly that the measured A levels are higher at a distance of 192 m (upper image) than at the measurement points further away. The A level at first increases with increasing wind speed.

The red dots represent the G-weighted sound level when the wind turbine is switched on, the green dots when the turbine is switched off. Similarly to the A level, it can also be seen for the G level that – despite higher scattering – it somewhat increases with increasing wind speed, and then remains constant (measurement point MP1).

The image above shows that at MP1, i.e. in the near field at a distance of 192 m from the turbine, the G-weighted sound pressure level during operation of WT 6 is significantly higher than the background noise when the turbine is off. This is much less pronounced at a distance of 305 m (centre image).

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.7-7 shows the A and G-weighted level development between 12:40 p.m. and 2:40 p.m. for the distances of 192 m and 705 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is easily recognisable through the considerably declining level developments. At measurement point MP3, a level drop with the turbine switched off due to the fluctuating background noise is hardly recognisable.

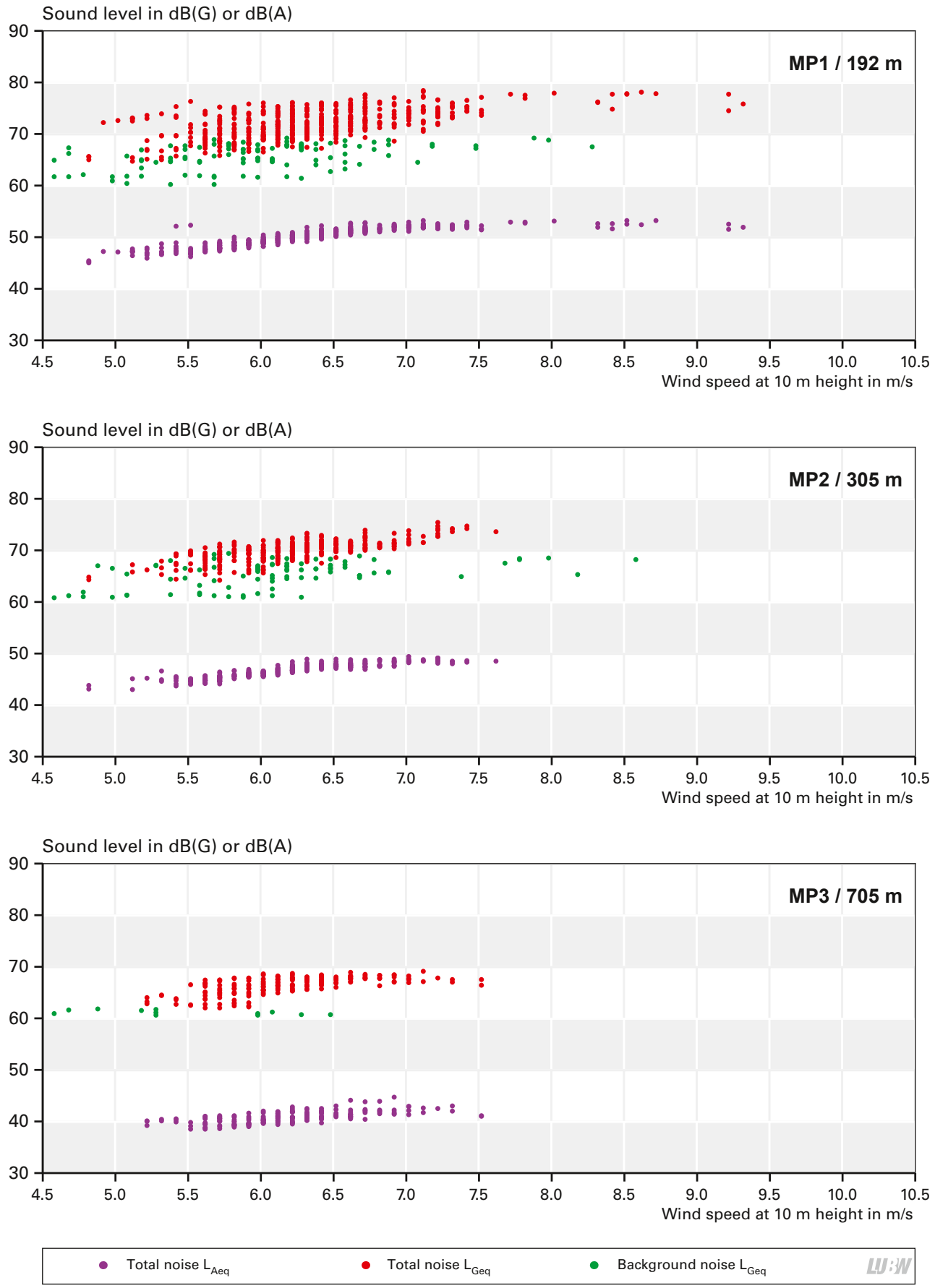


***Figure 4.7-6**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 6. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

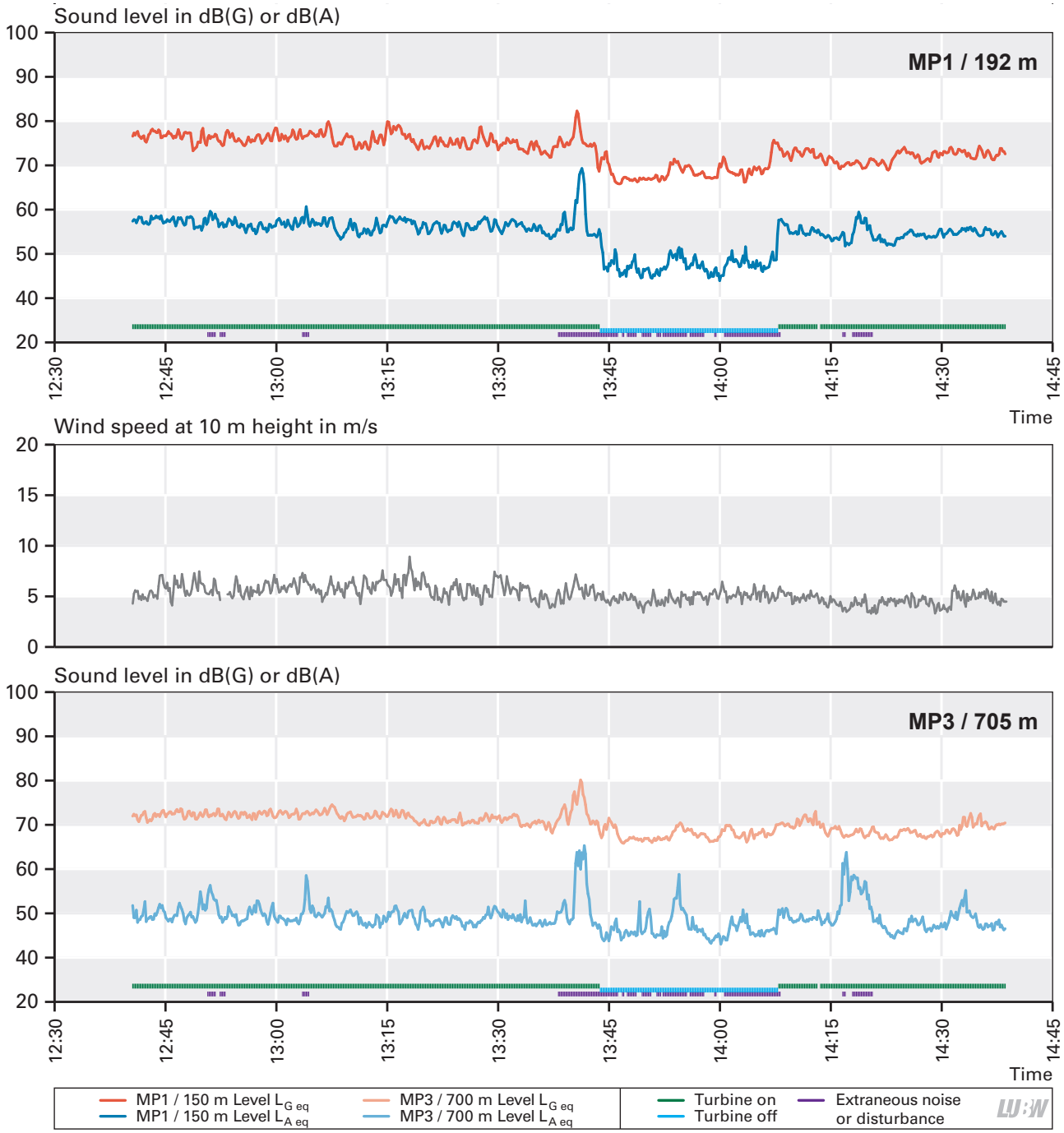


***Figure 4.7-7**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 6*

4.8 Vibrations at wind turbine 5: Nordex N117 – 2.4 MW

In order to determine a possible influence of the wind power plant on the surrounding area through vibration emissions, tremor measurements were carried out in addition to the sound assessments in the surrounding areas of wind turbine 5 (WT 5). The execution and analysis of the measurements was carried out in accordance with DIN 45669 [12] and DIN 4150 [13].

BASIC CONDITIONS

Wind turbine 5 (WT 5) is a unit by the company Nordex, type N117/2400, with a nominal generator capacity of 2.4 MW (see ***Figure 4.6-1***). The rotor diameter is 117 m, the hub height above ground is 140.6 m. The following is known about the building ground of the power plant: Up to a depth of 7 m there is cohesive ground (loam, weathering clay), which is judged to be not stable enough for the foundation of the power plant. Only after a depth of approx. 7 m is there Keuper rock, meaning that the foundation of the building structure or the load transfer has to be in this layer. It is not known whether this was accomplished with a pile foundation or a different procedure.

The vibration measurement was carried out in all three spatial directions with the help of vibration sensors. The x axis was radially aligned to the tower, the y axis tangentially and z axis vertically aligned. Measurements were taken at the same time at the following locations:

- MP A directly at the tower near the outer wall of the wind turbine on concrete, see ***Figure 4.8-1***
- MP B at a distance of 32 m from the WT's exterior wall on a ground spike
- MP C at a distance of 64 m from the WT's exterior wall on a ground spike
- MP D at a distance of approx. 285 m from the WT's exterior wall on a ground spike, see ***Figure 4.8-2***

For the connection of the sensors by means of ground spikes to the ground, holes with a diameter of approximately 50 cm and a depth of 20 cm to 40 cm were dug into the ground.

The following operational states were registered during the measuring time:

Figure 4.8-1: *Vibration measurement point MP A at the tower foundation of WT 5. Photo: Wölfel company*

Figure 4.8-2: *Vibration measurement point MP D on ground spike at a distance of 285 m from WT 5. Photo: Wölfel company*

- Operation of a wind turbine at wind speeds between approx. 6 and 12 m/s at a height of 10 m
- Switching off and subsequent restarting of the turbine
- Standstill of all wind power plants in the wind farm

During the measurement the wind turbine reached the maximum possible speeds starting from wind speeds of 6.6 m/s. Even at higher wind speeds no higher rotational speeds of the turbine are to be expected.

RESULTS

During the operation of the wind turbine, fluctuations in the signals were repeatedly seen, in particular at measurement point MP A directly by the tower. These can be attributed to individual gusts of wind. At the measurement points located farther away, these effects are less pronounced. A direct link between the changes in wind speed in the range of 6 to a maximum of 12 m/s and the vibrations in the ground cannot be seen. ***Table 4.8-1*** shows the ascer-

***Table 4.8-1**: Maximum values of the unweighted vibration velocities v in mm/s at the measurement points. The wind speeds measured at 10 m above ground level were between about 6 and 12 m/s.*

	MP A, at the tower		**MP B**, 32 m distance		**MP C**, 64 m distance		**MP D**, 285 m distance	
	z	x, y	z	x, y	z	x, y	z	x, y
Turbine on	0.5 - 1.0	0.30	0.03	0.08	0.02	0.04	< 0.01	0.01
Turbine off	0.04	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

tained maximum values of the unweighted vibration velocities v in mm/s for the different measurement points with uniform full load operation of the turbine. In the horizontal measurement directions the one with the highest value is stated; this was usually the x direction (radial, towards the tower).

Decreasing vibration velocity over the distance is shown graphically in ***Figure 4.8-3***. At the measurement point MP D at a distance of 285 m, the influence of the wind turbines is barely perceptible. For comparison, the spread calculated in accordance with [13] is also shown. When shutting down or restarting the turbine, the vibration level changes only slightly, see ***Figure 4.8-4***.

The evaluation of vibrational immissions with respect to possible exposure of people in buildings is carried out on the basis of DIN 4150 Part 2 [13]. The essential base parameter of this standard is the weighted vibration severity $KB_F(t)$. This is also an indication of the ability to sense vibrational effects. The perception threshold for most people lies in the area between $KB_F = 0.1$ and $KB_F = 0.2$. The KB_F value of 0.1 corresponds to an unweighted vibration velocity of approx. 0.15 to 0.30 mm/s. During the transition of tremors from the ground to building foundations there is usually a reduction of the vibration amplitudes. According to DIN 4150 Part 1, a factor of 0.5 should be taken. In the building itself, there may be an amplification, particularly if the excitation frequency is in the range of the ceiling's natural frequency. However, it is not expected that the effects established at the measurement point MP D could actually reach the level of the reference values according to DIN 4150 Part 2 in a building, since this would require an amplification by more than a factor of 20 within the building. At measurement point MP D at a distance of 285 m, mainly frequencies below 10 Hz were established, as shown in ***Figure 4.8-5***. In contrast, the natural frequencies for concrete ceilings in residential buildings are normally approx. 15 Hz to 35 Hz. For beamed ceilings, the natural frequencies are lower and can drop to approx. 10 Hz. Resonance excitation of the building ceilings can therefore not be expected.

CONCLUSION

The ground vibrations emanating from wind turbines can be detected by measurement. Already at a distance of less than 300 m from the turbine, they have dropped so far that they can no longer be differentiated from the permanently present background noise. No relevant vibrational effects can be expected at residential buildings.

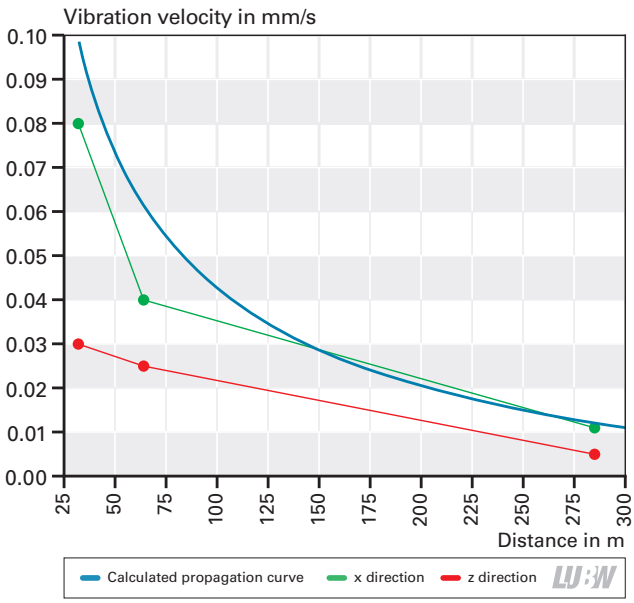


***Figure 4.8-3**: Comparison of prediction formula for [13] with the measured values*

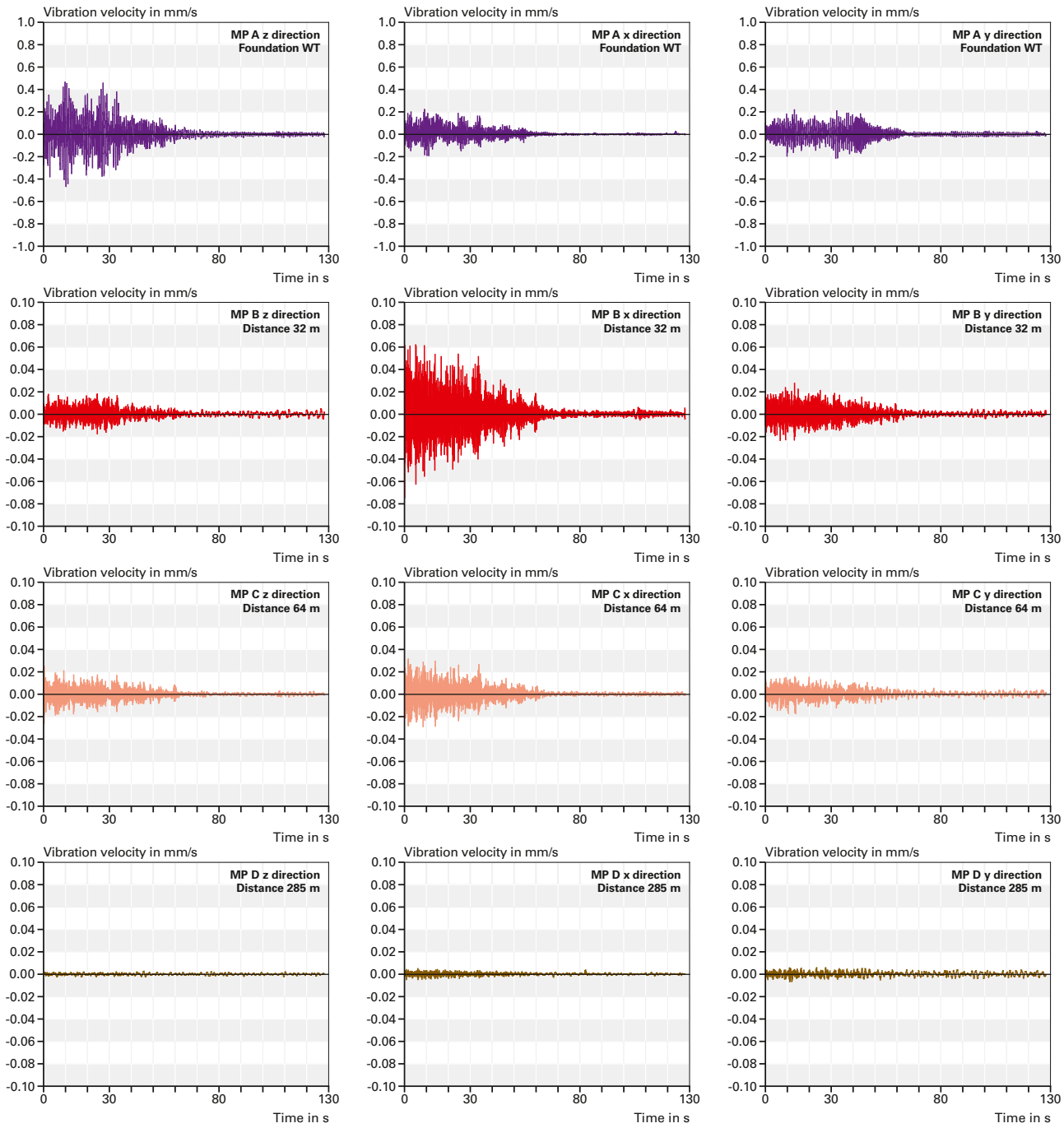


***Figure 4.8-4**: Representation of the decreasing vibration after shutdown of the wind turbine 5 for all measurement points and directions. From top to bottom: Measurement points MP A to MP D; left to right: Spatial directions z, x and y. The shutdown of the turbine followed at 12:32 p.m. – Note the different scale of the vibration velocity at the measurement point MP A (foundation, top row).*

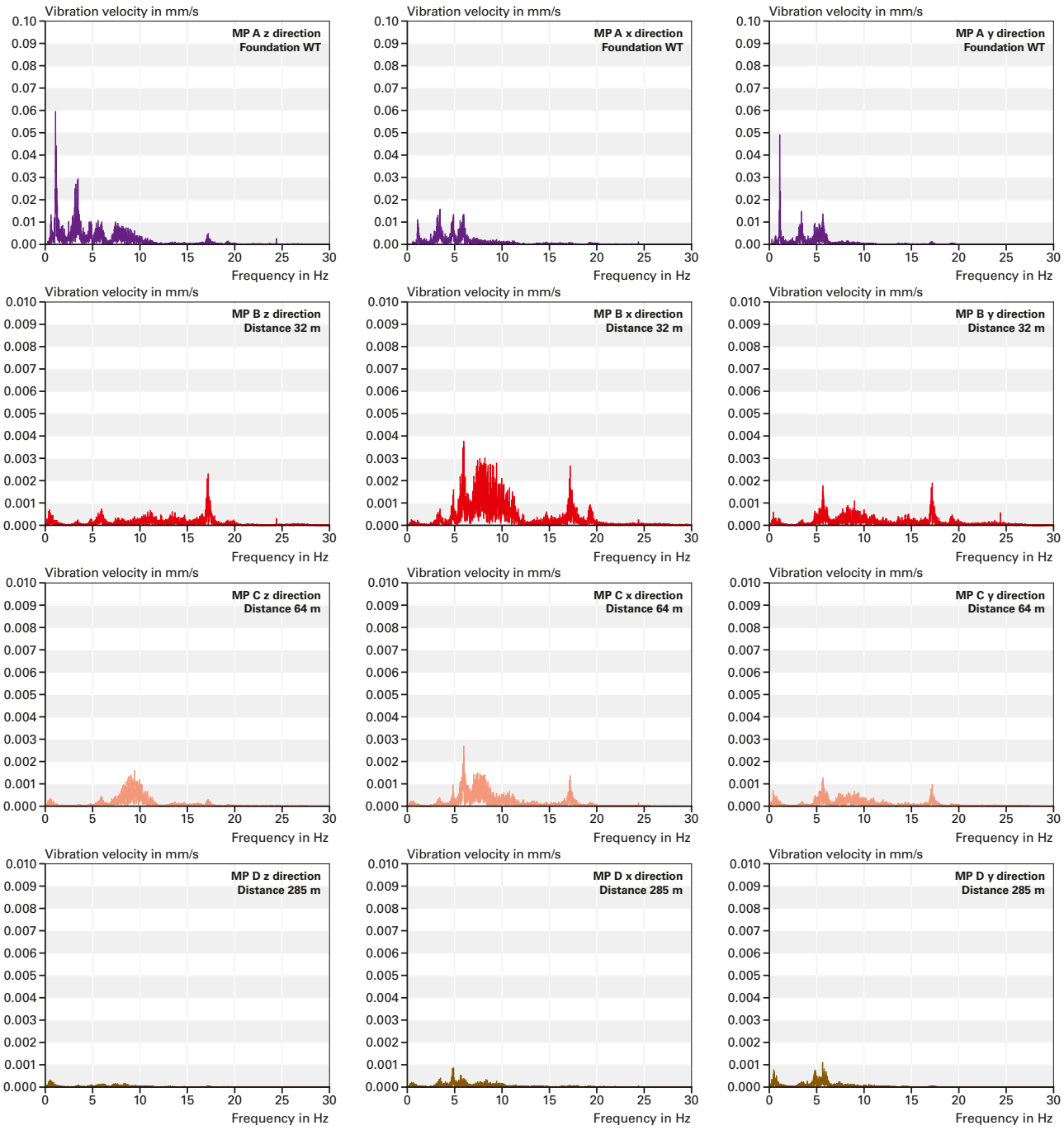


***Figure 4.8-5**: Representation of the frequency spectrum of the vibrations with uniform operation of the wind turbine 5 for all measurement points and directions. The measurement was taken at 11:12 a.m. at a wind speed of approx. 8 m/s at a height of 10 m. From top to bottom: Measurement points MP A to MP D; left to right: Spatial directions z, x and y. – Note the different scale of the vibration velocity at the measurement point MP A (foundation, top row).*

4.9 Measurement results from literature

In the following a few previously available, publicly accessible measurement results about infrasound and low-frequency noise at wind turbines shall be briefly discussed. Overall, the amount of available worldwide publications on this issue is modest but not low. The publications presented here partially refer to many other references. In this selection we have aimed to introduce German-speaking publications (Mecklenburg-Western Pomerania, Bavaria) as well as important European (Denmark) and international (Australia) studies and measurement programmes. However, the report at hand is no literature study, meaning that a restriction is necessary.

MECKLENBURG-WESTERN POMERANIA

The company Kötter Consulting, Rheine, carried out emissions and immissions measurements in 2005 and 2009 on behalf of the Federal State of Mecklenburg-Western Pomerania, State Office for the Environment, Nature Conservation and Geotechnology (LUNG) at a wind farm that contained a total of 14 turbines. The report is publicly available [14]. In summary, the authors come to the following conclusions:

- "The results of the emission measurement [...] show that at frequencies in the infrasound range at f < 10 Hz, the individual operating states cannot be distinguished from one another. Moreover, the dispersion of the sound pressure level is high." See ***Figure 4.9-1***.

- "In terms of emissions, however, the different operating states in the low-frequency range (16 Hz < f < 60 Hz) are metrologically detectable, whereas at the immission location, the turbine noise is indistinguishable from background noise."

- "The results of immission measurements show [...] that the reference values for the evaluation of low-frequency noise according to Supplement 1 of DIN 45680 [4] [...] are also complied with."

- "In terms of immissions, no noteworthy difference is perceivable between the operating state ‚all WT on' and background noise. The readings are clearly below the hearing threshold level curve in the infrasound range." See ***Figure 4.9-2***.

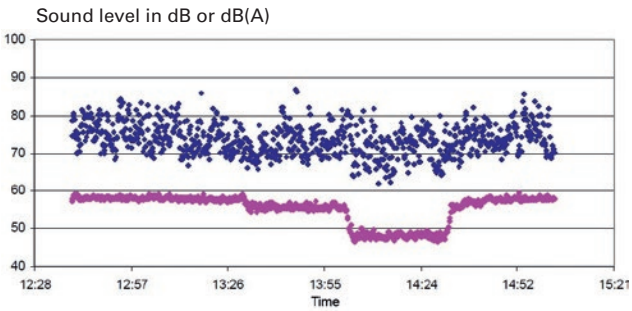


Figure 4.9-1: *Chronological sequence of level at the emission location (outside) near the turbine. The lower, magenta curve represents the sequence of the A-weighted audible noise level. The clearly identifiable gradual decrease in the sound level correlates with the various operating states (far left all turbines on, then two turbines off, then all turbines off). At the end, the A-weighted sound level increases again when all turbines are turned on (far right). Remarkably, the 8 Hz infrasound level hardly changes at all (blue, greater scattering of dots). The measurement report also includes illustrations for 20 Hz and 63 Hz; with these low frequencies, the operating conditions could be registered in the near field. Source: [14], Figure 9, page 24, details added.*

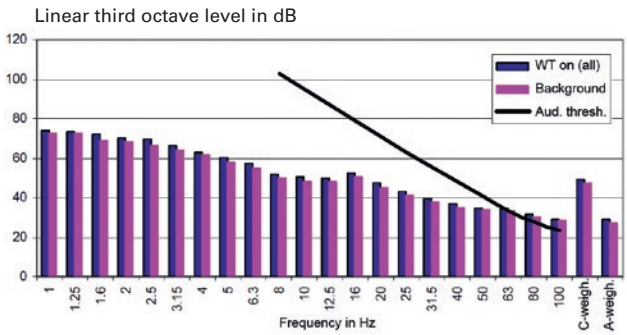


Figure 4.9-2: *Immission: Display of lower frequency levels subject to third octave frequency within a residential building at a distance of 600 m. No significant difference can be seen between the operating states "all WT on" and the background noise. The readings are clearly below the hearing threshold curve in the infrasound range. Source: [14], Figure 21, page 33*

BAVARIA

The Bavarian State Office for the Environment (LfU) carried out a long-term noise immission measurement from 1998 to 1999 at a 1 MW wind turbine of the type Nordex N54 in Wiggensbach near Kempten. ***Table 4.9-1*** and ***Figure 4.9-3*** show the main results. The study concludes that "the noise emissions of the wind turbine in the infrasound range are well below the perception threshold of humans and therefore lead to no burden". Furthermore, it was found that the infrasound caused by the wind is significantly stronger than the infrasound generated by the wind turbine alone [15] [16].

DENMARK

A Danish study from 2010 [17], in which data from almost 50 wind turbines with outputs between 80 kW and 3.6 MW was evaluated, comes to the following conclusion: "Wind power plants do certainly emit infrasound, but the levels are low when taking into account the human sensitivity to such frequencies. Even close up to the wind power plants, the sound pressure level is far below the normal auditory threshold, and the infrasound is therefore not seen as a problem for wind power plants of the same type and size as the ones examined" [15]. Further international publications on the issue are quoted in the study.

AUSTRALIA

In 2013 the Enviroment Protection Authorithy South Australia and the engineering company Resonate Acoustics published the study "Infrasound levels near windfarms and in other environments" [18]. The study includes results of measurements taken both outside as well as indoors. The measurement points were in close proximity to windparks and in regions without wind power plants.

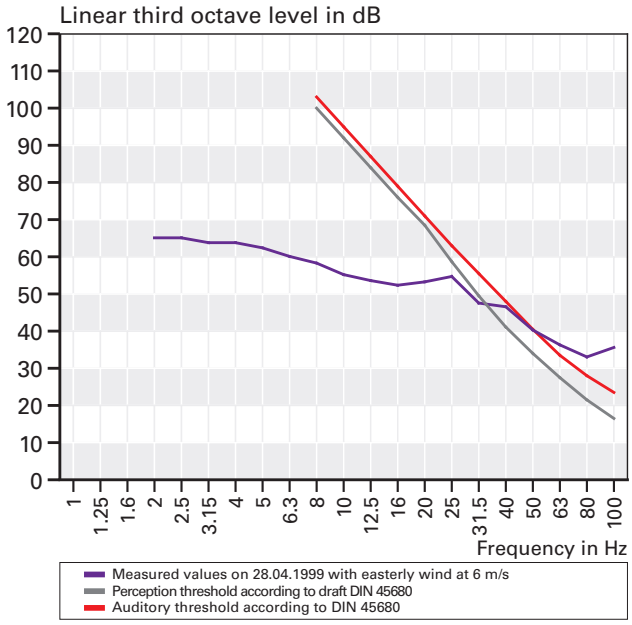


Figure 4.9-3*: The examined wind turbine causes sound waves that can be heard only above 40 Hz by a person standing on a balcony at a distance of 250 m. The infrasound range is not perceptible, since it lies clearly below the perception threshold. Source: [15]*

In summary, it was stated that the measured infrasound expositions, which were measured in close proximity to windfarms in residential buildings, correspond to the levels determined in comparable regions without wind power plants. The lowest infrasound levels determined in the measuring project were registered in a house standing in the proximity of a wind park.

The infrasound levels in close proximity to wind power plants are not higher than in other urban and rural regions, in which the contribution of wind power plants is negligible, compared to the background level of infrasound in those areas.

Table 4.9-1*: Infrasound level at a distance of 250 m from a 1 MW wind turbine with different wind velocities. Source: [15]*

Wind velocity		Linear third octave level in dB with a third octave centre frequency of				
		8 Hz	10 Hz	12.5 Hz	16 Hz	20 Hz
6 m/s	Breeze, the measured sound comes primarily from the wind turbine	58	55	54	52	53
15 m/s	Strong to stormy wind, the measured sound comes primarily from the wind	75	74	73	72	70

Quotation: "It is clear from the results that the infrasound levels measured at the two residential locations near wind farms (Location 8 near the Bluff Wind Farm and Location 9 near Clements Gap Wind Farm) are within the range of infrasound levels measured at comparable locations away from wind farms. Of particular note, the results at one of the houses near a wind farm (Location 8) are the lowest infrasound levels measured at any of the 11 locations included in this study. This study concludes that the level of infrasound at houses near the wind turbines assessed is no greater than that experienced in other urban and rural environments, and that the contribution of wind turbines to the measured infrasound levels is insignificant in comparison with the background level of infrasound in the environment". [18]

4.10 Conclusion of the measurements at wind turbines

- The low-frequency noise including infrasound measured in the vicinity of wind turbines consists of three parts: 1. Turbine noise; 2. Noise that results from the wind in the surrounding area; 3. Noise that is induced at the microphone by the wind. Wind always has to be considered as an interference factor (extraneous noise) when determining the turbine noise. The measured values are subject to a wide spread.

- The infrasound being emanated from wind turbines can generally be measured well in the direct vicinity. Below 8 Hz discrete lines appear in the frequency spectrum as expected, which are attributable to the constant movement of the individual rotor blades.

- At a distance of 700 m from the wind turbines, it was observed that when the turbine is switched on, the measured infrasound level did not increase notably or only increase to a limited extent. The infrasound was generated mainly by the wind and not by the wind turbines.

- The measured infrasound levels (G levels) at a distance of approx. 150 m from the turbine were between 55 and 80 dB(G) with the turbine running. With the turbine switched off, they were between 50 and 75 dB(G). At distances of 650 to 700 m, the G levels were between 55 and 75 dB(G) with the turbine switched on as well as off. A cause for the spread of the values is the strongly varying proportions of noise, which are caused by the wind (***Table 2-1***).

- For the measurements carried out even at close range, the infrasound levels in the vicinity of wind turbines – at distances between 150 and 300 m – were well below the threshold of what humans can perceive in accordance with DIN 45680 (2013 Draft) [5] or ***Table A3-1***.

- The vibrations caused by the wind turbine being examined were already minimal at a distance of less than 300 m. At distances as prescribed for reasons of noise pollution protection, no exposures that exceed the pervasive background noise are to be expected at residential buildings.

- The results of this measurement project comply with the results of similar investigations on a national and international level.

Table 4-11*: Tabular representation summing up the first measured values (infrasound and low-frequency noise) at wind turbines. The measured values were frequently subject to substantial fluctuations and always also contain wind noises. Since the measurements were carried out with a reverberant plate, a correction took place (see. Section 4.1).*

Wind turbine (WT)		Section	G-weighted level in dB(G)	Infrasound third octave level ≤ 20 Hz in dB *	Low-frequency third octave level 25-80 Hz in dB *
			WT on / off	**WT on**	**WT on**
WT 1	– 700 m – 150 m	4.2	55-75 / 50-75 65-75 / 50-70	– 55-70	– 50-55
WT 2	– 240 m – 120 m	4.3	60-75 / 60-75 60-80 / 60-75	– 60-75	– 50-55
WT 3	– 300 m – 180 m	4.4	55-80 / 50-75 55-75 / 50-75	– 50-70	– 45-50
WT 4	– 650 m – 180 m	4.5	50-65 / 50-65 55-65 / 50-65	– 45-55	– 40-45
WT 5	– 650 m – 185 m	4.6	60-70 / 55-65 60-70 / 55-65	– 50-65	– 45-50
WT 6	– 705 m – 192 m	4.7	55-65 / 55-60 60-75 / 55-65	– 55-65	– 45-50

* Linear third octave level in dB(Z)

5 Traffic

Within the context of the measurement project, not only wind turbines but also other sources of low-frequency sound incl. infrasound were to be examined. An obvious choice was to investigate the pretty-much ubiquitous road traffic. For this purpose, measurements was carried out at a road in Würzburg (by the company Wölfel) as well as at the federal motorway A5 south of Karlsruhe (by the LUBW). In addition, data from the inner-city continuous traffic noise measuring stations of the LUBW in Karlsruhe and Reutlingen was used, in order to assess the recorded data with respect to low-frequency noise incl. infrasound. The conditions were selected in such a way that neither wind noises in the vicinity nor wind-induced noises at the microphones arose, which can cause problems during the measurements at the wind turbines (see Section 4). The results represented in the following are therefore to be causally attributed to road traffic.

5.1 Inner-city roads – measurement in Würzburg

At the immission location of Rottendorfer Strasse in Würzburg it was possible to carry out the noise level measurements with a special focus on low-frequency noise and infrasound inside as well as outside of a residential building. The measurement point is predominantly in the direct sphere of influence of Rottendorfer Strasse, but also within the sphere of the federal road B 19, which leads from Bad Mergentheim to Würzburg, as well as the railway line Würzburg-Lauda (***Figure 5.1-1***). However, at the immission location, the noise from the road traffic on the Rottendorfer Strasse dominates (***Figure 5.1-2***), with an average traffic volume of 13,971 motor vehicles in 24 hours with a proportion of heavy goods traffic of approx. 3 % (data from the 2012 traffic survey).

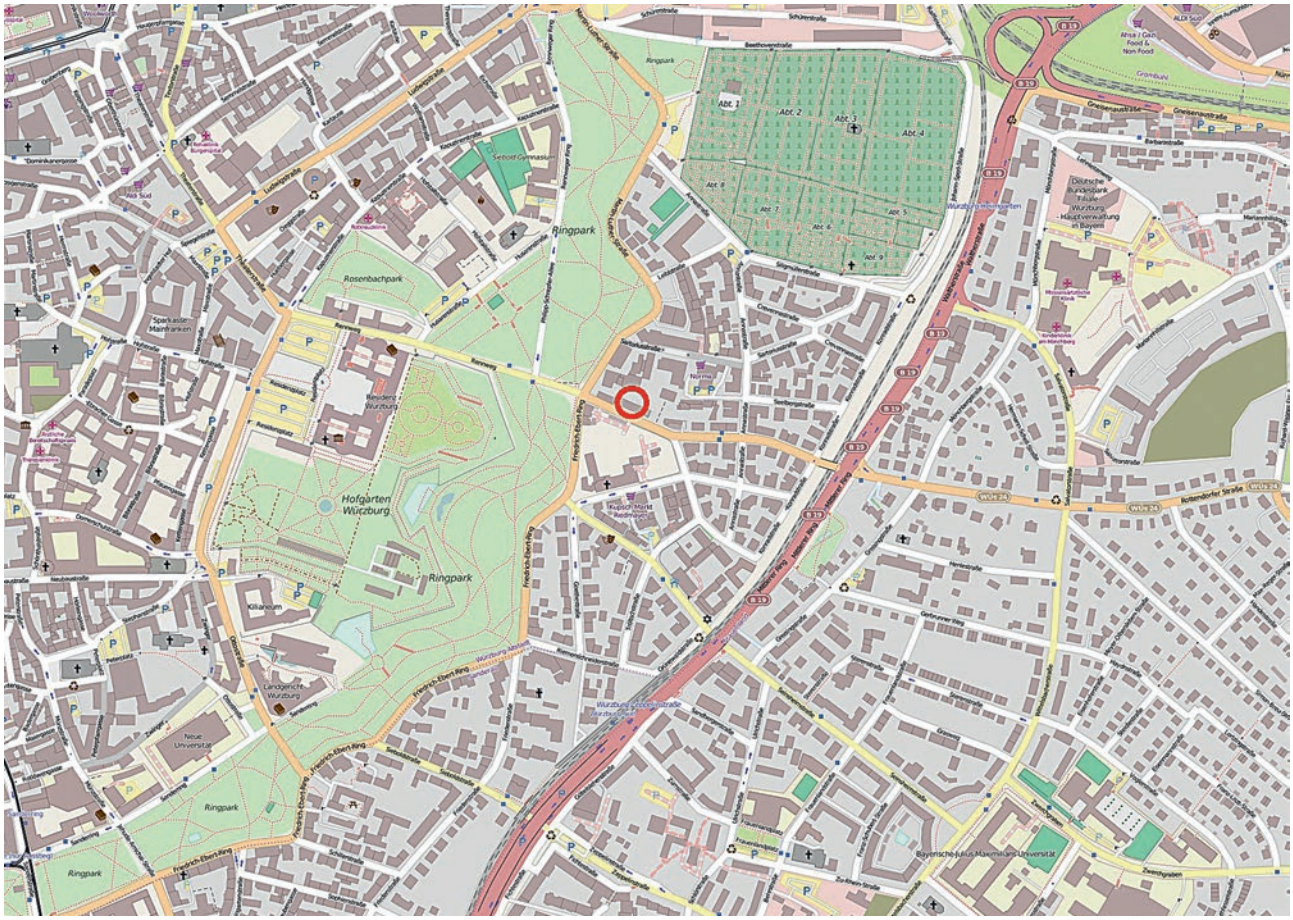


Figure 5.1-1: *Layout plan showing the immission location at Rottendorfer Strasse, Würzburg. Source: www.openstreetmap.org*

Figure 5.1-2 a/b*: View along Rottendorfer Strasse in Würzburg. Photo: Wölfel company*

A situation as can be found in many places was specifically selected. At measurement points with very high volumes of traffic and the thus associated traffic noise, the audible noise level is prioritised; this can already lead to situations that are a nuisance and possibly also harmful environmental effects. The low-frequency noise, incl. its share of infrasound, eminating from the road traffic could be measured without any disturbing wind noises. The measured levels are characteristic for the noise situation in the residential area.

The sound pressure level up to a lower threshold frequency of 1 Hz was measured at one measurement point in the open and one measurement point in a residential building. For the evaluation of the low-frequency effects, evaluations according to DIN 45680 (2013 draft) [5] were carried out for the measurement point within the building.

The execution of the measurement took place at two measuring locations. Measurement point MP1 was selected in accordance with DIN 45645 (1996) [8] and – in the same manner as the measurements at the wind turbines – with reverberant plate on the ground of the balcony facing the road. A second measurement point MP2 was located within the building in accordance with DIN 45680 (March 1997) [4]. The measurement was carried out as an observed measurement. The fully furnished and inhabited flat was not used during the measuring time. The size of the room was approx. 7.6 m x 4.3 m x 2.5 m. An informatively comparative measurement was carried out at a third measurement point located directly on the façade at the height of the windows. The third octave levels on the façade in the range below 25 Hz are between 0 and 3 dB lower than the third octave level on the floor of the balcony. Within the range between 25 Hz and 80 Hz, the third octave levels directly at the façade are up to 6 dB lower than the third octave levels on the floor of the balcony. In the frequency range above 100 Hz, on the other hand, they are 0 to 3 dB higher than the third octave levels on the floor of the balcony. The measuring data presented here for the floor of the balcony was not subjected to level corrections according to Section 4.1.

The measurement period extended from Thursday afternoon, 04.07.2013, 3:00 p.m., to the early morning of the following Friday, 05.07.2013, 6:00 a.m. The measuring period

was not during the school holidays and is representative for the burden of the immission location on a working day. The traffic volume is estimated as being comparable to the data of the traffic survey. During the measurement of traffic noise, the periods with significant external noise exposure (e.g. flight noise, animal sounds and noises by the measuring engineer) were marked and excluded from the analysis. The measurements were performed in a wind speed range of 0 to 4 m/s (a mean value of 0.5 m/s), a temperature range of 16.3 to 22.5 °C, and an air pressure range of 999 to 1,003 hPa.

RESULTS AT OUTDOOR MEASUREMENT POINT

As an example, third octave spectra for the time periods 4:00 p.m. - 5:00 p.m., 10:00 p.m. - 11:00 p.m. and 12:00 a.m. - 1:00 a.m. are presented in ***Figure 5.1-3*** for the measurement point MP1 (outside the building). The outside daytime levels in the low-frequency range were up to 100 Hz above the hearing or perception threshold. A significant peak in the frequency range 25 Hz to 80 Hz can be seen in the third octave spectra, which is due to vehicle traffic. In the area of 25 Hz to 63 Hz, the levels exceed 70 dB, partially up to 75 dB. At night, values of up to 65 dB are reached. For the infrasound up to 20 Hz, the outdoor daytime levels were below the hearing or perception threshold between 45 and 65 dB. The specified frequencies refer to the third octave centre frequency.

Figure 5.1-4 shows the one hour average linear third octave level for the low-frequency range below 100 Hz compared to the perception threshold in accordance with DIN 45680 (2013 draft) [5]. For values below 8 Hz, this was amended [11], see also ***Table A3-1***. The correlation of the values with the traffic situation is clearly recognisable: The heavier road traffic between 4:00 p.m. to 5:00 p.m. leads to higher values both in the infrasound range as well as in the other low-frequency ranges. Depending on the traffic volume, the perception threshold is exceeded between 20 Hz and 32 Hz (third octave centre frequency).

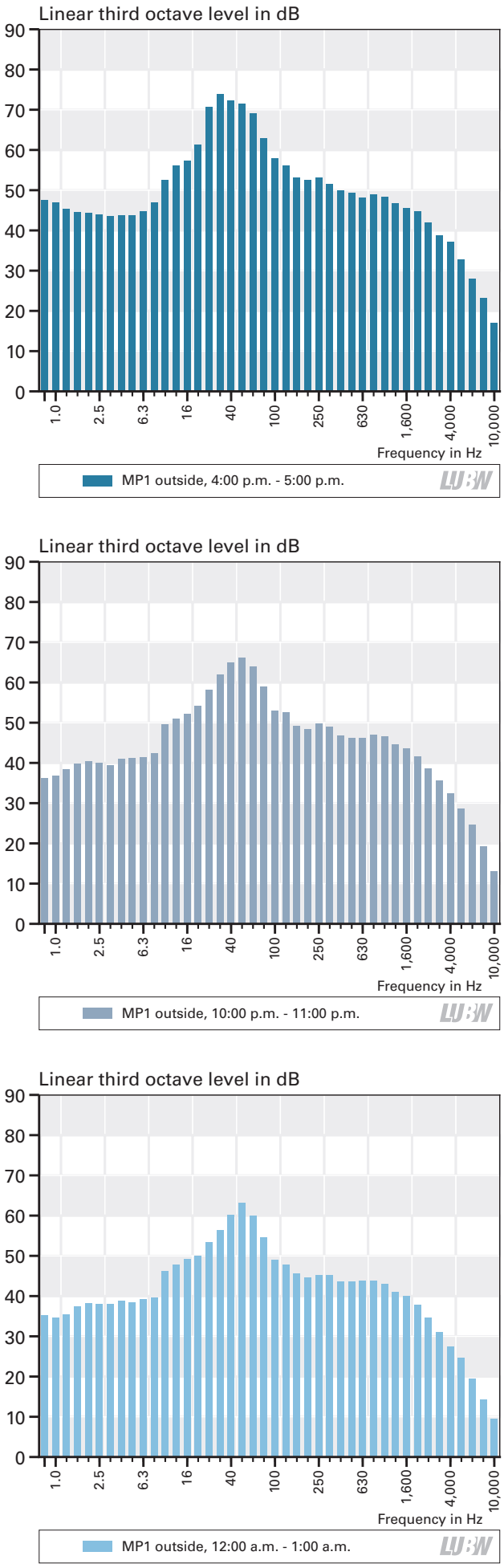


Figure 5.1-3*: Linear third octave spectra for the periods 4:00 p.m. - 5:00 p.m. (top), 10:00 p.m. - 11:00 p.m. (centre) and 12:00 a.m. - 1:00 a.m. (below) at the outside measurement point MP1. A significant peak in the frequency range 25 Hz to 80 Hz can be seen for the spectra, which is due to vehicle traffic.*

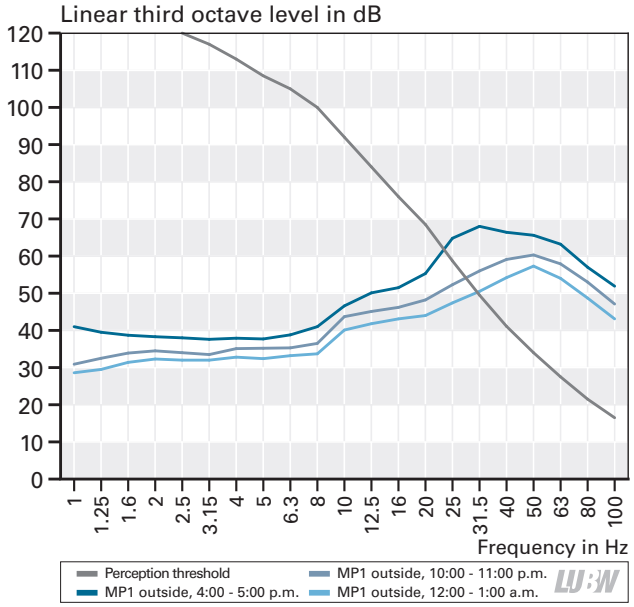


***Figure 5.1-4**: Comparison of the corrected linear third octave levels, determined at the measurement point MP1 (outside the building) for the averaging periods 4:00 - 5:00 p.m., 10:00 - 11:00 p.m., and 12:00 - 1:00 a.m. Furthermore, the perception threshold is also shown (see Section 4.1).*

The A and G-weighted sum level LAeq(t) and LGeq(t) recorded during the entire measuring period are shown in ***Figure 5.1-5***. While the A-weighting shows the audible sound as a single number value, the valuation focus of the G level is in the infrasound range. The curves show a significant bandwidth that is created by the variations of the sound influences. These variations are less pronounced for the G level. The relationship of the courses of the A and G levels can also be clearly seen. Both levels are significantly reduced at night, when there is less traffic. The G level reaches values of up to 80 dB (G) at daytime and minimum values of around 55 dB (G) at night, with strong fluctuations.

RESULTS AT INDOOR MEASUREMENT POINT

The third octave spectra for the time periods 4:00 p.m. - 5:00 p.m., 10:00 p.m. - 11:00 p.m. and 12:00 a.m. - 1:00 a.m. are presented in ***Figure 5.1-6*** for the measurement point MP2 inside the building. The interior levels for infrasound up to 20 Hz are below the hearing or perception threshold (< 55 dB) at day and night. Above 32 Hz to 40 Hz (third octave centre frequency), the values of the linear third octave level are above the hearing or perception threshold (up to 55 dB). In narrowband spectra (not shown here) a number of discrete, prominent maxima were detected, which were attributable to natural frequencies of the room and excited natural frequencies of the building.

Figure 5.1-7 shows the one hour average linear third octave level for the low-frequency range below 100 Hz compared to the perception threshold in accordance with DIN 45680 [5]. This was amended for values below 8 Hz [11]. In general, a decrease in the level can be seen the later it gets. Why

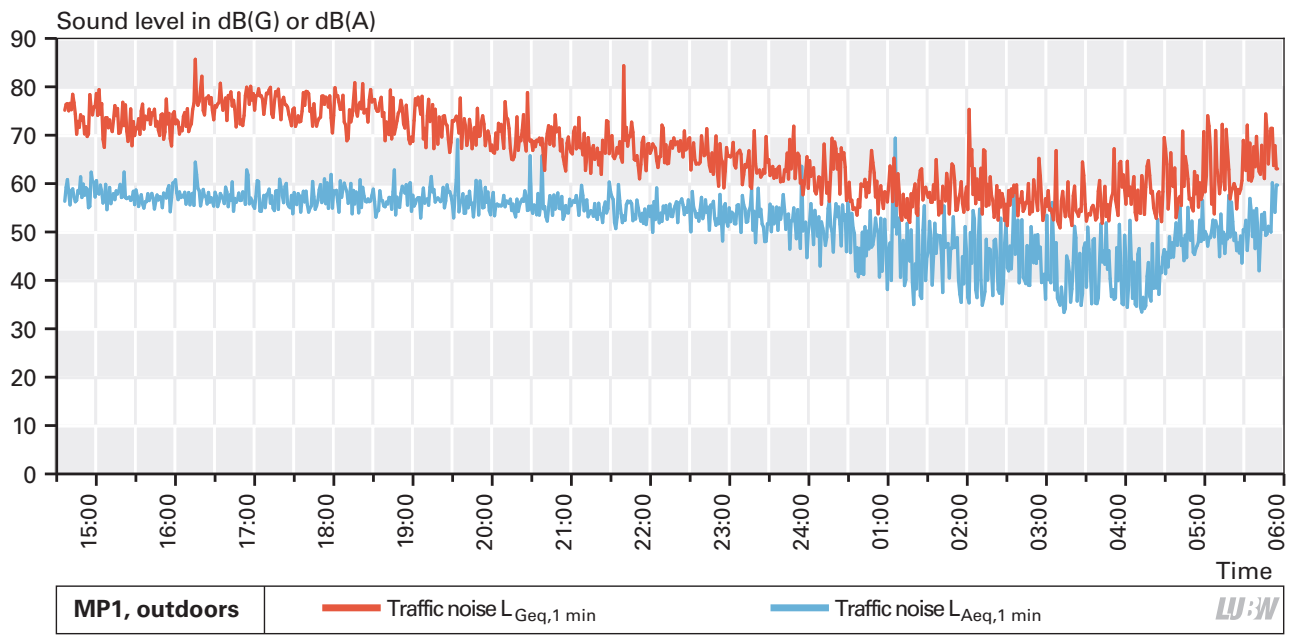
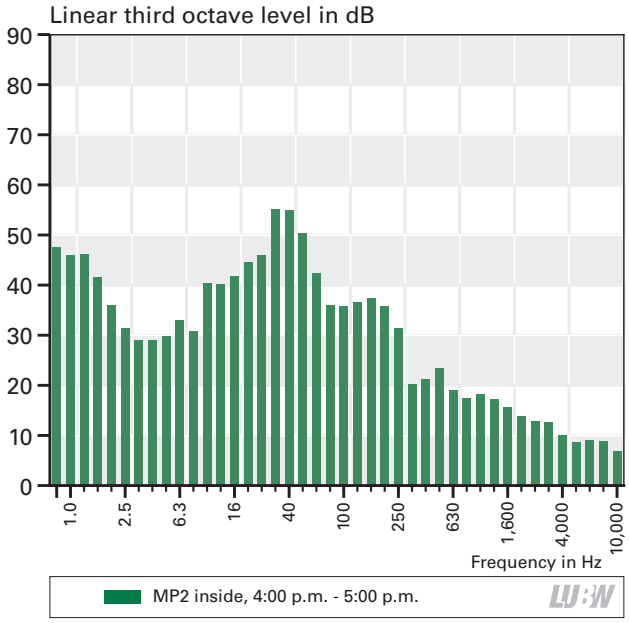
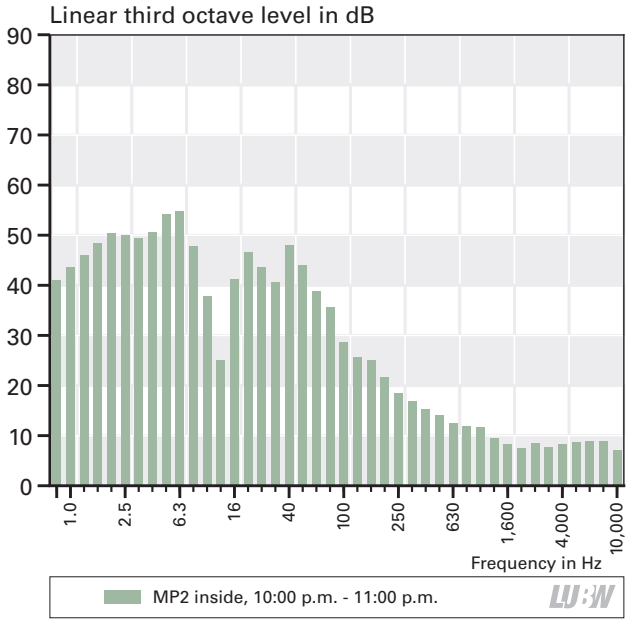
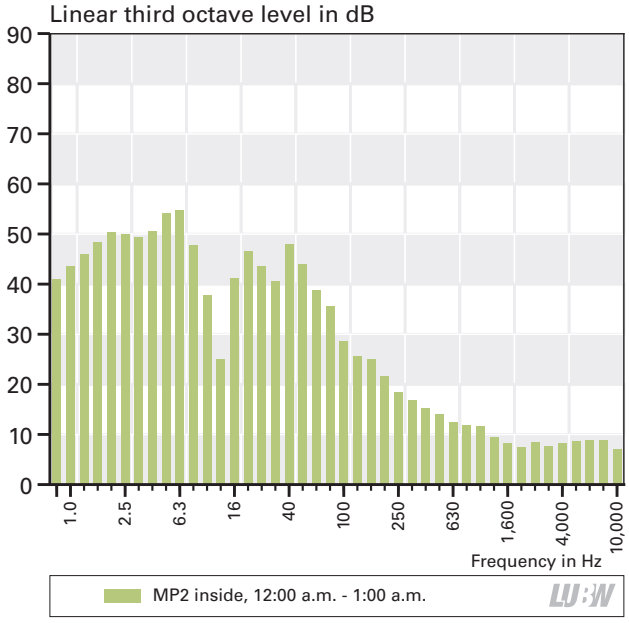


***Figure 5.1-5**: Distribution of the A-weighted sum level $L_{Aeq(t)}$ (blue) and the G-weighted sum level $L_{Geq(t)}$ (red) over the entire measurement period at the outdoor measurement point MP1*

the infrasound levels between 2 Hz and 8 Hz are higher at night is unclear. The G-weighted level during the time elapsed was between 40 dB(G) at night and 65 dB(G) at day.







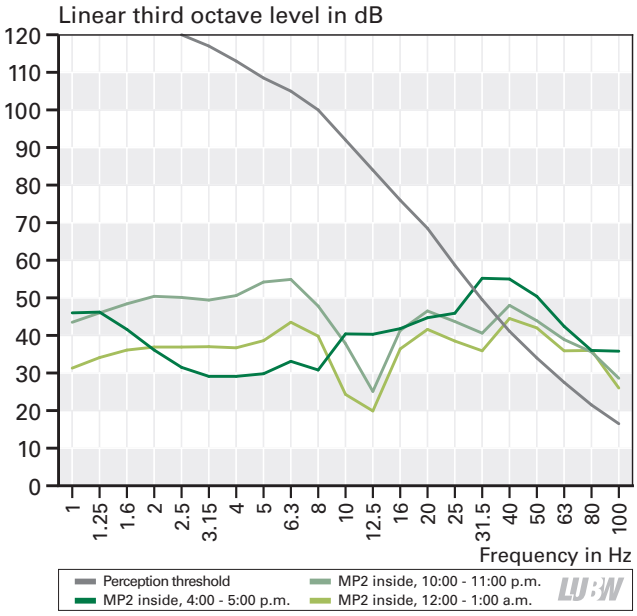


Figure 5.1-7 *(top): Comparison of the third octave levels at the measurement point MP2 (indoors) for the averaging periods 4:00 - 5:00 p.m., 10:00 - 11:00 p.m. and 12:00 - 1:00 a.m. The perception threshold according to Table A3-1 is also shown.*

Figure 5.1-6 *(left column): Linear third octave spectra for the time periods 4:00 - 5:00 p.m. (top), 10:00 - 11:00 p.m. (centre) and 12:00 - 1:00 a.m. (bottom) at the indoor measurement point MP2.*

5.2 Inner-city roads – permanent measuring stations Karlsruhe and Reutlingen

Since November 2012, the LUBW has been running a stationary road traffic noise monitoring station in Karlsruhe (Reinhold-Frank Strasse), and a further one in Reutlingen (Lederstrasse-Ost) since March 2013. This is where average and maximum levels of total noise are measured with the use of high-quality sound level measurement devices, as well as meteorological parameters such as temperature, wind speed and precipitation. In addition, the traffic data (vehicle type, quantity and speed) are recorded. Both stations are in areas with relatively high volumes of traffic: In Karlsruhe, approximately 24,000 vehicles/24h, however with a partial standstill of traffic, and in Reutlingen approximately 50,000 vehicles/24h (as of 2011).

In Karlsruhe, the microphone is positioned close to the road, meaning that the recorded levels do not directly depict the concerns of the population living somewhat further away. The distance to residential buildings is less than 10 m (***Figure 5.2-1***). The location of the measuring station in Reutlingen allows immediate statements to be made about the noise pollution for the people affected (***Figure 5.2-2***). Further information is available on the website www.lubw.de/aktuelle-messwerte (home page). The annual reports by the LUBW for the traffic noise monitoring stations can be found under the heading "Auswertungen" (Reports).

Based on the measurement data of the road traffic noise measuring stations in Karlsruhe and Reutlingen, evaluations were made by us with regards to low-frequency noise (incl. infrasound). In the following ***Figures 5.2-3 and 5.2-4*** frequency-selective representations of the noise level from 6.3 Hz to 125 Hz (third octave centre frequency) can be found for the two stations. Averaging was carried out over 30 minutes and summarized. Here only those time periods have been considered in which the wind speeds were less than one meter per second. These were approx. 2,000 half-hour averages for Karlsruhe and about 1,900 for Reutlingen, including many night hours. This avoided the occurrence and subsequent measurement of noise in the vicinity caused by the wind, and also ensured that no sound induced by the wind occurred directly at the microphone. Both

Figure 5.2-1*: LUBW measuring station for detecting road traffic noise in Karlsruhe, Reinhold-Frank-Strasse. The arrow shows the location of the microphone. Residential buildings visible in the background. Photo: LUBW*

Figure 5.2-2*: LUBW measuring station for detecting road traffic noise in Reutlingen, Lederstrasse. The arrow shows the location of the microphone. Photo: LUBW*

effects would have led to an increase in the level values at low frequencies and infrasound, as was the case during the measurements at the wind turbines.

To show the influence of traffic density, illustrations for higher and lower traffic volumes as well as for an average amount of traffic have been added (the exact data is given from the legend of ***Figure 5.2-3 and 5.2-4***). The proportion of heavy-goods traffic, based on the evaluated overall data, was 5 % in Karlsruhe and 11 % in Reutlingen.

Both evaluations show a striking increase between 31.5 Hz and 80 Hz above the perception threshold, which is attributable to motor vehicle traffic. Depending on traffic intensity, mean values of 72 dB (Karlsruhe) or 75 dB (Reutlingen) are reached. In the infrasound range (below 20 Hz) and below, the results of the measurements differ: This is where in Karlsruhe lower values are measured than in Reutlingen, which is probably due to different amounts of heavy-goods traffic, traffic volumes and speeds. In both cases, the third octave levels already exceed the perception threshold with a higher traffic volume between the 20 Hz and 25 Hz third. A similar result was at hand for the road measurement in Würzburg (Section 5.1, ***Figure 5.1-4***). The G-weighted sound levels were between 65 and 75 dB(G) in Karlsruhe and between 70 to 80 dB(G) in Reutlingen, see ***Table 5.2-1***.

5.3 Motorway – measurement near Malsch

The LUBW undertook sound measurements at the A5 (E52) motorway south of Karlsruhe near the town of Malsch on 26.06.2013 during the daytime between 1:00 p.m. and 3:00 p.m. The weather was sunny and practically windless. Wind-induced interfering noise at the microphone can therefore be ruled out. The distances of the microphone position to the middle of the centre strip of the motorway were 80 m, 260 m and 500 m (***Figure 5.3-1***). The measurement values at the measurement point at a distance of 500 m later had to be rejected due to the interference of the B3 main road and other interfering noise. Information on the used metrology can be found in Appendix A4.

The measurement results for the distances of 80 m and 260 m are graphically presented in ***Figure 5.3-2*** as a third

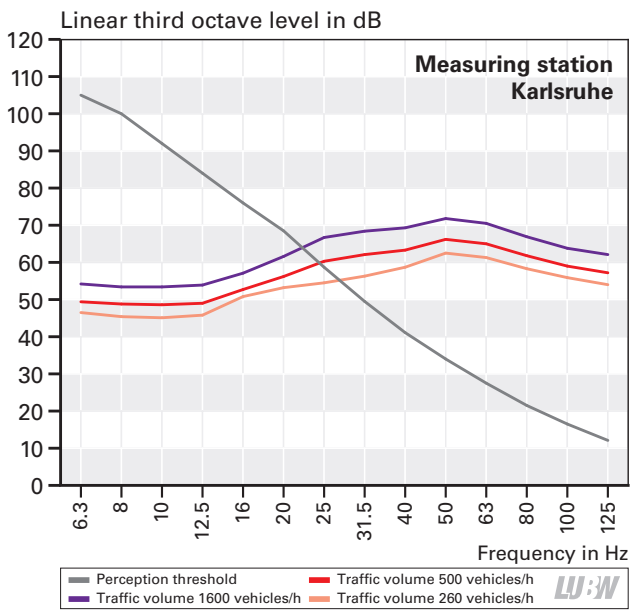


Figure 5.2-3: *Third octave spectra, measuring station Karlsruhe*

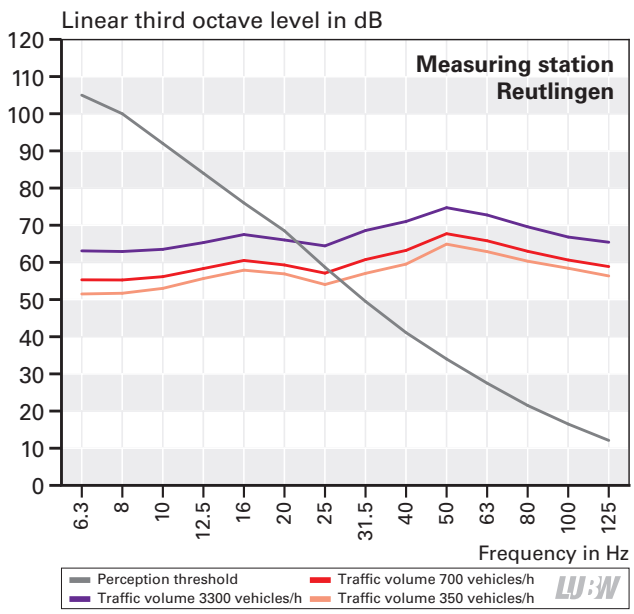


Figure 5.2-4: *Third octave spectra, measuring station Reutlingen*

Periods with zero wind or wind velocities below 1 m/s in the year 2013 were evaluated. Averages over 30 minutes each were formed and aggregated. The increased level in the range between the 31.5 Hz and 80 Hz thirds is caused by road traffic. The curves show the differences at various traffic volumes. Note: The representation begins at a frequency of 6.3 Hz (in other illustrations partly from 1 Hz.); this is due to the measuring technology. For comparison, the perception threshold according to Table A3-1 is shown.

***Table 5.2-1**: Summary of the measurement results for low-frequency noise (including parts of infrasound) at the traffic noise monitoring stations Reutlingen and Karlsruhe*

Source/situation	G-weighted level in dB(G)	Infrasound third octave level ≤ 20 Hz in dB *	Low-frequency third octave levels 25-80 Hz in dB *
Traffic noise measuring station Karlsruhe traffic volume >1600 vehicles/h	75	53 to 62	67 to 72
Traffic noise measuring station Karlsruhe average traffic volume: 500 vehicles/h	65	48 to 57	60 to 67
Traffic noise measuring station Karlsruhe traffic volume < 260 vehicles/h	69	45 to 54	55 to 63
Traffic noise measuring station Reutlingen traffic volume > 3300 vehicles/h	80	63 to 68	64 to 75
Traffic noise measuring station Reutlingen average traffic volume: 700 vehicles/h	70	55 to 61	57 to 68
Traffic noise measuring station Reutlingen traffic volume < 350 vehicles/h	73	52 to 57	54 to 61

* Linear third octave level in dB(Z)

***Figure 5.3-1**: Location of the measurement points at the A5 motorway south of Karlsruhe near Malsch, indicating the distances between the microphone positions and the centre of the motorway. The town of Malsch is located outside of the picture at the bottom left. The B3 main road is located above the picture. Picture source: LUBW, LGL*

octave representation. The third octave levels in the infrasound range are at levels of around 60 dB and slightly below. In the low-frequency range, approximately between 40 Hz and 80 Hz, a slight peak can be seen. Here the measured values are significantly above the hearing threshold. The average traffic intensity is approximately 3,000 vehicles/h with a share of heavy-goods traffic of around 15 %. The G-weighted infrasound levels were around 75 dB(G) at a distance of 80 m and around 71 dB(G) at a distance of 260 m. Additional information concerning the G level can be found in Appendix A3.

5.4 Noise inside car while driving

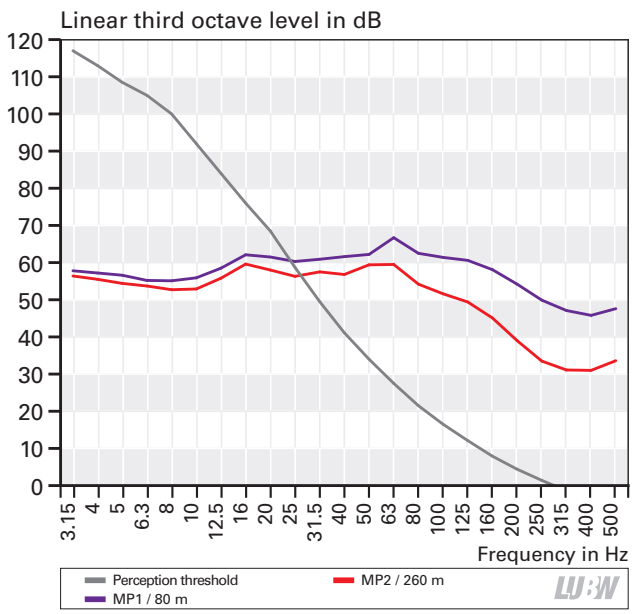
Below are the results of noise measurements carried out by the LUBW inside a moving car and a minibus on 06.09.2012. This is in fact no sound that occurs in the vicinity, i.e. no ambient noise or environmental noise in the strict sense. However, a lot of people are exposed to these sounds often and for longer periods of time, meaning that it surely makes sense to include such measurement values here. It became evident that relatively high levels in the infrasound range up to 20 Hz, as well as in the other low-frequency frequency range above 20 Hz occurred (***Firgure 5.4***, ***Table 5.4***). It must be noted that, with windows open, the levels that arise in the area of low frequencies incl. infrasound are so high that they are subjectively perceived as being painful. The values measured by us correspond to the respective specifications in literature (e.g. [19] [20]).

5.5 Conclusion of the road traffic measurements

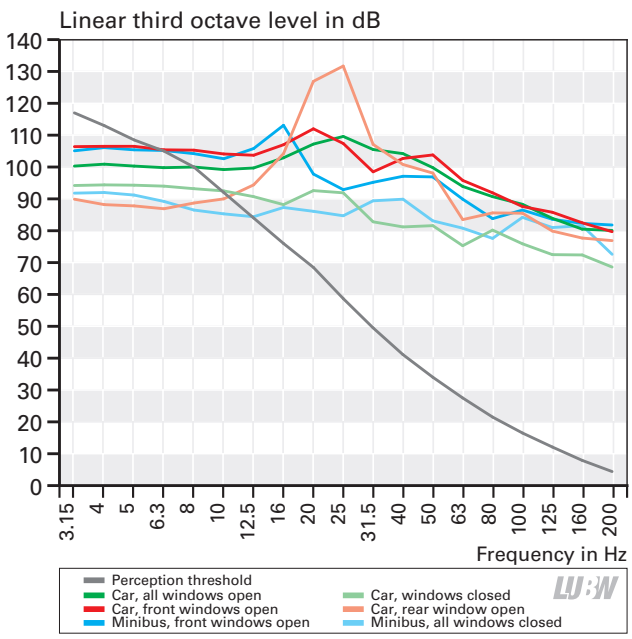
- It was possible to carry out the measurements for the low-frequency noise incl. infrasound resulting from road traffic without interfering wind noise. Unlike in the case of wind turbines, the recorded levels occur in the direct vicinity of residential buildings.

- As expected, it could be observed that the level of low-frequency noise including infrasound dropped at night. A good correlation with the traffic volume was also determined: The more the traffic, the higher the sound levels of low-frequency noise including infrasound.

- The Infrasound levels of traffic reach a maximum of 70 dB (unweighted) in individual thirds with respect to residential buildings in the vicinity. The G-weighted level



Firgure 5.3-2: *Frequency-dependent representation (linear third octave level) of a measurement at the motorway A5. As a comparison, the perception threshold according to Table A3-1 was also included. Note: The representation begins at a frequency of 3.15 Hz (in other illustrations partly from 1 Hz or 6.3 Hz). This is due to the measuring technology used.*



Firgure 5.4: *Low-frequency sound (averaging level) in the inside of car and minibus driving at approx. 130 km/h in comparison to the perception threshold according to Table A3-1*

***Table 5.4**: Infrasound level inside a passenger car or minibus while driving at 130 km/h*

Source	G-weighted level in dB(G)	Infrasound third octave level between 3.2 und 20 Hz in dB *
Interior noise in passenger car, all windows closed	105	88 to 94
Interior noise in passenger car, rear window open	139	87 to 127
Interior noise in minibus, all windows closed	100	85 to 93
Interior noise in minibus, side windows open	122	98 to 113

* Linear third octave level in dB(Z)

is in the range between 55 and 80 dB(G). This roughly corresponds to values found in literature for sea surf (***Table 2-1***).

- For road traffic, increased levels were detected in the frequency spectra in the range of between roughly 30 Hz and 80 Hz. Low-frequency noise in this area lies significantly above the hearing threshold and seems to be more relevant for an assessment than the infrasound level up to 20 Hz. The values in this low-frequency frequency range are significantly higher for the observed situations of road traffic than in the areas surrounding wind turbines (***Table 2-1***).
- The highest levels in the context of the measurement project were measured in the interior of a car travelling at 130 km/h. Even though these are not immission levels that occur in the free environment, they are an everyday situation that many people are frequently subjected to for a longer period of time. The measured values for both the infrasound as well as the other low-frequency areas are higher by several orders of magnitude than the values usually measured in road traffic or at wind turbines.

6 Urban background

The Friedrichsplatz in Karlsruhe was chose for the measurement of infrasound and low-frequency noise at day and night in an urban background. It is located in the heart of the city. The Friedrichsplatz is a rather quiet square located directly by the natural history museum. Benches, landscaped flower beds and a fountain invite passersby to linger and stop for a short break (***Figure 6-1***). The square extends for about 125 m from north to south and 100 m from east to west. The Erbprinzenstrasse crosses the Friedrichsplatz as a bicycle road. In a westerly and easterly direction are the Ritterstrasse and Lammstrasse respectively, with very slowly driving traffic. In the south, the square is limited by the natural history museum of Karlsruhe. To the west lies the Church of St. Stephan with forecourt. Apart from that, the Friedrichsplatz is surrounded by offices and commercial buildings, as well as a number of individual apartments. The next somewhat busier road is situated about 250 m to the south, shielded behind the natural history museum and the Nymphengarten (Kriegstrasse, B 10). Tram lines are located at a distance of several hundred metres, partially behind several blocks of buildings (***Figure 6-2***), and a construction site is located in a north-westerly direction.

The measurements were carried out simultaneously at three measurement points. The location of the measurement points is shown in the aerial view in ***Figure 6-3***. Measurement point MP1 was chosen in the inside of a building adjacent to the Friedrichsplatz (meeting room of the education authority of Karlsruhe). A second measurement point MP2 was placed on the ground of the Friedrichsplatz, a third measurement point MP3 on the roof of the museum of natural history (***Figures 6-4 to 6-6***). MP2 and MP3 were positioned on a reverberant plate.

The measurements were carried out from Friday, 20.09.2013, 3:00 p.m. to Saturday, 21.09.2013, 2:00 a.m. Preliminary

Figure 6-1: *Friedrichsplatz in Karlsruhe, looking south at the natural history museum. Photo: LUBW*

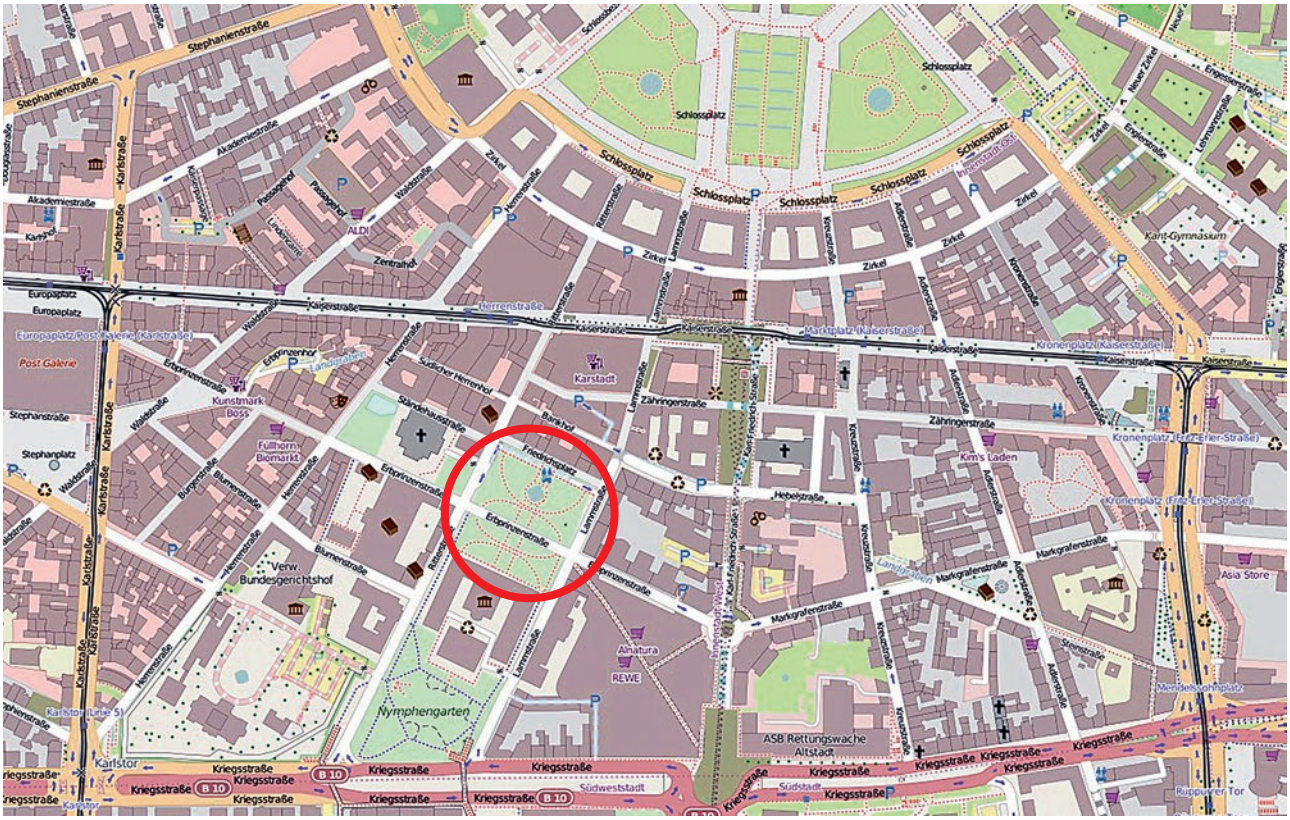


Figure 6-2: *City map of Karlsruhe with Friedrichsplatz (red circle) and the tram lines in the vicinity (dark and dashed lines). Source: www.OpenStreetMap.org*

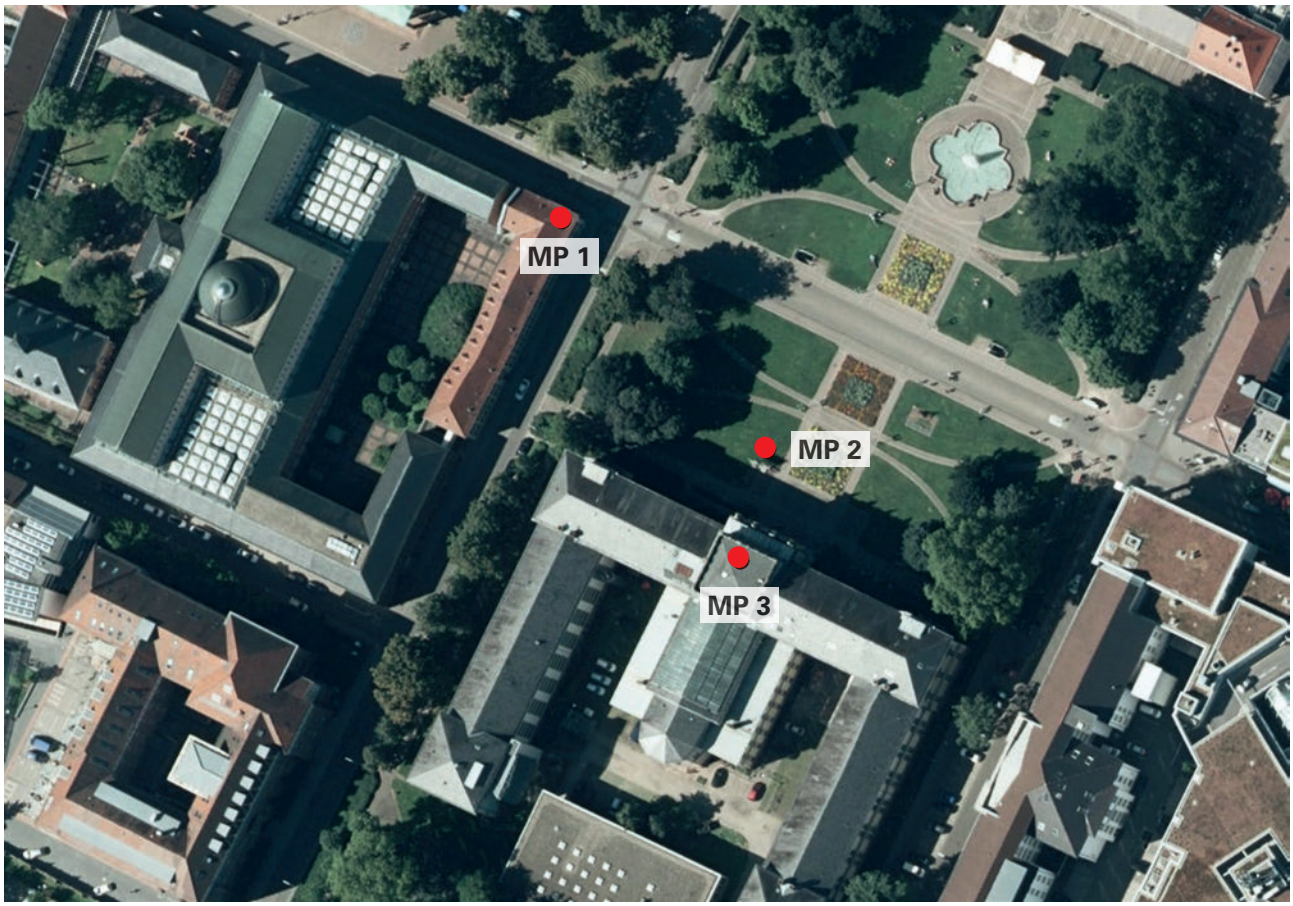


Figure 6-3: *Oriented aerial view of Karlsruhe Friedrichsplatz. Location of the three measurement points MP1 (meeting room of education authority), MP2 (on Friedrichsplatz) and MP3 (roof of museum of natural history). Source: LUBW, LGL*

measurements were taken by the LUBW on 26.06.2013. The measurements should enable conclusions to be made about the situation at day and at night. The volume of traffic (cars, pedestrians, cyclists) was typical for this site in the given weather conditions. In summer nights or during events, higher volumes will surely be the case.

Note: While the infrasound and low-frequency noise measured in the vicinity of operating wind turbines always contains a proportion of wind (and possibly also a share that is induced by the wind at the microphone), the conditions are much more favourable for the measurement of inner city noise. Here these effects related to the wind play virtually no role. The infrasound and low-frequency noise could be measured largely without any disturbing wind noise. Only on the roof of the museum of natural history did wind noise occur from time to time. For more information see page 73.

RESULTS

The measured third octave spectra for the three measurement points, each for the time periods 4:00 p.m. - 5:00 p.m., 10:00 p.m. - 11:00 p.m. and 12:00 a.m. - 1:00 a.m. are shown in ***Figure 6-8*** and are explained in the following:

At the measurement point MP1 (education authority, indoor measurement), third octave levels between just under 20 dB to 45 dB were measured in the infrasound area below 20 Hz. The values are all below the perception threshold. It is clearly visible that the infrasound levels drop at night by about 10 dB. In the further low frequency range a significant rise from 25 Hz to 63 Hz can be found, which is probably due to traffic noise and electrically powered equipment (the building was not without electrical power). All in all, the lowest levels are found at the indoor measurement at MP1 as a result of the absorption through the building envelope. The results of the indoor measurement were evaluated according to DIN 45680 (1997) [4],

Figure 6-4: *Setup of the measurement point MP1, indoor measurement at the education authority of Karlsruhe. Photo: LUBW*

Figure 6-5: *Measurement point MP2 on the Friedrichsplatz in front of the natural history museum Karlsruhe. Photo: LUBW*

Figure 6-6: *Microphone position at measurement point MP3 (roof of museum) with view over Karlsruhe. The meteorology was also determined at MP3. Photo: LUBW*

Figure 6-7: *View from measurement point MP3 (roof of museum) looking north over Karlsruhe. The floodlights of the KSC stadium in the Wildpark can be seen. Photo: LUBW*

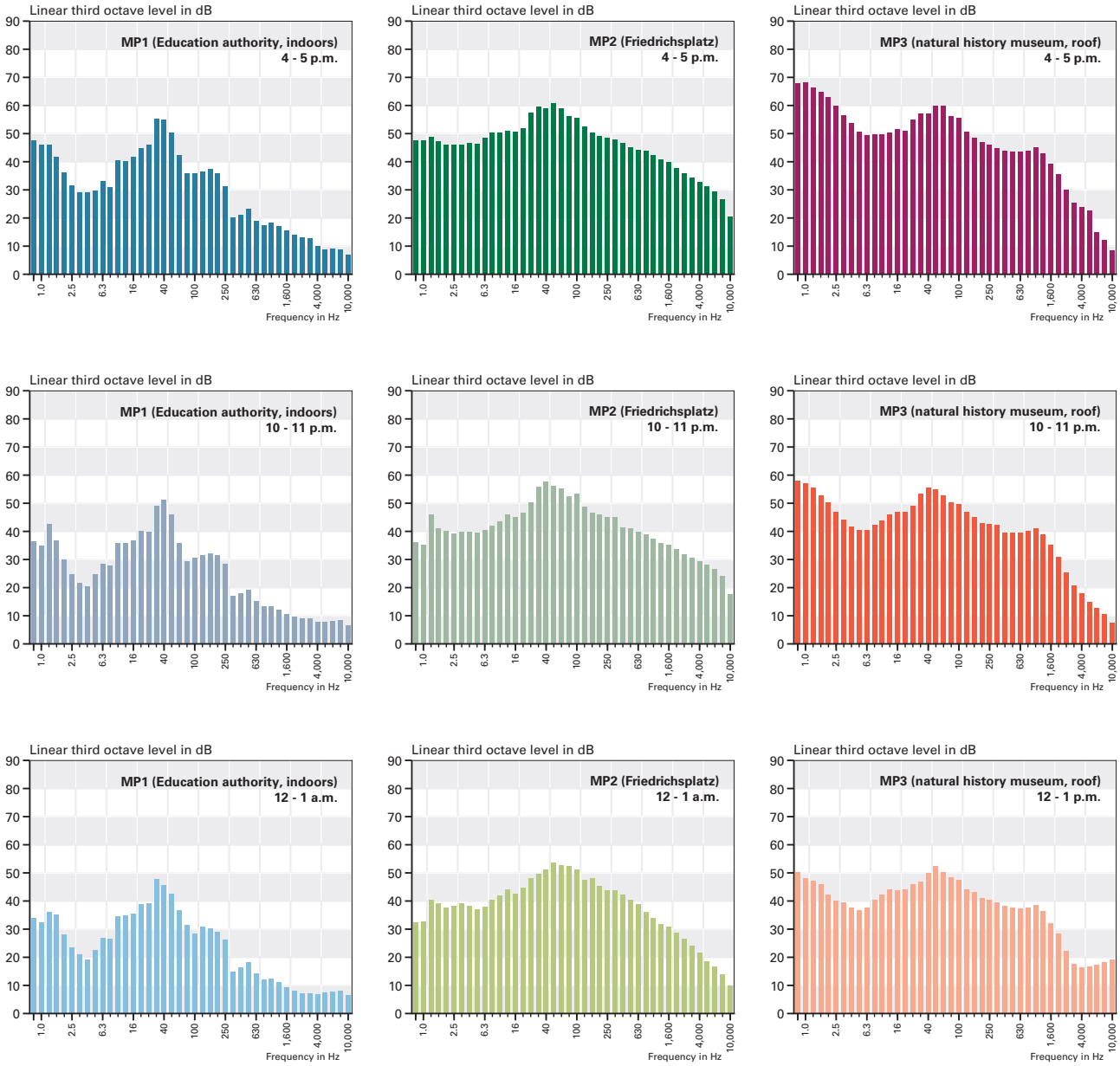


***Figure 6-8**: Measured third octave spectra for the three measurement points at different times of the day and at night. Left column: Measurement point MP1 (education authority, indoors); centre column: Measurement point MP2 (Friedrichsplatz); right column: Measurement point MP3 (natural history museum, roof). For explanations see text.*

even if the scope of this standard does not cover road traffic noise. Time periods with substantial influence of background noise at measurement point MP1 were excluded from the evaluation. The following periods of time were chosen: For the night period (10:00 p.m. - 11:00 p.m., loudest hour), as well as in accordance with the procedure of DIN 45680 (1997) [4] for the day period (4:00 p.m. - 5:00 p.m., loudest hour) as well as informatively for the night hour from 12:00 a.m. - 1:00 a.m. The reference values taken from the supplement sheet "Beiblatt 1" for above-stated norm (these are formally only valid for the operation of industrial plants) were exceeded in the daytime as well as night time periods. There were no clearly protruding single tones. For informative purposes, the measurement data was also evaluated according to the revised draft of DIN 45680 (2013) [5]. The reference values taken as a comparison (these are formally only valid for the operation of industrial plants) were exceeded in the daytime as well as night time periods.

The data of the measurement points MP2 and MP3 was respectively corrected according to Section 4.1 (reverberant plate). At the measurement point MP2 (Friedrichsplatz in front of the museum), third octave levels between

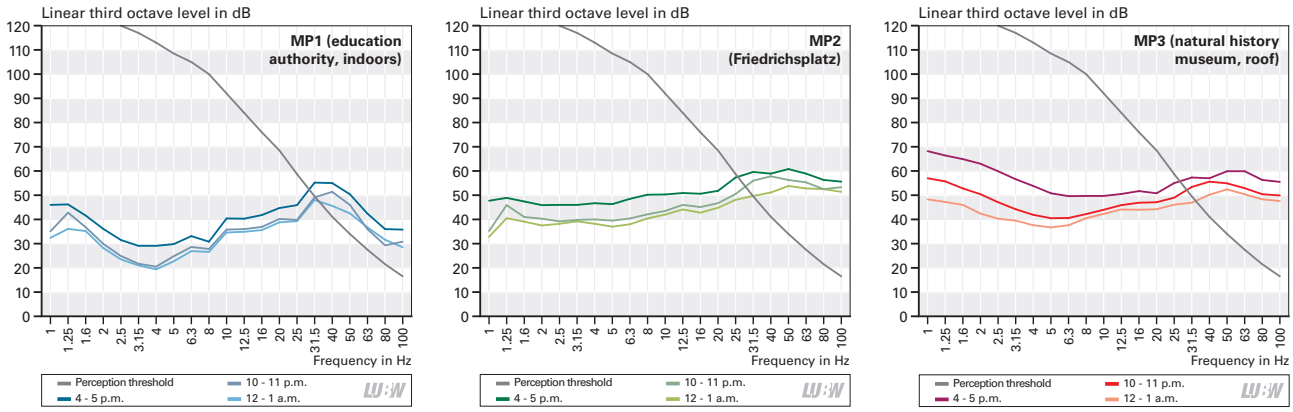


***Figure 6-9**: Comparative frequency-dependent representation of the third octave sound level for the three measurement points at different times of the day and at night. The results for MP2 and MP3 have been corrected (reverberant plate, see Section 4.1). The perception threshold was also shown as a means of orientation. Left: measurement point MP1 (education authority, indoors); Centre: measurement point MP2 (Friedrichsplatz); right: measurement point MP3 (natural history museum, roof).*

just under 35 dB and a little over 50 dB were measured in the infrasound range up to 20 Hz. Here too, a decrease of the infrasound can be recognised later at night. In the low-frequency range, an excessive increase can also be seen, which can be attributed to the road traffic. This is where levels above 55 dB are also reached at night in the range of 32 Hz to 80 Hz, which is above the perception or hearing threshold. An interesting effect can be seen for the 1.25 Hz third, which, for example, clearly stands out in the third octave spectrum for MP2 between 10:00 p.m. and 11:00 p.m. This concerns a natural frequency of the Friedrichsplatz, which is largely surrounded by buildings (half a wavelength corresponds to merely the extent of the square). This effect can be analysed further in the narrow band spectrum (not shown here).

At the measurement point MP3 (museum roof), similar conditions as for MP2 can be seen – with two differences: For the infrasound below 5 Hz, an excessive increase can be seen, which here is attributed to the somewhat increased wind speed on the roof and the corresponding wind effects. An increase arising in the range above 500 Hz can at least partially be attributed to the rolling noises of cars on roads located further away, such as the B 10 (Kriegstrasse). These were noticeable on the roof, but were otherwise screened off. In the evening, it was possible to get a direct view of the KSC football club's Wildpark stadium, where a match was taking place (***Figure 6-7***).

In a further analysis of the narrow band spectra (not listed here), some individually protruding lines could be detected at some frequencies. However, these could not all be associated with specific sources.

In ***Figure 6-9*** the developments of the linear third octave levels in the range from 1 Hz to 100 Hz are presented for the measurement points MP1 to MP3 in comparison to the perception threshold (according to draft of DIN 45 680 [5]; below 8 Hz supplemented by literature values [11]). See also ***Table A3-1***. The results for MP2 and MP3 were corrected, as shown in Section 4.1, due to the use of a reverberant plate.

Figure 6-10 shows the course of the A-weighted and G-weighted sound level during the measurement at the measurement point MP2 (Friedrichsplatz). It can be clearly seen that the G level, which represents the low-frequency noise including infrasound, slowly and steadily decreases in the evening hours. The G levels at the measurement point MP1 (indoors) were mostly between 45 dB(G) and 60 dB(G) during the measuring period, and at times even above that. At the measurement points MP2 (Friedrichsplatz) and MP3 (roof), the values were mostly between 55 dB(G) and 65 dB(G), and partially reached levels above 70 dB(G).

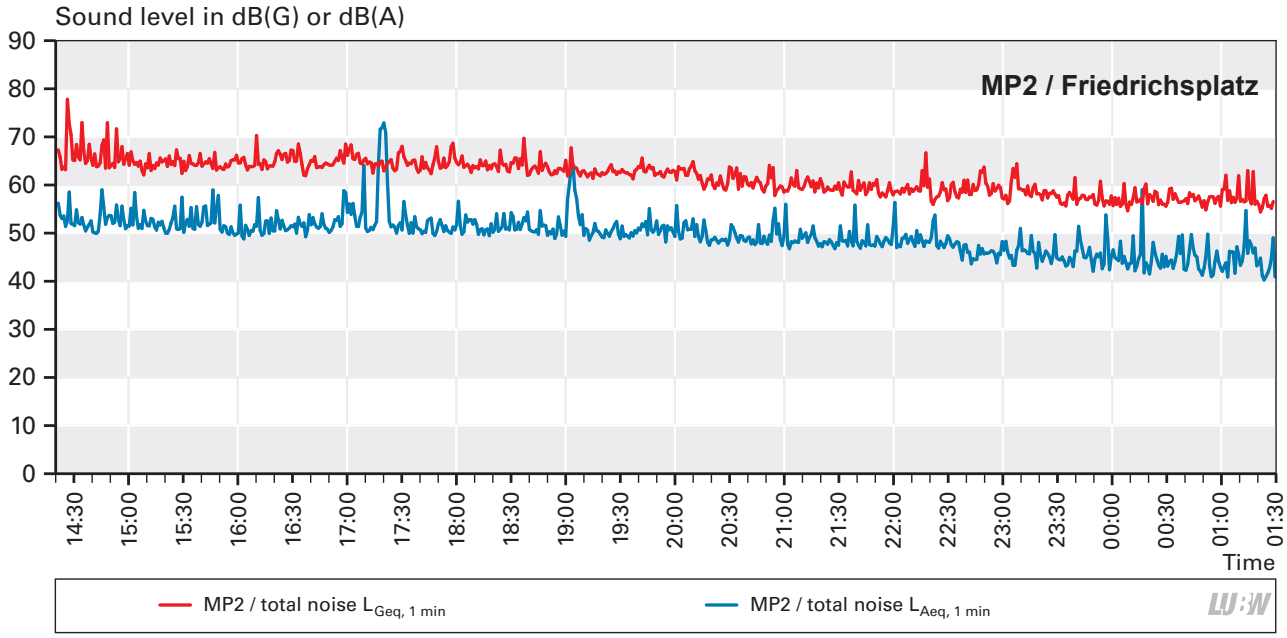


***Figure 6-10**: Course of the A and G-weighted sum level $L_{Aeq}(t)$ und $L_{Geq}(t)$ at the measurement point MP2 (Friedrichsplatz) in the time period 20.09.2013, approx. 2:30 p.m. to 21.09.2013, 1:30 a.m.*

7 Sources of noise in residential buildings

Life in the modern household is characterized by the use of technical devices, which are used to facilitate everyday life. The locations of the devices are normally chosen on the basis of the existing supply connections for electricity, water or gas. When doing so, people also generally pay attention to ensuring a preferably trouble-free use of the living quarters. Devices such as fridges or ventilation systems are permanently or intermittently in operation, while other devices such as vacuum cleaners or electronic tools are used only briefly. During operation, every technical device emits characteristic sounds. Depending on the source, different sound patterns can also be caused by different operating modes.

With the help of manufacturer's instructions, buyers can inform themselves about the expected noise levels prior to the acquisition of technical devices. However, the data sheets often only specify the A-weighted levels. These provide no indications of how the sound spreads across different frequencies.

In order to also be able to present low-frequency noise that may occur in a living environment in a comparative manner, the LUBW carried out sound level measurements in a residential building in the city centre of Tübingen. The apartment building in half-timbered construction style dates from the second half of the 19th century. The compartments of the walls are made of sandstone and the wood-beamed ceilings are filled with clay. The ceilings and walls are additionally covered with a 3-4 cm thick layer of lime plaster. In the course of renovation work during the last few years, the worksite sandstone slabs or tiles were moved onto a layer of reinforced cement screed in some areas, such as in the bathrooms. The building is located in a restricted traffic area; the next multilane roads are about 150 m away. Any traffic noise emanating from there is largely shielded by the building density of Tübingen city centre. The acoustic situation around the building is significantly characterized by the communication noise of passers-by.

The measurements on 04.08.2015 registered two washing machines from various manufacturers, one refrigerator, one oil heating and one gas heating. For detailed information on the used measuring instrumentation please refer to Appendix A4.

7.1 Washing machine

The washing machines were located in two apartments on the 1st and 2nd floor of the house. The measurements were each taken at a measurement point MP1 at close range within the room of the installation itself, as well as at a measurement point MP2 in a separate room. When measuring washing machine 1 on the 1st floor, the measurement point MP1 in the middle of the room was approx. 0.5 m from the washing machine. Measurement point MP2 was located approx. 3 m vertically above MP1 on the 2nd floor. Washing machine 2 was located on the 2nd floor. Here measurement point MP1 was also positioned in the middle of the room approx. 0.5 m from the washing machine, while measurement point MP2 in the adjoining room – separated by a wall – was positioned approx. 5 m away.

RESULTS

The measurements of the two washing machines took place in the period from 10:50 a.m. to 11:30 a.m. Periods with extraneous noise effects were excluded from the evaluation.

With washing machine 1 in operation, third octave levels between 44 dB and 76 dB in the infrasound range under 20 Hz were measured at measurement point MP1 (***Figure 7.1-1***). The highest levels occurred during the spin cycle and the lowest ones during the wash cycle. At measurement point MP2, third octave levels of 29 dB to 60 dB occurred below 20 Hz during the measurement of washing machine 1. Here, too, the higher levels were registered during the spin cycle.

At washing machine 2, the third octave levels at measurement point MP1 in the infrasound range below 20 Hz were between 35 dB and 70 dB (***Figure 7.1-2***). Here too, the highest third octave levels were registered in the spin cycle. The measurements at measurement point MP2 showed third octave levels between 26 dB and 71 dB in the same frequency range.

The curves for the individual modes of operation of the two measured washing machines are almost parallel for the measurement points MP1 and MP2 in the infrasound range below 20 Hz. In contrast, it can be seen that above 20 Hz the difference between the third octave levels measured at both measurement points increases with increasing frequency. This can be attributed to the sound insulation effect of the building components (ceiling or wall). The building components reduce the higher-frequency sound to a significantly higher degree than is the case in the infrasound range.

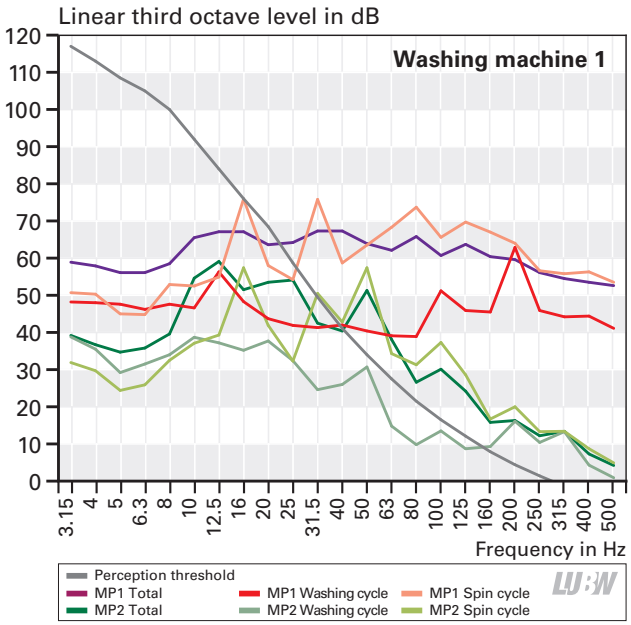


***Figure 7.1-1**: Third octave noise level of washing machine 1 at measurement points MP1 and MP2 for different operating states, with perception threshold according to Table A3-1 for comparison. "Total": Average level over the entire wash cycle.*

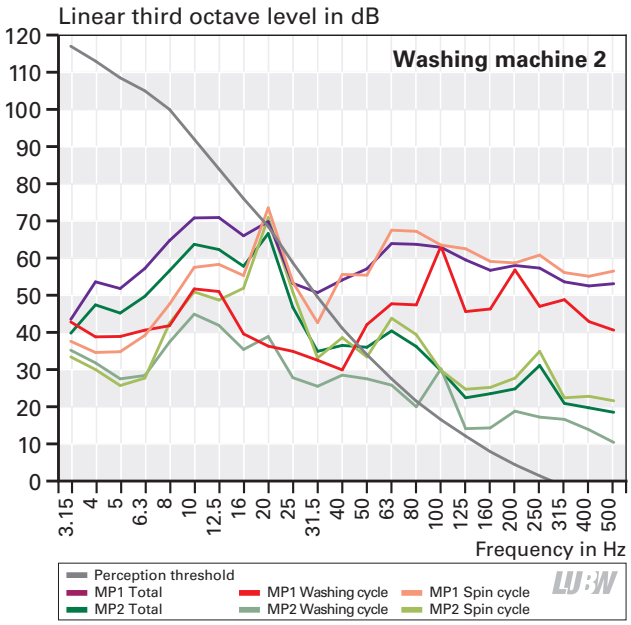


***Figure 7.1-2**: Third octave noise level of washing machine 2 at measurement points MP1 and MP2 for different operating states, with perception threshold according to Table A3-1 for comparison. "Total": Average level over the entire wash cycle.*

The single tone at 16 Hz (washing machine 1) as well as 20 Hz (washing machine 2) are caused by the respective rotational speed during the spin cycle. The 16 Hz third octave correlates with 960 rpm, the 20 Hz third octave with 1,200 rpm. The additionally emerging single tone at washing machine 1 at about 31.5 Hz is a harmonic overtone of the 16 Hz third octave. Depending on the operating mode, single third octave levels can reach the perception threshold according to ***Table A3-1*** between roughly 16 Hz and 20 Hz; above 50 Hz the third octave levels are generally in the audible range.

7.2 Heating and refrigerator

The two heating units measured were an oil boiler in the basement with pressurised atomiser burner on the one hand, and a gas water heater installed on a wall in the bathroom of the 2nd floor on the other. The fridge was located on the 2nd floor in a corner of the kitchen. The measurements of these noise sources were each carried out at a measurement point at a distance of about 0.5 m.

RESULTS

The third octave spectra during operation of the two heating systems as well as the refrigerator in the period from 11:40 a.m. to 1:30 p.m. were measured using technical measuring equipment. The results of the measurements are shown in ***Figure 7.2-1***. As was the case for the other measurements, extraneous noise, e.g. caused by measuring staff or passers-by outside, was excluded from the assessment.

Levels of approx. 55 dB to 70 dB were measured at the oil heating in the infrasound range below the 20 Hz third octave. In the low-frequency range between 20 Hz and 80 Hz, the third octave levels are between 55 dB and 60 dB. A single tone with a third level of 74 dB is recognisable at 100 Hz. Levels between 40 dB and 50 dB were measured at the gas water heater in the infrasound range below 20 Hz. In the low-frequency range between 20 Hz and 80 Hz, the

third octave levels measured at the gas heating are between 40 dB and 50 dB. The difference between the levels measured at the oil heating and the gas water heater in the low-frequency range is between 10 dB and 40 dB.

The fridge measured in the kitchen of the 2nd floor delivered third octave levels of between 32 dB and 50 dB in the infrasound range. Third octave levels between 17 dB and 50 dB were measured at the refrigerator between 20 Hz and 80 Hz. While the third octave spectrum of the oil heating clearly sets itself apart from the other measured units through higher levels, the third octave spectra of the gas water heater and the refrigerator are very similar.

SUMMARY

During the measurements in the residential building, the highest levels at washing machines were recorded during the spin cycle. Tonalities in individual third octaves correlate with the rotational speed of the drum of the washing machine during the spin cycle. As expected, building components dampen higher frequency noise components more than at low frequencies. The perceptual threshold according to ***Table A3-1*** was reached for the washing machines in the frequency range above 16 Hz and 20 Hz respectively. With the other devices, the infrasound level did not reach this threshold.

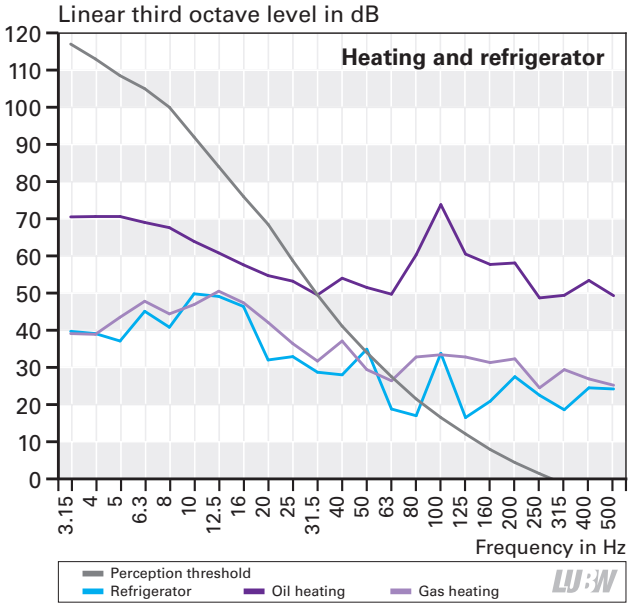


Figure 7.2-1*: Third octave sound level of the noise from oil heating, gas heating and refrigerator at a distance of 0.5 m from the unit, with perception threshold according to Table A3-1 for comparison*

8 Natural sources

8.1 Rural environment

In order to make statements about how much infrasound is caused by wind in the great outdoors, sound level measurements were carried out within the framework of the measuring programme on 09.05.2015 with strong winds in an open field (measurement point MP1), on the edge of a forest (measurement point MP2) and in a forest (measurement point MP3). The three points were aligned downwind of each other, starting with MP1. As with the wind power plants, the sound level measurements were carried out on a reverberant plate with a primary and secondary wind screen. At the same time, the wind speed was measured at 10 m height (open field) at the measurement point MP1. ***Figures 8.1-1 to 8.1-3*** provide an impression of the positioning of the measurement points. The measurement point MP1 lies approx. 130 m from the edge of forest.

The evaluation was carried out for the frequency range between 1 Hz and 10 kHz. The procedure corresponded to the analysis of the measurements at wind power plants, as described in Section 4. Two time periods were examined per measurement point at different wind speeds (6 m/s and 10 m/s at the measurement point MP1, open field), within which the wind blew evenly if possible. As a result, two situations with widely differing environmental conditions were recorded. Due to the spatial situation at the measurement points MP2 (edge of forest) and MP3 (forest) it can be assumed that at the same given point in time the wind speed is lower there than at the measurement point MP1 (open field).

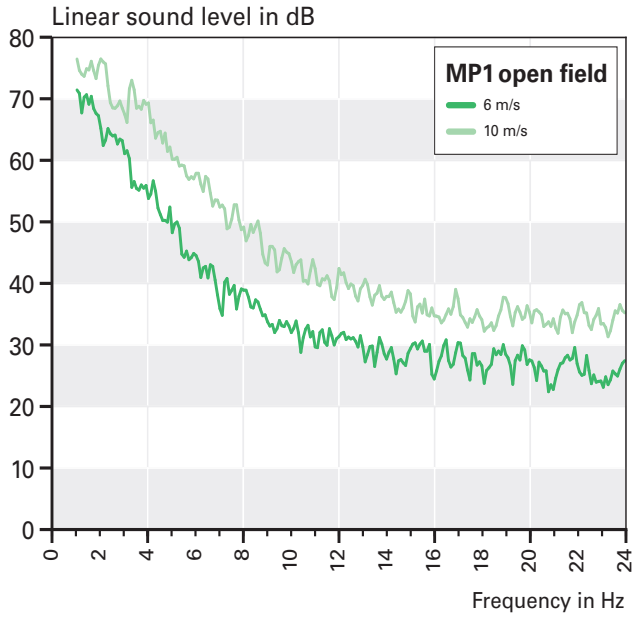
RESULTS: NARROW BAND LEVEL

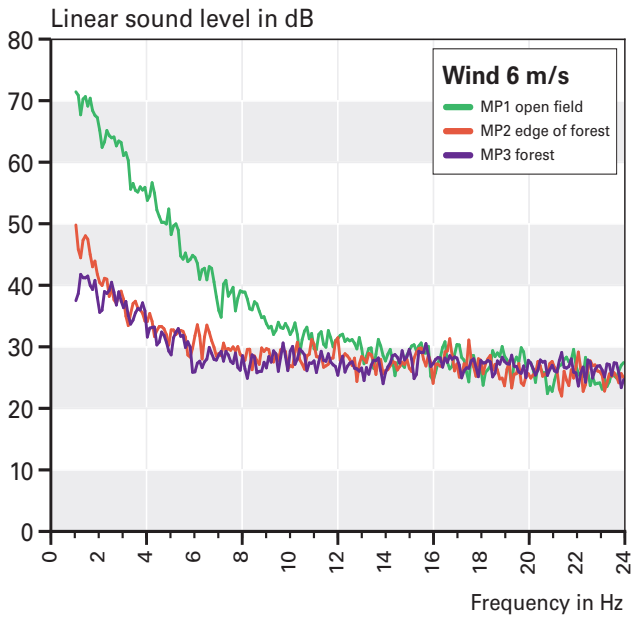
Figure 8.1-4 shows the narrow-band spectra determined from the audio signals at an average wind speed of approx. 6 m/s and 10 m/s at a height of 10 m (measured at the measurement point MP1). The three charts in the left column enable a comparison of measurement results for the two wind speeds at each measurement point. The two graphs in the right column show the sound levels that were recorded at the three measurement points for each of the wind speeds 6 m/s and 10 m/s. It can be seen clearly how the le-

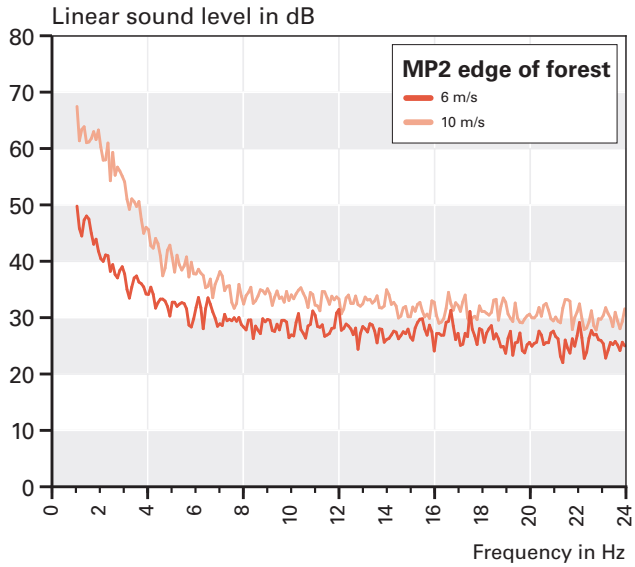
Figure 8.1-1: *Measurement point MP1 on open field (left) and meteorology mast (right), looking in direction of forest. Photo: Wölfel company*

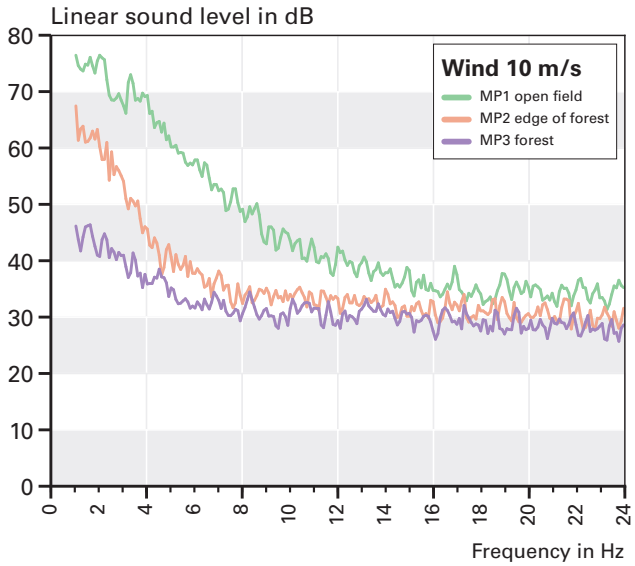
Figure 8.1-2: *Measurement point MP2, edge of the forest. Photo: Wölfel company*

Figure 8.1-3: *Measurement point MP3 in the forest, approx. 90 m from measurement point MP2. Photo: Wölfel company*









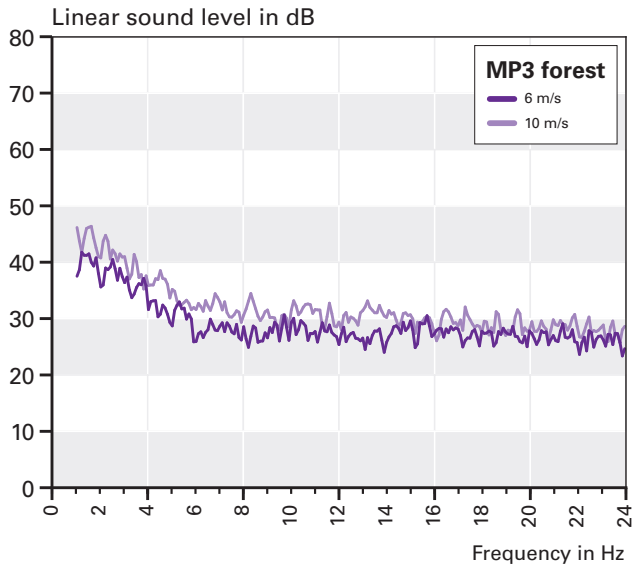


***Figure 8.1-4**: Narrow band spectra of noise at the measurement point MP1 (open field), MP2 (edge of forest) and MP3 (forest) for the frequency range of infrasound at different wind speeds. The wind measurement was always carried out at the measurement point MP1 (open field).*

Left column: Comparison of narrow band levels for the various wind speeds, separately presented for the measurement points MP1 (open field), MP2 (edge of forest) and MP3 (forest).

Right column: Comparison of the narrow band level at the three measurement points, represented separately for the wind speed 6 m/s (above) and 10 m/s (below)

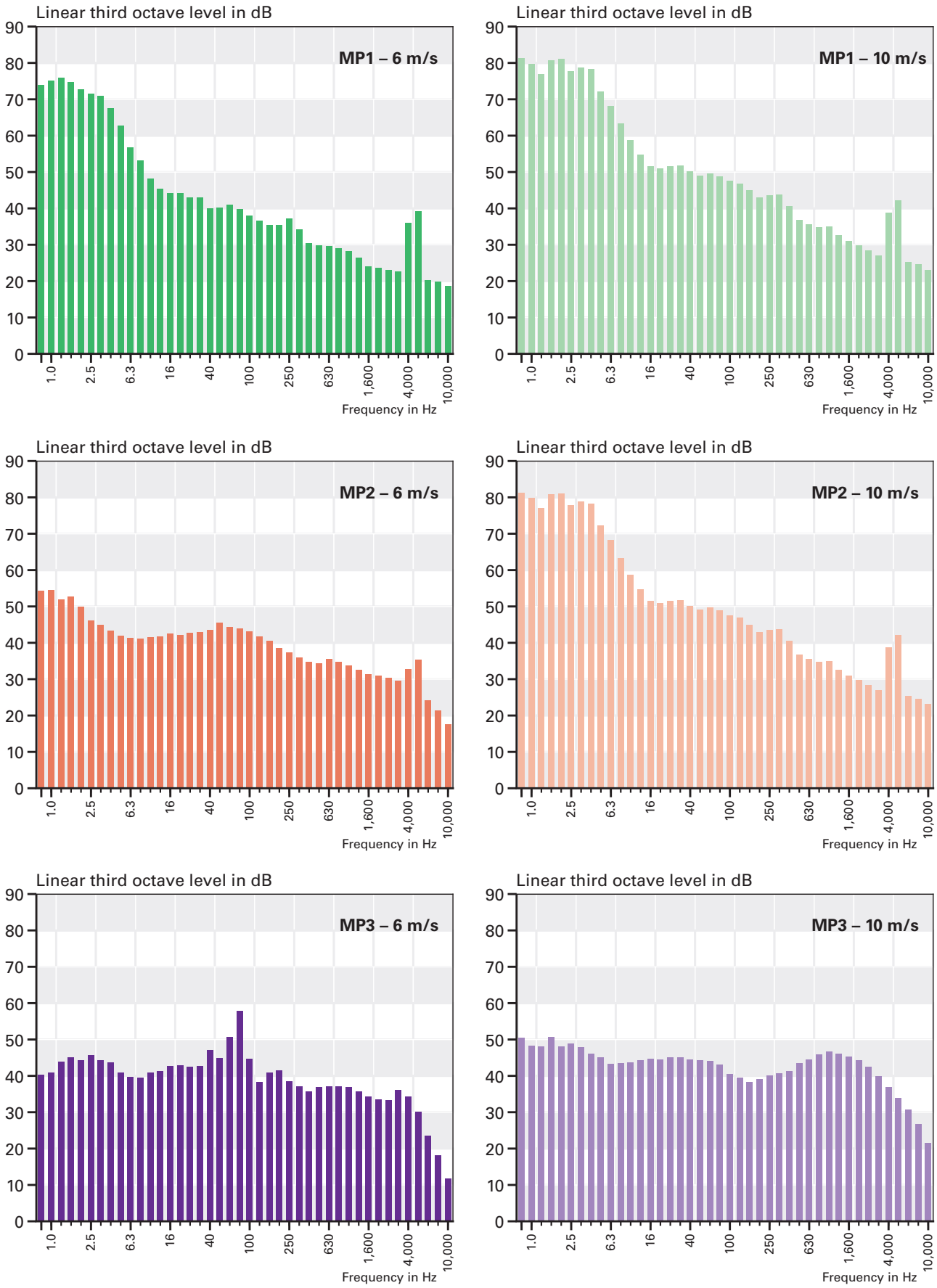


***Figure 8.1-5**: Third octave spectra of the background noise at the measurement point MP1 (open field), MP2 (edge of forest), and MP3 (forest). Left column: Wind speed 6 m/s; right column: Wind speed 10 m/s. The wind measurement was always carried out at the measurement point MP1 (open field).*

vels depend on the measuring position and the wind speed. On an open field, the levels are about 10 to 15 dB higher at a wind speed of 10 m/s than at a wind speed of 6 m/s. At the edge of the forest, this difference is somewhat weaker for frequencies above roughly 5 Hz. The difference is only 5 to 10 dB. In the forest, the difference is 5 dB or less. The spread of the measured values between the three measurement points falls from roughly 30 dB at the lowest end of the spectrum to 0 to 5 dB at the upper end, depending on the wind speed. Noteworthy level differences between the edge of the forest and the forest occur only below 10 Hz. The differences in level between open field and forest, on the other hand, become less only above 20 Hz.

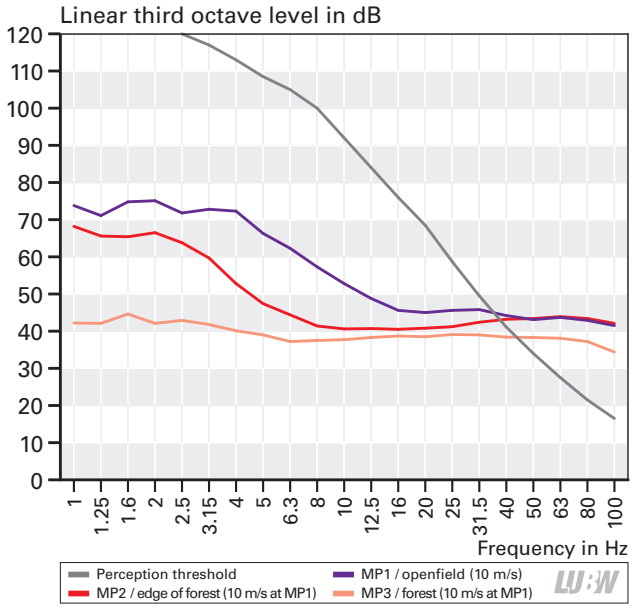


***Figure 8.1-6**: Comparison of the third octave spectra of the total noise at the measurement points MP1 (open field), MP2 (edge of forest) and MP3 (forest) with the perception threshold according to Table A3-1. The measured values were corrected in accordance with Section 4.1.*

RESULTS: THIRD OCTAVE LEVEL

The third octave spectra of the background noise at all three measurement points for the frequency range from 0.8 Hz to 10,000 Hz are presented in ***Figure 8.1-5***. The wind speed was 6 m/s (left column) and 10 m/s (right column). On the open field, the low frequencies are predominant in the spectrum; at the edge of the forest and even more so in the forest, however, a shift to higher frequencies can be seen. While the wind becomes less the closer it gets to the forest, and less wind noise is therefore induced at the microphone, the noise from the leaves in the forest increases considerably. The peak values at about 4,000 Hz are due to the chirring of crickets and chirping of birds.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 8.1-6 shows the third octave spectra of the total noise at the measurement points field, edge of forest and forest for the frequency range from 1 Hz to 100 Hz along with the perception threshold for comparison. The wind speed was 10 m/s. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

The data in ***Figure 8.1-7*** shows that both the audible sound level (A level) and the infrasound level (G level) increase with increasing wind speed. Worth noting is the decrease in level of the G-weighted level from the measurement point MP1 (open field) in the direction of the measurement point MP3 (forest). This correlates with the decreasing wind speed when moving from the open field towards the forest. Wind-induced effects on the microphone can be generally ruled out (see Section 4.5 and 4.6, measurement in hole in the ground). The A-weighted level increases the closer you get to the forest, which can be attributed to the rustling of leaves, which is reflected in the A level.

***Table 8.1-1**: Infra sound in a rural location at the three measurement points at different wind speeds*

Measurement point	G-weighted level in dB(G) Wind 6 / 10 m/s	Infrasound third octave level ≤ 20 Hz in dB * Wind 6 / 10 m/s
MP1 open field, 130 m from forest	50-65 / 55-65	40-70 / 45-75
MP2 edge of forest	50-60 / 50-60	35-50 / 45-75
MP3 forest	50-60 / 50-60	35-40 / 40-45

* Linear third octave level in dB(Z)

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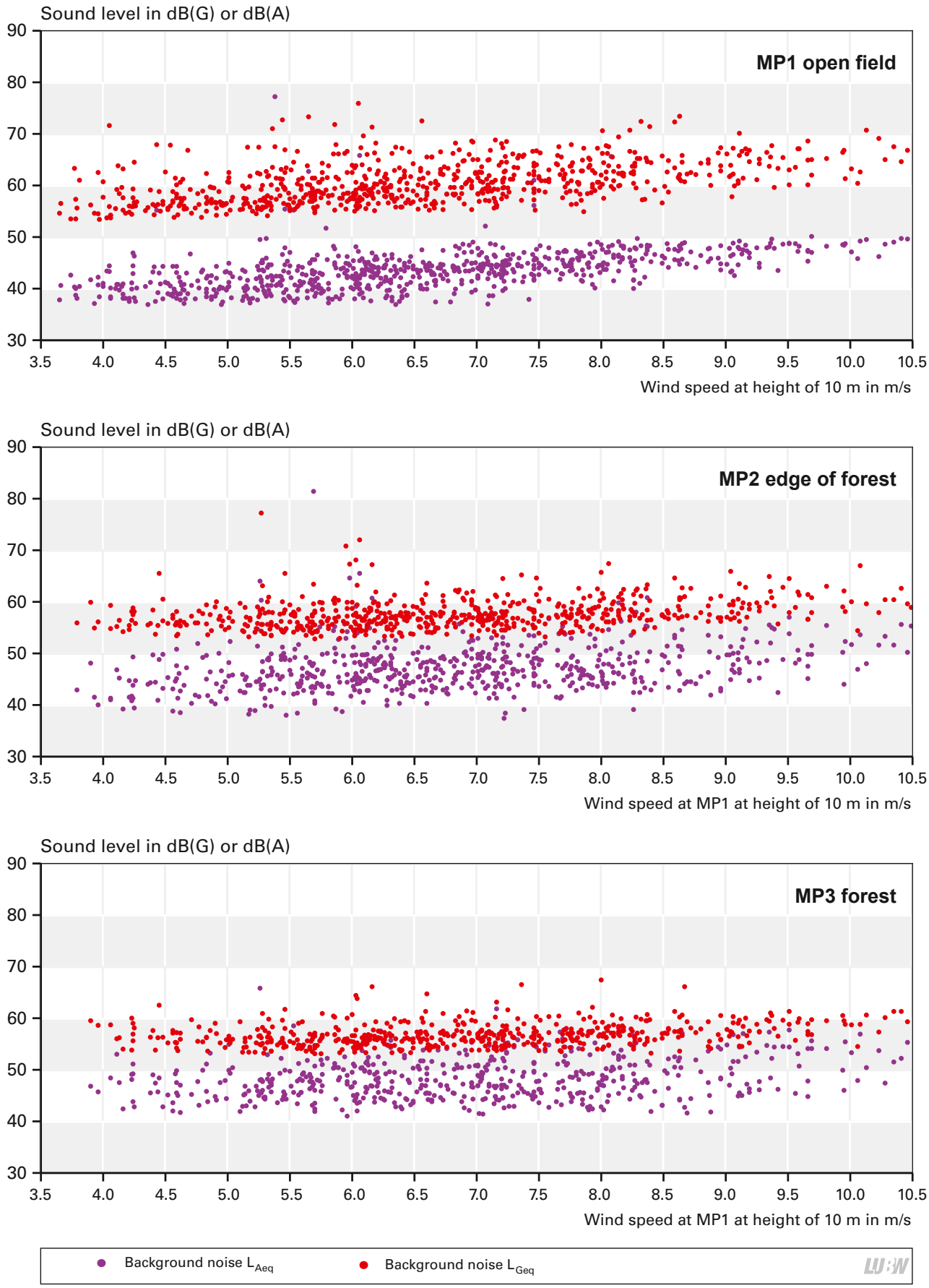

***Figure 8.1-7**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the three measurement points MP1 (open field), MP2 (edge of forest) and MP3 (forest). The G levels (red dots) and the A levels (violet dots) are shown. The wind measurement was always carried out at the measurement point MP1 (open field).*

CONCLUSION

The infrasound shows a strong dependence on the measuring position. The linear levels in the narrow-band spectrum measured in the open field were up to 30 dB higher than the levels measured in the forest (***Table 8.1-1***). The differences are not as pronounced above 16 Hz, but a tendency towards higher levels can be seen in the open field compared to the forest at low frequencies. Higher levels were measured for A-weighted audible sound in the forest, which is attributable to the rustling of leaves.

8.2 Sea surf

In addition to wind noise, sea surf is a widespread natural source of low-frequency noise and infrasound. The LUBW was not able to take its own measurements at the coast within the framework of this project. Therefore, currently published values shall be drawn upon in order to provide an order of magnitude. In 2012 Turnbull, Turner and Walsh published metrics for sea surf as a natural source of infrasound [21]. Accordingly, the G-weighted infrasound level on a beach was 75 dB(G) at a distance of 25 m from the waterline, 69 dB(G) at a distance of 250 m from a cliff, and 57 dB(G) at a distance of 8 km from the coast (***Table 8.2-1***). Near the coast, the third octave levels at different frequencies below 20 Hz were in the range of 53 dB to 70 dB (***Figure 8.2-1***).

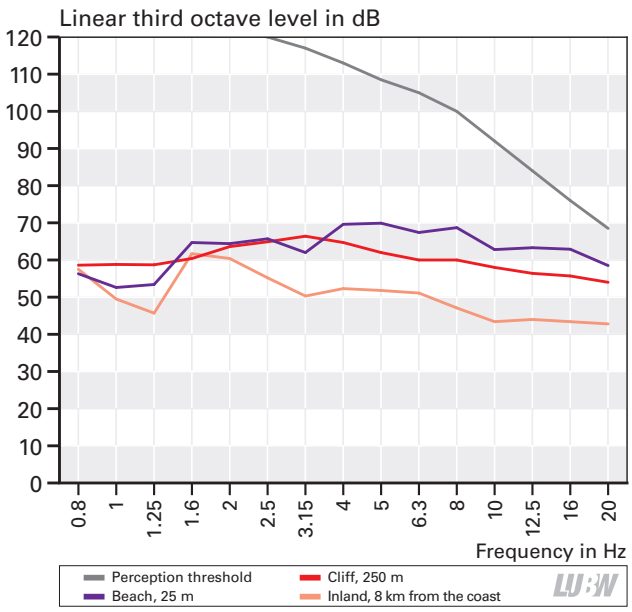

Figure 8.2-1: *Third octave spectra of the total noise of surf, different boundary conditions according to [21], perception threshold according to Table A3-1 for comparison*

Table 8.2-1: *Infrasound levels of sea surf for different boundary conditions*

Source	G-weighted level in dB(G)	Infrasound third octave level ≤ 20 Hz in dB *
Beach, 25 m from the waterline	75	53 to 70
Cliff, at distance of 250 m	69	54 to 65
Inland, 8 km from the coast	57	43 to 63

* Linear third octave level in dB(Z)

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9 Design of a long-term measuring station for low-frequency noise

9.1 Task

An integral part of the measurement project "Low-frequency noise incl. infrasound from wind turbines and other sources" was the setup of a feasibility concept for a self-sufficient long-term measuring station with which to measure and document the noise situation at wind turbines. In particular, low-frequency effects were to be taken into account. When designing the concept, it was assumed that such a measuring station is to be used primarily in the context of monitoring measurements or in connection with complaint cases. Furthermore, the long-term measuring station should also provide a possibility to carry out special studies, e.g. for the determination of infrasound or sound modulations or before/after analyses. The following specifications had to be taken into account:

- DIN EN 61400-11 "Windenergieanlagen – Teil 11: Schallmessverfahren" (2013) [6]
- Technical guidelines for wind turbines, part 1, revision 18 (as of 01.02.2008, issued by FGW Fördergesellschaft Windenergie e.V.) [7]
- Technical instructions on noise abatement – "TA Lärm" (1998) [10]
- DIN 45680 "Messung von Bewertung tieffrequenter Geräuscheinwirkungen in der Nachbarschaft" (1997) [4] as well as DIN 45680 "Messung und Beurteilung tieffrequenter Geräuschimmissionen" (2013 draft) [5].

In addition, a mains voltage-independent operation of the measuring station should be ensured for a period of two to four weeks.

9.2 Concept

The design of the measuring station was to include in particular the technical equipment, the evaluation of the measured data as well as the evaluation of the results in the context of immission protection. In principle, the projected long-term measuring station is divided into the following functional modules:

- Unit for detecting the operating parameters of the wind turbine
- Meteorology measuring unit
- Noise measuring unit
- Device monitoring (remote control unit)
- Data centre (database and data analysis)

If the task requires it, the long-term measuring station could contain several similar measurement units. The basic design of a possible long-term measuring station is shown in ***Figure 9.2-1*** dargestellt.

9.3 Individual modules for data acquisition

FACILITY AND OPERATING PARAMETERS

Approximate statements regarding the operating state of a wind power plant can be derived from wind data determined near the measuring location. However, this does not apply for special operating modes of the system (e.g. low noise operation, system downtime in case of insufficient wind conditions).

Reliable results for the current performance of a wind turbine require the continuous determination of the actual turbine and operating parameters such as system power, rotor speed, nacelle angle, blade angle, wind speed and wind direction. Typically, the system operator already records these parameters as part of standard procedure. However, taking over such data from the operator into the collective of the data determined by the long-term measuring station is often difficult, if not impossible, in practice. It is therefore much more reliable, yet more bothersome, to record the turbine operation data on one's own measuring system. In order to do so, the turbine signals would have to be decoupled from the turbine control system of the wind

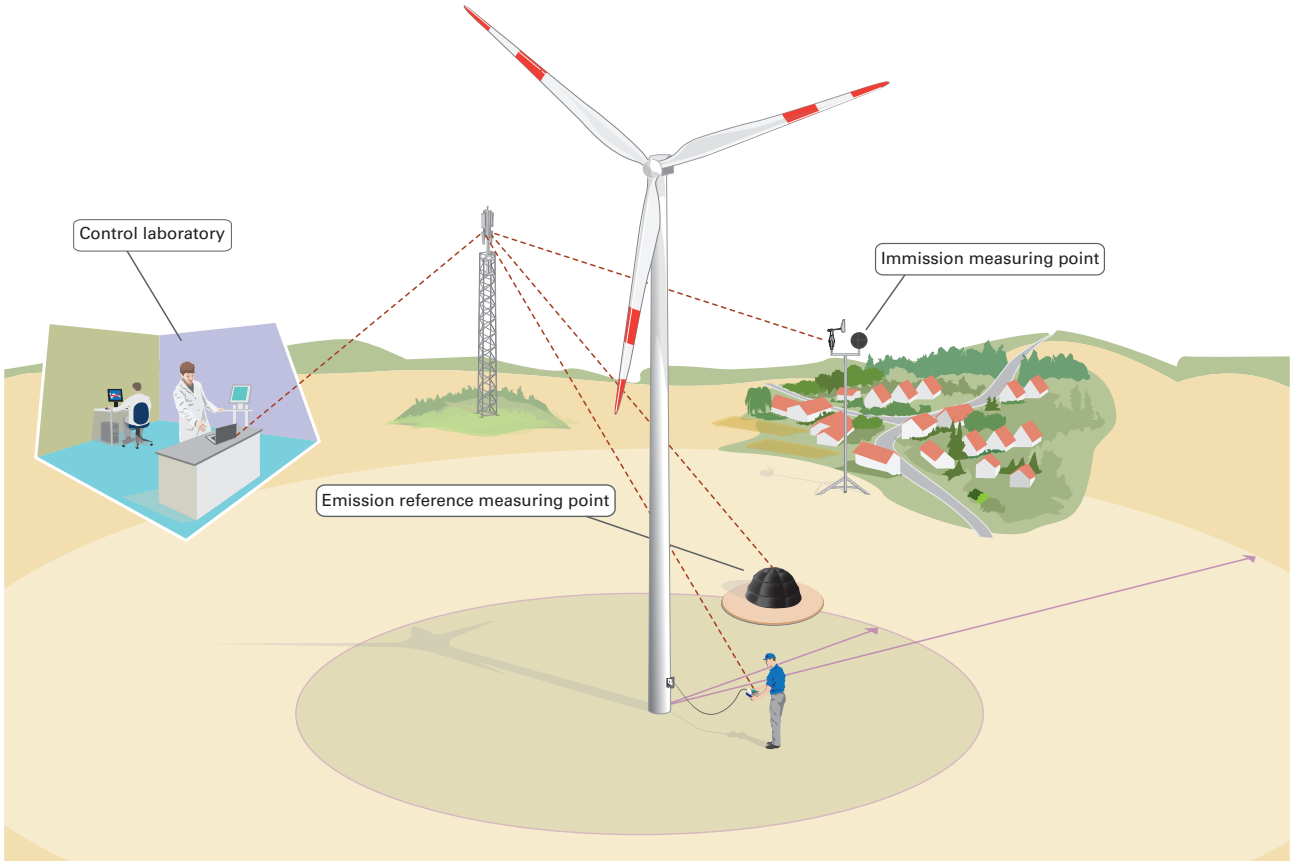

***Figure 9.2-1**: Basic design of a possible long-term monitoring station*

power plant via transducers or existing interfaces, and be registered by the appropriate data loggers. With this type of gathering of data, the data recording (sampling sequence, data formats, etc.) can be devised according to its own standard. Thus, optimal data integration into the overall system would be guaranteed. However, this would certainly require the support by trained personnel during the setup and connection of the measuring system to the turbine control.

WEATHER DATA

In addition to the noise measurement data, the meteorological variables – mean wind speed, mean wind direction (each in 10 s intervals) – as well as precipitation, air temperature and air pressure have to be determined. Commercially available weather stations (sensors and data loggers) equipped with sufficient data storage could be used for this purpose. The collected meteorological parameters are then linked with the other metrics in the data centre. If technically possible, the recording of meteorological data could already be carried out on location together with the noise measurement data in the sound level analyser. The wind data should be collected at a height of up to 10 m above ground. The respective masts that can also be used on rough terrain are provided by a number of manufacturers.

ACOUSTIC DATA

In order to measure the acoustic data, a combination of devices consisting of a standard sound level analyser and changeable microphone unit can be used. As far as necessary or appropriate, further functional units such as controller, monitoring system or meteorology recording can be included or attached. The noise measuring system is fundamentally suitable for determining emissions (DIN EN 61400-11 [6]), noise immissions (TA Lärm [10]) and low-frequency noise (DIN 45680 [4]). The following specifications must be met by the sound level analyser:

- Calibratable sound level meter according to DIN EN 61672-1:2003 [22] Class 1, with standard microphone and third octave filters according to DIN EN 61260:2003 [23] Class 1

- Usable range of levels: 18 dB(A) to 110 dB(A), usable frequency range: 1 Hz to 20 kHz
- Ongoing collection of different sound levels (L_{Aeq}, L_{AFmax}, L_{Ceq}, L_{CFmax}, $L_{TerzAeq}$, $L_{TerzAFmax}$) in periodic times of 0.1 s to 10 s
- Continuous recording of the audio signal and hourly storage as a WAV file. The data storage capacity must be sufficient for records of at least two weeks, or in the case of a restricted frequency range of the audio recording for recordings of at least four weeks
- Extensive trigger management (timed triggering and external trigger option)
- Alternatively usable infrasound microphone (lower limiting frequency ≤ 1 Hz, uncertainty at 1 Hz ≤ ± 3 dB)
- Additional weatherproof microphone plate with primary and secondary wind screens according to DIN EN 61400-11 [6]
- Additional primary and secondary wind screens for mounting on tripod or measuring mast for immission measurements according to TA Lärm [10]

DEVICE MONITORING

Ideally, the possibility should be given to monitor and control all measuring systems wirelessly via an Ethernet or GSM connection from the data centre. If permitted by the data connection, a transfer of the stored data to the data centre should also be possible.

In order to increase the transparency of the respective measuring project, a real-time display of measurement results on a publicly accessible website could also be enabled.

GENERAL REQUIREMENTS

In general, it must be possible to operate all devices of the long-term measuring station with 12 V direct voltage independently from the public power supply network. The measuring station should be equipped with the respective power supply units. A maintenance-free continuous operation of four weeks ought to be ensured. The long-term measuring station should generally be designed in a weatherproof manner. As far as necessary, all parts should be sufficiently protected from the weather (precipitation, sun, wind). Operation in an air temperature range of -5 °C to +30 °C must be made possible. The long-term measuring station must be fitted with safety features against damage by animals, against vandalism and against theft.

9.4 Central data evaluation

The evaluation of the data gathered on location and its compilation to measurement reports is generally carried out in the data centre after the end of the measurements. The nature and scope of the evaluation depends on the predefined task. The actual data evaluation can largely be carried out automatically. Analysis programmes for this purpose are commercially available. The following points should be considered for the evaluation:

- Data preparation: Individual data that is required but cannot be determined on location can be derived from the measured data or the audio recordings. (e.g. G-weighted noise levels, narrowband frequency analyses, tonalities, impulsiveness).
- Data synchronization: The individual values of the turbine data, the meteorological measurements and the acoustic measurements are to be consolidated for the same period lengths (e.g. 10 s) and to be synchronised to the same absolute points in time.
- Rectifying faults: If there is extraneous noise at the measurement point as well as noise from the wind power plant, this could lead to misinterpretations of the noise situation. The levels of the noise influenced by extraneous sources therefore must be excluded when determining the turbine noise levels. This requires a comprehensive plausibility check of all measured data for every individual case. Impulsive background noise can often be well recognized from the level curve, ongoing external noise interference can often be seen only on the basis of the level curves of individual frequency bands. When in doubt, the audio recordings will have to be referred to.

9.5 Applicability and benefits

The affected population is often rather sceptical when it comes to projected noise levels or measurements of wind turbines that are taken within a matter of hours. It is thus that the people affected often assume that the applied procedures do not take into account all facets of possible disturbances. Also, it is believed that the worst operating mode of the wind turbine is often not the basis for the noise measurements. In such cases, the use of a long-term measuring station is a good idea. In order to increase its acceptance, the general population could also be involved in the evaluation proceedings.

FIELDS OF APPLICATION

- Determination of the noise emissions and immissions caused by wind power plants subject to wind and plant operating conditions. Generation of different statistics on noise occurrence, plant parameters or wind conditions.
- Comparison of the results with the reference values and indicators in the TA Lärm and DIN 45680 [4, 5], as well as the level values used or specified in the approval procedure.
- Determination of the infrasound influencing a measurement point, possibly depending on the wind and plant operating conditions.
- Determination of noise exposure at a location before and after commissioning of wind turbines.
- Identification of specific or not regularly occurring noise or sound effects, for example implemented by complainants.
- Ultimately, the operation of such a long-term measuring station could be seen as a contribution towards the protection of the population against the harmful effects of noise, and in particular as a contribution to the pacification of the conflict situation on location.
- The use of a long-term measuring station is not suited as a means of carrying out acceptance tests. Such measurements require direct support through expert staff.

Appendix A1 – General information

The following sections provide information on infrasound and low-frequency noise in generally understandable form. This concerns the development, occurrence, spreading as well as the evaluation and perception of infrasound and low-frequency sound [15] [19] [24] [25] [26] [27] [28].

A1.1 LOW-FREQUENCY NOISE AND INFRASOUND

Put simply, sound consists of compressional waves. When such pressure fluctuations spread in the air, one refers to them as airborne noise. A human's sense of hearing is able to capture sound, the frequency (see Appendix A3) of which lies between approximately 20 Hz and 16,000 Hz (for children this value is about 20,000 Hz). Low frequencies correspond to low notes while high frequencies correspond to high notes. Sound below the audible range, i.e. with frequencies below 20 Hz, is called infrasound. Noise above the audible range, i.e. with frequencies above 20,000 Hz, is known as ultrasound. Low-frequency noise is defined as sound which is primarily within the frequency range below 100 Hz. Infrasound is thus a part of low-frequency sound.

Periodic air pressure fluctuations spread with a velocity of approximately 340 meters per second. Low-frequency vibrations have large wave lengths while high-frequency vibrations have small wave lengths. For example, the wavelength of a 20 Hz tone in air is about 17 m, while a frequency of 20,000 Hz has a wavelength of 1.7 cm (see ***Table A1-1***).

A1.2 SOUND PROPAGATION

The propagation of infrasound and low-frequency sound follows according to the same physical laws as all kinds of air-borne noise. A single sound source, such as a wind turbine generator, emits waves that spread in all directions in a spherical manner (***Figure A1-1***). As the sound energy is distributed across an ever growing area, the noise intensity decreases per square meter in an inverse proportion: With increasing distance it quickly becomes quieter (roughly 6 dB per doubling of distance). In addition, there is also the effect of absorption of sound through the air. A small part of the sound energy is converted into heat during the spread of the waves, resulting in additional absorption. This air absorption depends on the frequency: Low-frequency sound is only slightly absorbed while high-frequency is absorbed more. In comparison, the decrease of the sound level over distance significantly outweighs the decrease through air absorption. When spreading across flat surfaces, interference can occur, leading to highly fluctuating sound levels. A pressure build-up may occur in front of large obstacles leading to an increase in the sound pressure level. Standing waves may occur outdoors between the facades of buildings. Furthermore, a special feature of low-frequency sound waves is their low absorption through walls or windows, meaning that effects can also occur inside of buildings. Here too, the formation of standing waves may be the case. However, in the infrasound range these can arise only in large halls or churches; in common residential buildings the fundamental oscillations are at higher frequencies.

Table A1-1: *Relationship between frequency and wavelength for sound waves in the air*

Frequency	1 Hz	10 Hz	20 Hz	50 Hz	100 Hz	2,000 Hz
Wavelength	340 m	34 m	17 m	6.8 m	3.4 m	17 cm

LUBW

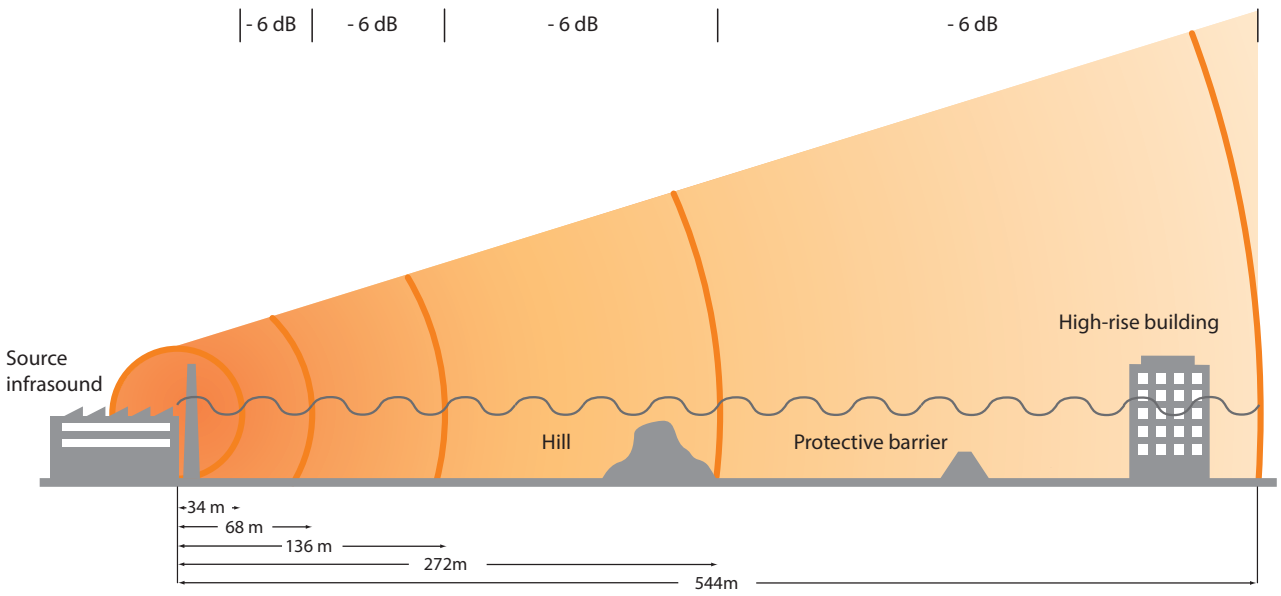

***Figure A1-1**: Exemplary presentation of spread of infrasound with a frequency of 10 Hz. The associated wavelength of 34 m is larger than the height of houses, trees and protective barriers. Therefore these hardly absorb the sound. However, the sound pressure level nevertheless decreases according to the same law as for audible sound: Each doubling of distance from the source results in a decrease in sound level of 6 dB. Image source: Bayerisches Landesamt für Umwelt [15]*

A1.3 INCIDENCE AND OCCURRENCE

Infrasound and low-frequency noise are everyday components of our environment. They are produced by a large number of different sources. These include natural sources, such as wind, waterfalls or sea surf, just as much as technical sources, such as heating and air conditioning systems, road and rail traffic, airplanes or speaker systems in nightclubs, etc.

A1.4 EVALUATION

The measurement and assessment of low-frequency noise are regulated in the technical instructions for the protection against noise (TA Lärm [10], please refer to Chapter 7.3 and Appendix A1. 5) as well as the standard DIN 45680 [4]. The impact of noise can be safely determined on the basis of these regulations. In this case the frequency range from 8 Hz to 100 Hz is considered. The crucial aspect when it comes to possible noise pollution is the human hearing threshold or perception threshold, which is outlined in the standard. See also the next section.

An own frequency weighting, the so-called G-weighting, exists for the area of infrasound. The relevantly weighted levels are specified as dB(G) – "decibel G". The A-weighting of noise dB(A) – "decibel A" – is more common, which is derived from human hearing. The G-weighting is focused at 20 Hz. Levels are amplified between 10 Hz and 25 Hz. Above and below that, the valuation curve quickly falls. The purpose of G-weighting is to characterise a situation regarding low frequencies or infrasound with only a single number. A disadvantage is that frequencies below 8 Hz and above 40 Hz hardly contribute at all. For more information please refer to "Frequency Evaluation" in Appendix A3, where you will also find an evaluation curve (***Figure A3-1***).

A1.5 PERCEPTION

In the area of low-frequency noise below 100 Hz there is a smooth transition from hearing, i.e. the sensations of volume and pitch, to feeling. Here the quality and nature of the perception changes. The pitch sensation decreases and does not apply at all for infrasound In general, the following applies: The lower the frequency, the higher the

***Table A1-2**: Hearing and perception threshold (in decibels) in the range of infrasound. The lower the frequency, the louder the noise or sound intensity has to be in order for a person to perceive something. At 8 Hz the sound pressure level has to be at 100 decibels. Humans can hear best in the area of 2,000 to 5,000 Hz. That is where the average hearing threshold is at 0 decibels and even below it (up to minus 5 decibels).*

Frequency (as a third octave centre frequency)	8 Hz	10 Hz	12.5 Hz	16 Hz	20 Hz
Hearing threshold according to DIN 45680 (1997) [4]	103 dB	95 dB	87 dB	79 dB	71 dB
Perception threshold according to draft DIN 45680 (2013) [5]	100 dB	92 dB	84 dB	76 dB	69 dB

sound intensity has to be so that the noise is heard at all (see ***Table A1-2***). Low-frequency impact with high intensity is often perceived as ear pressure and vibrations. Permanent exposure to such high noise levels can lead to buzzing, vibrating sensations or a feeling of pressure in the head. In addition to the sense of hearing, other sensory organs can also register low-frequency sound. For example, the sensory cells of the skin convey pressure and vibration stimuli. Infrasound can also affect cavities in the body, such as lungs, sinuses and middle ear. Infrasound of very high intensity has a masking effect for the middle and lower acoustic range. That means: In the case of very strong infrasound, your hearing is unable to perceive quiet tones in frequencies above it.

But where are the limits between hearing, feeling and "no longer perceiving"? ***Table A1-2*** shows some levels of the hearing and perception thresholds for different frequencies. The hearing threshold of DIN 45680 (1997) [4] is defined in such a way that 50 % of the population will no longer perceive the respective frequency below the specified level. The perception threshold of DIN 45680 (2013) [5] is defined so that 90 % of people will no longer perceive the sound below this level. The limit from which low-frequency sound can be heard, varies from person to person. This is nothing unusual, as it is similar to what we are accustomed to regarding audible sound in everyday life. For almost 70 % of people, the hearing threshold lies in a range of ± 6 dB around the values shown in ***Table A1-2***. For particularly sensitive individuals, who make up around two to three percent of the total population, the hearing threshold is at least 12 dB lower. ***Figure A1-2*** provides a graphic depiction of the relationship of the two thresholds. The differences are relatively small.

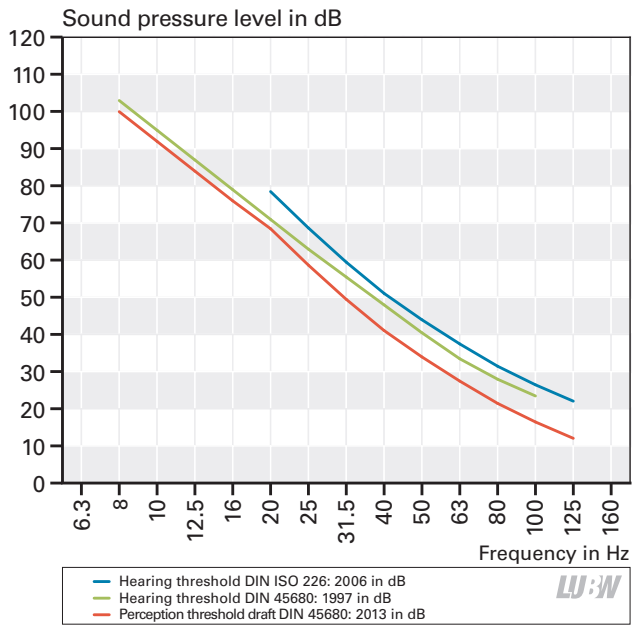

***Figure A1-2**: Representation of hearing and perception threshold according to ISO 226 [29], DIN 45680 (1997) [4] and draft DIN 45680 (2013) [5]. The perception threshold according to the draft of DIN 45680 is roughly 10 dB lower than the values of ISO 226.*

Laboratory tests on the impact of infrasound have shown that high intensities above the perception threshold are tiring and have an adverse effect on concentration, and can influence performance. The best proven reaction by the body is increasing fatigue after several hours of exposure. The balance system can also be affected. Some test persons had feelings of insecurity and anxiety, while others displayed a reduced respiratory rate. Furthermore, as is the case with audible sound, very high sound intensities can lead to a temporary hearing impediment – an effect often known by people who go to nightclubs. Long-term exposure to strong infrasound can also lead to permanent hearing loss. However, the infrasound levels that occur in the vicinity of wind power plants will hardly be able to cause any such effects, as they fall far short of the hearing or perception threshold. In scientific literature, any health effects could so far be shown only at sound levels above the hearing threshold. Below the hearing threshold, no effects on humans caused by infrasound could so far be proven [25].

Appendix A2 – Sources and literature

[1] Windenergieerlass Baden-Württemberg – common administrative regulation of the Ministry of Environment, Climate and Energy (and other ministries) from 09.05.2012, joint official journal of the federal state of Baden-Württemberg from 30.05.2012, 2012 Edition, No. 7, pg. 413-441, Internet: um.baden-wuerttemberg.de, enter "Windenergieerlass" in the search field

[2] Law for the protection against harmful environmental impacts caused by air pollutants, noises, vibrations, and similar occurences (Bundes-Immissionsschutzgesetz – BImSchG) as amended by the notice from 17 May 2013 (BGBl. I pg. 1274) that was altered by article 1 of the law from 2 July 2013 (BGBl. I S. 1943).
Internet: http://www.gesetze-im-internet.de/bimschg

[3] Fourth Ordinance for the Implementation of the Federal Immission Protection Law (Ordinance on Installations Requiring a Permit – 4th BImSchV) from 2 may 2013 (BGBl. I pg. 973, 3756). Internet: http://www.gesetze-im-internet.de/bimschv_4_2013/BJNR097310013.html

[4] DIN 45680: Messung und Bewertung tieffrequenter Geräuschimmissionen in der Nachbarschaft (mit Beiblatt), date of issue 1997-03

[5] DIN 45680: Draft: Messung und Bewertung tieffrequenter Geräuschimmissionen (September 2013), date of issue 2013-09, with respect to perception threshold identical with draft 2011-08

[6] IEC 61400-11: Acoustic noise measurement techniques, Edition 2.1, date of issue 2006-11 – German version: DIN EN 61400-11: Windenergieanlagen – Teil 11: Schallmessverfahren, date of issue 2013-09

[7] Technische Richtlinie für Windenergieanlagen, Teil 1: Bestimmung der Schallemissionswerte, revision 18, as of 01.02.2008, editor: FGW Fördergesellschaft Windenergie und andere Erneuerbare Energien e. V.

[8] DIN 45645: Ermittlung von Beurteilungspegeln aus Messungen, Teil 1: Geräuschimmissionen in der Nachbarschaft, date of issue 1996-07

[9] ISO 7196: Acoustics – Frequency-weighting characteristic for infrasound measurements, date of issue 1995-03

[10] Technische Anleitung zum Schutz gegen Lärm – Sechste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz from 26 August 1998 (TA Lärm), GMBL 1998 Nr. 26, pg. 503-516, Internet: http://www.verwaltungsvorschriften-im-internet.de/bsvwvbund_26081998_IG19980826.htm

[11] Møller H. & Pedersen C. S. (2004): Hearing at low and infrasonic frequencies, Noise & Health, Vol. 6, Issue 23, S. 37-57

[12] DIN 45669: Messung von Schwingungsimmissionen Teil 1: Schwingungsmesser – Anforderungen und Prüfungen, date of issue 2010-09; part 2: Messverfahren, date of issue 2005-06

[13] DIN 4150: Erschütterungen im Bauwesen, Teil 1: Einwirkungen auf Menschen in Gebäuden, date of issue 2001-06; Teil 2: Einwirkungen auf Menschen in Gebäuden, date of issue 1999-06; Teil 3: Einwirkungen auf bauliche Anlagen, date of issue 1999-02

[14] Henkemeier F. & Bunk O. (2010): Schalltechnischer Bericht Nr. 27257-1.006 über die Ermittlung und Beurteilung der anlagenbezogenen Geräuschimmissionen der Windenergieanlagen im Windpark Hohen Pritz, Mai 2010, Messungen der Fa. Kötter, im Auftrag des Landes Mecklenburg-Vorpommern, Landesamt für Umweltschutz, Naturschutz und Geologie (LUNG), Rheine, Internet: http://www.lung.mv-regierung.de/dateien/infraschall.pdf

[15] Bayerisches Landesamt für Umwelt & Bayerisches Landesamt für Gesundheit und Lebensmittelsicherheit (2014): Windkraftanlagen – beeinträchtigt Infraschall die Gesundheit?, Augsburg/Erlangen, Internet: http://www.lfu.bayern.de/umweltwissen/ doc/uw_117_windkraftanlagen_infraschall_gesundheit.pdf

[16] Bayerisches Landesamt für Umweltschutz (2000): Langzeit-Geräuschimmissionsmessung an der 1 MW-Windenergieanlage Nordex N54 in Wiggenbach bei Kempten (Bayern),

Augsburg, Internet: http://www.lfu.bayern.de/laerm/messwerte/doc/windenergieanlage.pdf

[17] Møller H. & Pedersen C. S. (2010): Low-frequency noise from large wind turbines, Journal of the Acoustical Society of America, Vol. 129, No. 6, June 2011, S. 3727-3744

[18] EPA – Environment Protection Authority South Australia & Resonate Acoustics (2013): Infrasound levels near windfarms and in other environments, Adelaide, Internet: www.epa.sa.gov.au/files/477912_infrasound.pdf

[19] Borgmann R. (2005): Leitfaden Nichtionisierende Strahlung – Infraschall, Fachverband für Strahlenschutz, Garching, Internet: www.fs-ev.org

[20] Betke K. & Remmers H. (1998): Messung und Bewertung von tieffrequentem Schall, in: Deutsche Gesellschaft für Akustik (DEGA) (ed., 1998): Fortschritte der Akustik, Tagungsband der Deutschen Akustiktagung 1998, Oldenburg, Internet: http://www.itap.de/wp-content/uploads/2015/11/tieffrequent.pdf

[21] Turnbull C., Turner J. & Walsh D. (2012): Measurement and Level of Infrasound from Windfarms and other sources, Acoustics Australia, Vol. 40, No. 1, April 2012, pg. 45-50

[22] DIN EN 61672-1: Elektroakustik – Schallpegelmesser, Teil 1: Anforderungen (IEC 61672-1:2013); German version EN 61672-1:2013, date of issue 2014-07

[23] DIN EN 61260: Elektroakustik – Bandfilter für Oktaven und Bruchteile von Oktaven (IEC 61260:1995 + A1:2001); German version EN 61260:1995 + A1: 2001, date of issue 2003-03

[24] LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (2015): Windenergie und Infraschall – Tieffrequente Geräusche durch Windenergieanlagen, 6th edition October 2015, Karlsruhe, Internet: www.lubw.de/servlet/is/223628

[25] Twardella D. (2013): Importance of the expansion of wind energy for human health, in: UMID Umwelt und Mensch – Informationsdienst, pg. 14-18, Internet: www.umweltbundesamt.de/sites/default/files/medien/360/publikationen/umid_03_2013_internet_neu.pdf

[26] LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (2015): Fragen und Antworten zu Windenergie und Schall – Behauptungen und Fakten, Karlsruhe, Internet: www.lubw.de/servlet/is/255800

[27] Robert Koch-Institut (2007): Infraschall und tieffrequenter Schall – ein Thema für den umweltbezogenen Gesundheitsschutz in Deutschland?, Bundesgesundheitsblatt – Gesundheitsforschung – Gesundheitsschutz, Nr. 50, pg. 1582-1589, Internet: http://www.rki.de/DE/Content/Kommissionen/UmweltKommission/Archiv/Schall.pdf

[28] HA Hessen Agentur GmbH im Auftrag des Hessischen Ministeriums für Wirtschaft, Energie, Verkehr und Landesentwicklung (2015): Faktenpapier Windenergie und Infraschall, Internet: www.energieland.hessen.de/faktenpapier_infraschall

[29] DIN ISO 226: Akustik – Normalkurven gleicher Lautstärkepegel, date of issue 2006-04

[30] ISO 7196: Akustik – Frequenzbewertungs-Charakteristik für Infraschallmessungen, date of issue 1995-03

[31] DIN 45641: Mittelung von Schallpegeln, date of issue 1990-06

[32] Hau E. (2014): Windkraftanlagen: Grundlagen, Technik, Einsatz, Wirtschaftlichkeit, 5th edition, Berlin/Heidelberg

[33] Weinheimer J. (2014): Höhere Schallleistungspegel von Windenergieanlagen bei höherer Turbulenz?, in: Kötter Consulting Engineers (ed., 2014): Good Vibrations, Windenergie – Bauphysik – Immissionsschutz, September 2014, pg. 2/3, Internet: http://www.koetter-consulting.com/coRED/_data/149-14_gv_71_versand.pdf

[34] Watanabe T. & Møller H. (1990): Low frequency hearing thresholds in pressure field and in free field, Journal of Low Frequency Noise and Vibration, Vol. 9, No. 3 , pg. 106-115

Appendix A3 – Explanation of terms and parameters

A-weighting

Frequency-dependent alteration of a noise or sound signal by means of A filter according to DIN EN 61672-1:2003 [22]. See also frequency weighting and dB(A).

Averaging level

See sound pressure level

Background noise

Noise with the wind power plant switched off. It consists particularly of the sound caused by wind in the vicinity and of noise coming from other sources of noise in the vicinity. The background noise may also include sound induced by the wind at the microphone. Also referred to in the report as the operating condition "turbine off".

C-weighting

Frequency-dependent alteration of a noise or sound signal by means of C filter according to DIN EN 61672-1:2003 [22]. See also frequency weighting and dB(C).

dB

Decibel, unit of measurement for the identification of levels, in this case sound pressure level (quod vide).

dB(A)

Decibel A, unit of sound pressure level in A-weighting. See also sound pressure level and A-weighting.

dB(C)

Decibel C, unit of sound pressure level in C-weighting. See also sound pressure level and C-weighting.

dB(G)

Decibel G, unit of sound pressure level in G-weighting. Is used particular with low-frequency noise incl. infrasound. See also sound pressure level and G-weighting.

dB(Z)

Decibel Z, unit of sound pressure level in Z-weighting that corresponds to the linear sound pressure level unweighted in terms of frequency. Formerly also referred to as dB(lin).

Emission

See sound emission

Extraneous noise

Noise that is not caused by the turbine being measured and can temporarily lead to an increase of background noise. Disturbing extraneous noise is excluded from the evaluation by placing markers, and is therefore included neither in the represented total noise nor in the background noise.

Frequency

Number of oscillations per second; the unit is hertz (Hz). The total audible frequency range is divided into:

- Infrasound: Sound with frequencies below 20 Hz
- Audible sound: Sound in the range of 20 Hz to about 16,000 Hz (limit is age-dependent)
- Ultrasound: Sound above roughly 16,000 Hz
- Low-frequency sound: Sound at frequencies below 100 Hz, including infrasound

Frequency weighting (noise)

The frequency content of noise is weighted differently according to the specific objective. In addition to the generally usual A-weighted and C-weighted noise levels, G-weighted and Z-weighted noise levels are also determined and represented in this study.

By default, the frequency weighting A is used for the valuation of sound signals in the normal audible sound range. It approximately constitutes the hearing sensitivity of the human ear in the low and medium sound intensity level. The description and assessment of noise emission and immissions generally follows by means of A-weighted levels. The evaluation of low-frequency noise including infrasound requires separate restrictions of the frequency ranges; A-weighted sound levels that are determined across the entire frequency band are unsuitable for this.

The frequency weighting C approximately corresponds to the auditory sensation of the ear at high volumes. It is applied in particular when assessing noise level peaks in the scope of occupational safety and health. In addition, the

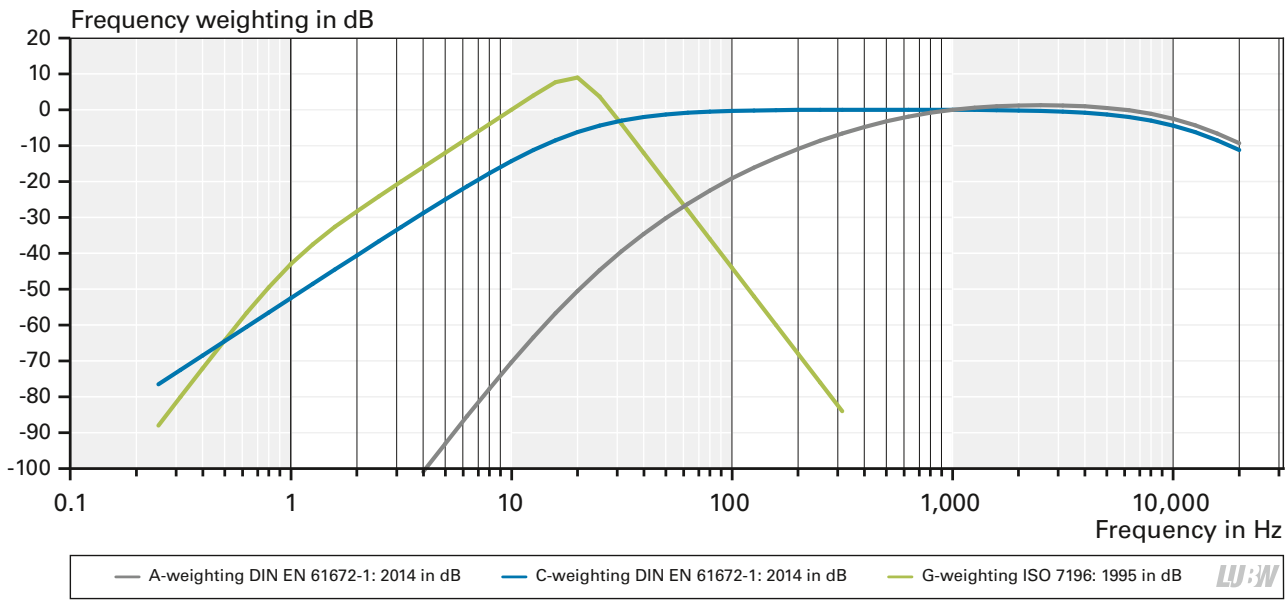

***Figure A3-1**: Course of the frequency weighting curves A, C and G in the range below 500 Hz according to ISO 7196 and DIN EN 61672-1 (2013) [22]*

level difference of measured C-weighted and A-weighted levels is seen as an indicator for possible low-frequency noise contamination in the area of immission control.

The frequency weighting G is a filter that was defined for the effect adaptation of infrasound. Its focus lies at 20 Hz (see Figure A3-1). However, no relevant reference or comparative values are known for the quantitative classification of any infrasound effects or determined G-weighted levels.

The frequency weighting Z (zero) describes a linear band pass filter without any effect on the frequency.

Frequency spectrum

See spectral analysis

G-weighting

Frequency-dependent change of noise or sound signal using G filter according to ISO 7196:1995 [30]. See frequency weighting and dB(G).

Hearing threshold

See Appendix A1.5

Immission

See sound immission

Infrasound

See Appendix A1.1

Level

Logarithm of the relationship of two identical sizes. For the sound pressure level, the ratio of sound pressure, which is caused by noise, to a fixed reference size (hearing threshold) is formed. See also sound pressure level.

L_{eq}

Energy equivalent average of the (time-varying) sound pressure level course within a reference period. See also sound pressure level.

L_{max}

Maximum sound pressure level in a measurement interval. See also sound pressure level.

Low-frequency sound

See Appendix A1.1

Narrowband spectrum

See spectral analysis

Noise

Noise can be considered unwanted, disturbing or harassing sound. While sound can be well-measured and characterized as a physical phenomenon, human feelings also play a part when it comes to noise.

Operating noise

Noise with wind turbine switched on, including background noise. Is referred to as total noise throughout the report.

Perception threshold

The perception threshold used in this report is composed of the perception threshold according to Table 2 in DIN 45680 (2013 draft) [5] and values from literature.

The values of the draft standard are based on DIN ISO 226 [29]; they are 10 dB below the hearing threshold specified therein. For frequencies of 8 Hz to 20 Hz they are supplemented by the values determined by WATANABE & MØLLER [34]. The course corresponds to the 90 % percentile of audible threshold distribution.

Since no standardized threshold levels exist in the frequency range below 8 Hz, the values of the hearing threshold proposed by MØLLER & PEDERSEN [11, Figure 10] were taken for the representations in this measurement report in the range of 1.6 Hz to 8 Hz (***Table A3-1***).

Sound

Put simply, sound consists of compressional waves. Airborne sound is the propagation of pressure fluctuations in the air as a wave motion. If this happens in solid materials, e.g. the floor or walls, it is called structure-borne sound. In order to characterize sound, variables such as sound level (characterizes the strength of the sound) or frequency (denotes the pitch) are used.

Sound emission

The noise coming from a turbine in accordance with § 3 para. 3 BImSchG [2]

Sound immission

The noise effecting humans, animals, etc. in accordance with § 3 para. 2 BImSchG [2]

Sound pressure level L

Often simply referred to as sound level. 20-fold decimal logarithm of the ratio of a given effective value of sound pressure to a reference sound pressure (e.g. hearing threshold), where the effective value of the sound pressure is determined with a standard frequency and time weighting (L in dB). Sound pressure levels of the normal range of hearing are determined primarily by the frequency weighting A and the time rating F according to DIN EN 61672-1 [22] (see also frequency weighting). The types of frequency and time weightings are usually indicated as indices of the formula sign, e.g. L_{AF} in dB(A). The definition of the sound pressure level L for a sound pressure p is:

$$L = 10 \cdot lg \frac{p^2}{p_0^2} (dB) = 20 \cdot lg \frac{p}{p_0} (dB)$$

Here p_0 is a reference sound pressure in the region of the hearing threshold, defined as $2 \cdot 10^{-5}$ Pa. Sound level differences of 1 dB are only just recognisable, differences of 3 dB can be heard clearly. Sound level differences of 10 dB correspond to roughly double or half the impression of loudness respectively.

- The addition of two identical sound levels (doubling of the sound power) leads to an increase of the sum level by 3 dB.
- The reduction of a road's traffic volume by half results in a 3 dB lower level.
- In the case of a single point source, a doubling of distance leads to a reduction of the sound level by 6 dB.

The instantaneous sound pressure level is the current level value of a time-varying noise, for example specified as $L_{AF}(t)$ in dB(A).

The maximum sound pressure level or maximum level is the maximum value of the fluctuating sound pressure level curve within a reference period, referred to as L_{max} in dB. For the frequency weighting A and the time rating F, the level is referred to as L_{AFmax} and specified in dB(A).

The average sound level or equivalent continuous sound level L_{eq} is the energy equivalent mean value of the temporally variable sound pressure level curve L(t) within a reference period, expressed in dB. It is formed according to DIN 45641 [31] or directly with a measuring instrument

according to DIN EN 61672-1 [22]. For the frequency weighting A and time weighting F, the time-average sound pressure level is referred to as L_{AFeq} and expressed in dB(A).

Spectral analysis

Spectral analysis is an important tool for the analysis of acoustic signals. The signal is fragmented into defined frequency bands and a sound level is determined for each individual band. A distinction is made between frequency bands of absolute and relative bandwidth.

In the case of narrowband spectra, the frequency range that is to be analysed is divided up into bands of the same absolute width. Here in this report, a bandwidth of 0.1 Hz was consistently used. That enabled a high resolution depiction of the frequency spectra of the sound signal.

Octave and third octave spectra (1/3-octave spectra) are composed of frequency bands of relative bandwidth. The centre frequency of an octave band has a ratio of 1:2 to the centre frequency of the adjacent bands; third octave bands have a ratio of 1:1.26. The starting value for the determination of the centre frequencies is the frequency of 1,000 Hz. The frequency bandwidths within octave or third octave spectra thus differ. The third octave centre frequencies from 1 Hz are: 1 Hz, 1.25 Hz, 1.6 Hz, 2 Hz, 2.5 Hz, 3.15 Hz, 4 Hz, 5 Hz, 6.3 Hz, 8 Hz, 10 Hz, 12.5 Hz, 16 Hz, 20 Hz, 25 Hz, 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz etc. – see also [23].

Third octave representation

Representation of a sound signal in a frequency spectrum. See also spectral analysis and third octave spectrum.

Third octave level

Sound pressure level within a third octave frequency band. See also spectral analysis.

Third octave spectrum

Frequency spectrum in which the frequency range and the corresponding level proportions are divided into thirds. See also spectral analysis.

Total noise

Noise with wind turbine switched on, including background noise. Also referred to in the report as the operating condition "turbine on".

Turbulence intensity

The turbulence intensity (also known as degree of turbulence) was here formed from the average of the quotients of standard deviation and arithmetic mean of the wind speed. It is a measure of the variation of the wind speed (gusts). The turbulence intensity is given in percent and is subject to many influences, e.g. ground roughness, medium wind speed, atmospheric situation or buildings. Its lowest values (5 % or less) are reached over the sea, the highest (20 % or more) are reached over built-up areas and forest [32]. While the turbulence intensity has no significant effect on measurements in the A level range (audible sound) [33], this is not documented for low frequencies. Here an influence can by all means be expected. Some manufacturers of wind turbines link the warranty condition for their guaranteed values of acoustic power to maximum turbulence intensities during measurement, e.g. 16 %. The turbulence intensity is determined in accordance with DIN EN 61400-11 [6].

Vibrations

Vibrations are oscillations of solid bodies.

Vibrational immissions

Vibrational immissions are the oscillations that occur at the measurement point.

Vibration velocity

The vibration velocity (speed) is the velocity of an oscillating mass at the measurement point in the predetermined measurement direction, stated in millimetres per second (mm/s). This variable is based on the assessment of vibration impacts on buildings and on people in buildings. The vibration is defined initially through the ground motion, i.e. the vibration displacement (amplitude), characterized as a function of time. The vibration velocity can then be derived by differentiating with respect to time.

***Table A3-1**: The hearing threshold levels used to represent the perception threshold in the report according to [5] and [11]*

Source	Third octave centre frequency in Hz	Perception threshold level W_{Terz} in dB
Threshold level - taken from [11]	1.60	124.0
	2.00	122.0
	2.50	120.0
	3.15	117.0
	4.00	113.0
	5.00	108.5
	6.30	105.0
Threshold level - taken from [5]	8.0	100.0
	10.0	92.0
	12.5	84.0
	16.0	76.0
	20.0	68.5
	25.0	58.7
	31.5	49.5
	40.0	41.1
	50.0	34.0
	63.0	27.5
	80.0	21.5
	100.0	16.5
	125.0	12.1

Vibration severity

In the vibration frequency range of 1 Hz to 80 Hz that is relevant for the perception of vibration, the perceptibility is proportional to the vibration velocity. Below approximately 10 Hz, the perception at lower frequencies is significantly lower. This is taken into account for the evaluation of measurement data through the use of special filtering, the so-called KB-evaluation according to DIN 4150 Part 2. Inputs above 80 Hz are cut off by a blocking filter (band limitation) as they do not contribute to perception. The band-limited, frequency and time-weighted signal is designated as weighted vibration severity $KB_F(t)$. The highest value achieved during the assessment time, the maximum weighted vibration strength KB_{Fmax}, is an important evaluation parameter for the tactility of vibration effects.

Wavelength

For a wave (here acoustic wave), the distance from a "wave crest" to the next "wave crest" or "trough" to "trough" is referred to as wavelength (general distance from one point to the next point of the same phase). The wavelength is related to the frequency as follows: The wavelength is the propagation speed divided by the frequency of the wave. Sound waves in air can generally be registered by the human ear in the approximate wavelength range of 2 cm to about 20 m.

Z-weighting

Unweighted or linear noise or sound signal according to DIN EN 61672-1:2003 [22]. See frequency weighting and dB(Z).

Appendix A4 – Measuring systems used

Below is a description of the used measurement systems and equipment. The sound level measuring instruments used meet the specifications for Class 1 for sound level meters according to IEC 61672. The dynamic range of the microphone capsule type 40AZ is 14 dB(A) to 148 dB according to the manufacturer, the usable frequency range is 0.5 Hz to 20 kHz. For the remaining microphone capsules used, the usable frequency range is 3.15 Hz to 20 kHz.

Measurements at wind turbines (Section 4)

- 4 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40AZ on reverbrant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  - Air pressure, humidity and temperature sensor type DTF 485, manufacturer: Reinhardt System- und Messelectronic GmbH, D-86911 Diessen-Obermühlhausen
  - Wind sensor type WMT 701, manufacturer: Vaisala GmbH, D-22607 Hamburg

- 1 acoustic emission measurement system type RoBin, manufacturer: Wölfel Meßsysteme, D-97204 Höchberg

- 4 vibration meters type SM 6 (triaxial) according to DIN 45669, consisting of:
  - Sensor Nederland / Wölfel Meßsysteme
  - Supply and AD conversion: System Red Sens with radio modules
  - Coupling of the measuring sensors according to DIN 45669-2. The measuring chain was checked before and after the measurement.

- 1 data acquisition system, consisting of:
  - Notebook Dell Latitude with Elovis radio antenna for Red Sens
  - Measurement and evaluation software MEDA
  - Sampling: upper limit frequency, 400 Hz corresponds to sampling rate of 976.6 µs, manufacturer: Wölfel Meßsysteme, D-97204 Höchberg

Road traffic measurements (Section 5.1)

- 1 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" Type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 2 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40AZ, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  - Air pressure, humidity, temperature and wind sensor type WXT 520, manufacturer: Vaisala GmbH, D-22607 Hamburg

LUBW Long-term measuring stations (Section 5.2)

- 2 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40CD, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 2 meteorology sensors, consisting of:
  - Precipitation monitor model 5.4103.10.00, manufacturer: Adolf Thies GmbH & Co. KG, D-37083 Göttingen
  - Temperature and humidity sensor type HMP 155, manufacturer: Vaisala GmbH, D-22607 Hamburg

- Ultrasonic aemometer type 85004, manufacturer: R. M. Young Company, USA-2801 Aero Park Drive

Measurements at motorway (Section 5.3)

- 3 sound level meters combinations type NOR 140, consisting of:
  - Sound level analyser type Nor 140, manufacturer: Norsonic AS, N-3421 Lierskogen
  - Free-field microphone 1/2" type 1225, manufacturer: Norsonic AS, N-3421 Lierskogen

Interior noise measurements car, minibus (Section 5.4)

- 1 sound level meter combination type NOR 140, consisting of:
  - Sound level analyser type Nor140, manufacturer: Norsonic AS, N-3421 Lierskogen
  - Free-field microphone 1/2" type 1225, manufacturer: Norsonic AS, N-3421 Lierskogen

Urban background measurements (Section 6)

- 2 sound level meter combinations type DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB-Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 sound level meter combination DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB-Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40AZ, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  - Air pressure, humidity, temperature and wind sensor type WXT 520, manufacturer: Vaisala GmbH, D-22607 Hamburg

Measurements in a residential building (Section 7)

- 1 sound level meter combination type NOR 140, consisting of:
  - Sound level analyser type Nor 140, manufacturer: Norsonic AS, N-3421 Lierskogen
  - Free-field microphone 1/2" type 40AZ, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 sound level meter combination type NOR 140, consisting of:
  - Sound level analyser type Nor 140, manufacturer: Norsonic AS, N-3421 Lierskogen
  - Free-field microphone 1/2" type 1225, manufacturer: Norsonic AS, N-3421 Lierskogen

Measurements in rural area (Section 8.1)

- 2 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" Type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  - Air pressure, humidity, temperature and wind sensor type WXT 520, manufacturer: Vaisala GmbH, D-22607 Hamburg

Note on the inherent noise of the measuring chain

In order to determine the minimum noise limit of the deployed acoustic measuring chain, sound level measurements were carried out inside buildings at two different locations during the night. The locations were chosen so that the least possible background noise was at hand. The measured values in the range of 1 Hz to 1 kHz are at least 20 dB below the sound levels to be determined here. The influence of the inherent noise of the measuring chain on the measurement results is therefore negligible.

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