Modèles de source étendue pour la propagation à grande distance du bruit des éoliennes

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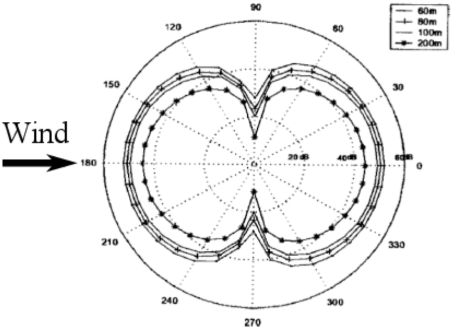
Journées Techniques Acoustique et Vibrations, 15-16 mai 2019, Strasbourg

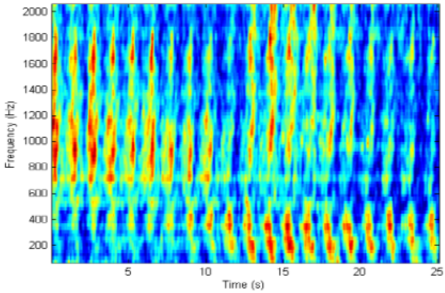
Motivation

Need for accurate wind turbine noise predictions at long ranges



Model predictions of Zhu *et al.* (2005)

- spectra and directivity
- amplitude modulation
- meteorological effects

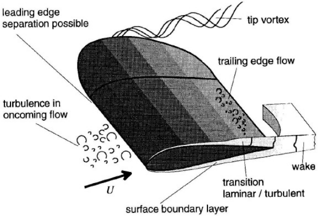


Wind turbine noise measurement (Smith *et al.* (2012) - www.dickbowdler.co.uk)

Need accurate models for the aeroacoustic sources and the atmospheric propagation effects

Aeroacoustic source models

- semi-empirical models (e.g. BPM for self-noise)
- analytical models : Amiet, Howe, Ffowcs Williams Hawkings, ...
- numerical simulations : hybrid approaches (e.g. TNO-Blake+RANS or LES+acoustic analogy)



Wagner (1996)

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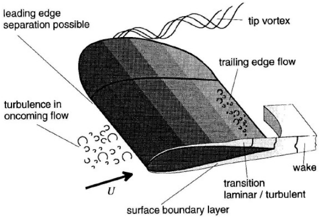
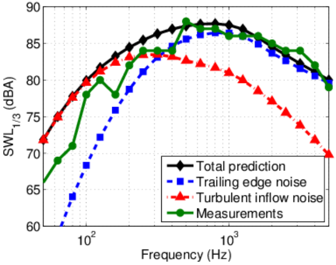


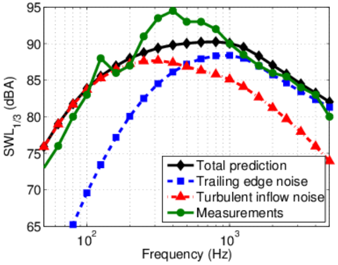
Wagner (1996)

Results of Yuan Tian PhD (2016) - Tian and Cotté (Acta Acustica 2016)

$U_{ref} = 6\,\mathrm{m/s}$



$U_{ref} = 8\,\mathrm{m/s}$



Sound propagation models in an inhomogeneous atmosphere

- geometric approximation (ray-tracing)
- parabolic approximation (scalar PE or vector PE)
- FDTD solution of the linearized Euler equations

Point source approximation

$$L_p(f) = L_W(f) - 10\log_{10}(4\pi R_1^2) + \Delta L(f) - \alpha(f) R_1$$

Prospathopoulos and Voutsinas (2005)

Point source assumption questionable in the context of wind turbine noise

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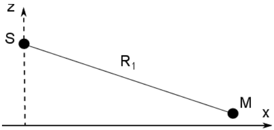

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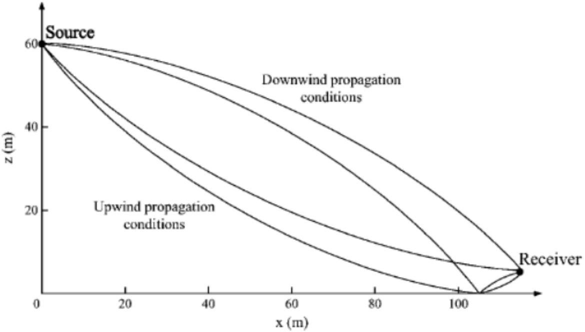

Fig. 12 Downward and upward refraction of eigenrays for downwind and up

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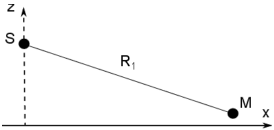

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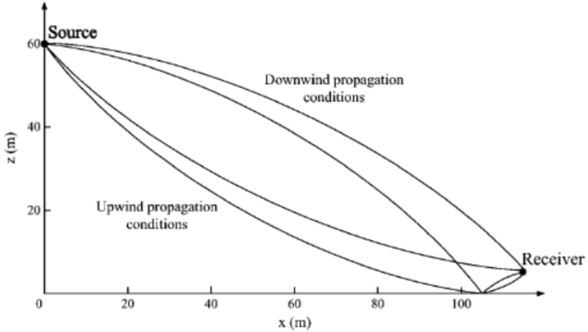

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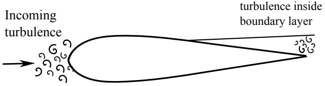
Outline of the presentation

GOAL

Propose methods to couple or chain an aeroacoustic source model based on Amiet's theory and a parabolic equation code for wind turbine long range propagation in an inhomogeneous atmosphere

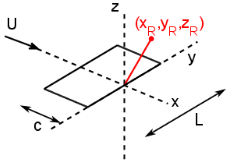
1. Description of the models and of the coupling/chaining methods
2. Validation of the methods in homogeneous conditions
3. Results in a neutrally stratified atmosphere
4. Some perspectives

Amiet theory for a fixed airfoil



PSD of acoustic pressure calculated for $L/c > 3$

$$S_{pp}^{F}(\mathbf{x_R}, \omega) = A(\mathbf{x_R}, \omega)\Pi(\mathbf{x_R}, \omega)\,|\mathcal{I}(\mathbf{x_R}, \omega)|^2$$



$\Pi(\mathbf{x_R}, \omega)$: spectrum of turbulent fluctuations
$|\mathcal{I}(\mathbf{x_R}, \omega)|^2$: aeroacoustic transfer function that contains the source directivity

Trailing edge noise directivity :

- $f = 16\,\text{Hz}$ ($kc = 0.2$)
- $f = 50\,Hz (kc = 0.7)$
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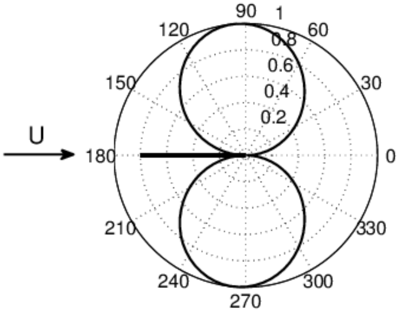

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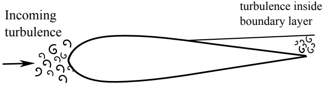

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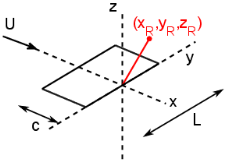

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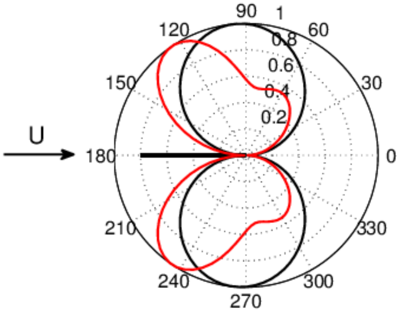

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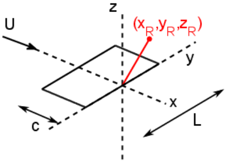

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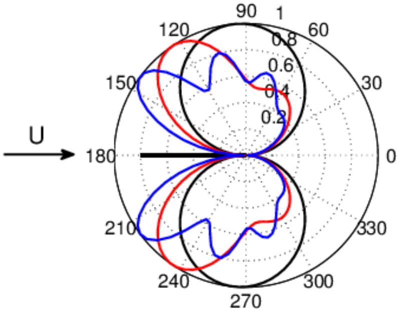

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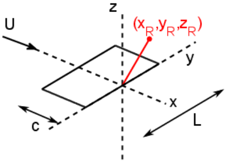

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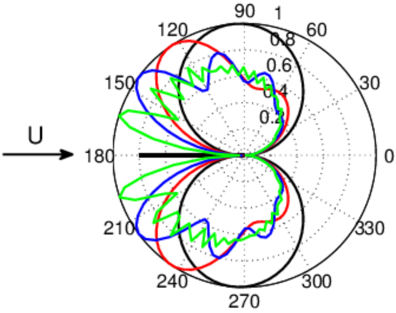


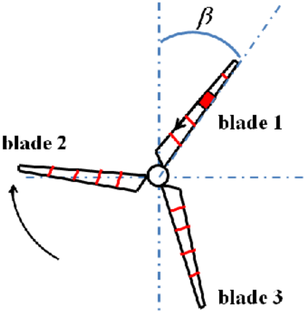
Application to a rotating blade

- each blade is divided into N_s segments (strip theory)
- For each segment at each angular position β :
  - contribution of segment at the receiver calculated using Amiet theory
  - correction due due to Doppler effect

$$S_{pp}^{R}(\mathbf{x_R^T}, \omega, \beta) = \frac{\omega_e}{\omega} S_{pp}^{F}(\mathbf{x_R^B}, \omega_e, \beta)$$

    $\mathbf{x_R^T}$: receiver coordinates in the wind turbine reference system
    $\mathbf{x_R^B}$: receiver coordinates in the blade reference system

  - logarithmic summation



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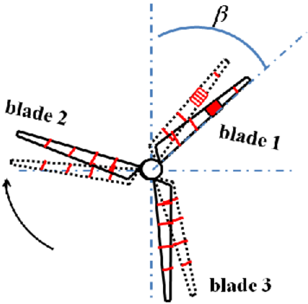
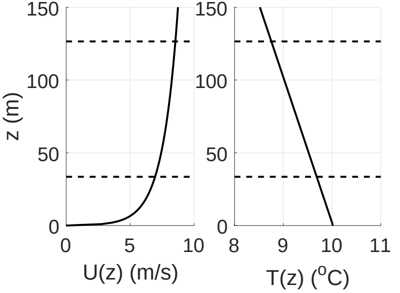


Wind turbine propagation effects

Assumptions :

- flat and homogeneous ground
- wake effect neglected
- simple wind speed and temperature profiles from Monin-Obukhov similarity theory for a neutral atmosphere :

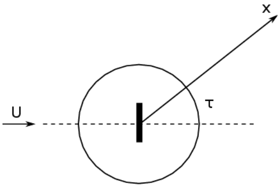


$$\bar{u}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

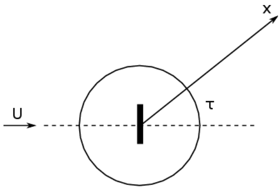
$$\bar{T}(z) = T_0 + \alpha_0 z \quad \text{with} \quad \alpha_0 \approx -0.01\,\text{K/m}$$

Effective sound speed approximation

$$c_{eff}(z) = c(z) + U(z)\cos\tau = \sqrt{\gamma r T(z)} + U(z)\cos\tau$$



Acoustic propagation in the parabolic approximation



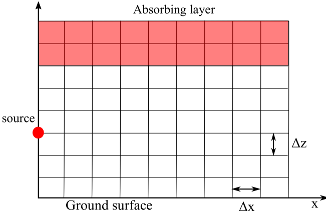
- axisymmetric approximation of the inhomogeneous Helmholtz equation with $n(z) = c_0/c_{eff}(z)$:

$$\left[\frac{\partial^2}{\partial x^2} + \left(\frac{\partial}{\partial z^2} + k_0^2 n(z)^2\right)\right] q_c = 0 \quad \text{with} \quad q_c = p_c\sqrt{x}$$

- decoupling waves propagating towards $+x$ and $-x$:

$$\left(\frac{\partial}{\partial x} - \gamma i \mathcal{Q}\right) q_\gamma = 0 \quad \text{with} \quad \mathcal{Q} = \left(n(z)^2 + \frac{1}{k_0^2}\frac{\partial}{\partial z^2}\right)^{1/2}$$

$\gamma = +1$: forward-propagation
$\gamma = -1$: back-propagation



- approximation of operator $\mathcal{Q}$: use the Split-Step Padé (N,N) method of Collins (1993) to increase the angular validity and Δx

  $\Rightarrow \Delta x \leq 2\lambda$ with Split-Step Padé (2,2) method

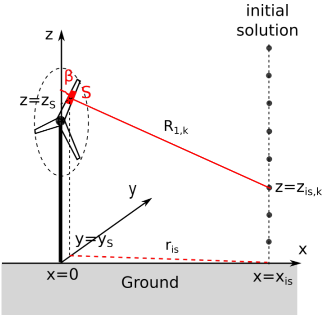
Method 1 : coupling based on the backpropagation method

For each segment and each angular positions :

- numerical starter at $x = 0$ obtained by backpropagating ($\gamma = -1$) a known initial solution from $x = x_{is}$ in homogeneous conditions (Collins, 1991 ; Dragna, 2011)
- initial solution at $x = x_{is}$ obtained using Amiet's model over a rigid ground :

$$q_c(z_{is,k}) = \sqrt{S_{pp}^R(\mathbf{x_R^T}, \omega, \beta)}\sqrt{x_S}\left(e^{ik_0 R_{1,k}} + \frac{R_{1,k}}{R_{2,k}} e^{ik_0 R_{2,k}}\right)$$

- strictly valid only at the receiver at $x = x_R$
- $N_s \times N_\beta$ PE calculations per frequency and per propagation direction



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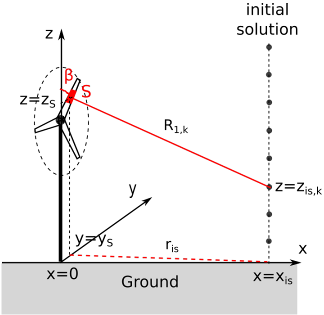

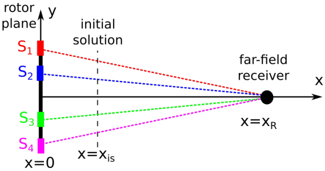

Method 2 : chaining using moving monopoles model

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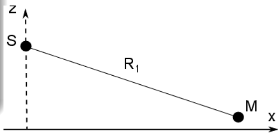

- angle-dependent sound power level $L_W(f,\beta)$ obtained from Amiet model
- relative SPL $\Delta L(f)$ obtained from a set of PE calculations at N_h different heights

  $\Rightarrow$ closest point interpolation based on the segment height at angle β
- N_h PE calculations per frequency and per propagation direction

example with 6 segments and $N_h = 5$

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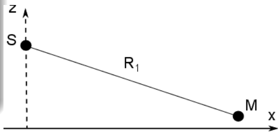

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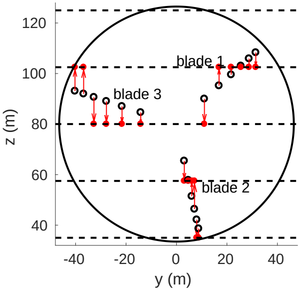

example with 6 segments and $N_h = 5$

Validation test cases

- 2.3 MW wind turbine with tower height 80 m
- 3 blades of length 45 m cut into $N_s = 8$ segments (Tian and Cotté, Acta Acustica 2016)
- variable porosity impedance model for a natural ground (Dragna *et al.*, JASA 2015)
- test-case 1 : only trailing edge noise and homogeneous conditions ($c(z) = c_0$)
  $\Rightarrow$ analytical solution based on image source available
- test-case 2 : both source mechanisms and Monin-Obukhov profiles of $T(z)$ and $U(z)$ in a neutral atmosphere

Calculation parameters :

- third octave band between 100 Hz and 2000 Hz (49 frequencies)
- domain : 1200 m along x and 300 m along z
- 30 angular positions β
- method 1 : initial solution calculated at $x_{is} = 100$ m
- method 2 : N_h varied between 1 and 19

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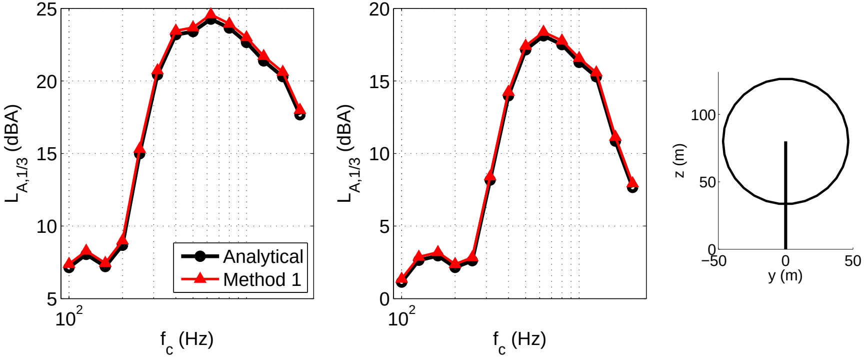
Third octave band spectra in homogeneous conditions

spectra at $z = 2\,\mathrm{m}$ and at $x = 500\,\mathrm{m}$ or $x = 1000\,\mathrm{m}$ downwind ($\tau = 0^o$)



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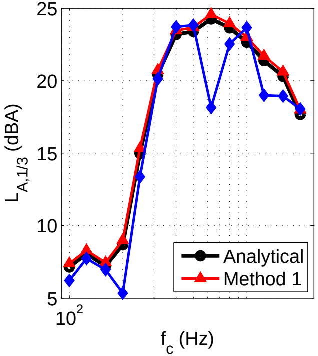

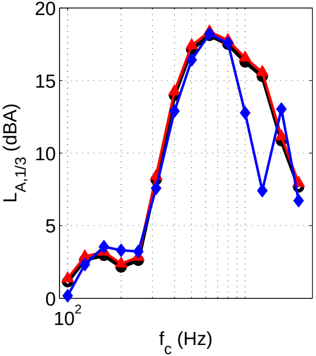

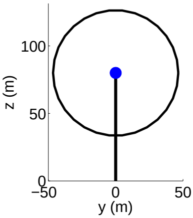

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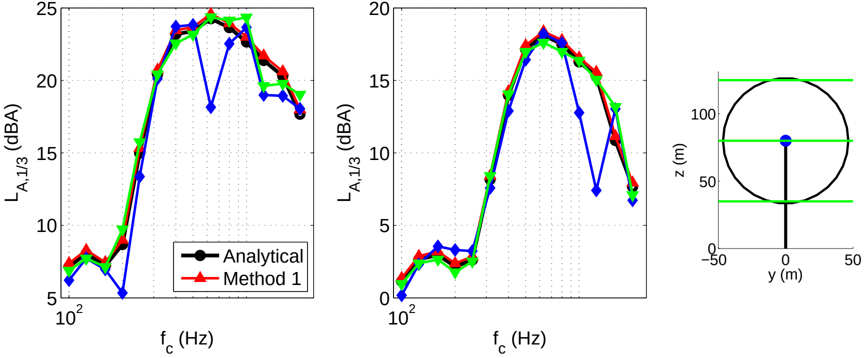

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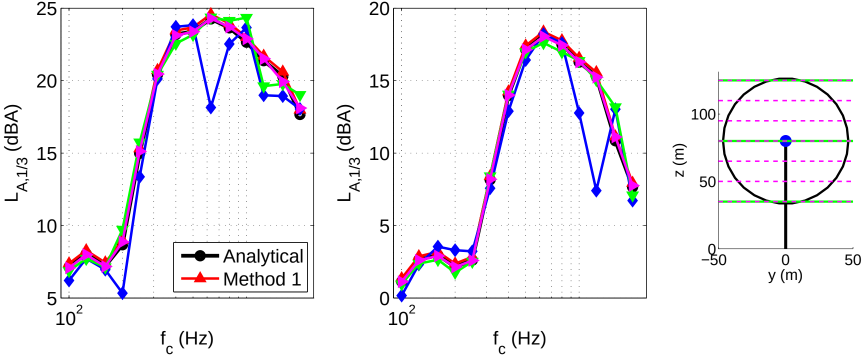
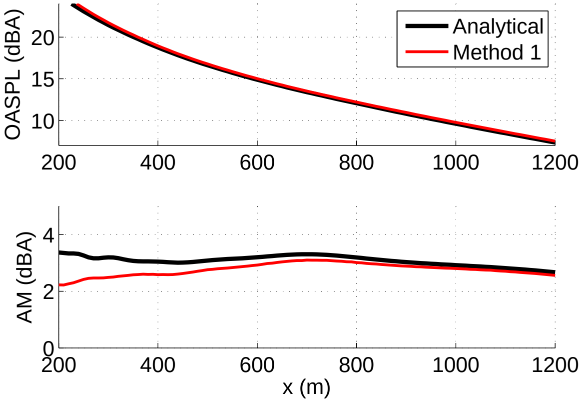


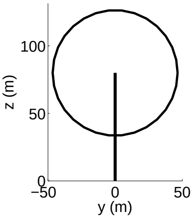
Overall SPL and amplitude modulation

Overall SPL averaged over one rotation (OASPL)

Amplitude Modulation : AM $= \max_{\beta} \text{OASPL}(\beta) - \min_{\beta} \text{OASPL}(\beta)$

$\boxed{\text{OASPL and AM at } z = 2\,\text{m crosswind } (\tau = 90^o)}$





Overall SPL and amplitude modulation

Overall SPL averaged over one rotation (OASPL)

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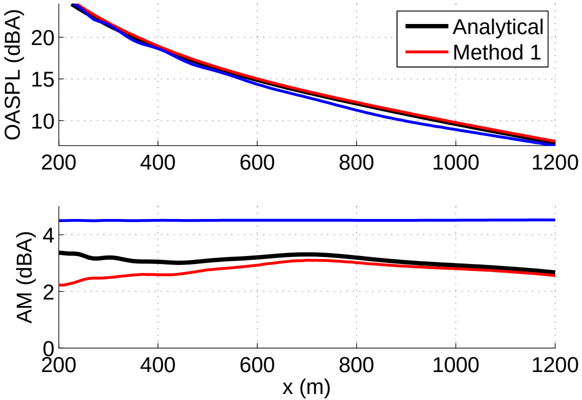

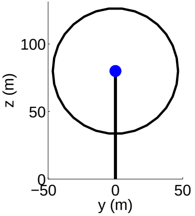

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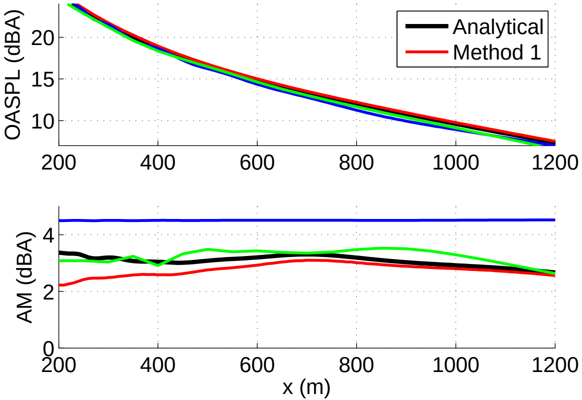

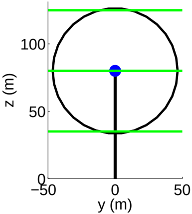

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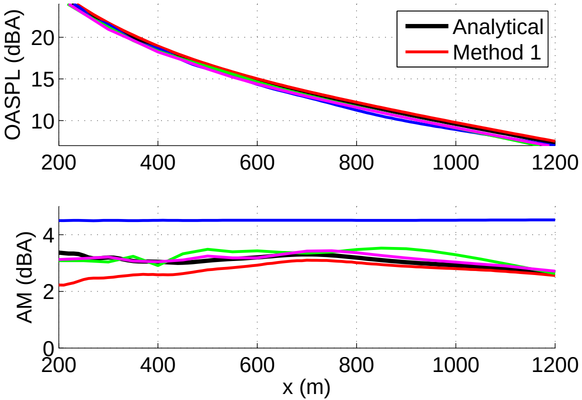
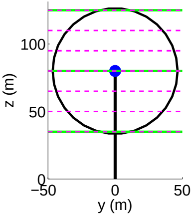
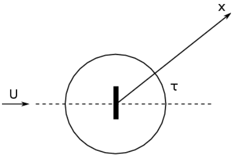
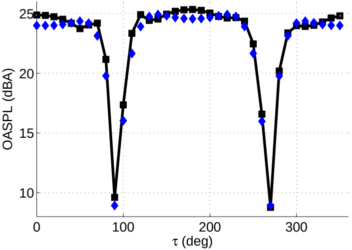


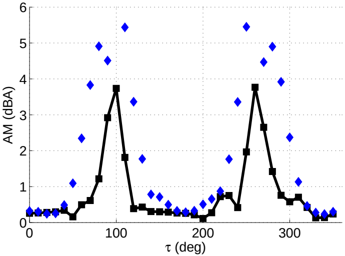


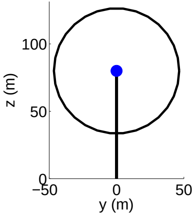
Horizontal directivity of OASPL and AM in homogeneous conditions

$\boxed{\text{Directivity at } x = 1000\,\text{m and } z = 2\,\text{m}}$









- Large errors with point source approximation
- Excellent results with $N_h = 7$ heights
  $\Rightarrow$ CPU time is $N_s N_\beta / N_h \approx 34$ times smaller compared to method 1 !

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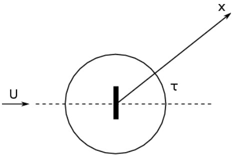

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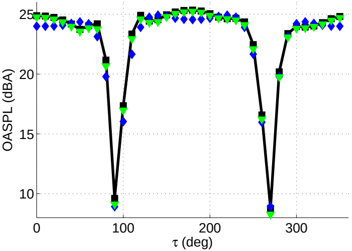

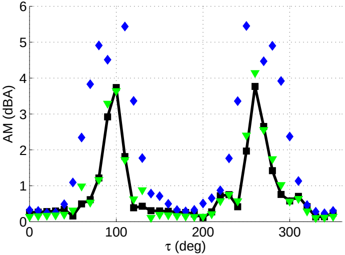

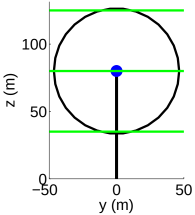

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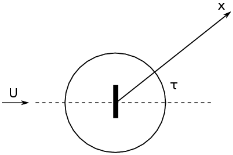

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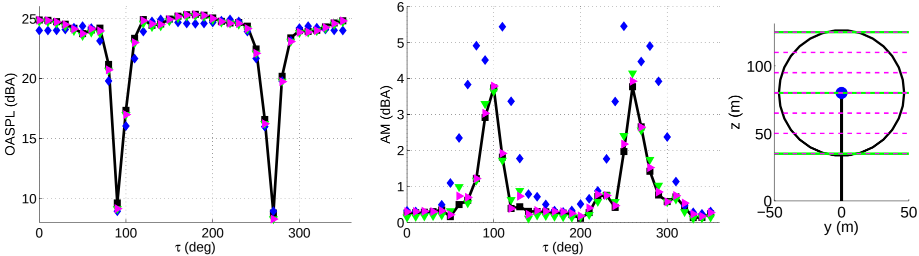

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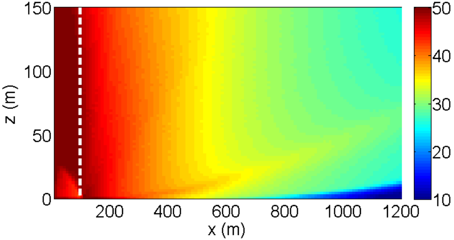
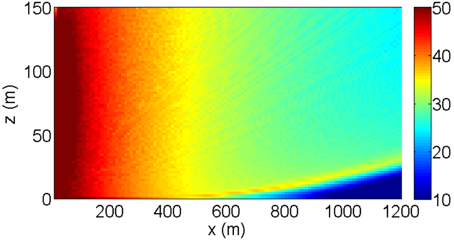
Pressure maps in a neutral atmosphere

Difference between extended source model (method 1) and point source approximation for $\tau = 180^o$ (upward-refraction conditions)

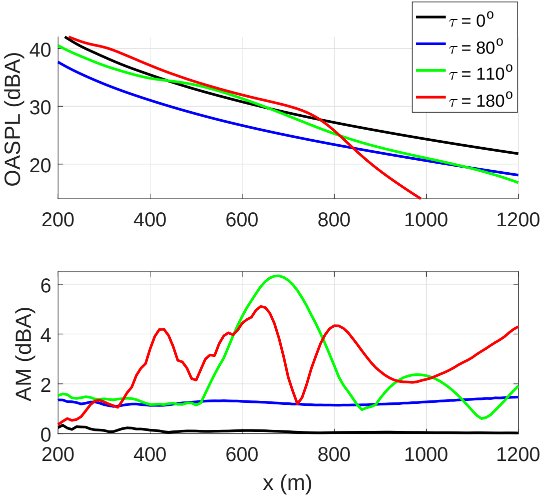
Extended source

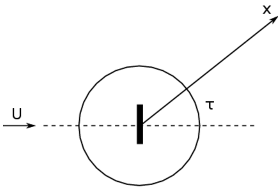


Point source



Comparison of both methods in a neutral atmosphere





Solid lines : method 1

Dashed lines : point source approximation

Crosses : method 2 with 10 heights

Crosses : method 2 with 19 heights

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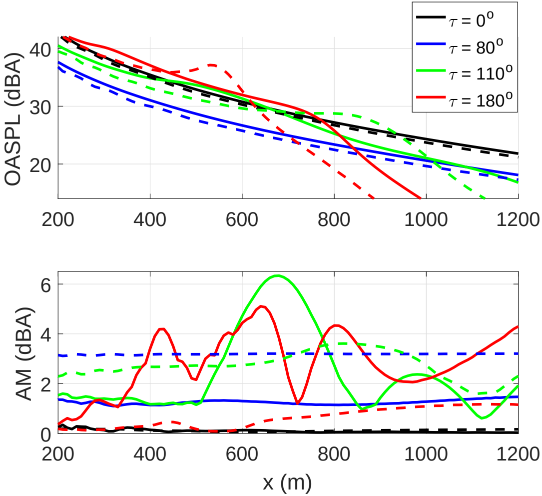

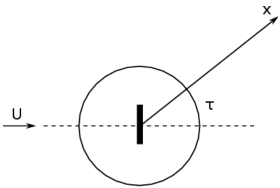

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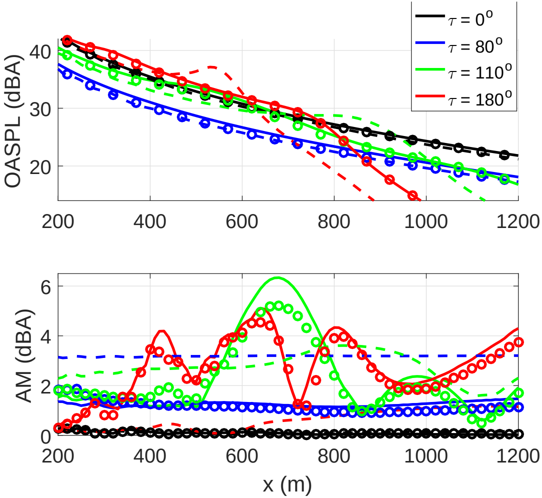

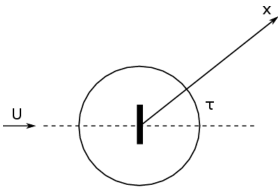

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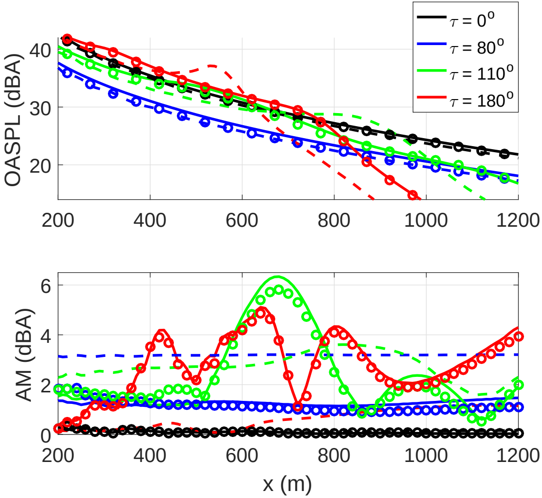

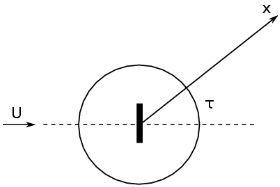

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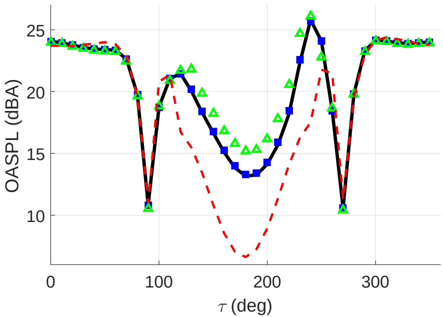
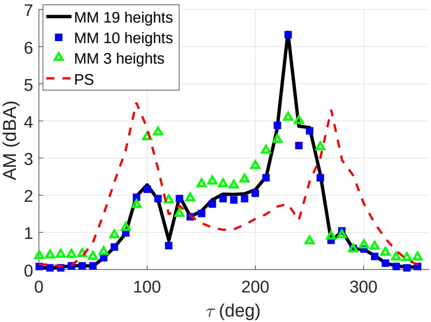
Directivity of OASPL and AM in a neutral atmosphere

Directivities calculated at $x = 1000\,\mathrm{m}$ and $z = 2\,\mathrm{m}$

OASPL

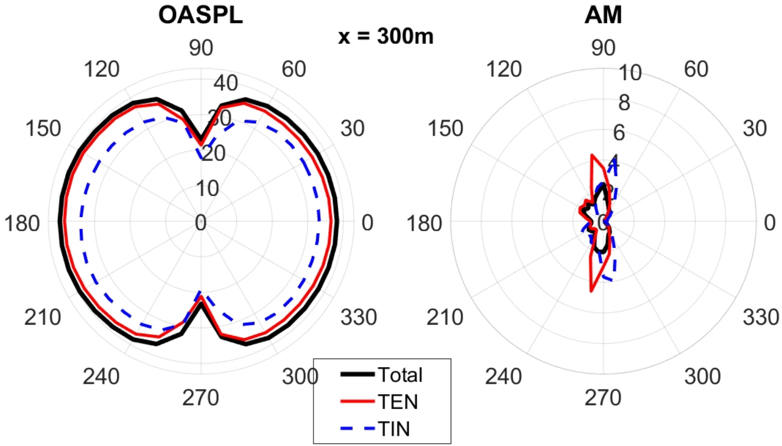


AM



At least 10 source heights are needed correctly capture the AM behavior upwind

Contribution of TEN and TIN in a neutral atmosphere



Conclusion and perspectives

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- coupling method based on backpropagation of a near-field initial field : excellent results but very computationally intensive
- chaining methods based on rotating moving monopoles : very good results with only a few PE calculations

Some perspectives :

- improve source model by including separation/stall noise mechanisms (ANR project PIBE)
- apply the moving monopole model to very stable atmospheres (and/or low level jet conditions), and compare predictions with field experiments
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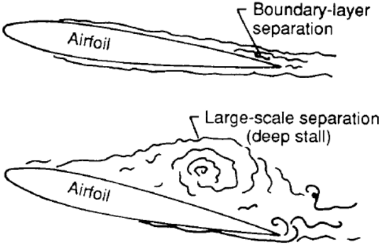

Separation-stall noise