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Doppler analysis and processing for the localization of low frequency tonal sound sources on blades: an experimental approach.

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Summary

An experimental characterization of the noise of a wind turbine in Switzerland is described with the aim to answer questions about the generation and collection of low-frequency noise of wind turbines.

The time dependent noise footprints of a 101-m diameter wind turbine are measured over periods lasting 10 days for each season with collection of data from four sound level meters, one meteorological station, one LIDAR and an array of microphones. Turbine operations parameters are recorded with instantaneous values (0.5 sec.) for short sequences and with mean values (10 min.) for the entire campaign. The study focuses on the fine analysis of recordings presenting tonal sounds with Doppler frequency shift in the 50 Hz to 125 Hz band of frequency.

The Doppler frequency shift and inverse Doppler processing are described by using time-frequency decomposition of the recordings to determine the nature of the tonal sound sources and to locate them. In regards to the variable turbine operation parameters, the sound sources located on the three pales are sliding along the blades depending on the rotation speed of the turbine. A strong correlation is found between the location and central frequency of the tonal sounds with turbine operational parameters. As a result, amplitude modulations are described and explained by using a simple model of dipole sound sources located near by the blades which could be related to the stall noise.

These data characterizes the amplitude modulation depth of low-frequency of the wind turbine and it allows extracting a generic proposal for low-frequency noise mapping at different angular azimuthal locations around the wind turbine. These results allow to define strategies for observation of wind turbine noise for these frequency bands and to offer useful guidance to the reduction of the low-frequency noise generated by the wind turbine.

1. Introduction

PLEASE CONSIDER THAT IT WILL BE A POSTER EPLAINING METHODS USED TO GET THE RESULTS GIVEN IN THE PAPER “20150205_Paper_01_WTN2015_Falourd.docx”

I put number of pictures figuring the context and the obtained results. The poster will contain information on the signal processing and simulations of inverse Doppler analysis to fit the experimental data. Please do not consider as finished the black text extracted from the paper.

2. Wind turbine site and descriptions

N° DUO 01dB	Distance	Wind reference
1*	150 m	Upwind
2	480 m	Upwind
3	270 m	Downwind
4	550 m	Downwind

Table 1: Location of sound level meters to the mast of the turbine.

Figure 1 : Location of wind turbine (red), soundlevel meters (upwind: yellow, downwind: blue). The mountain relief is on bottom side. (credit Google Earth)

3. Wind turbine operations parameters

Turbine type	**Enercon E-101**
Number of turbines	1
Number of blades	3
Rotor diameter [m]	101
Hub height [m]	99
Cut-in speed [m/s]	2
Nominal wind speed [m/s]	13
Cut-off wind speed [m/s]	34
Capacity [kW]	3'000

Table 2: Wind turbine technical specifications

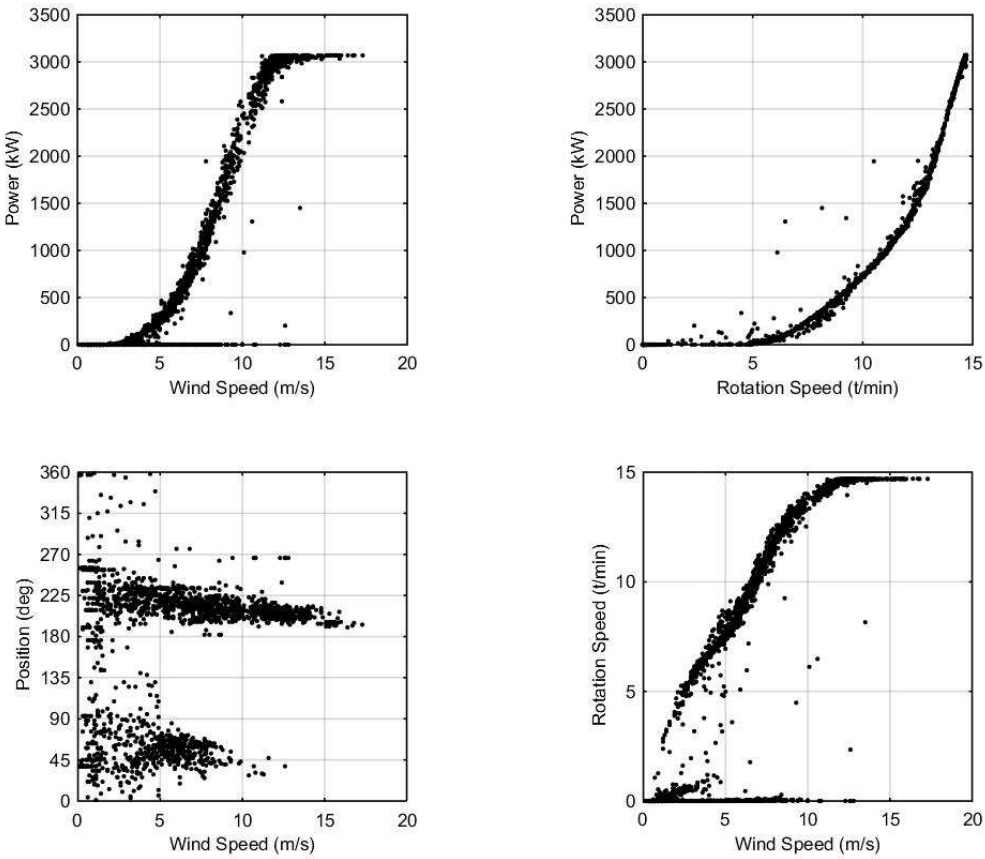
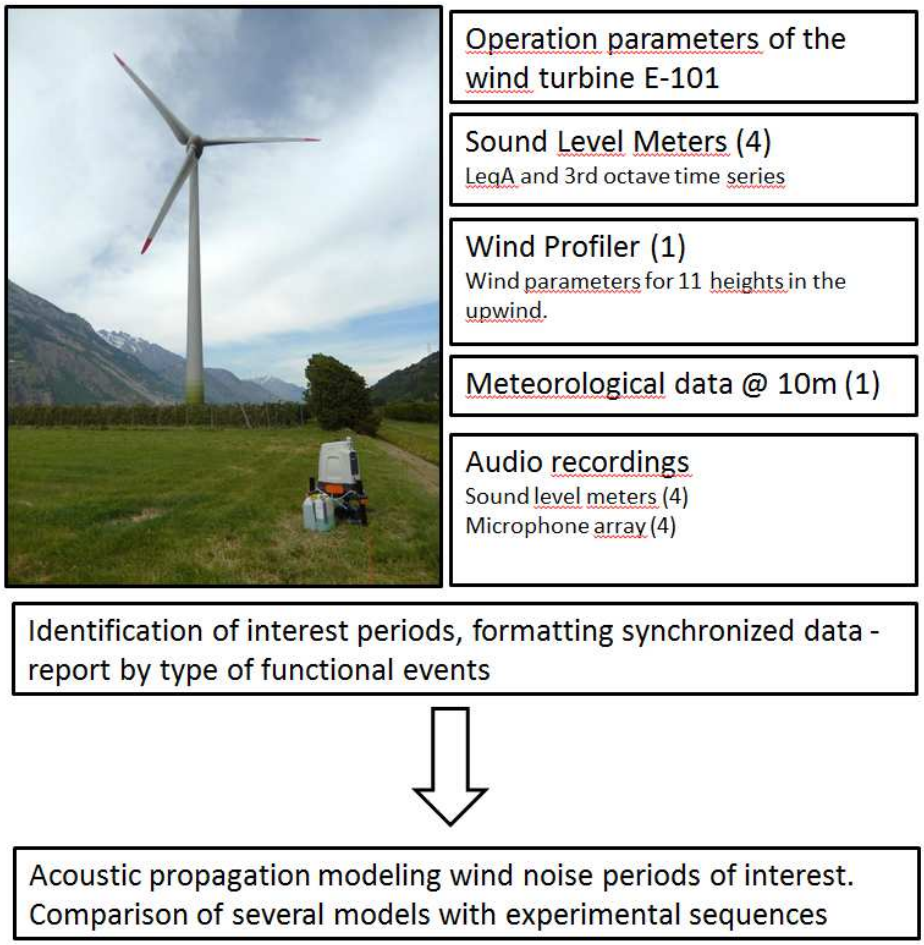
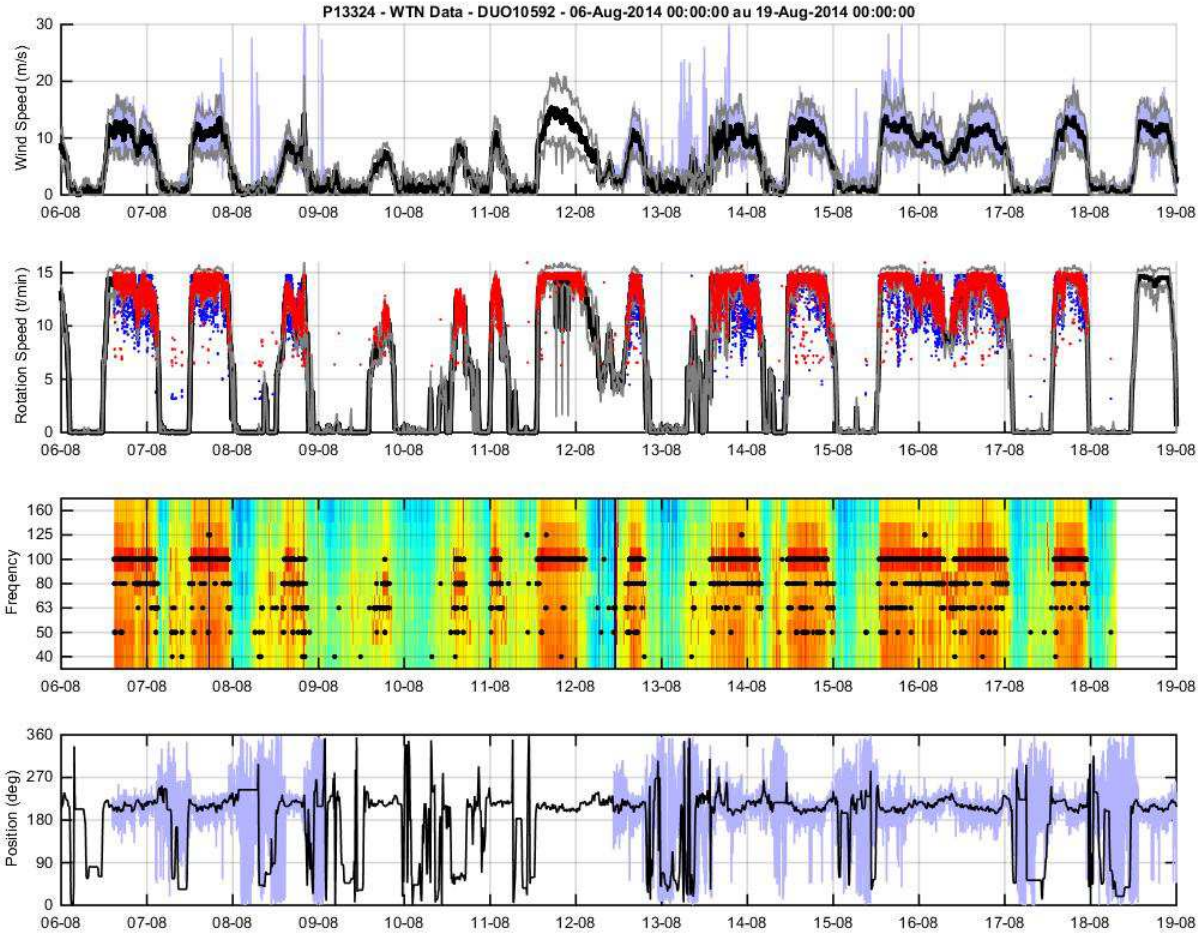


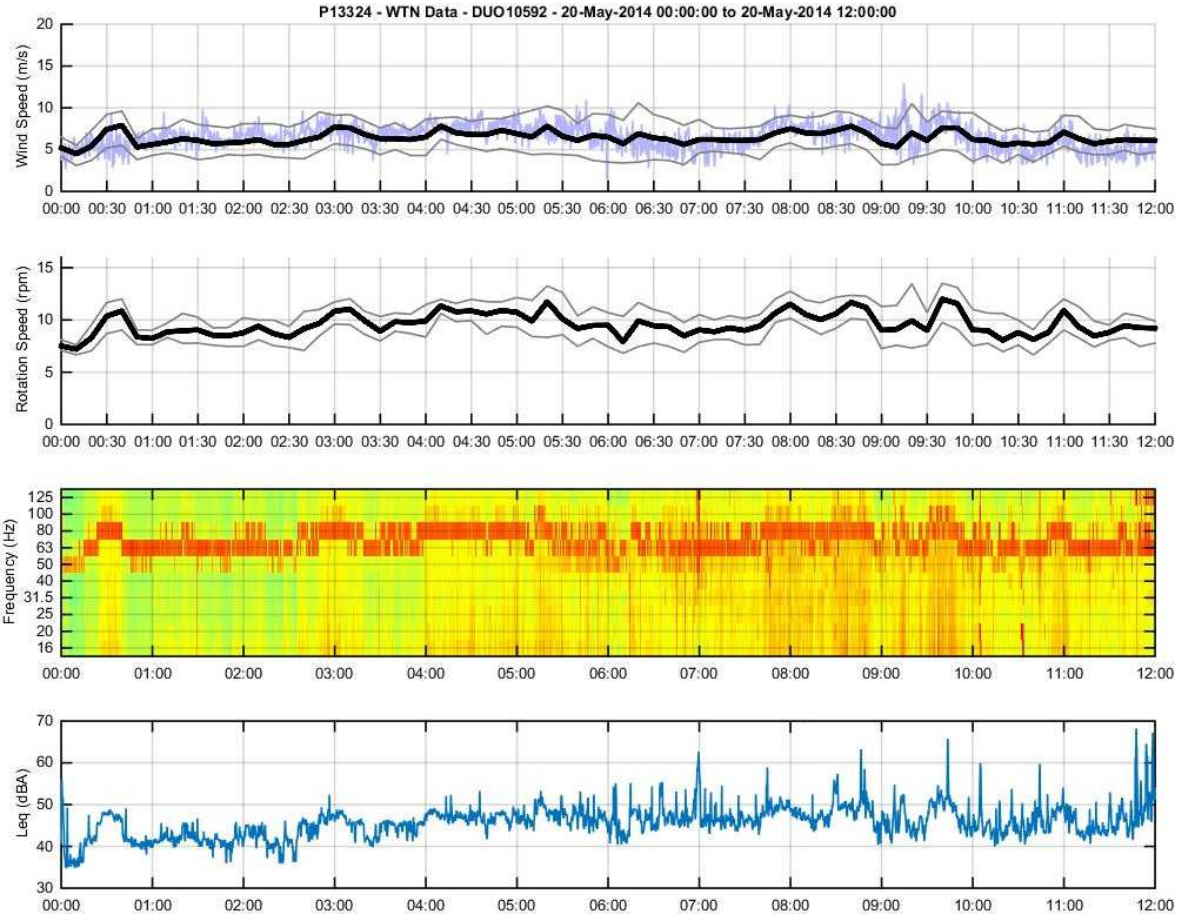
Figure 2: Wind Turbine statistics (12 days / May 2014)

4. Noise monitoring, meteorological parameters



5. Correlation between wind parameters and 3rd octave low frequencies





6. Locating the swish sound / estimation of the rotation speed on the 3rd octave time series

a. Tetrahedric microphone array (5.35 m) for “swish” tracking

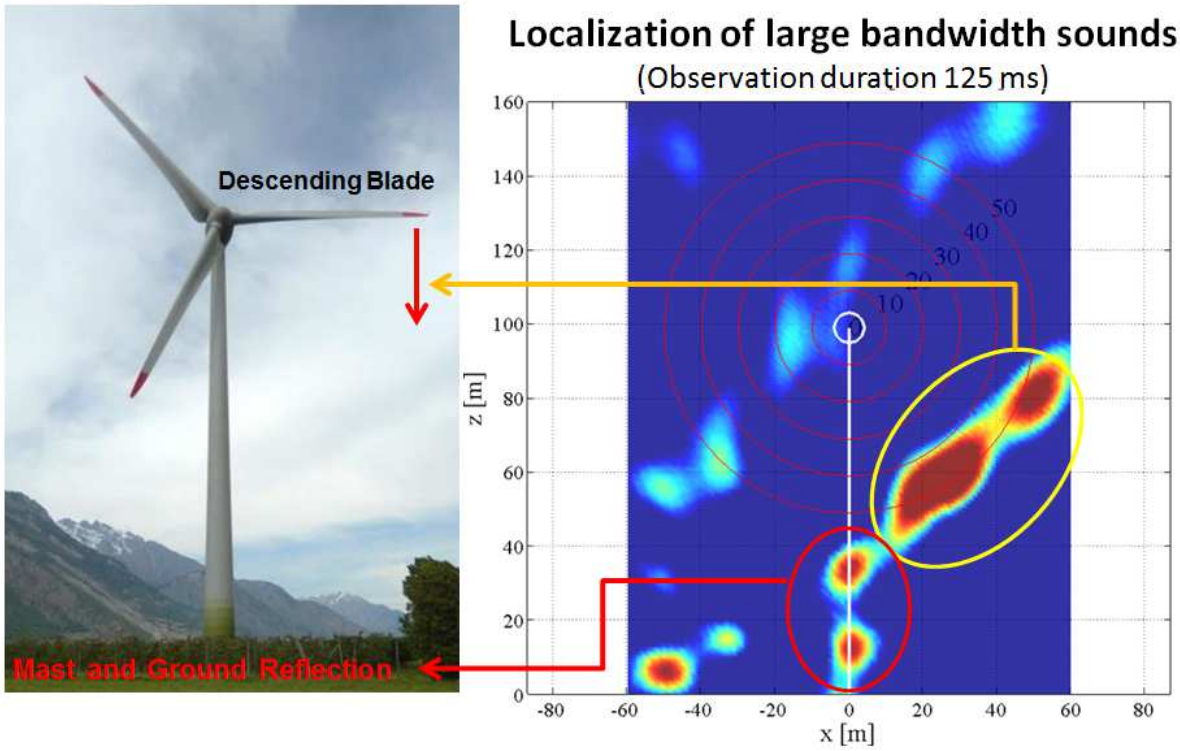
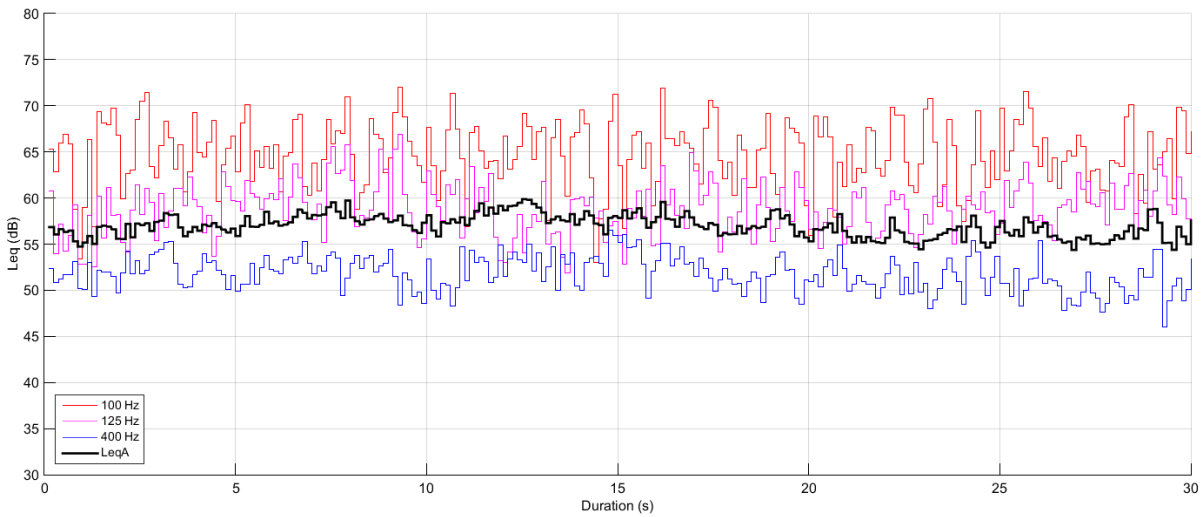


Figure 3 : Localization of the swish from the descending blade – proof of reliability to use the swish sound to estimate the RPM.

b. Low-frequency tonal components amplitude modulation related to the rotation speed estimated by the “swish” tracking



7. Tracking tonal components in spectrograms

a. Empirical relation between RPM and Dopplerized central frequency

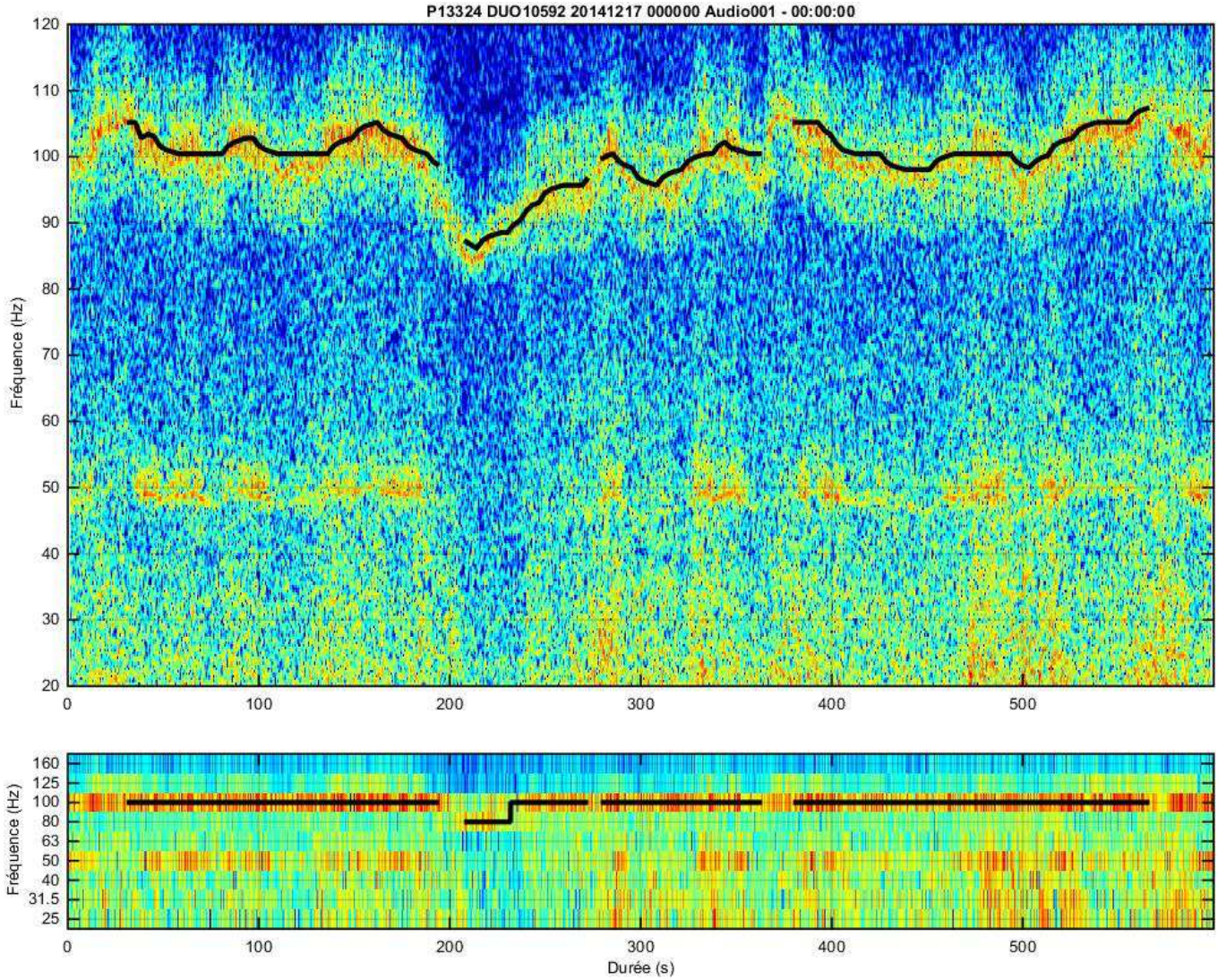


Figure 4 : Top: STFT spectrogram of one 10 minutes duration recording with the tracking of the central frequency. Bottom: 3rd Octave spectrogram of the recording

8. Amplitude modulation of low frequency tonal components

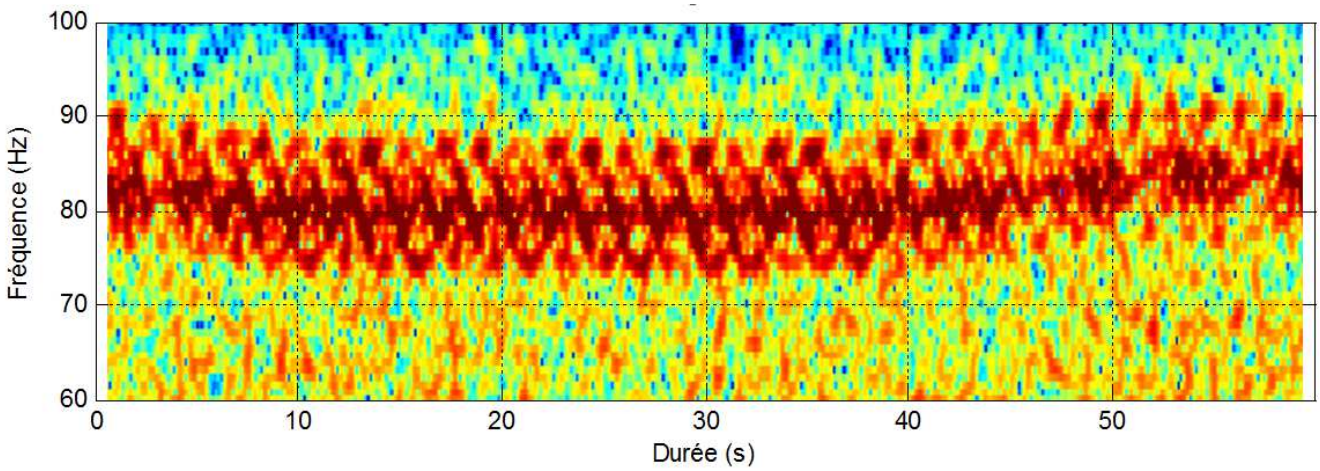


Figure 5: STFT spectrogram of a 60 seconds audio recording presenting 3 central frequencies with Doppler shift.

9. Comparison of real data and synthetized data

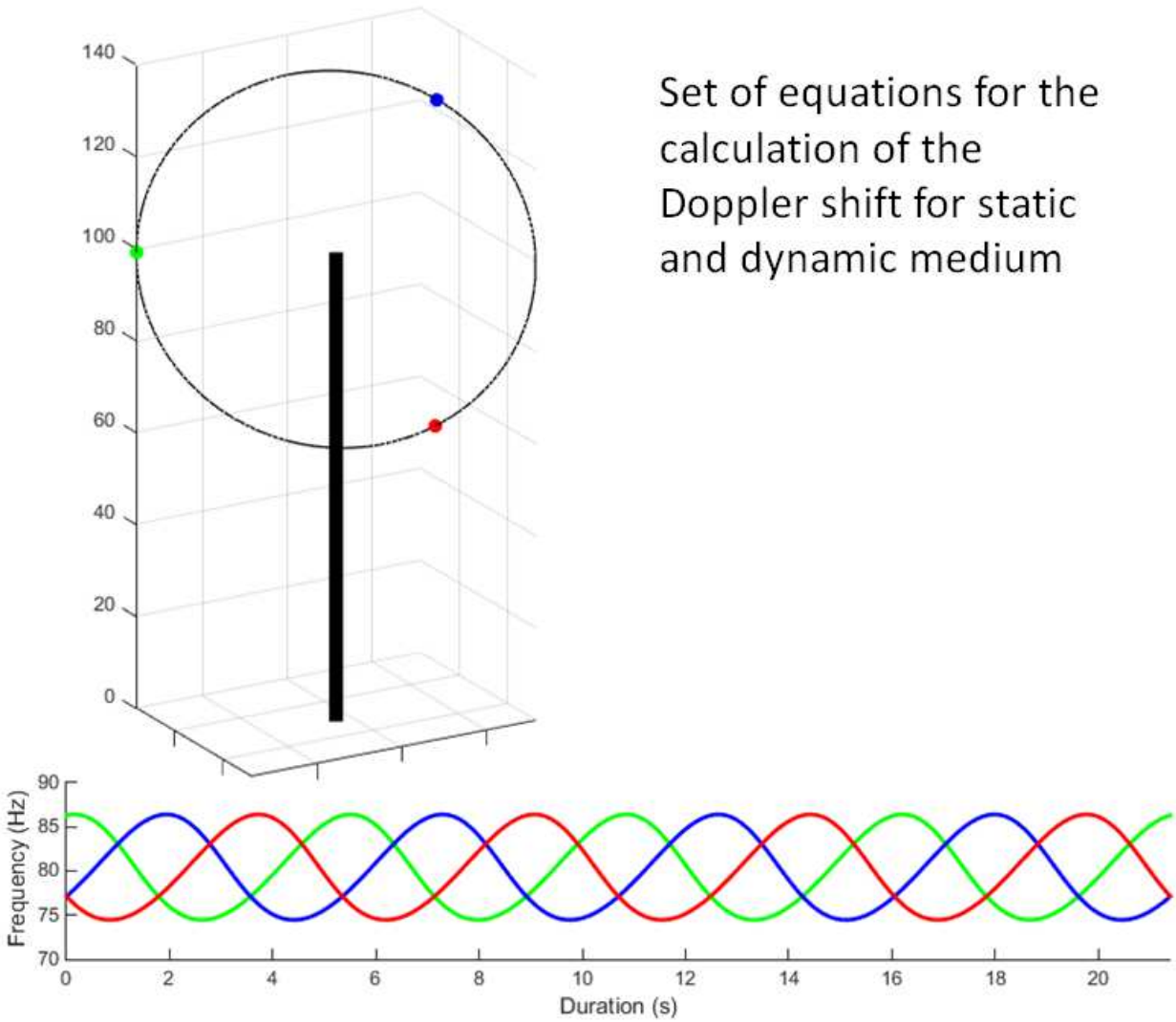
Inputs of the model:

a) Central Frequency calculated from the rotation speed of the blades

b) Range and azimuth of the receivers and the discrete positions of sources on blades

c) Period of revolution of the blades (rotation speed of the blades)

d) The medium is considered without motion at this first stage.



The result of this analysis can explain experimental observations; Doppler pattern of three single-frequency sources revolution movement to justify the frequency modulations observed. Figure 6 illustrates the spectrogram of a short sequence of a recording (left) and of the simulated (synthetized) sound signal extracted by real physical parameters:

a) Central Frequency is set to 80 Hz

b) Period of revolution is set to 5.35 seconds (11.2 rpm)

c) Location of the source is set to 41 m far from the nacelle

d) The medium is considered without motion first approx).

e) Sound sources are defined as monopoles with modulated amplitudes (first approx).

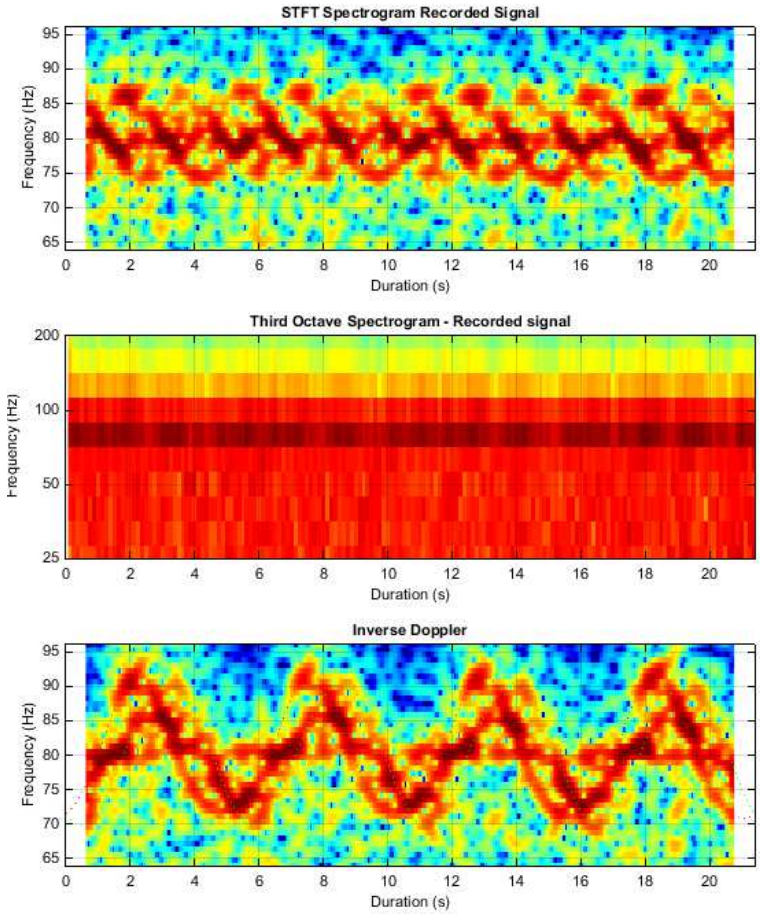
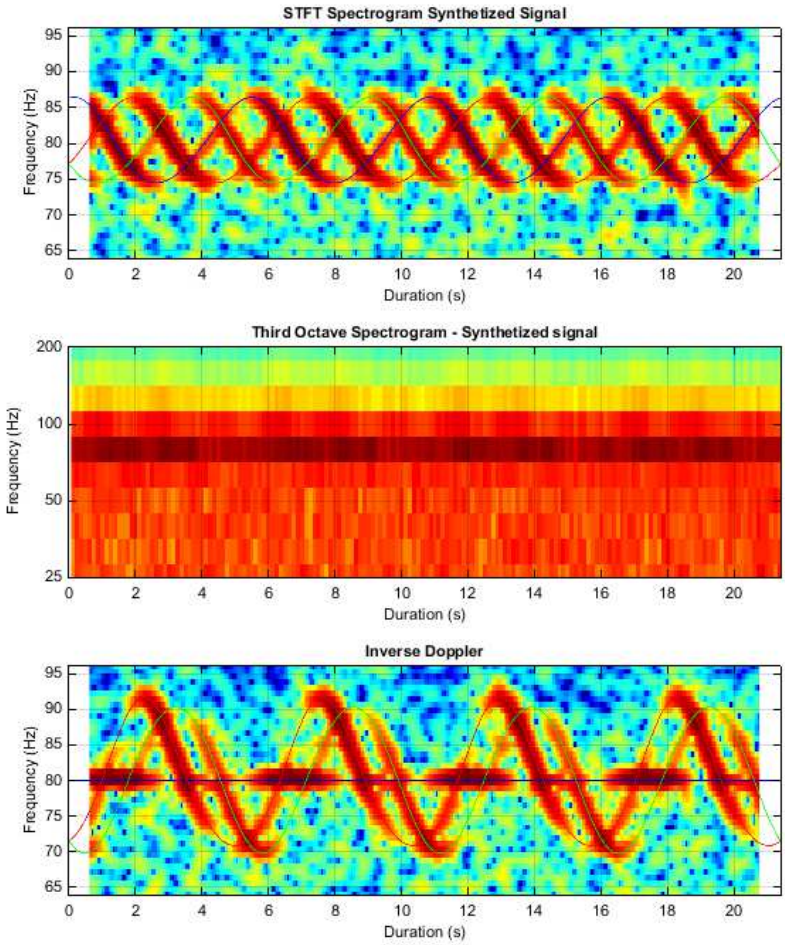


Figure 6: top to bottom: STFT spectrogram, 3rd octave spectrogram and inverse Doppler STFT of a real signal; Figure 10: idem for a synthetized signal



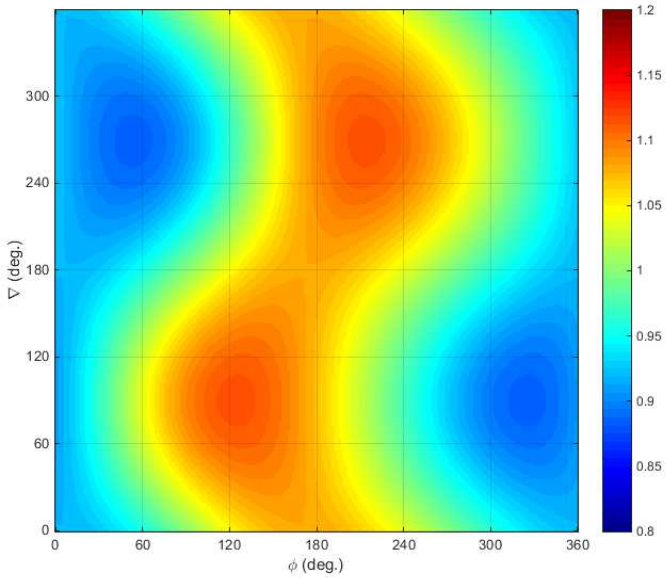
Right: spectrograms for the synthetized signal.

10. Dedopplerization to fit physical parameters

Audio signal processing methods to dedopplerize the signal
Function of maximisation to find solution by tracking the central dedopplerized central frequency

- **Location of the sound source on the blade (precision, error mapping)**
- **Estimation of the rotation speed of the blades and their orientation**
- **Estimation of the sound radiation of the sound source on the blade**
- **Doppler Effect due to wind**

Error mapping for identified parameters → available soon!



11. Doppler azimuthal mapping for AM and FM of low frequencies – Medium static

A first validation of the Doppler Effect hypothesis consists in analyzing the STFT spectrogram of the signal recorded synchronously at two different locations (receivers are quasi in-line in the upwind). Figure 7 illustrates that the Doppler Effect related to the modulation of frequency is attenuated for the receiver n°2 more distant to the wind turbine than the receiver n°1 as predicted by the theory. This specificity of the Dopplet Effect will permit to fit the parameters of the physical parameters affecting the frequency shift by the analysis of noise monitoring using adequate locations of microphones around the wind turbine.

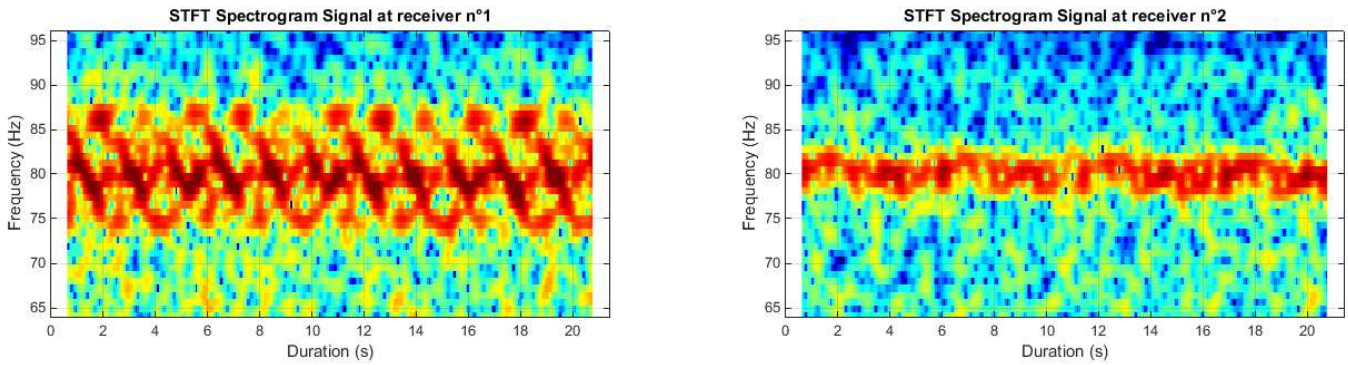


Figure 7: Left: STFT of a real signal at receiver n°1; Right of a real signal at receiver n°2.

Figure 8 illustrates the amplitude modulation of the 3rd octave central frequency at 80 Hz for both receivers. In contrary to the FM modulation, the receiver the farthest from the wind turbine presents higher amplitude modulation (AM1 = 14.5 dB, AM2 = 19.4 dB). It can be explained by the interference of the three dopplerized tonal frequencies which are dependent of the sound radiation of the acoustic source located on the blade and the position of the blade during one complete revolution.

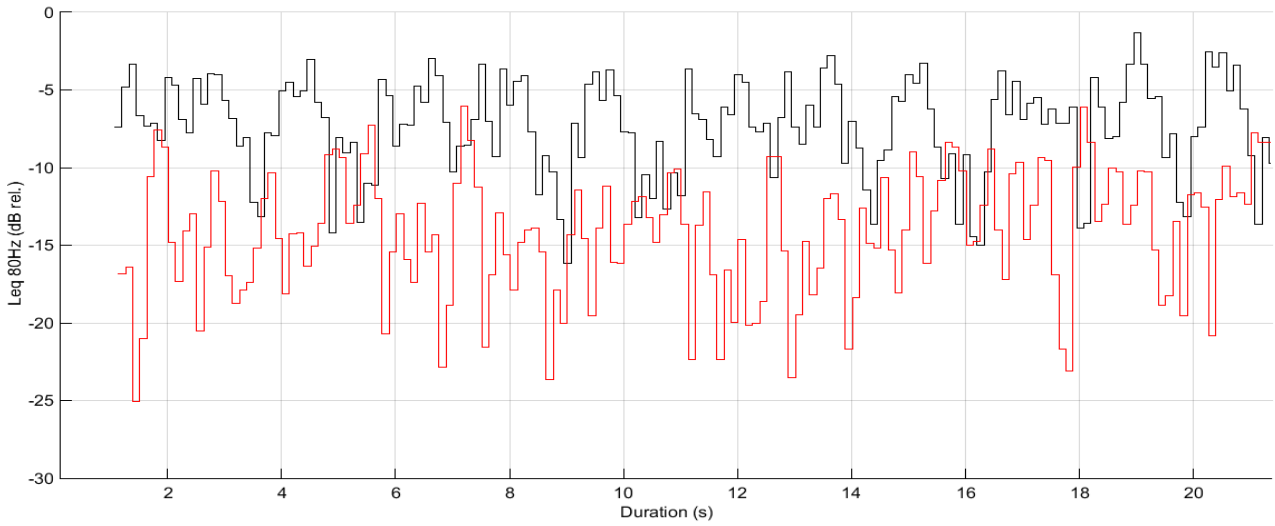


Figure 8: Time series of 3rd octave Leq (80Hz) for receiver n°1 (black) and n°2 (black).

This hypothesis of an acoustic source with a periodic movement of revolution allows thus to generate an azimuthal mapping around the turbine of the frequency dilatation coefficient due to the Doppler Effect and thus to understand the low frequency amplitude modulations for azimuthal distribution of receivers around the wind turbine.

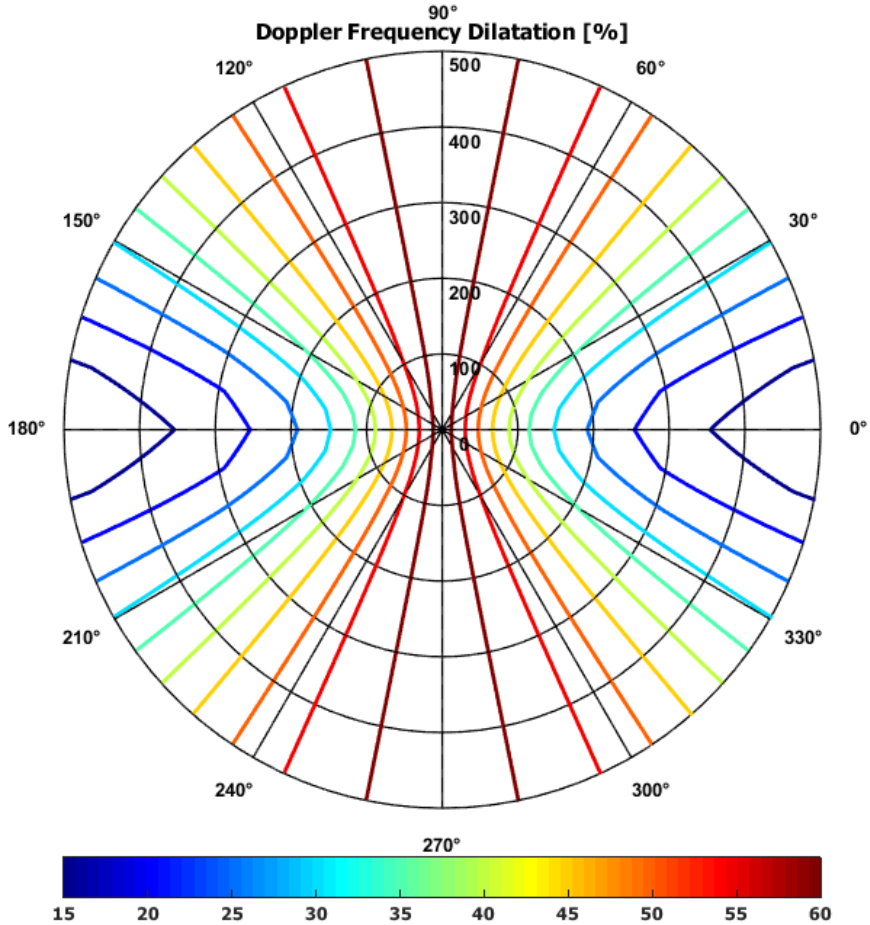
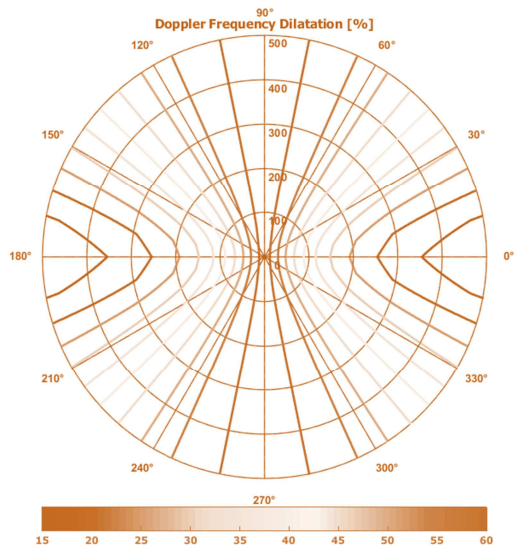


Figure 9: Example of an azimuthal mapping of the frequency dilatation coefficient due to the Doppler Effect for different ranges and and angles of the receiver around the turbine. The plane of the turbine is on the 90°-270° axis. Medium of propagation considered static

12. Doppler azimuthal mapping contracted by wind

Available soon !



13. Conclusions

14. Acknowledgements

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1. References

[1] Oppenheim, Alan V., Ronald W. Schafer, and John R. Buck. Discrete-Time Signal Processing. 2nd Ed. Upper Saddle River, NJ: Prentice Hall, 1999.
[2] D. Bowdler, Geoff Leventhall. Wind turbine noise, Brentwood, Essex : Multi-Science Publishing, 2011.