



Prévision fine des niveaux
d'exposition au bruit éolien
et simulation auditive

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OPTIMISER LE BRIDAGE DES ÉOLIENNES

- Développement et exploitation des parcs éoliens en France
- Réglementation acoustique impose des niveaux **limites d'émergences** par rapport au bruit résiduel
- Bridages des éoliennes qui en résulte : 1^{ère} cause de perte de production électrique
- Besoin d'un **outil prévisionnel de l'émergence** du bruit éolien pour **optimiser le bridage des éoliennes**

FAVORISER L'ACCEPTABILITÉ DES ÉOLIENNES

- Outil de simulation avancé permettant une prévision fine des niveaux d'exposition y compris leurs **variabilités temporelles**
- **Simuler auditivement** le bruit éolien pour une évaluation par l'écoute du bruit ambiant dans différentes situations



"Towards a more efficient exploitation of on-shore and urban wind energy resources"

Wind turbine noise

Aerodynamic noise modelling

- Turbulent-inflow noise
- Trailing-edge noise

Assessment of the acoustic annoyance

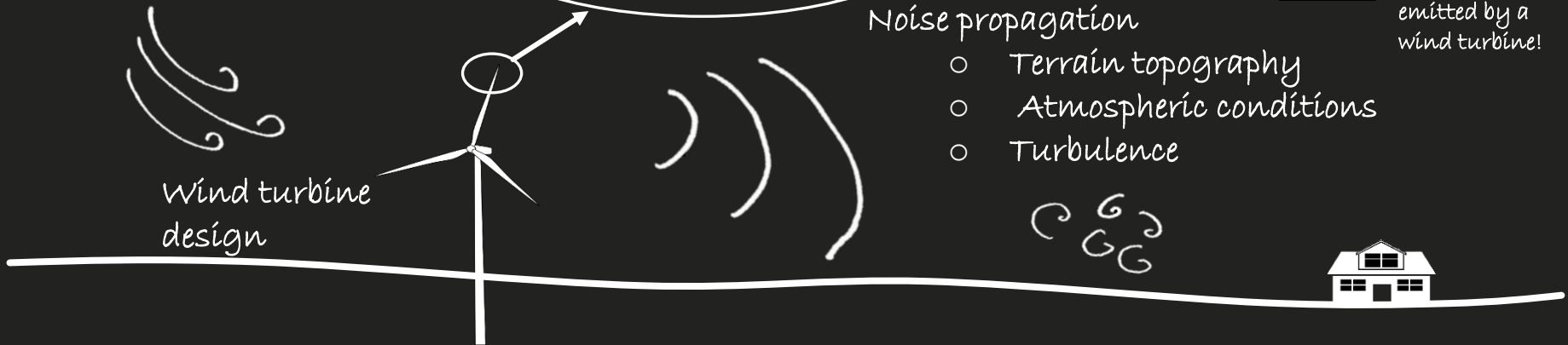
- Audio signals
- Listening tests



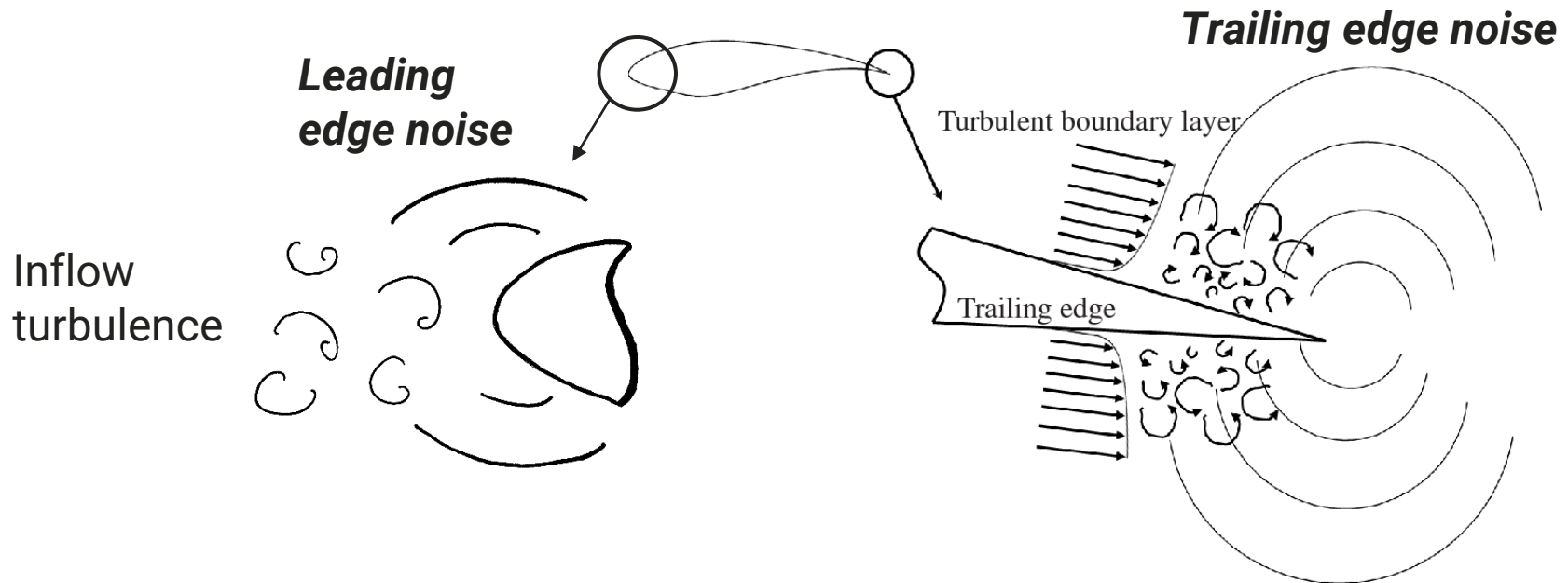
Scan the QR code to hear the noise emitted by a wind turbine!

Noise propagation

- Terrain topography
- Atmospheric conditions
- Turbulence



The project ZEPHYR has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860101.



Leading- and trailing-edge noise generation, modified from [1]

[1] Barone, M. F., 2011, Report SAND2011-5252, Sandia National Laboratories.

Approche *Modélisation des sources*

3D CAD of
the rotor
blade

Extraction
of 2D blade
sections

2D RANS
simulations

Boundary
layer
parameters

Amiet's
theory

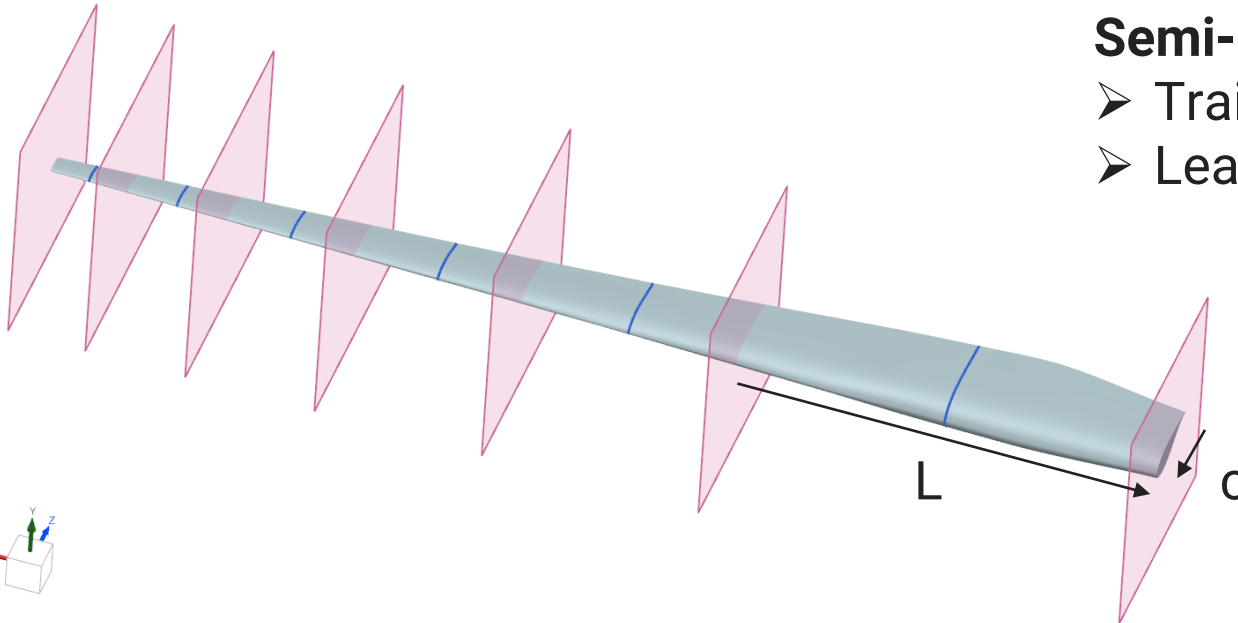
Sound
directivity

Simcenter 3D

STAR-CCM+

Semi-analytical Amiet's theory for

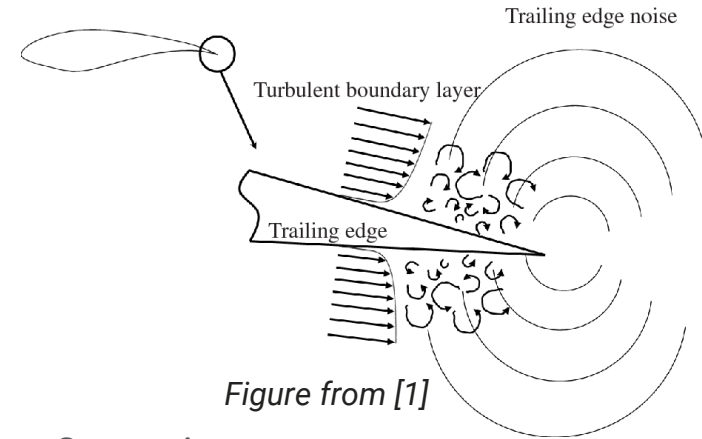
- Trailing-edge noise
- Leading-edge noise



Semi-analytical Amiet's theory for trailing-edge noise

Main assumptions:

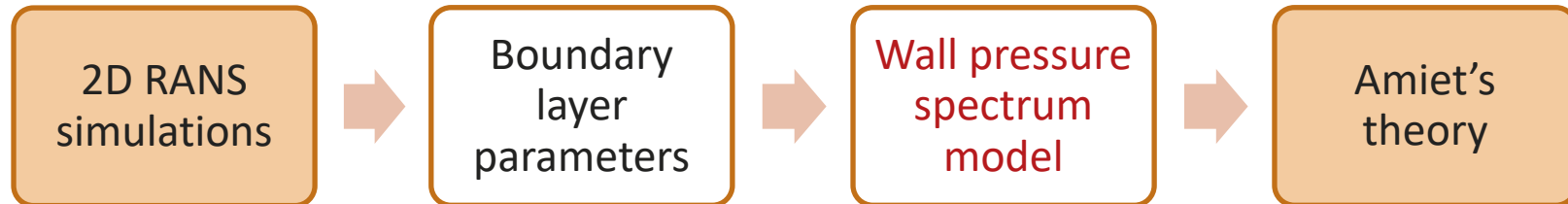
- Flat plate at $\alpha = 0$
- Receiver in the far-field
- Large aspect ratio ($L/c > 3$)



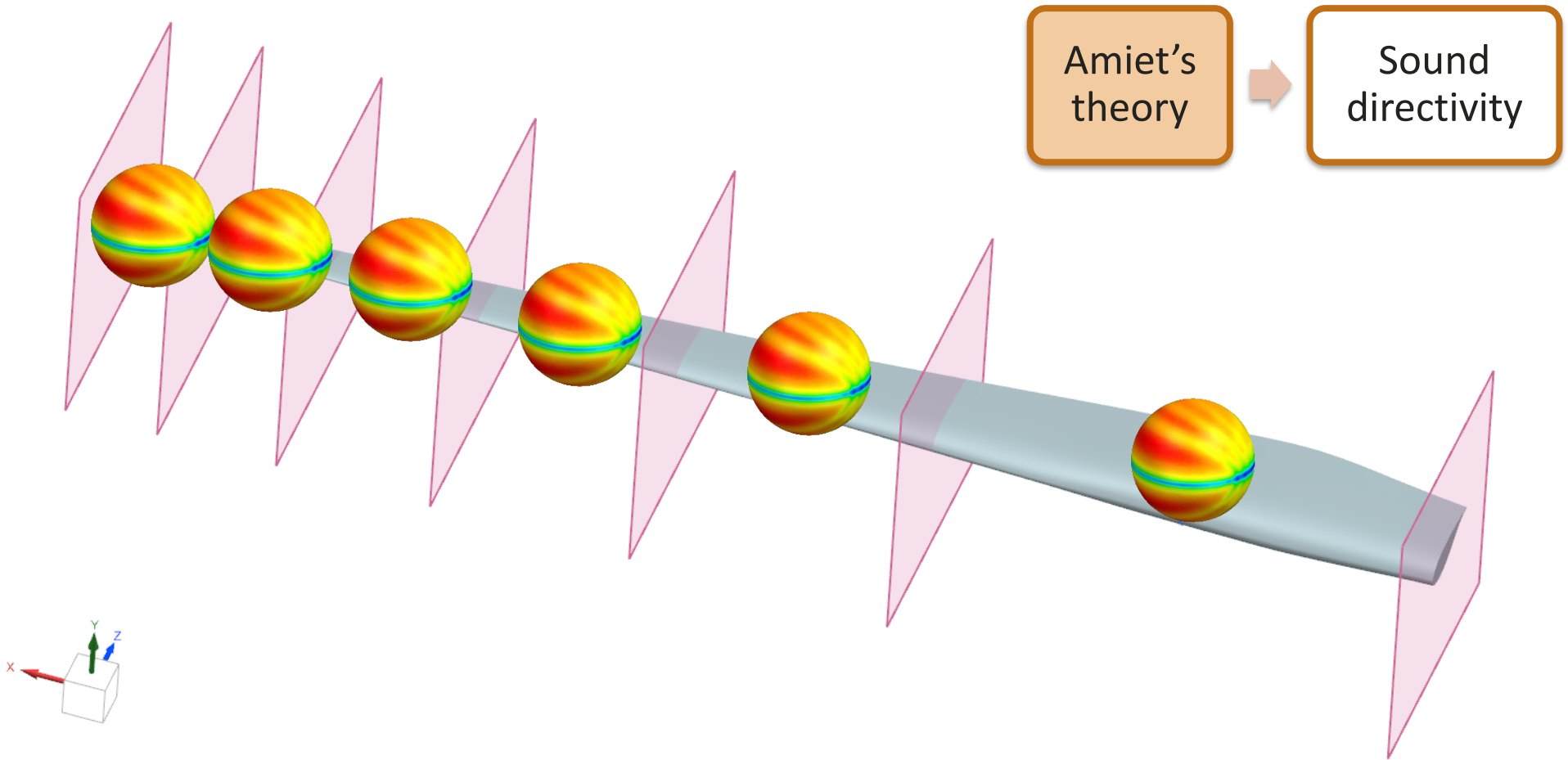
Power spectral density

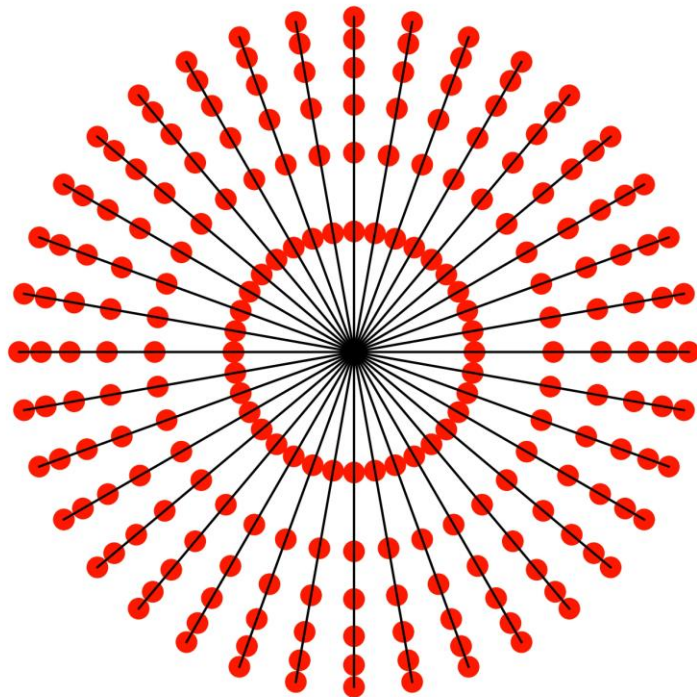
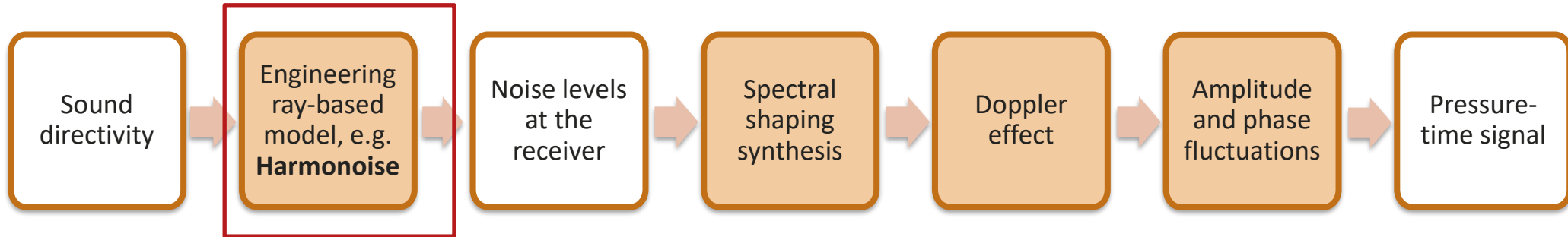
$$S_{pp}^{TE}(\mathbf{x}, \omega) = \left(\frac{\omega Z c}{4\pi c_0 \sigma_0^2} \right)^2 2L \left| J(\mathbf{x}, k_c, k_y) \right|^2 l_y(k_c, k_y) \Phi_{pp}(k_c, k_y)$$

Wall pressure fluctuation spectrum



[1] Barone, M. F., 2011, Report SAND2011-5252, Sandia National Laboratories.





Harmonoise

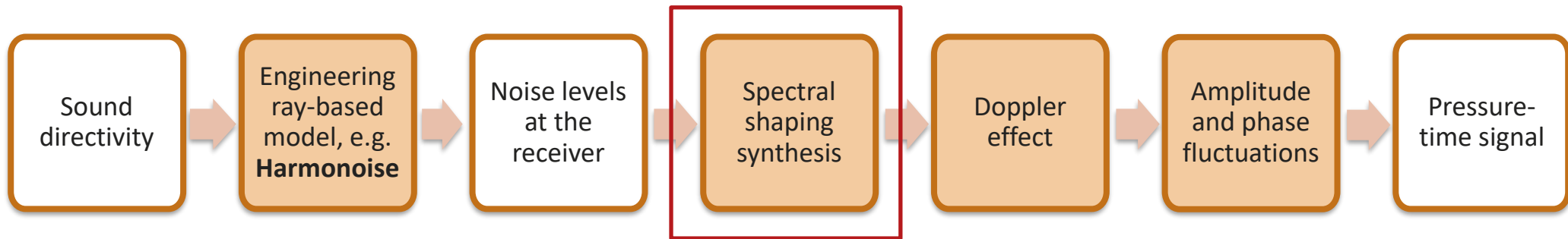
1. Discretization in the azimuthal direction
2. For each source i : $L_{p,i} = L_{w,i} - A_{E,i}$
3. Compute noise levels as function of the azimuthal position of a blade by summing the contributions from the active sources

Noise level at the receiver for each 1/3-octave band

Sound directivity (Amiet)

Spherical divergence + Excess attenuation:

- Air absorption
- Ground reflection
- Atmospheric refraction
- Atmospheric turbulence scattering



Time domain spectral shaping synthesis

For each segment of each blade:

$$\tilde{p}(t) = \sum_{f=1}^{N_b} p_{rms,f}(t) \frac{n_f(t)}{n_{rms}}$$

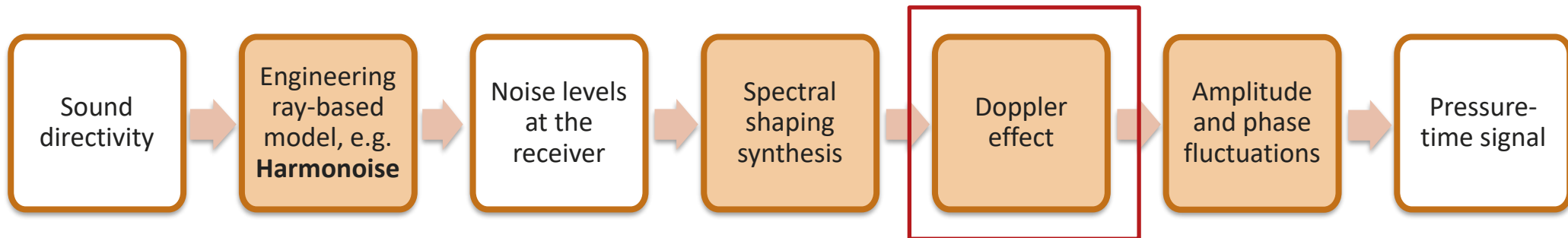
Normalized pink noise

with

$$p_{rms,f}(t) = \sqrt{p_0^2 10^{\frac{L_p(t)}{10}}}$$

Noise level at the receiver

and $p_0 = 2 \cdot 10^{-5}$ Pa.



Doppler effect and fractional delay interpolation

For each segment of each blade:

$$p(t) = \tilde{p}(t - \tau(t))$$

with the time delay $\tau(t)$ computed as

$$\tau(t) = \frac{d(t_e)}{c_0}$$

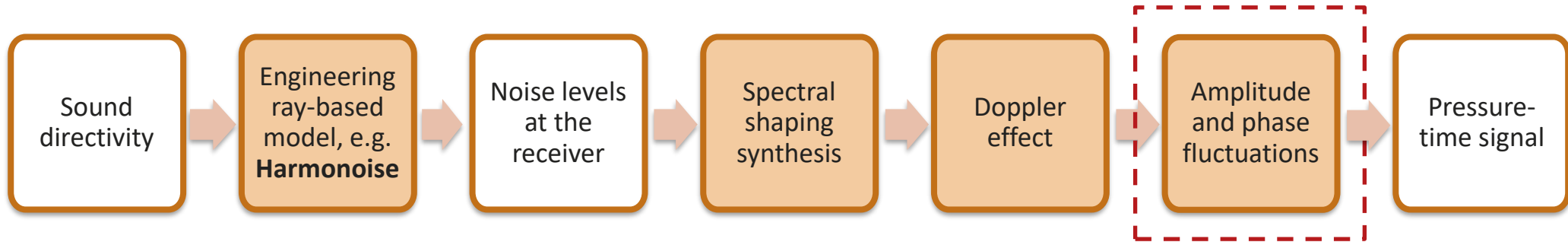
Source-receiver distance
at emission time

and $c_0 = 343$ m/s and $t_e = t - \tau(t)$.

Problem: The discrete time signal is delayed by a non-integer number $\tau(n)$

$$p(n) = \tilde{p}(n - \tau(n))$$

Solution: Fractional delay interpolation with 3rd order Lagrange polynomials.



Amplitude and phase fluctuations

On-going work on acoustic scintillations.

« *Physics-based scintillations for outdoor sound auralization* »

A. P. C. Bresciani, J. Maillard, L. D. de Santana

Accepted for publication in The Journal of the Acoustical Society of America

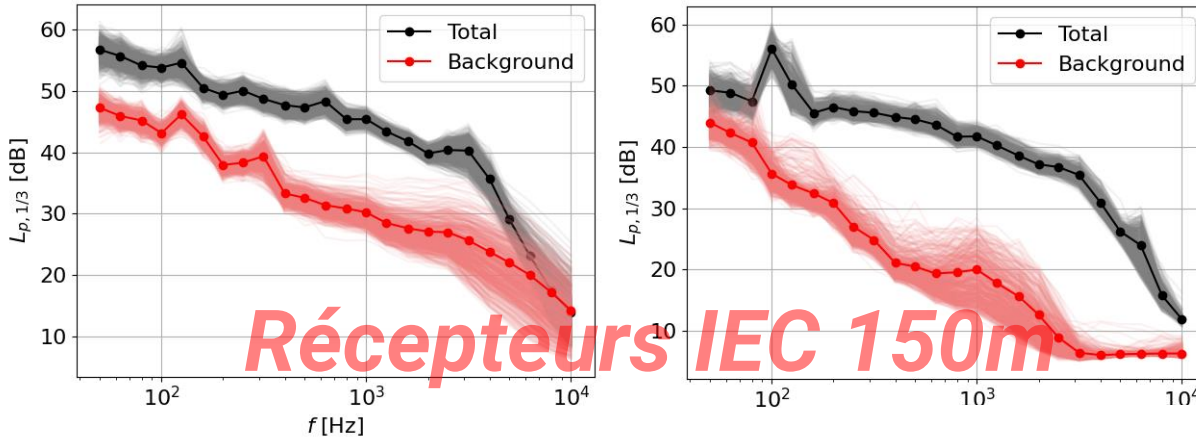
Résultats

Comparaison avec mesures sur site réel(*)



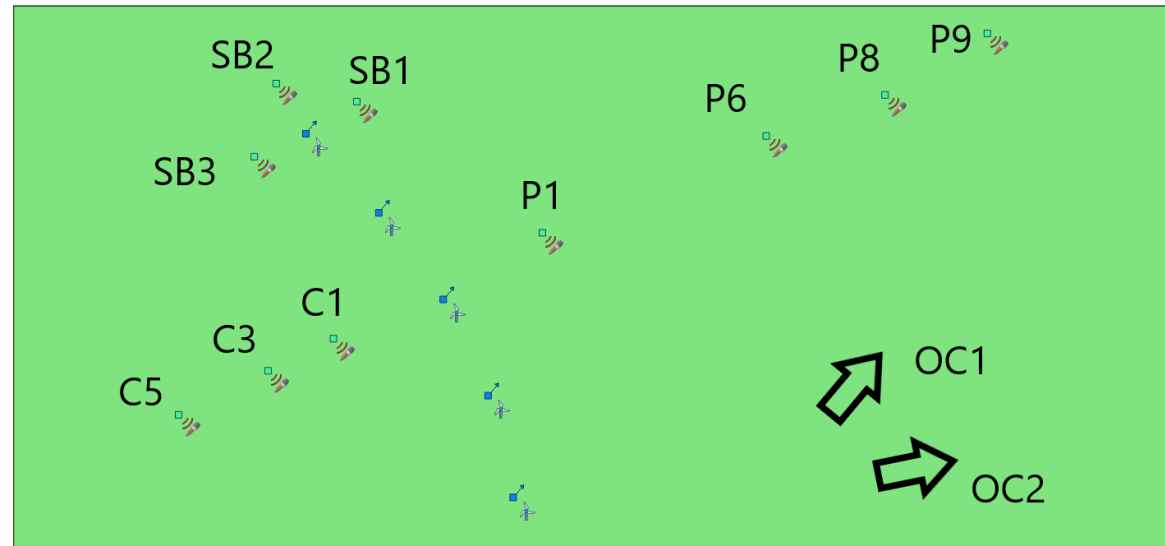
Operating Conditions 1 (OC1)

Operating Conditions 2 (OC2)



Récepteurs IEC 150m

MithraSOUND 2D view of the modeled site



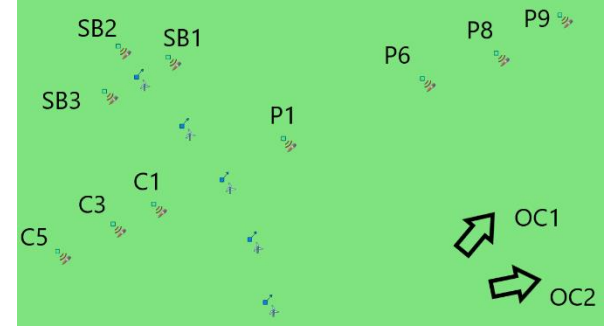
**SWT 2.3-93 wind turbine
(2.3 MW rated power and 93 m diameter)**

	OC1	OC2
Rotor speed [rpm]	15.10	13.72
Pitch angle [°]	7.8	0.0
Wind speed at 100 m [m/s]	12.2	7.54
Wind speed at 10 m [m/s]	8.3	5.1
Wind orientation [°]	220	259
Turbulence intensity [%]	13.0	7.75
Turbulence length scale [m]	300	300
Humidity [%]	86	98
Temperature [°C]	5	8
Nebulosity [okta]	2	8
Time	Night	Night

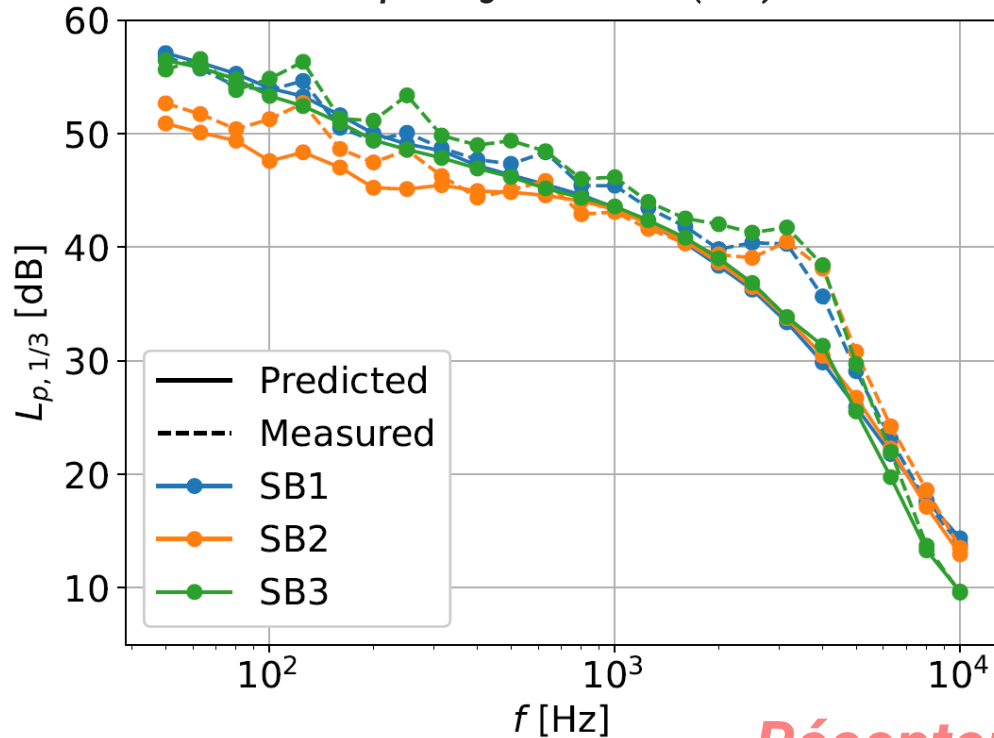
(*) données ENGIE Green avec la collaboration de UMRAE

Résultats

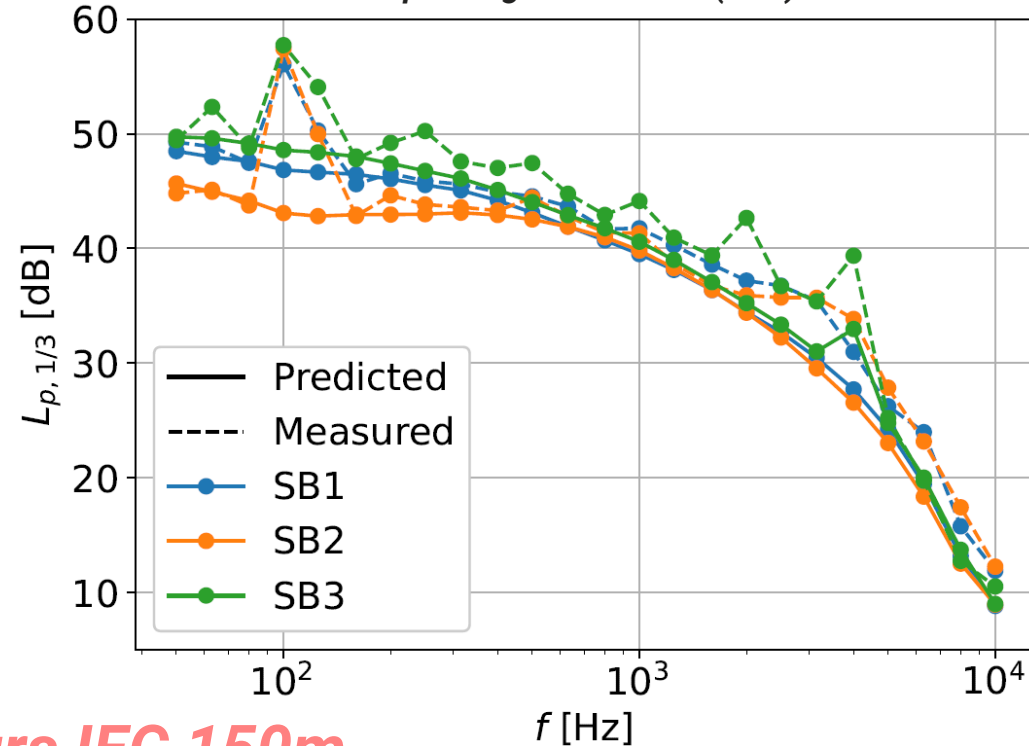
Mesures / Calculs points IEC (150 m)



Operating Conditions 1 (OC1)



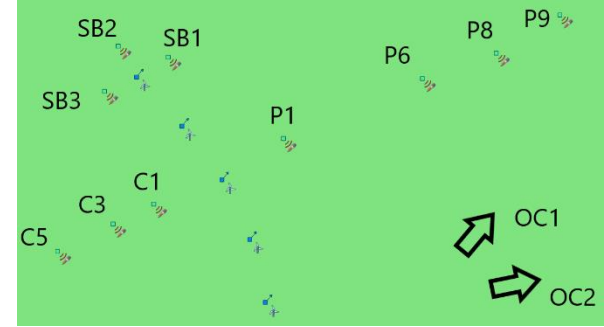
Operating Conditions 2 (OC2)



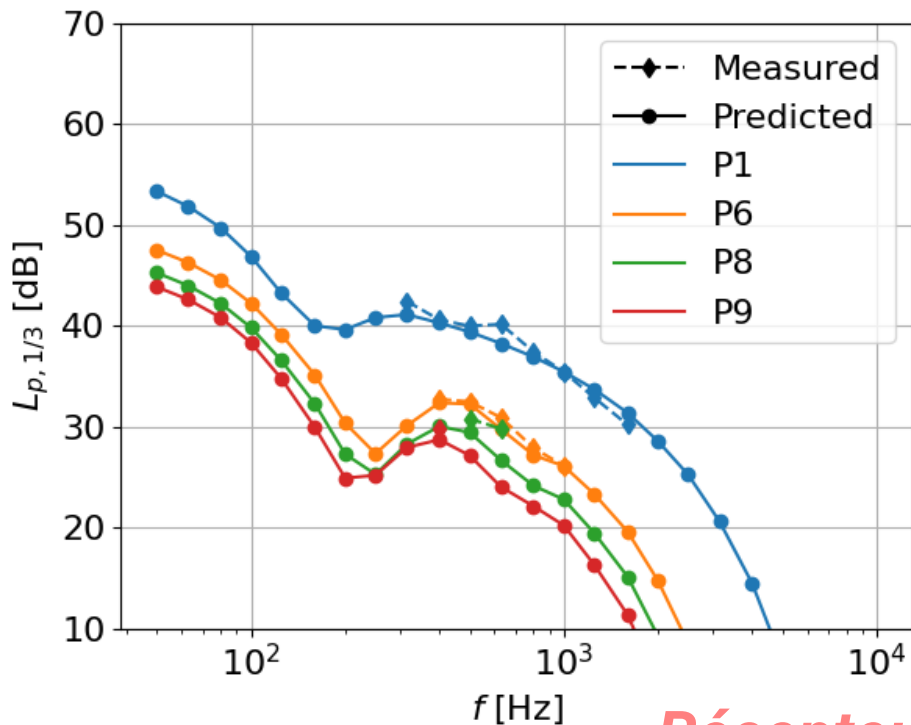
Récepteurs IEC 150m

Résultats

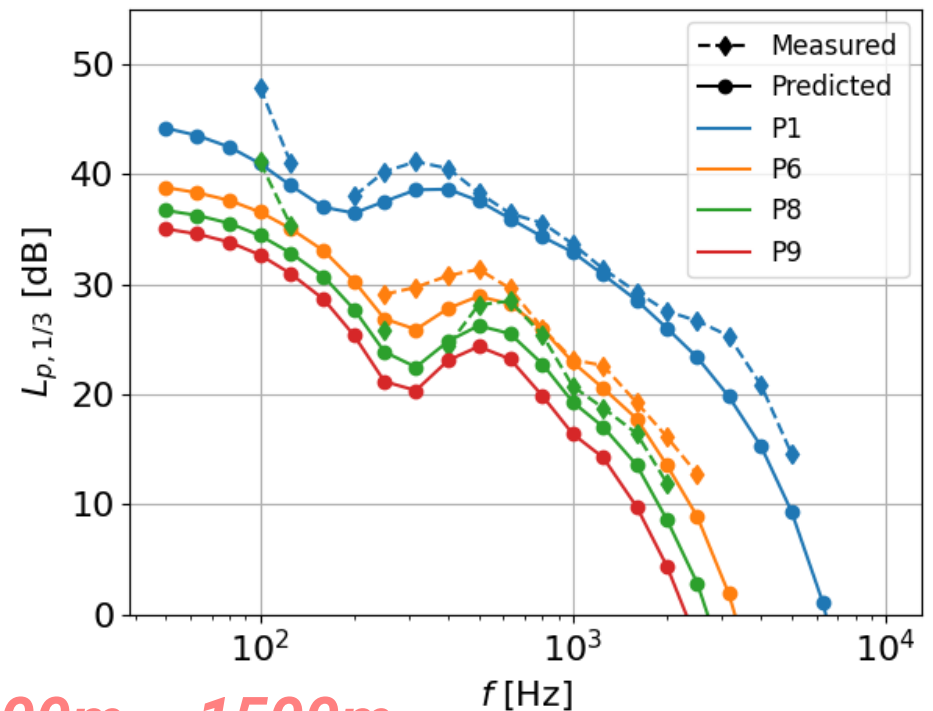
Mesures / Calculs points éloignés



Operating Conditions 1 (OC1)



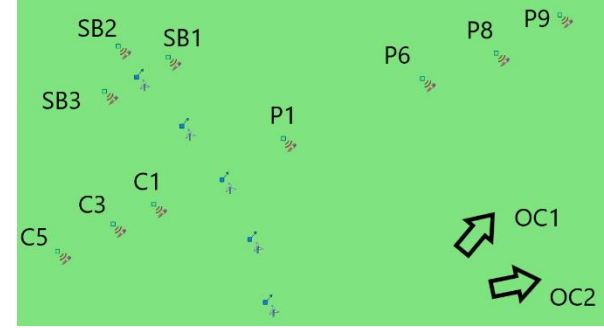
Operating Conditions 2 (OC2)



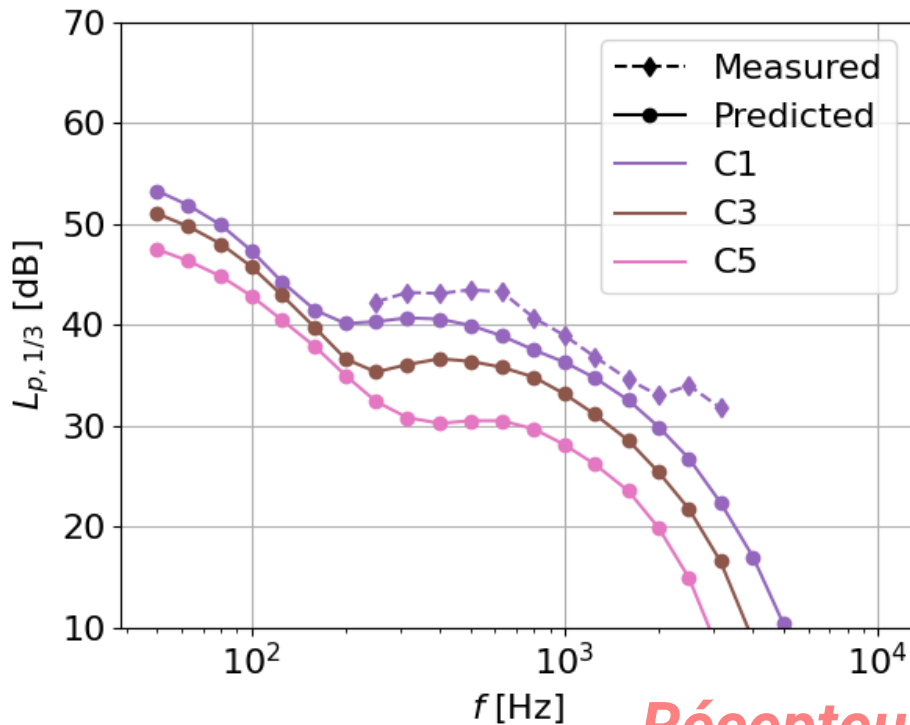
Récepteurs 300m – 1500m

Résultats

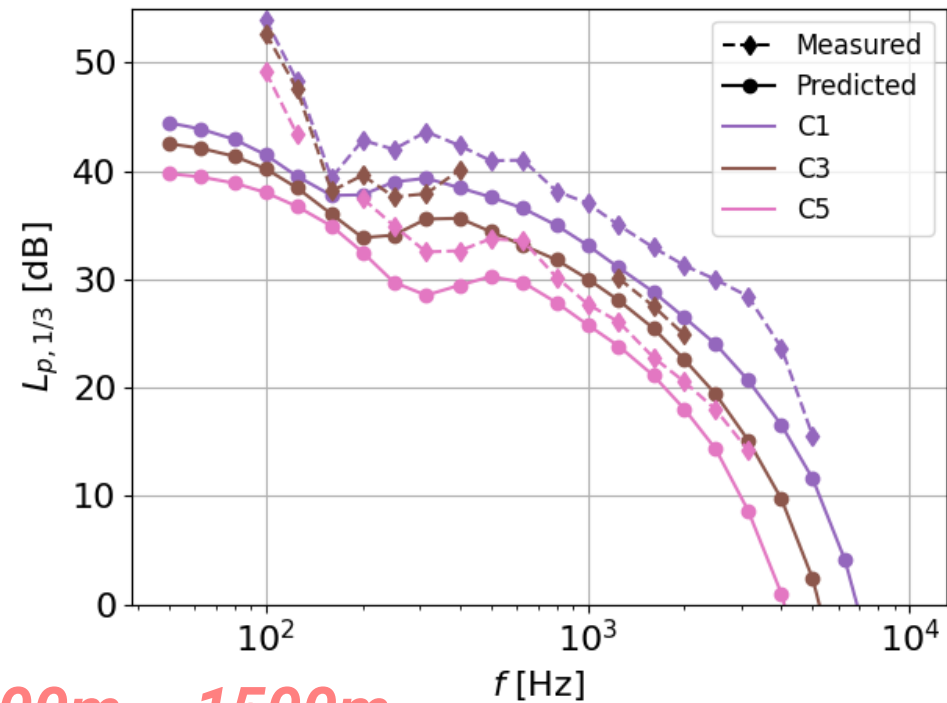
Mesures / Calculs points éloignés



Operating Conditions 1 (OC1)



Operating Conditions 2 (OC2)

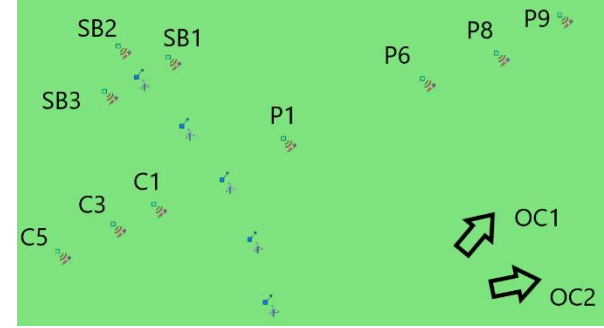


Récepteurs 300m – 1500m

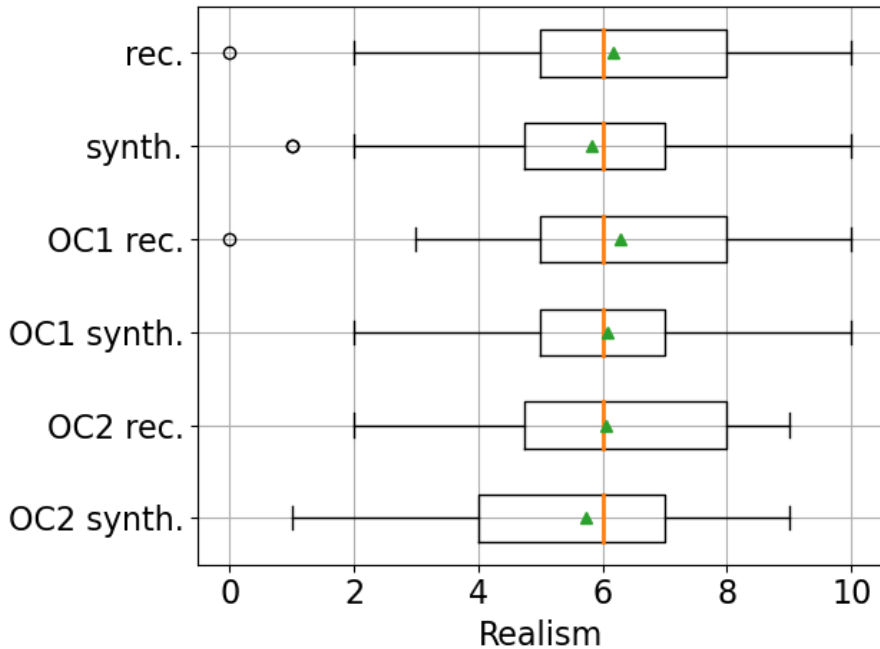
Résultats

Tests d'écoute – Points ICE

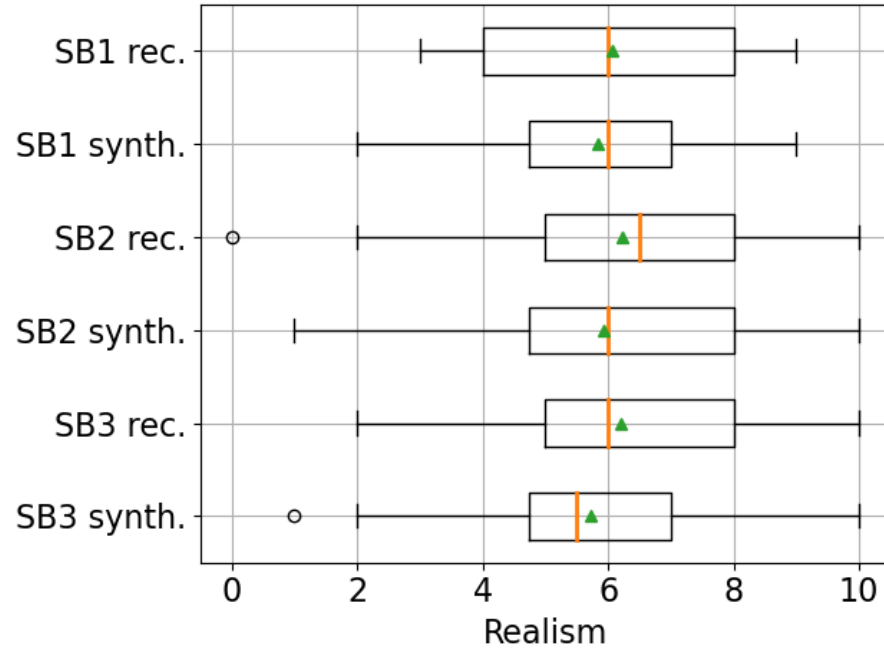
- 20 subjects – no experts
- 12 audio samples, ~15 sec
- 2 conditions, 3 receivers, auralized (synth) & recorded (rec)
- Judge realism on a 0 to 10 scale



Overall realism and per operating condition



Realism per receiver



OC1	OC2

Green marker average score
 Orange line median value
 Box 25 to 75% spread
 Bar statistical min and max
 Circle outlier

Calibration 74 dB(A)



MÉTHODE DE PRÉVISION DU BRUIT DES ÉOLIENNES

- Basée sur un **modèle physique** de l'émission des segments de pôle (puissance, directivité)
- Couplage au modèle de propagation Harmonoise
- Calcul rapide des **niveaux de bruits instantanés et moyennés**
- **Auralisation** pour une évaluation de la gêne et la communication aux futurs riverains

PERSPECTIVES

- Poursuivre le travail de validation sur des récepteurs éloignés (> 500 m)
 - Niveaux
 - Réalisme des séquences sonores
- Construction base de données éoliennes
 - Profils de pôle
 - Conditions de fonctionnement



Merci pour votre attention

