WindTUNE: a new tool for modelling wind farm noise uncertainties

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PIBE project (2019-23)

Pibe Prévoir l'Impact du **Bruit des Éoliennes**

Université Gustave Eiffel · RÉPUBLIQUE FRANÇAISE · Cerema · ÉCOLE CENTRALE LYON · ENSTA ParisTech · université PARIS-SACLAY · EDF · DTG · EDF renouvelables

https://www.anr-pibe.com/

I. Noise generation

characterization of dynamic stall noise

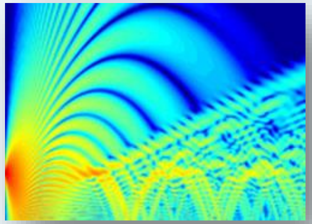
measurement of stall noise *in situ*

modelling of wind turbine noise amplitude modulations

II. Noise prediction

estimation of uncertainties related to sound emission and sound propagation

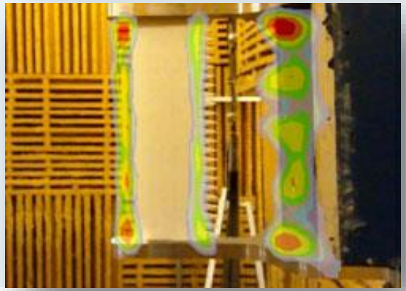
experimental validation of the uncertainty model.



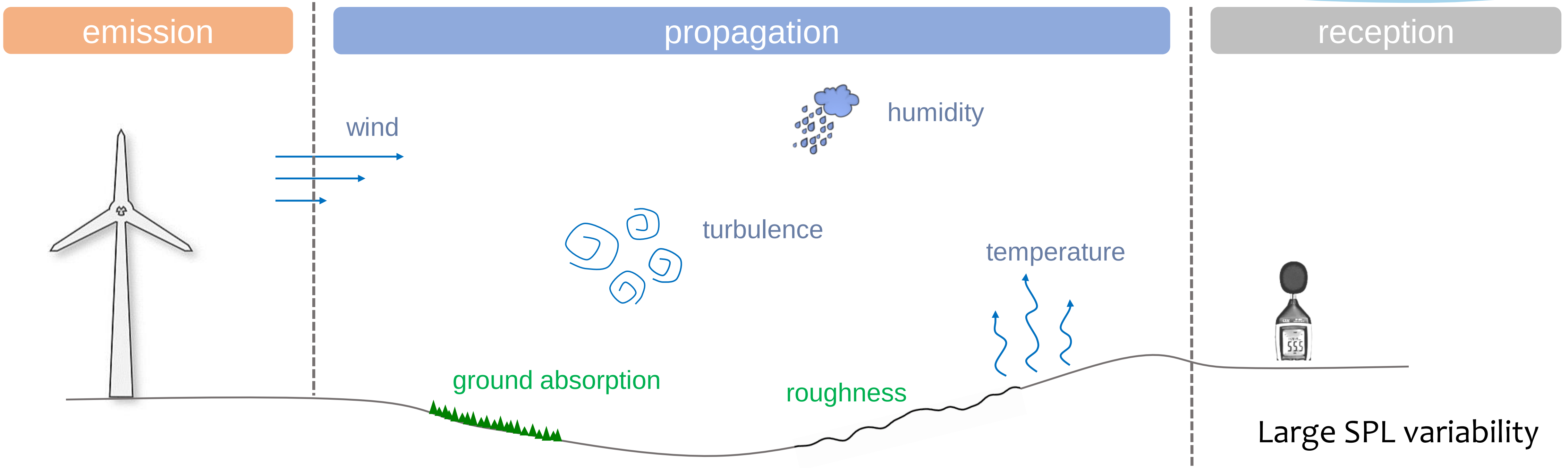
III. Noise reduction

research and design of systems that minimize the generation of aerodynamic noise at the blade level.

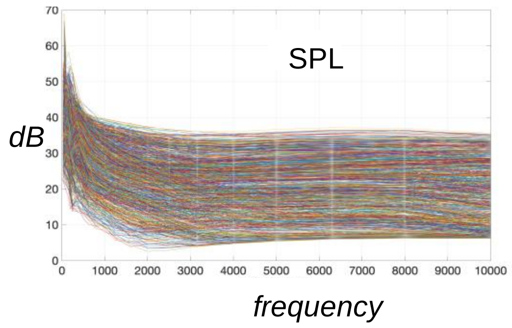
wind tunnel evaluation of these different types of devices



Wind turbine noise uncertainties

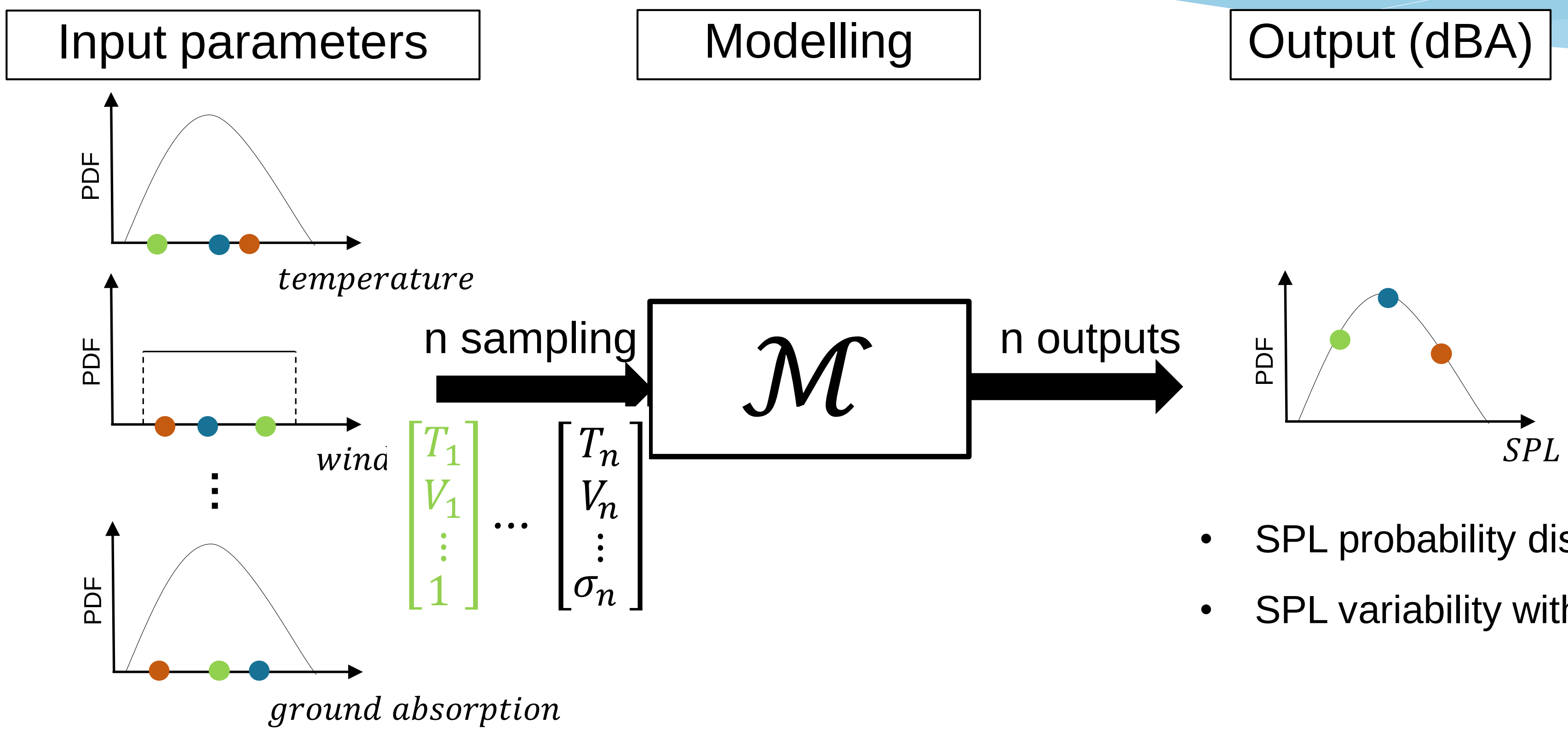


Large SPL variability



$\Delta_{source} \pm \Delta_{meteo} \pm \Delta_{ground}$

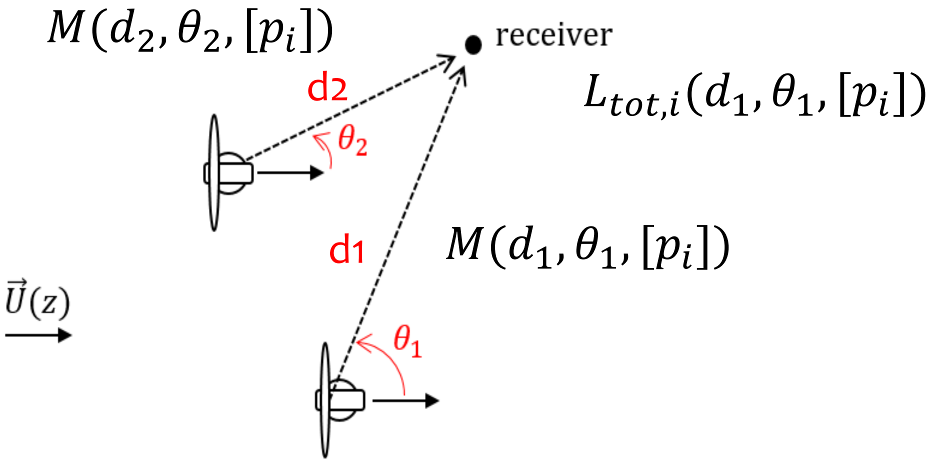
Stochastic estimation of uncertainties



- SPL probability distribution
- SPL variability with distance, frequency, etc…

➔ Monte Carlo or quasi-Monte Carlo methods

Wind farm modeling



For each parameters sample [pi] :

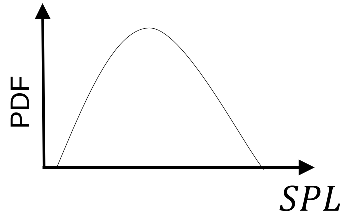
| For each wind turbine j :

| $L_{WT_j} = M(d_j, \theta_j, [p_i])$

$L_{tot,i} = \bigoplus_{j=1:n} L_{WT_j,i}$

-> L_{tot} statistical distribution

-> statistics (mean, stdev, CI …)



<u>High computational cost</u>

→ Need to develop a fast surrogate (or *meta*) model to replace $\mathcal{M}$

Meta-Modelling for 1 WT: summary

→ Need to build a metamodel for downwind AND upwind conditions

Ref. models → Training sample → *Meta*-model → Validation

Emission model

- *Turbulent inflow noise*
- *Trailing edge noise*

Propagation model

Parabolic equation model :

- *Atmospheric effects*
  → power law wind profile
  → *log temperature profile*
  → *atmospheric scattering*

- *Ground effects*
  → *Miki impedance model*
  → *roughness model*

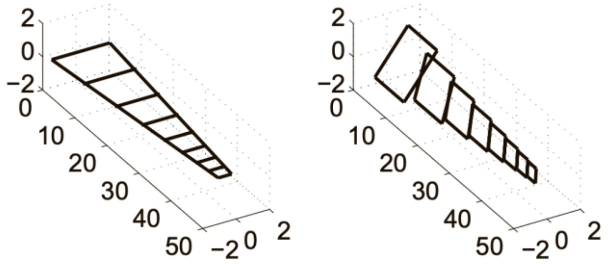
Noise emission & propagation

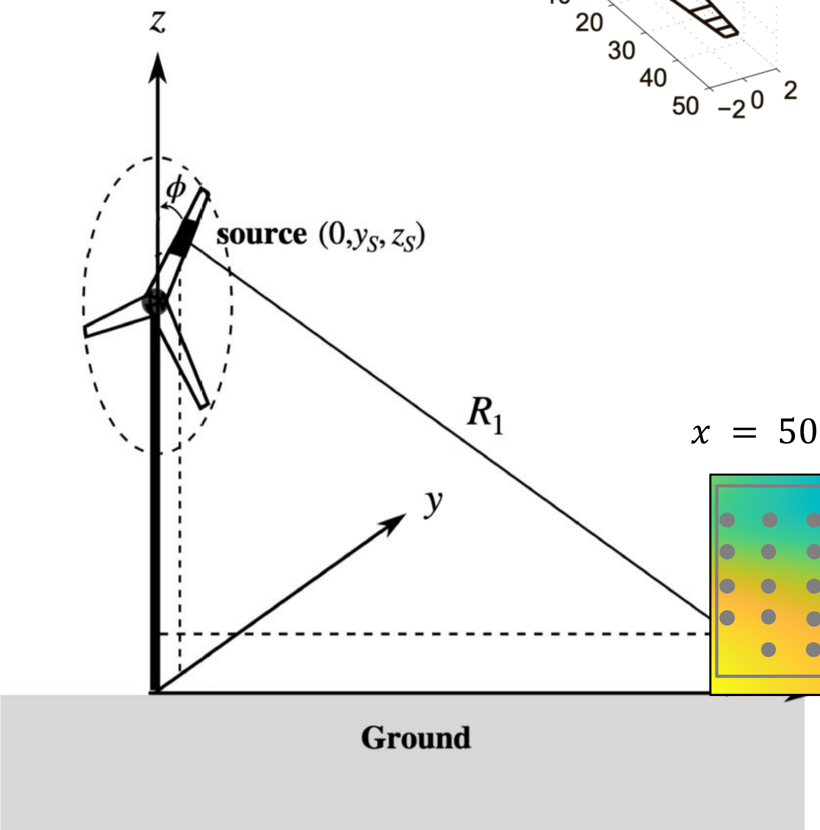
Noise emission [1] : strip theory (divides the blade in $S = 8$ segments)

✓ Complex blade geometry

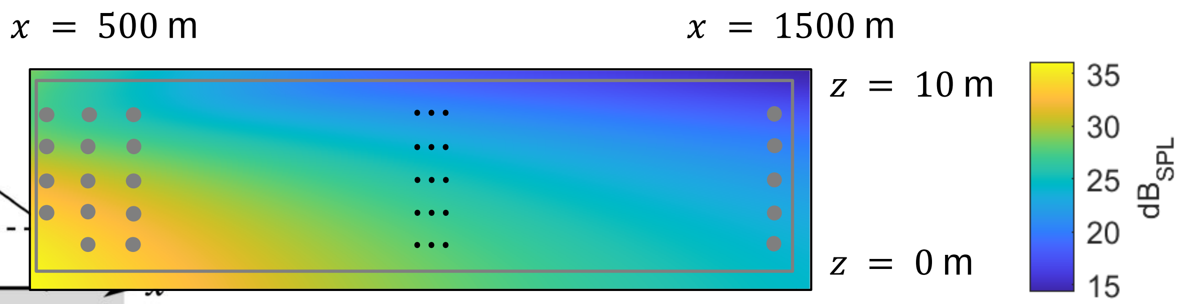
✓ Non uniform incident flow along the blade

→ **Amiet theory: Turbulent inflow noise** & **Trailing edge noise**





$$\mathrm{SPL_{seg}}(\omega,\Phi) = \underbrace{\mathrm{SWL}(\omega,\Phi)}_{\text{emission}} - \underbrace{10\log 4\pi R_1^2}_{\text{geo. spreading}} + \underbrace{\Delta L(\omega,\Phi) - \alpha(\omega)R_1}_{\text{propagation effects}}$$



[1] Cotté, B. (2019). Extended source models for wind turbine noise propagation. The Journal of the Acoustical Society of America, 145(3):1363–1371.

Modelling: atmospheric scattering

The WAPE can take into account turbulence by perturbing refractive index, but the computational cost is too high.

We choose to use *Harmonoise* technique, that corrects ΔL with a scattering contribution.

$$\Delta L = 10 \log_{10}\left(10^{\frac{\mathrm{SPL_{noscatter}}}{10}} + 10^{\frac{\mathrm{SPL_{scatter}}}{10}}\right),$$

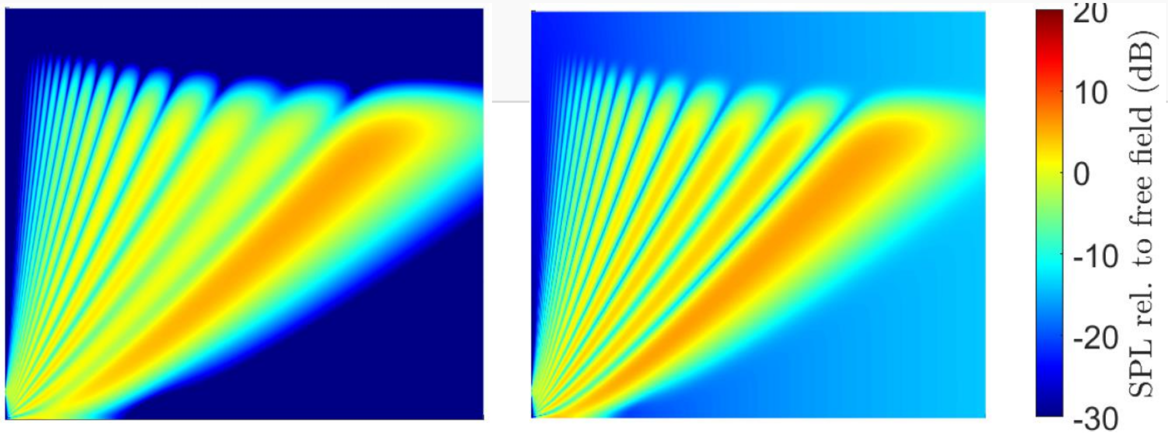
$$\mathrm{SPL_{scatter}} = 25 + 10\log_{10}\gamma_T + 3\log_{10}\frac{\omega}{1000} + \log_{10}\frac{r}{100},$$

Where $\omega = 2\pi f$,

r is the source receiver distance

γ_T is the turbulence strength

Example:



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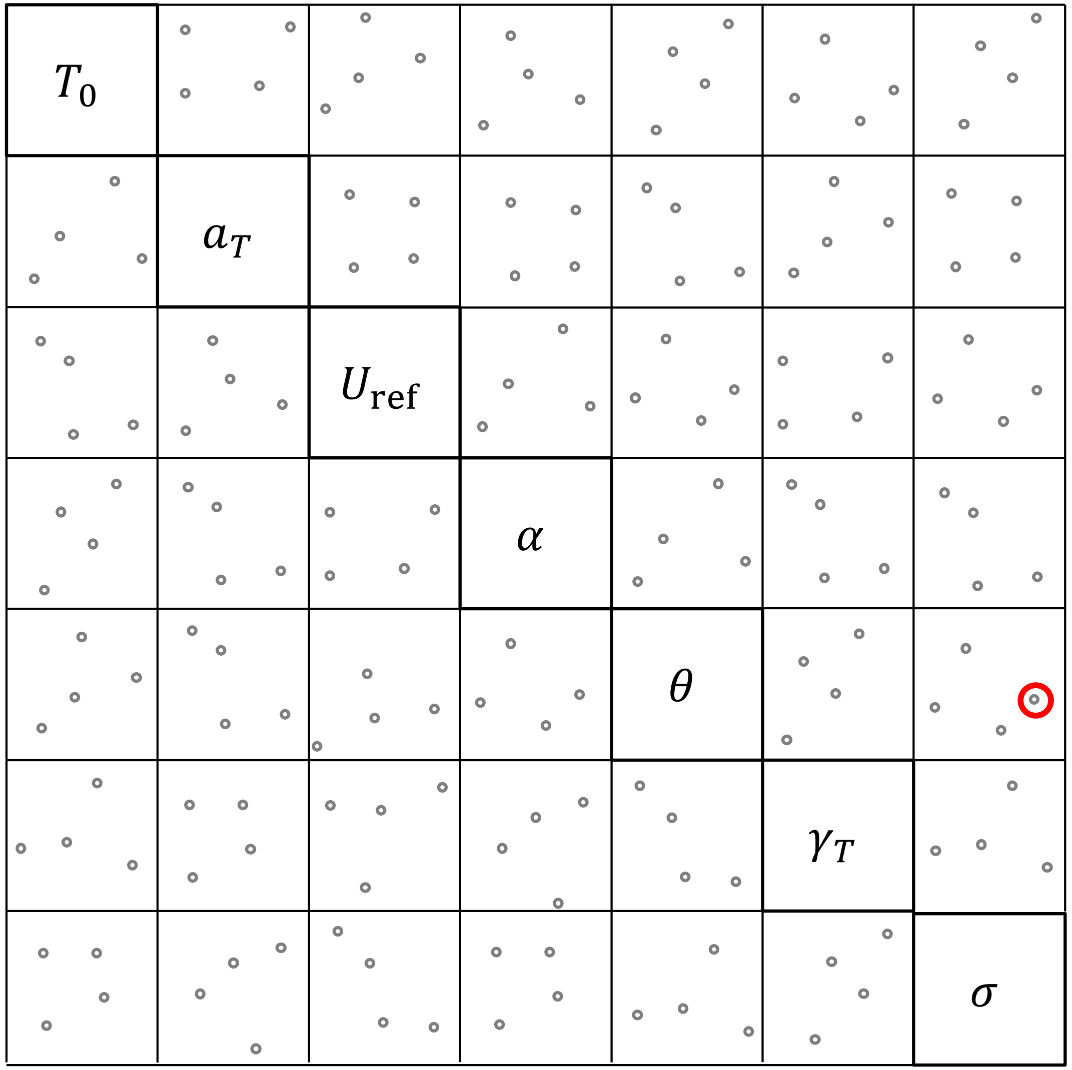
Super-computer
- *1000 training maps per frequency*
- 14 frequencies with $f \in [50\,;1000]\ Hz$

$\approx 3\ weeks\ calculations$

Training sample

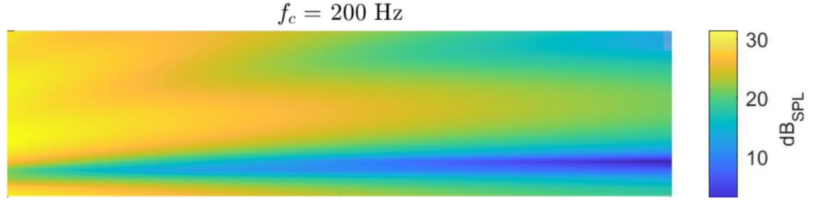
7D Space



→ 1000 x 14 maps (14/freq)

$$f = 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000 \text{ Hz}$$

Parameters	Description	Value
σ (kN·s·m^{-4})	airflow resistivity	$\in [50; 5000]$
l_c (m)	correlation length of roughness	0.5
σ_h (m)	standard deviation of roughness	0.025
h_r (%)	air humidity	80
T_0 (°C)	surface atmospheric temperature	$\in [-20; 40]$
a_T (K·m^{-1})	thermic coefficient	$\in [-0.5; 0.25]$
α	wind shear exponent	$\in [0.05; 0.6]$
U_{ref} (m·s^{-1})	reference wind speed	$\in [3; 13]$
θ (°)	propagation angle	$\in [0; 180]$
γ_T	turbulence strength	$\in [10^{-7}; 10^{-4}]$



! Output is not a scalar: 1 map = 100020 receivers

⇒ Need to reduce output dimension before emulation

⇒ Express each map into reduced subspace: PCA

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$\approx$ *3 weeks of duration*

***Meta*-model**

Principal Component Analysis

Kriging interpolation

Validation

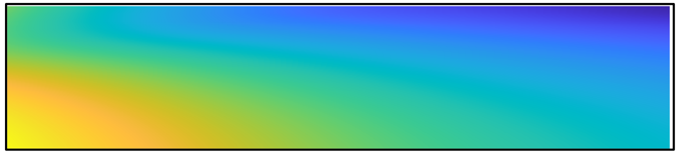
Meta-modelling

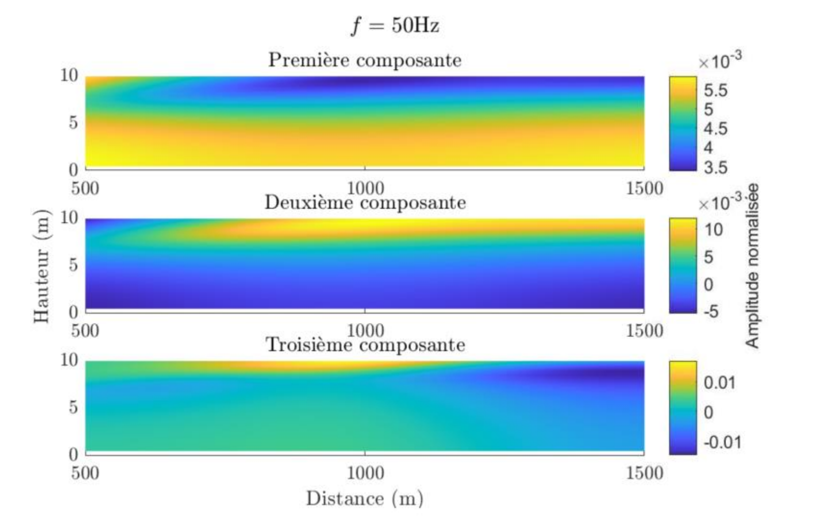
Reduce the output dimension:

→ PCA of the training sample (1000 maps).

→ Each noise map $\mathbf{y}$ can be expressed as a sum of principal component $\mathbf{\Psi}$:

$$\mathbf{y} \in \mathbb{R}^{100020} \backsimeq \hat{a}_1 \mathbf{\Psi}_1 + \hat{a}_2 \mathbf{\Psi}_2 + \cdots \hat{a}_{15} \mathbf{\Psi}_{15}$$





$\mathbf{\Psi}_1$

$\mathbf{\Psi}_2$

$\mathbf{\Psi}_3$

⋮

$\mathbf{\Psi}_{15}$

Fast interpolation:

→ For each new simulation, we only need to compute the weights $\hat{a}_n$

→ We use kriging interpolation technique to do so.

More details about the methodology in: Kayser, B., Gauvreau, B., Ecotière, D., and V., Mallet (2022). *Wind turbine noise uncertainty quantification for downwind conditions using metamodeling.* The Journal of the Acoustical Society of America, 151(1): 390-401

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***Meta*-model**

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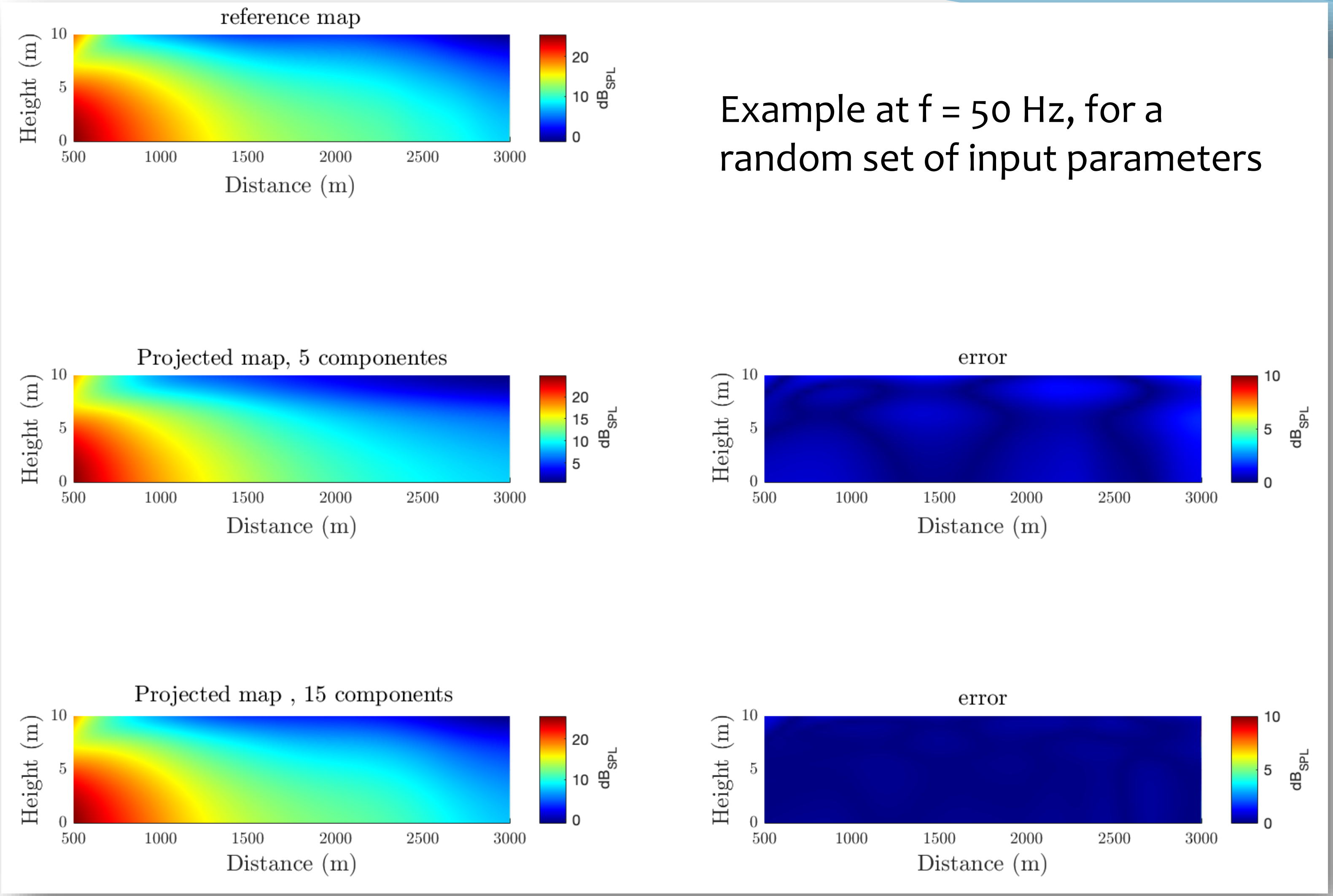
Kriging interpolation

Validation

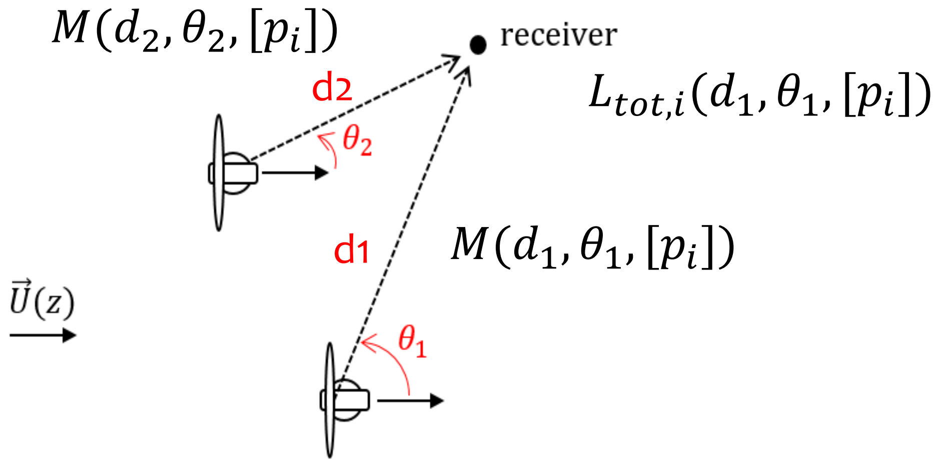
Comparison with initial model

Validation

Example at f = 50 Hz, for a random set of input parameters



Wind farm modeling



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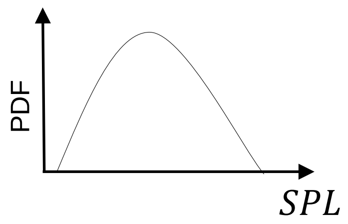
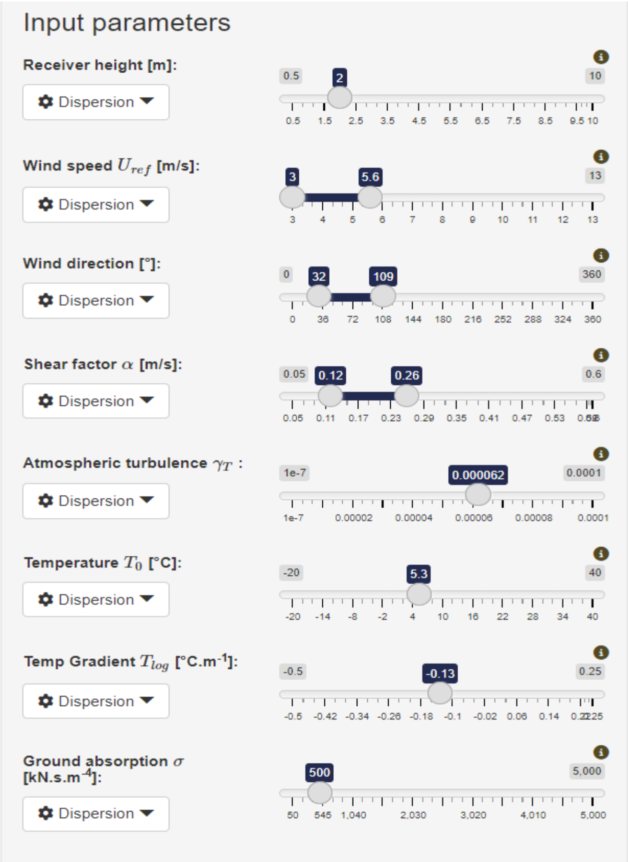
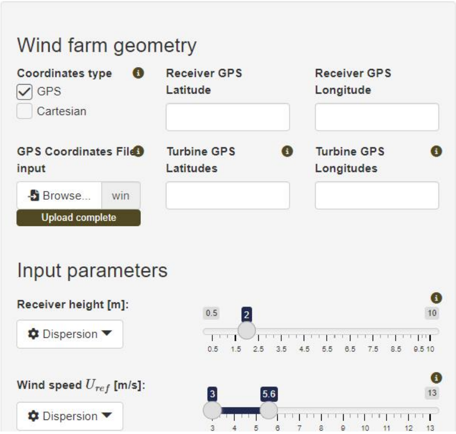
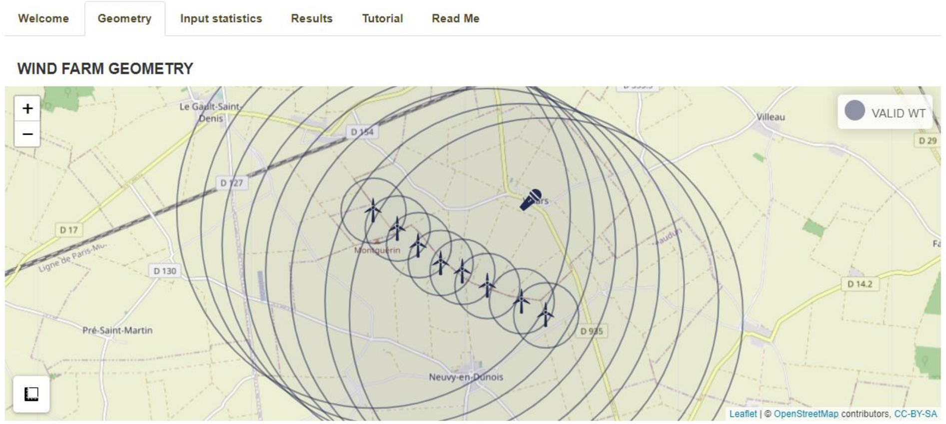


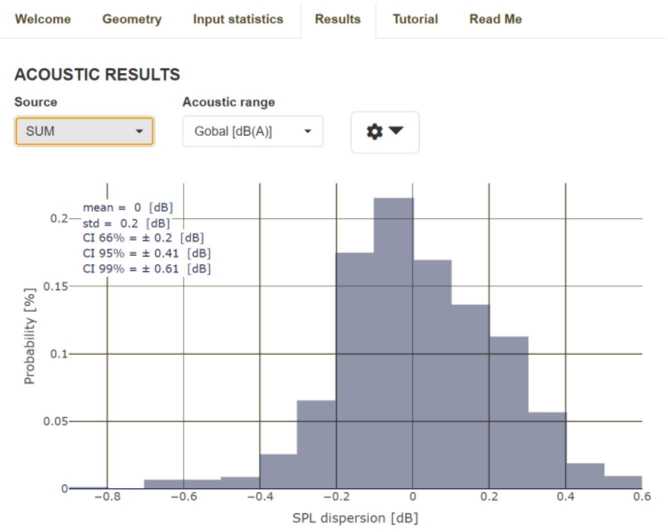
Online free app (R shiny)

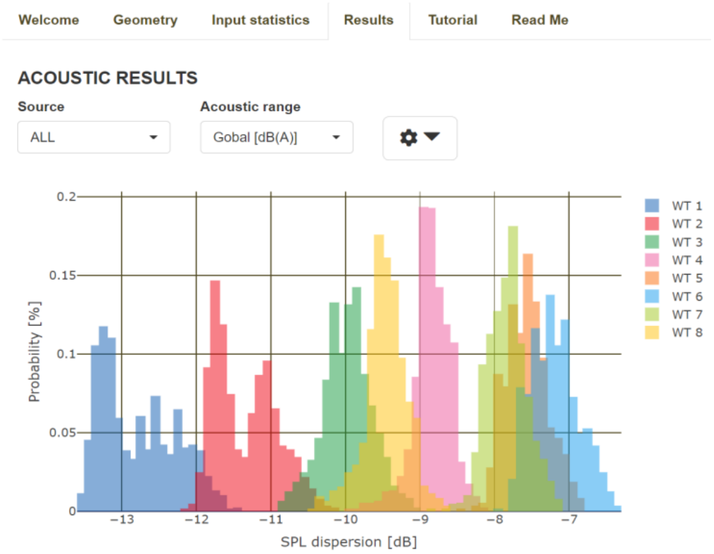


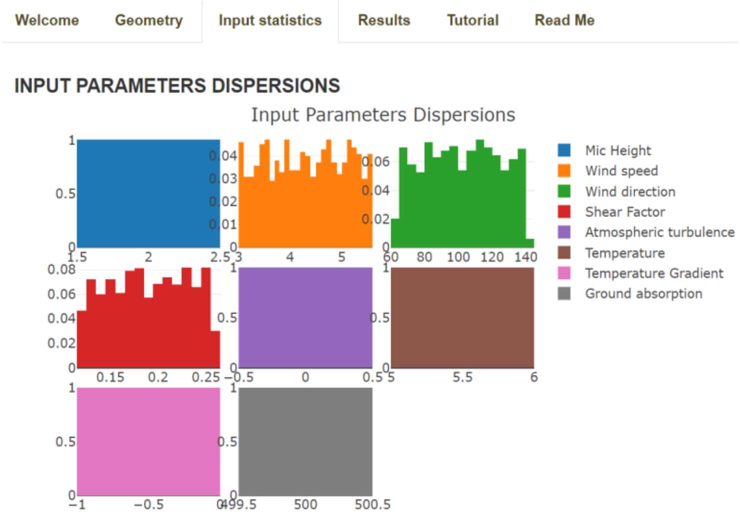




- Outputs
  - Sound level distributions







  - Statistics properties (mean, st deviation, CI…)

Outlooks

- Validation against field measurements
  - Experimental data: 400 days long-term campaign [Ecotière *et al*, Internoise 2022]

    -> Forum Acusticum 2024, Torino [Bianchetti *et al*, Forum Acusticum 2023]

- WindTUNE online (free access) at the beginning of 2024
  - anr-pibe.com/projet/productions
  - umrae.fr/productions/logiciels-applications-et-methodes-de-calcul

Thank you for your attention

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