

# On Wind Turbine Noisescape Reproduction for Perceptual Evaluation

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## Introduction

In the course of the transition towards renewable sources of energy the expansion of wind energy is giving rise to discussions about its social acceptance. Some of the skeptical arguments refer to the acoustical emissions of wind parks and their possibly negative impact on health and well-being of residents close to wind parks. Most legal regulations consider noise limits as fixed, time-averaged total sound pressure with only little regards to psychoacoustic impairment parameters, which is why compliance with these regulations says little about actual perceptual properties like annoyance or unpleasantness. For the psychoacoustic analysis of wind turbine noise, methods from soundscape research will therefore be applied in this work in order to include multimodal and contextual effects. The assessment of soundscapes or noisescapes as interdependent construct of acoustics, context and human subjectivity[1] is often undertaken by means of soundwalks where subjects are let through soundscapes and asked to rate certain perceptual aspects in-situ. Since this approach is in most cases not reproducible and highly impractical in the context of wind turbine noise, this work focuses on the capturing, processing and reproduction of noisescapes under laboratory conditions. With a successful implementation large-scale user studies including varying acoustic conditions and instantaneous comparison become feasible. To maintain as much context as possibly, the proposed procedure aims on multidimensional acoustic capturing and processing as well as the reproduction with loudspeakers to avoid the potentially unfamiliar wearing of headphones. To approach this task, a set of criteria and dimensions has to be identified that covers relevant psychoacoustic properties of wind turbine noisescapes.

## Dimensionality of Wind Turbine Noisescapes

For the development of a valid technical capturing, processing and reproduction chain it is necessary to be aware of the general and specific properties of the soundscape. As mentioned before, as much of the overall context should be preserved in order to be able to reconstruct the soundscape in a plausible way. Context is made up on the one hand of sound sources in an acoustic environment and on the other hand of perception-based dimensions. Both aspects have to be identified and suitable methods for capturing and representation have to be found. Wind turbine noisescapes consist of several tangible components whose combination is important for an overall auditory impression as shown in in Figure 1

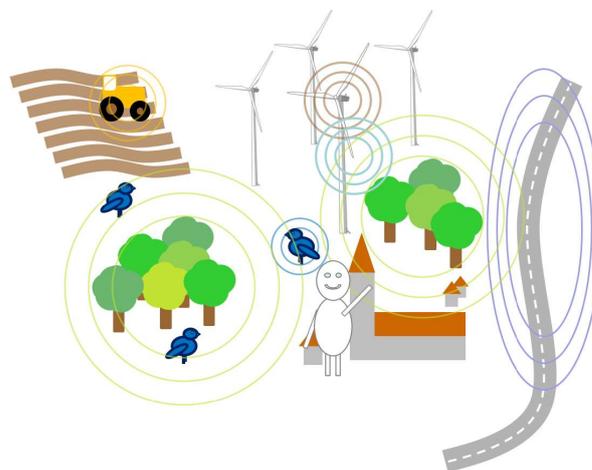


Figure 1: Schematic representation of wind turbine noisescape components.

which is why it is important to integrate the relevant sound sources into their natural environment rather than having an isolated observation to make up for an overall auditory evaluation.

- Distinct primary sound sources
  - Aerodynamic sound (turbulences at blade tips)
  - Tonal sounds (generator induced structure-borne and air-borne sounds)
- Environmental secondary sound sources
  - Wildlife
  - Infrastructure (traffic ways, agriculture, other industry)
- Ambient sound
  - Vegetation (wind-induced)
  - Non-assignable background noise

In terms of human perception and cognition of noisescapes, dimensions of a higher abstraction level can be proposed as follows:

**Timbre** Spectral composition and distribution

**Localization** Ability to assign directions of distinct sound sources

**Spatiousness** General auditory envelopment, direct-to-reverberant ratio and spatial variation (movement)

**Time** Modulation; general temporal variation rather than exact progression of acoustic events

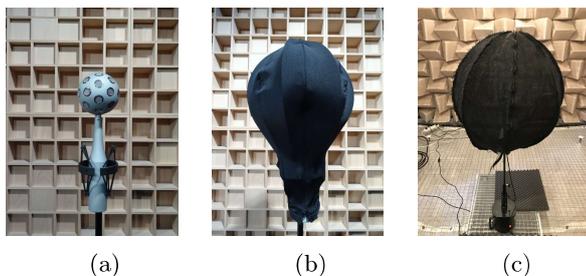


Figure 2: Spherical microphone array *mhacoustics Eigen-mike* with primary (b) and secondary (c) wind shield.

These perception-motivated dimensions thus form the criteria which are employed for a general description of a noisescapes and for the validation of plausibility of its reproduction. The following section proposes a workflow and methods for noisescapes capturing, processing, reproduction and validation with respect to the above mentioned perceptual dimensions.

### Noisescapes Reproduction Process Chain

The plausible reproduction of noisescapes consists of multiple stages of electro acoustic conversion and signal processing. In doing that two main paths can be defined. On the one hand side signals are acquired and processed that are directly used for the reproduction stage. On the other hand side higher level features can be obtained that are used for an abstract noisescapes description as well as for validating the reproduced noisescapes. Since these different approaches dictate specific requirements, the process chain has to be adjusted accordingly. However the general stages of data acquisition, processing and validation are common for both main paths.

#### Signals for reproduction

Since one of the main goals of the proposed noisescapes reproduction is to maintain the spatial cues, the data acquisition of the soundfield has to be accordingly. For that, spherical microphone arrays are commonly employed. For the noisescapes capturing presented here a microphone array with 32 nearly uniformly distributed sensors on a rigid sphere of radius  $r = 4.2$  cm is used, the *mhacoustics Eigenmike*. The capturing of in-situ acoustic scenarios also require some protective measures against wind-induced artifact noise. In order to also capture wind turbine scenarios with high wind speeds, one single wind shield (regardless of type) may not be sufficient to avoid wind noises. Since there are few commercially available wind shields that meet these requirements for the selected microphone (arrays), a self-developed wind shield was utilized. Figure 2 shows the microphone array (a), a proprietary primary (b) and a self-developed secondary (c) wind shield. The output signals of the microphone array can be transformed into the spherical harmonic domain and subsequently used for reproduction with e.g. higher-order Ambisonics rendering. The processing is based on the Spherical Harmonic

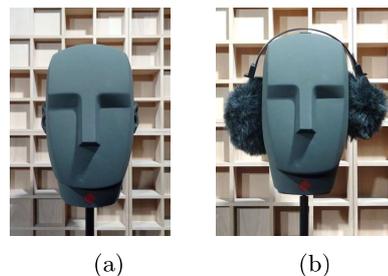


Figure 3: Binaural dummy head *Neumann KU-100* (a) used for high level feature capturing with primary wind shield (b).

Transformation[2]

$$p_{nm}(r, \omega) = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} P(\mathbf{x}, \omega) Y_n^m(\theta, \varphi)^* \sin \theta \, d\theta \, d\varphi \quad (1)$$

where  $\mathbf{x}$  denotes a three dimensional position vector in appropriate cartesian or spherical coordinates respectively,  $Y_n^m(\theta, \varphi)^*$  the complex conjugate spherical harmonics of order  $n$  and degree  $m$  and  $P(\mathbf{x}, \omega)$  the sound pressure at the corresponding position on a sphere. Beside Ambisonics rendering the captured soundfield allows directional analysis of the incoming sound. Dominant sound sources may be detected by means of methods of the direction of arrival (DOA) such as intensity analysis[3] or sensor magnitude weighting[4]. These methods may also be applied to moving sound sources such as sound emitted by a wind turbine rotor. Spherical beamforming into the direction of arrival may be used to separate distinct sound sources which in turn may be utilized for manipulating the captured acoustic scene during reproduction in terms of emphasizing or attenuation of certain sound sources. With this signal processing, both distinct sound sources and the ambient sound field are represented.

#### Signals for higher level feature deduction

The signals for the higher level descriptive features may be obtained by chosen microphones of the spherical microphone array as well as by a binaural dummy head which already employs some of the features that are relevant for human auditory perception. Again, primary and secondary wind shields were employed. Figure 3 shows the used dummy head *Neumann KU-100* with the primary wind shield whereas a additional secondary wind shield shown in Figure 2(c) is applied. The binaural signals form the basis of most of the above mentioned dimensions. For description of the timbre three higher level cues were selected. The centroid represents the spectral center of gravity and gives information on which frequency range dominates the spectral energy distribution. The spectral spread describes the deviation of the magnitude spectrum from its centroid and can be used to distinguish between broadband and narrowband signals. Similarly the spectral flatness, calculated as ratio

between geometrical mean and arithmetical mean of the spectral magnitude, characterizes whether a spectrum is tonal (flatness  $\rightarrow 0$ ) or noise-like (flatness  $\rightarrow 1$ ). Formulae for all mentioned spectral features can be found in [5], while the binaural rate map was employed which can be seen as perceptual-motivated spectrogram [6]. For the localization on the horizontal plane time-frequency dependent interaural level and time differences are used. The spaciousness is represented by the ratio between direct and reverberation sound (DRR) as well as the diffuseness[3] which can both be calculated from either the intensity vector or from DOA-based directional analysis.

### Reproduction with loudspeakers

The reproduction of the noisescapes is based on the previously captured and processed signals. For the different components suitable audio reproduction paradigms may be applied. The separated, distinct sound sources should be reproduced by a technique which maintains good localization like VBAP (and descendants) whereas the surrounding ambient part of the soundfield should be reproduced with a focus on enveloping for which HOA is suitable. However, before auralization of the noisescapes, thoughts have to be applied on a valid reproduction environment to maintain relevant perceptual cues. The recommendation ITU-R BS.1116-3[7] defines certain aspects of room acoustical properties that should be met for the subjective assessment in multichannel audio systems. Beside the reverberation time and the ratio of early reflections, the operational room response of the loudspeakers in use have to fulfill certain requirements. For the reproduction of the noisescapes presented here, the *Immersive Media Lab* at the Institute for Communication Technology is employed. The room acoustical and infrastructural properties are described in [8] and the room response equalization proposed in [9] was applied. Figure 4 shows the reproduction with installed loudspeakers and a acoustical transparent projection screen for visualization which adds further context. The audio system consists of 36 spatially distributed loudspeakers with higher density at the frontal plane. It is fed by a dedicated playback and measurement PC connected via a Dante audio network and designated DSP devices for loudspeaker equalization. Currently the reproduction is conducted by 7th-order Ambisonics rendering with all-round Ambisonics panning and decoding[10].

### Validity of Reproduction

For perceptual assessment of wind turbine noisescapes it is critical to maintain relevant perceptual cues during reproduction. To keep control over these properties, the previously identified features are monitored and compared between the original capture and the reproduction. Even though these features do not give any guarantee over ecological validity, it is a useful basis for comparison. Figure 5 shows the aggregated features for an exemplary original and reproduced soundscape. The individual fea-



(a)



(b)

Figure 4: *Immersive Media Lab* for audiovisual reproduction with installed loudspeakers (a) and projection screen (b).

tures that represent the noisescapes' dimensionality are visualized along the axes of the polygon as a temporal histogram including the minimum in the center and the maximum at the outside in the denoted range. It gives general information on chosen properties of the noisescapes and indicates similarities and differences within comparisons. Due to the aggregation, similarity is a necessary but not sufficient condition for valid soundscape reproduction. The presented result shows significant differences between original and reproduction that have to be investigated subsequently in detail. For example the localization features ITD and ILD are evenly distributed in the original whereas these features can only be reproduced with much lower dynamic range and steeper distribution. It is thus expected that lateral localization will be perceived less distinct, since the overall value range of the ITD and ILD cannot be reproduced correctly. Other imperfect properties are the spaciousness features, namely less direct sound and higher diffuseness. The reproduction for which the results are shown here, does not include a separate treatment of distinct sound sources, i.e. no source separation and subsequent additional reproduction but merely Ambisonics rendering of the microphone array signals. It turns out that for a valid diffuseness reproduction this procedure is not sufficient which is why this aspect has to be treated in future implementations with high priority. It can be expected

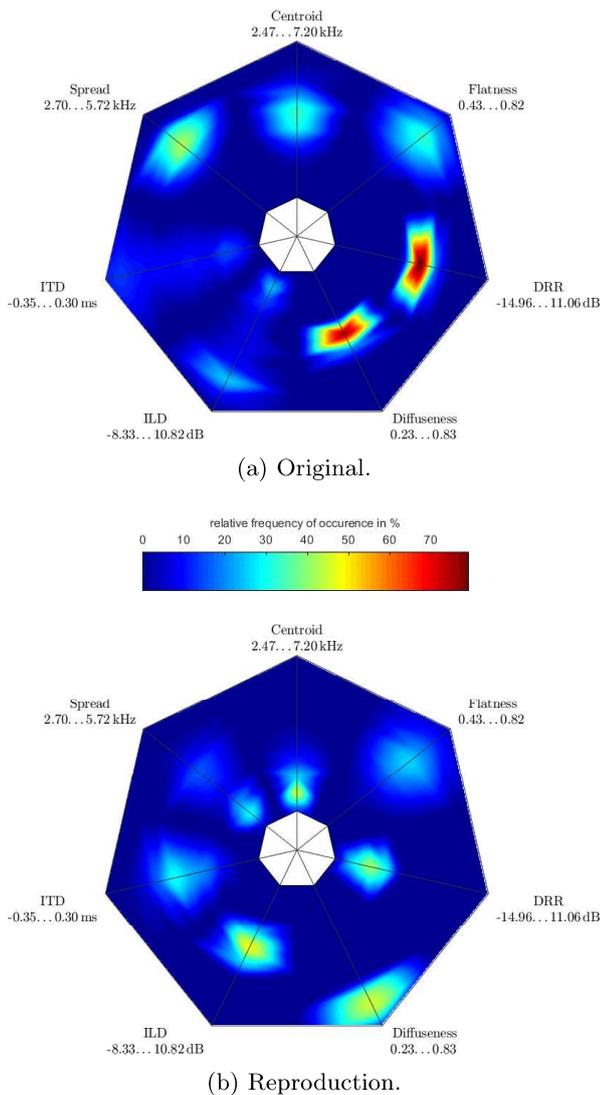


Figure 5: Aggregated descriptive high level features of original captured soundscape (a) and its laboratory resynthesis (b).

that the previously mentioned localization in terms of ILD and ITD will also improve with this measure. Even though the reproduction seems to fail clearly in terms of the defined perceptive dimensions, this evaluation gives notification which physical or signal-related property has to be improved. With this information the signal processing and reproduction chain can be adapted to approach maintaining the proposed dimensions.

## Summary

The presented paper proposes approaches, methods and tools for soundscape reproduction. It discusses components and perceptual dimensions of wind turbine soundscapes which can be evaluated to give information on ecological validity. For this the dimensions timbre, localization, spaciousness and time have been identified as relevant and suitable signal-based features were assigned. Further, a practical production workflow consisting of data acquisition, processing and reproduction was presented including practical implications that come

along. Subsequently the reproduction of an exemplary soundscape was conducted and the developed validation measures were applied. It could be shown, that the current reproduction does not yet fulfill the qualitative criteria that were identified, however the validation process gives precise information which physical properties have to be improved in future revision. Here, the most prominent aspect concerns the treatment of distinct sound sources to improve the localization and general perception of relevant direct sound.

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