Development of the HARMONOISE Point-To-Point MODEL

Prediction of Excess Attenuation in Outdoor Noise Propagation

Dirk van Maercke

CSTB

24, rue Joseph Fourier

F-38400 Saint-Martin d'Hères

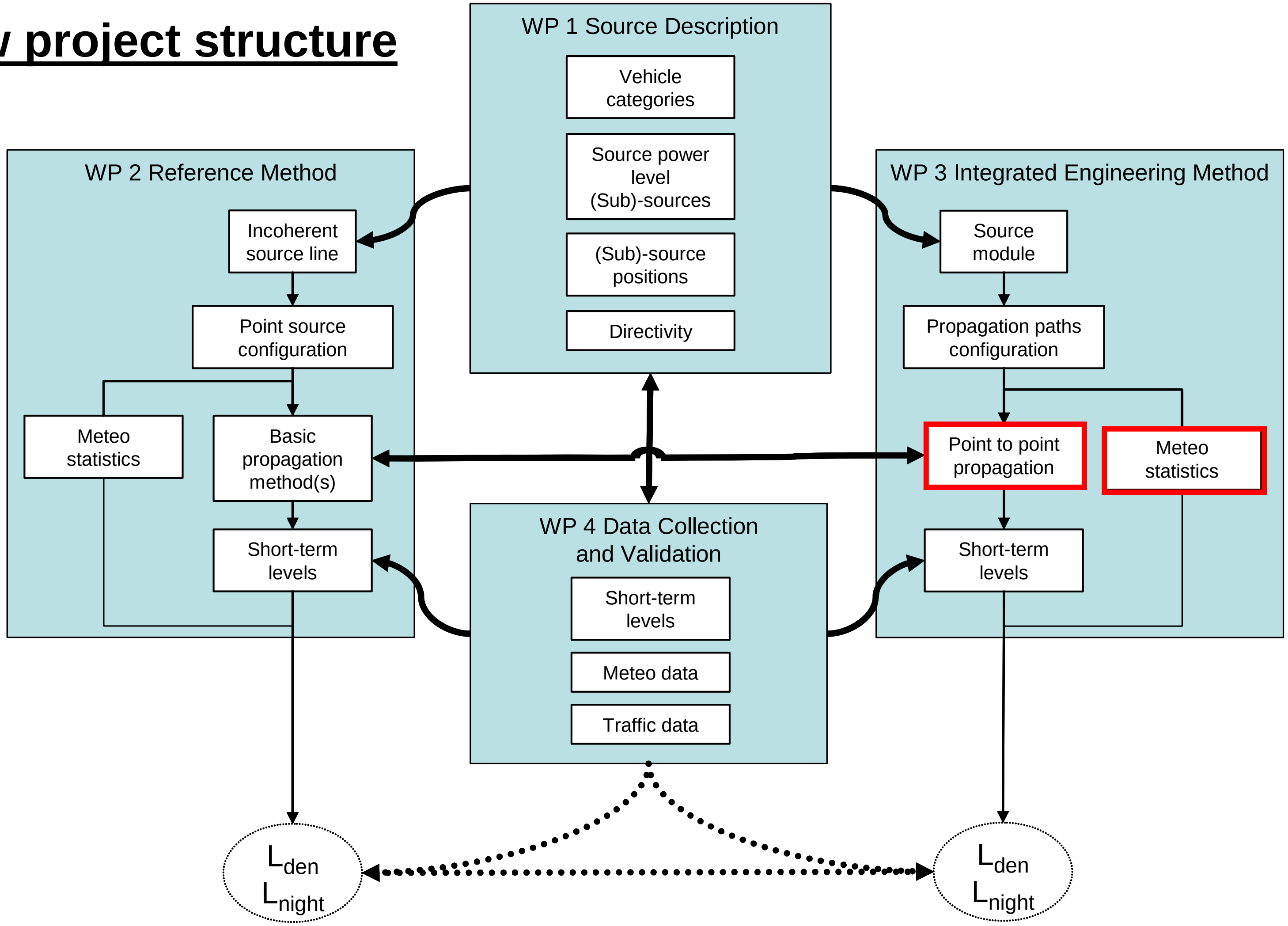
FRANCE

dvm@cstb.fr

THE HARMONOISE PROJECT

- ☞ Application of the European Noise Directive
- ☞ Provide "… the future harmonized prediction methods" (by 2012)
- ☞ Noise mapping of major cities and transport infrastructures
- ☞ Using harmonized indicators: L_{den} / L_{night} (long time averaged)
- ☞ 20 partners from 9 European countries
  - TNO, DGMR,… ⇨ SRM-II
  - CSTB, LCPC, SNCF ⇨ NMPB
  - DELTA, SP, SINTEF,… ⇨ Nord 2000
- ☞ Budget : 5,2 M€ (50% funding under 5th Framework)
- ☞ 3 + ½ years (01/08/2001 – 31/01/2005)
- ☞ Follow-up: IMAGINE project
  - Use of GIS data
  - Measurement methods & determination of L_{den} / L_{night}
  - Traffic management
  - Aircaft & industrial noise

Overview project structure



CSTB
le futur en construction

Calculation of noise levels:

$$L_p = L_w + \Delta L_{geo} + \Delta L_{path} + \Delta L_{air} + \Delta L_{excess}$$

Source models

Reflexions and lateral diffractions

Source segmentation
Propagation paths

Air absorption

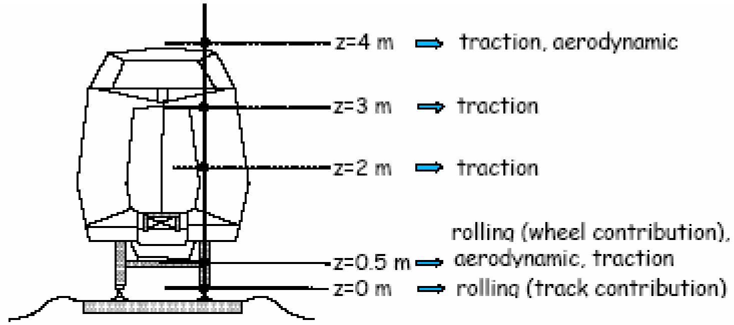
Excess attenuation
- ground
- diffraction
- meteo

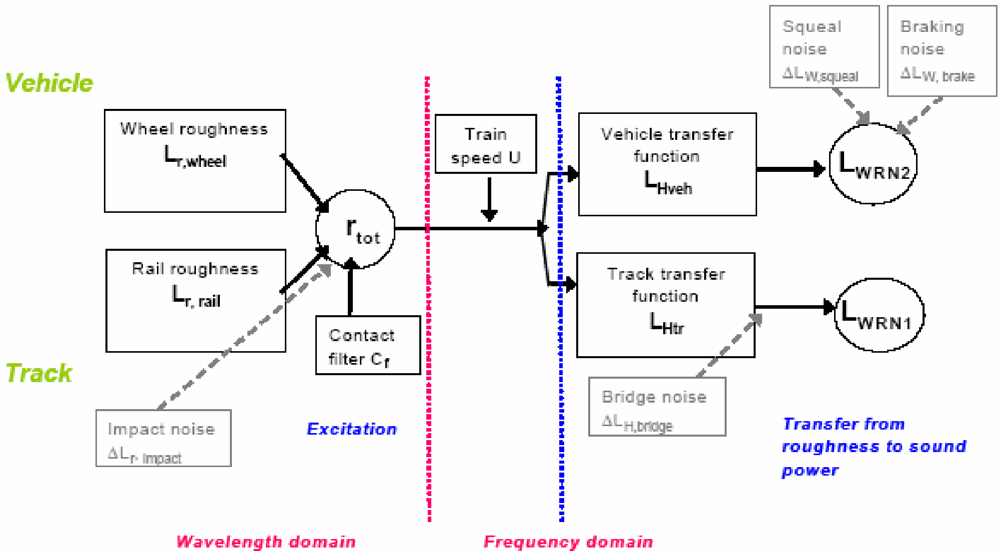
HARMONOISE

IMAGINE

Source / vehicle models

- ☞ Point sources at different heights
- ☞ Separation of noise generation mechanisms
- ☞ Analytical expressions for L_W as a function of operation conditions
- ☞ Database: coefficients and corrections : default, generic, national data



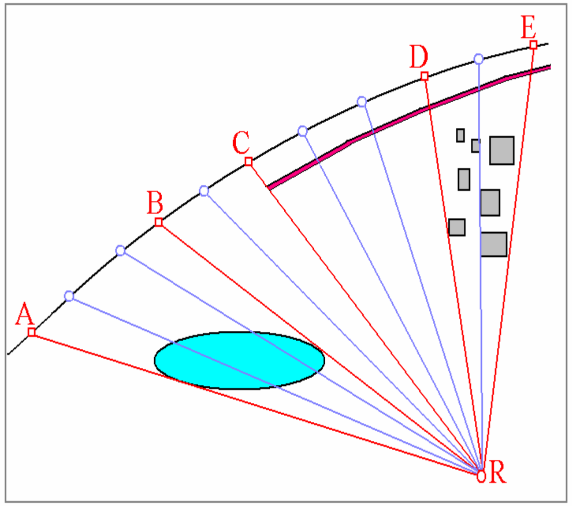


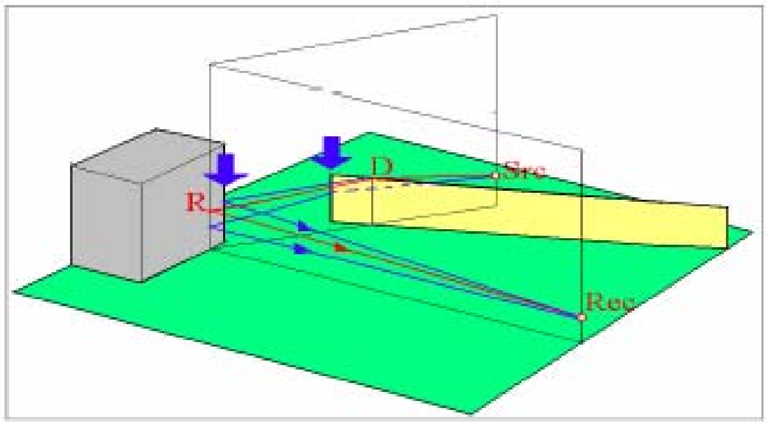
Coupling source and propagation

- Individual vehicles
- Model the contribution of a large number of moving vehicles as a single “incoherent” source lines

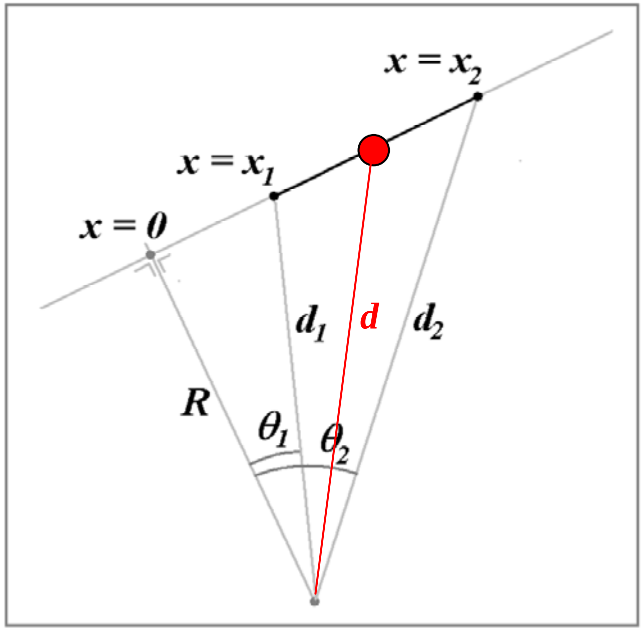
$$L'_{w,T} = 10 \log \left(\frac{1}{T} \sum_{i=1}^{N} \frac{W_i}{v_i} \right)$$

- Segmentation / integration over homogeneous sectors
- Equivalent point sources and propagation paths





Source segmentation & integration : ΔL_{geo}



ΔL_{geo} applies to:

- ⇨ point sources
- ⇨ line sources
- ⇨ surface sources

☞ **Definition**:

$$\Delta L_{geo} = \int_{\Omega} \frac{D(\theta,\varphi)}{4\pi . d^2} d\Omega$$

☞ **Exact, integration over line segment**:

$$\Delta L_{geo} = -10\log \frac{\theta_2 - \theta_1}{4\pi \, R}$$

☞ **Point source decomposition**:

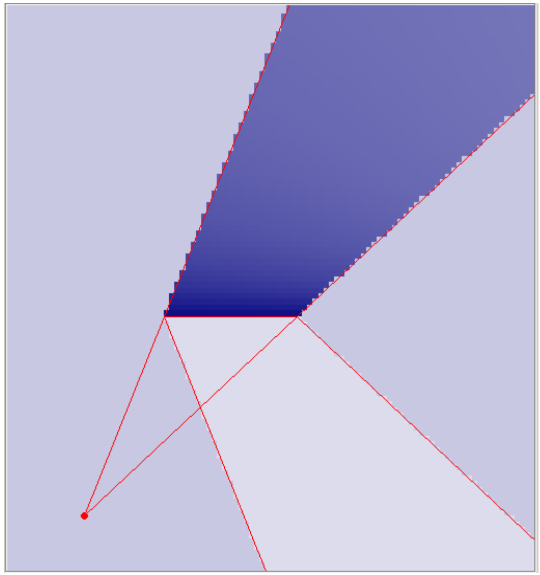
$$\Delta L_{geo} \approx -10\log \frac{\Delta x}{4\pi \, d^2}$$

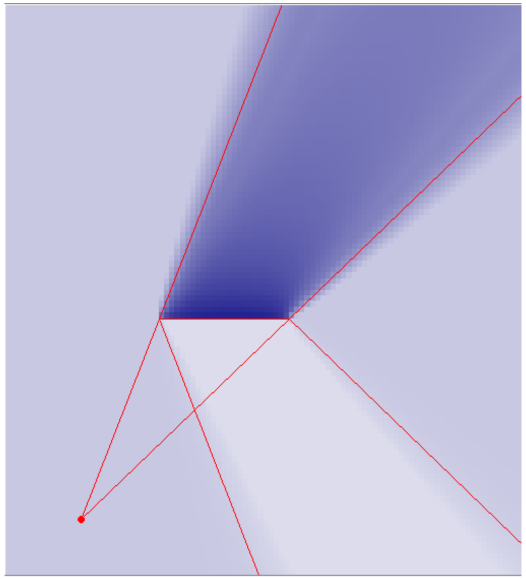
☞ **Constant angular sector tracing**

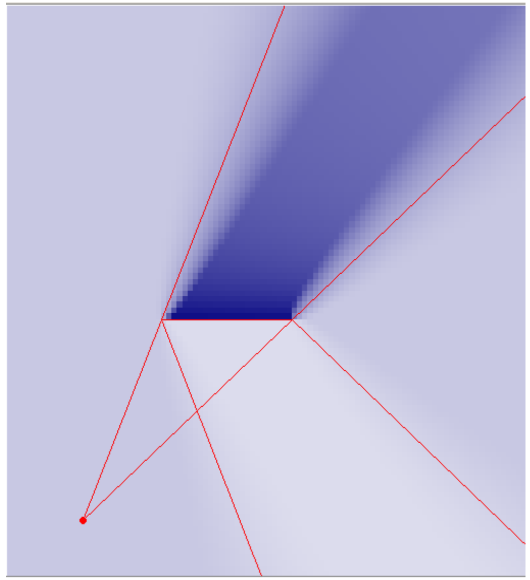
$$\Delta L_{geo} \approx -10\log \frac{\Delta\theta}{4\pi \, d . \cos\theta}$$

ΔL_{path} : corrections for finite size of reflecting& diffracting obstacles

Optical fields	**Exact**	**Approximation**
	based on GTD	using Fresnel weights







The Point-To-Point module

Calculation of excess attenuation: $$\Delta L_{excess} = 10\log\left|\frac{p}{p_{free}}\right|^2$$

⇨ over any kind of ***terrain profile***, including multiple diffractions & reflections by natural and man-made obstacles

⇨ under different representative ***meteorological conditions***

⇨ using ***physical models***, based on “recent” progress in outdoor propagation

⇨ more accurate than existing (national, ISO 9613-2 based) models

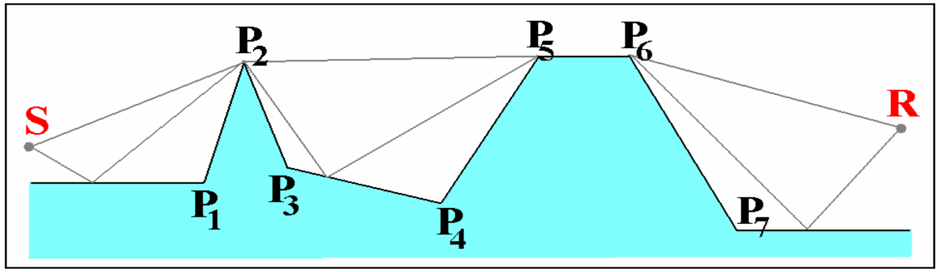
⇨ limited computation time ⇒ ***“just good enough”***

⇨ continuous results, no excessive sensitivity to accuracy of input data

⇨ compatible or comparable with basic principles of existing models

⇨ ready to be integrated in existing noise mapping software

INPUT TO THE P2P MODEL



- ⇨ cross-section profile

  ⇒ $P_i\,(x_i\,,y_i),\ i = 0,1,\ldots N$ where $x_{i+1} > x_i$

  ⇒ each segment $(P_i,\ P_{i+1})$ = impedance value / class

- ⇨ source and receiver height

  ⇒ $h_S \pm \Delta h_S$ and $h_R \pm \Delta h_R$

- ⇨ any number of diffractions (thin screens, wedges, thick barriers,…)

- ⇨ no distinction between ground (terrain), road surfaces, embankments, barriers, buildings, roofs,…

INPUT TO THE P2P MODEL (continued)

⇨ Impedance values

- User defined
- Delany-Bazley (flow resistivity and layer thickness)
- Impedance classes (Nord 2000) + predefined impedance values

⇨ Frequency range

- Default: 1/3 octave bands, 25 – 10000Hz
- User defined

⇨ Atmospheric conditions

- Sound speed (default = 340 m/s)
- Temperature and humidity (ISO 9613-1)
- Sound speed gradient
- Turbulence strength

Point-To-Point MODEL DEVELOPMENT

- Step-by-step, increasing complexity:
  - ⇨ Ground effect
  - ⇨ Diffraction
  - ⇨ Ground + diffraction
  - ⇨ Combined model : ground + multiple diffraction
  - ⇨ Meteorological effects
  - ⇨ Long time averaging
- Approach:
  - ⇨ Analytical model (base solution, simple situation)
  - ⇨ Heuristics (extension & adaptation to more realistic situations)
  - ⇨ Validation against numerical “reference” calculations
  - ⇨ Validation against experimental results

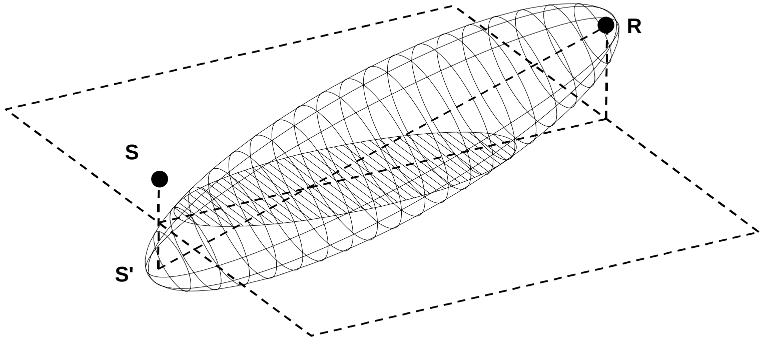
The P2P model : GROUND REFLECTION

- Chien-Soroka

$$\Delta L_G = 20\log\left|1+\frac{p_{free}(S',R)}{p_{free}(S,R)}.Q(k,Z,\theta)\right|$$

- Mixed ground & Fresnel weighting

$$\Delta L_{G,flat} = \sum_i w_i . \Delta L_{G,i}$$



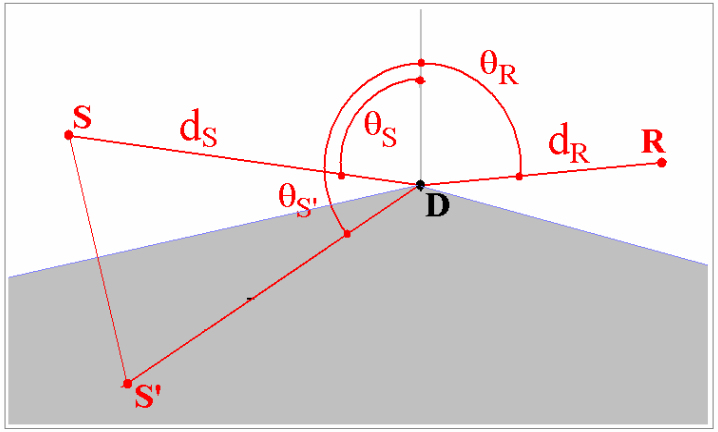
- Deep valley solution

$$\Delta L_{G,valley} = 20\log\left|1+\sum_i w_i . Q_i \frac{p_{free}(S_i',R)}{p_{free}(S,R)}\right|$$

The P2P model : WEGDE DIFFRACTION

☞ Hadden & Pierce + heuristics

$$p = p_{dif}(S,D,R) + Q_S . p_{dif}(S',D,R) + Q_R . p_{dif}(S,D,R') + Q_S . Q_R . p_{dif}(S',D,R')$$



☞ Approximation (from NMPB):

$$p \approx p_{dif}(S,D,R).\left(1 + Q_S \frac{p_{dif}(S',D,R)}{p_{dif}(S,D,R)}\right).\left(1 + Q_R \frac{p_{dif}(S,D,R')}{p_{dif}(S,D,R)}\right)$$

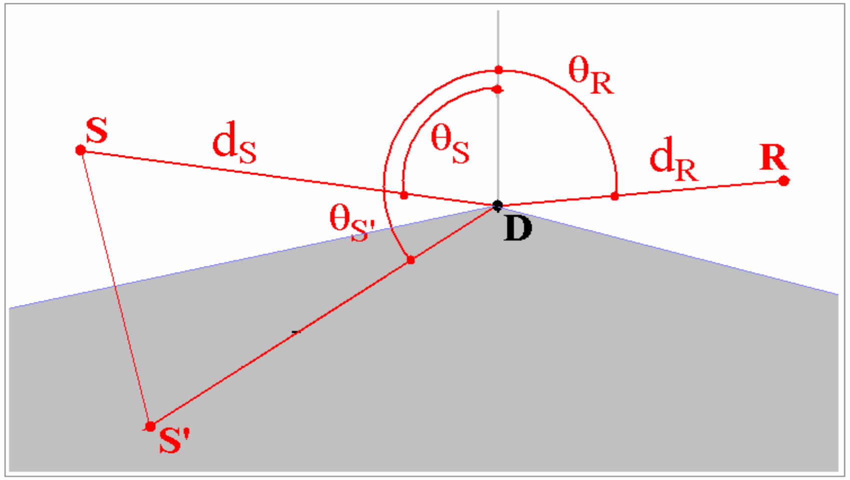
The P2P model : simplified diffraction formula

$$\Delta L_{wedge} \approx \Delta L_D + \Delta L_{G,S} + \Delta L_{G,R}$$

$$\Delta L_D = 20\log\left|\frac{p_{dif}(S,D,R)}{p_{free}(S,R)}\right|$$

$$\Delta L_{G,S} = 20\log\left|1 + Q_S\frac{p_{dif}(S',D,R)}{p_{dif}(S,D,R)}\right|$$

$$\Delta L_{G,R} = 20\log\left|1 + Q_R\frac{p_{dif}(S,D,R')}{p_{dif}(S,D,R)}\right|$$



DIFFRACTION : INSERTION LOSS

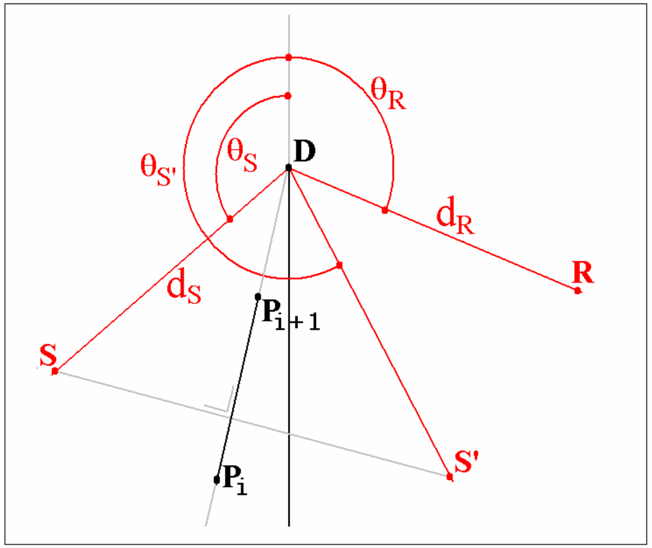
Deygout's approximation

$$\Delta L_D(N) = 20\log\left|\frac{p_{dif}(\theta, d_S, d_R)}{p_{free}(\theta, d_S, d_R)}\right|$$

$$N = \frac{2\delta}{\lambda}$$

$$\begin{aligned}
\Delta L_{dif}(N) &= 0 && \text{if } N < -0.25 \\
&= -6 + 12\sqrt{-N} && \text{if } -0.25 < N < 0 \\
&= -6 - 12\sqrt{N} && \text{if } 0 < N < 0.25 \\
&= -8 - 8\sqrt{N} && \text{if } 0.25 < N < 1 \\
&= -16 - 10\log(N) && \text{if } N > 1
\end{aligned}$$

special case : $\theta >> \pi$

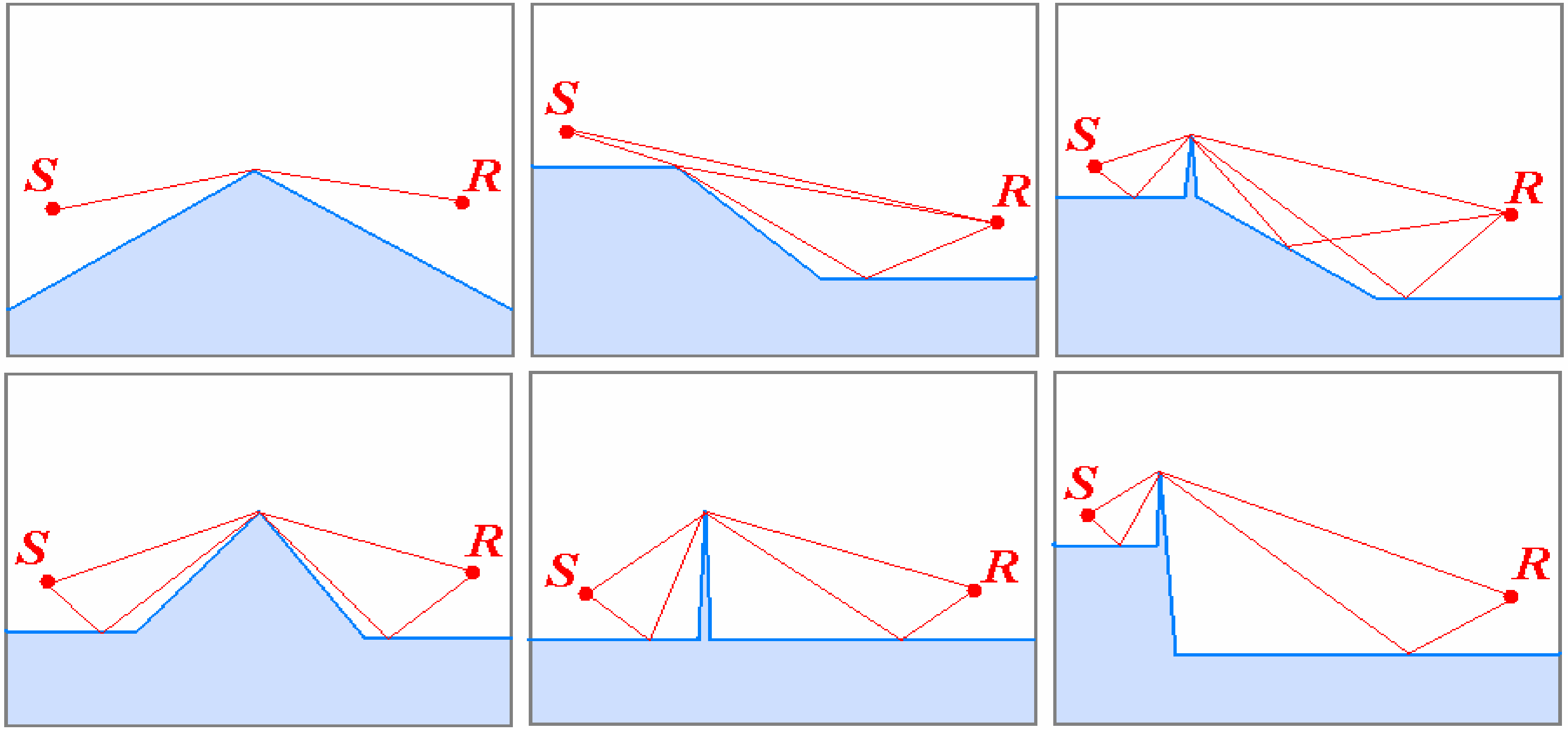


$$\delta = (d_S + d_R).\left(\frac{\xi^2}{2} + \frac{\xi^4}{3} + \ldots\right)$$

$$\xi = \frac{\sqrt{d_S\, d_R}}{d_S + d_R}(\theta - \pi)$$

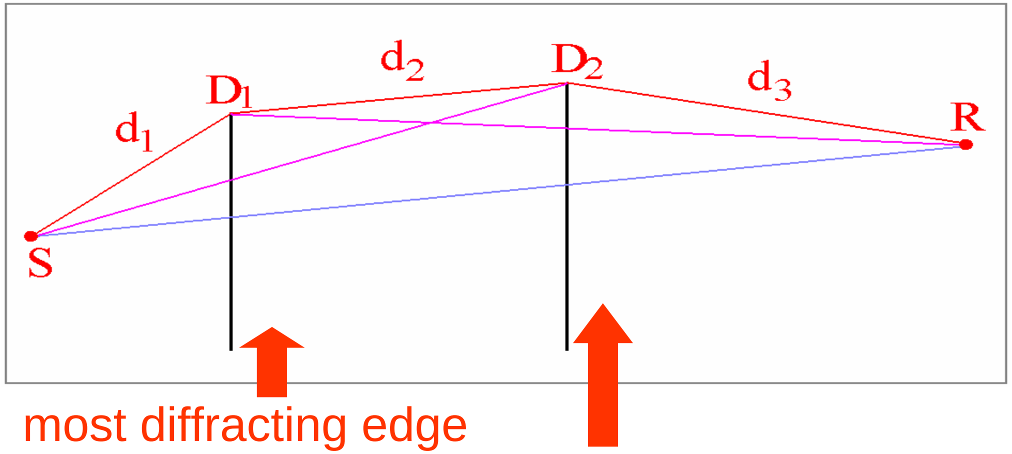
DIFFRACTION + GROUND

$$\Delta L_{diff+ground} = \Delta L_D + \Delta L_{G,S} + \Delta L_{G,R}$$



MULTIPLE DIFFRACTION

- two screens, no ground

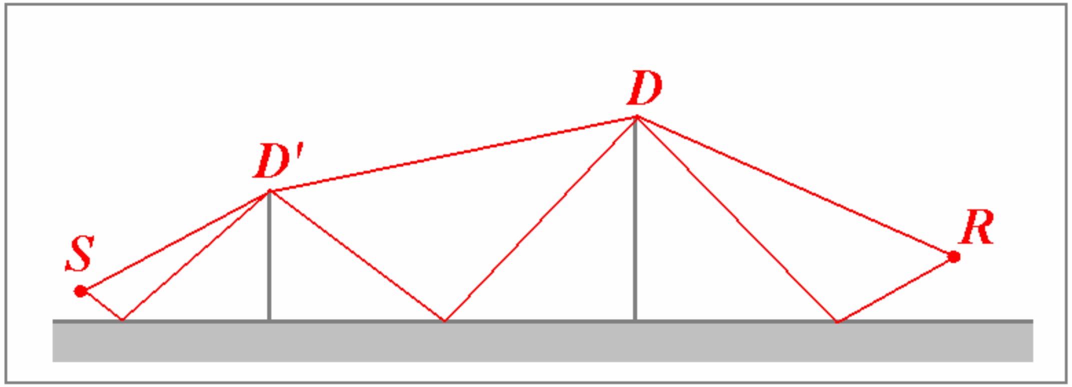


$$\Delta L_{dif,1+2} = \Delta L_D\,(S, D_1, R) + \Delta L_D\,(D_1, D_2, R)$$

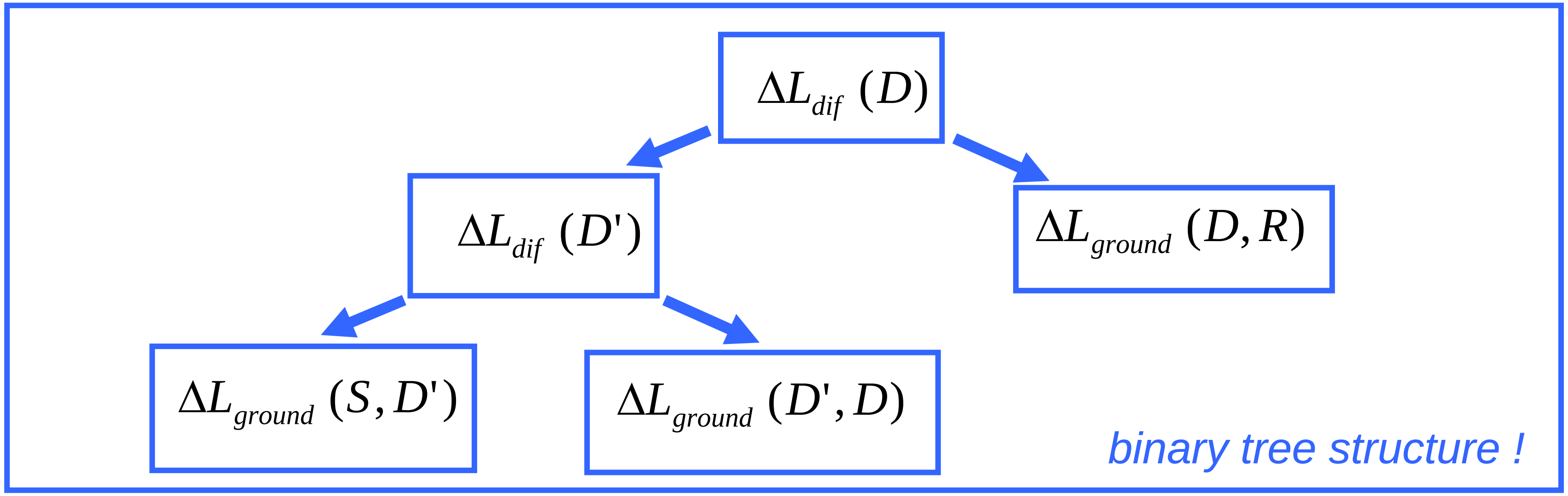
- extension to multiple screens : recursively !

$$\Delta L_{dif}(P_0, P_1, \ldots P_N) = \Delta L_D(P_0, P_k, P_N) + \Delta L_{dif}(P_0, P_1, \ldots P_k) + \Delta L_{dif}(P_k, P_{k+1}, \ldots P_N)$$

MULTIPLE DIFFRACTION + GROUND

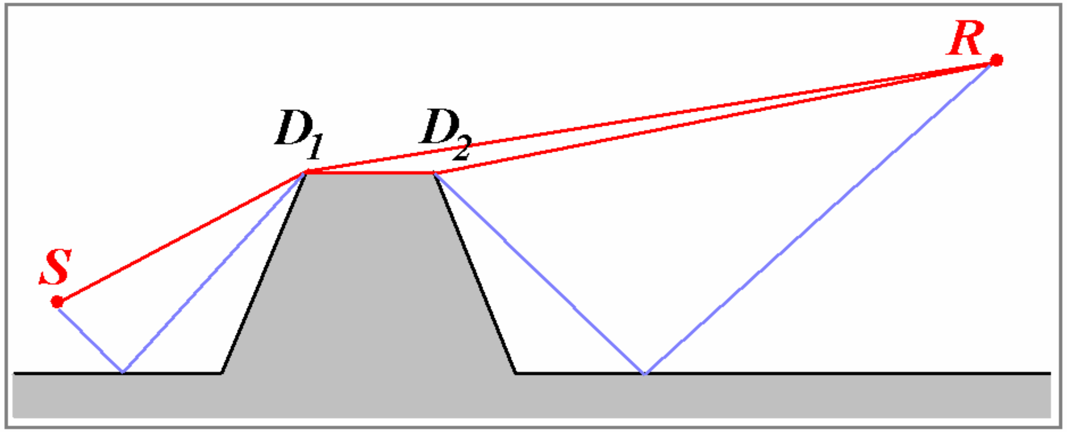


$$\begin{aligned}\Delta L &= \Delta L_{dif}(D)\\ &+ \Delta L_{dif}(D')\\ &+ \Delta L_{ground}(S,D')\\ &+ \Delta L_{ground}(D',D)\\ &+ \Delta L_{ground}(D,R)\end{aligned}$$



MULTIPLE DIFFRACTION & WIDE BARRIERS

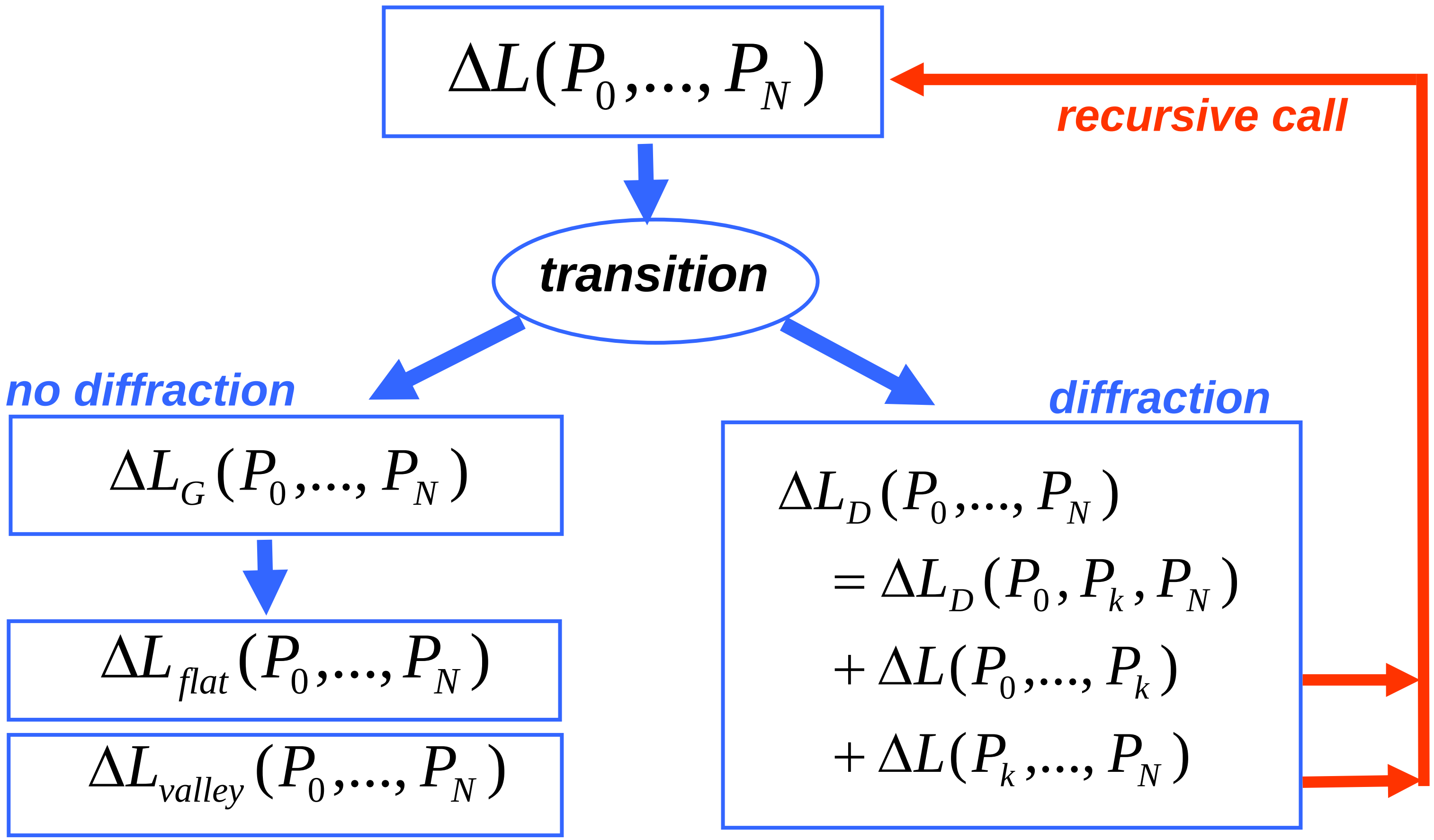
$$\begin{aligned}\Delta L &= \Delta L_G(S, D_1) \\ &+ \Delta L_{dif}(S, D_1, R) \\ &+ \Delta L_G(D_1, D_2) \\ &+ \Delta L_{dif}(D_1, D_2, R) \\ &+ \Delta L_G(D_2, R)\end{aligned}$$



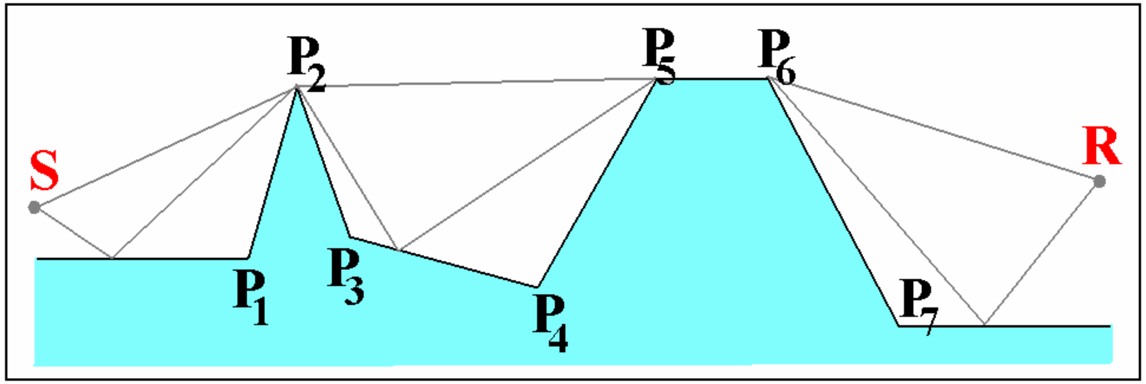
$$as\ D_1 \to D_2\ :\ \Delta L_G(D_1, D_2) = +6dB\ \ and\ \ \Delta L_{dif}(D_1, D_2, R) = -6dB$$

$$in\ case\ \ Z \neq \infty\ \ and\ \ \theta \approx \pi/2:\ \ \Delta L'_G = 6 + 0.3\ (\Delta L_G - 6)$$

The P2P model : MULTIPLE DIFFRACTION + GROUND



COMBINED MODEL : COMPUTANIONAL EFFORT ?



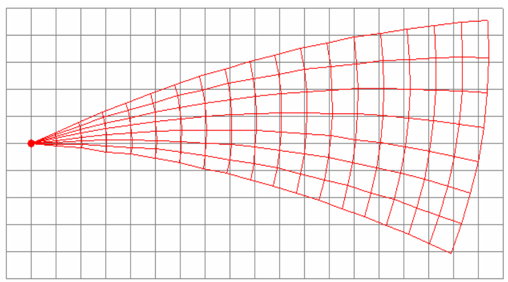
$$\Delta L_{excess} = \sum_{i=1}^{M} \Delta L_{D,i} + \sum_{i=j}^{N} \Delta L_{G,j}$$

☞ the computation time varies as linearly as *O(M+N)*

METEOROLOGICAL REFRACTION

- ☞ Linear sound speed gradient ⇨ analytical construction of rays
- ☞ Curved rays… curved ground analogy ? Conformal mapping !

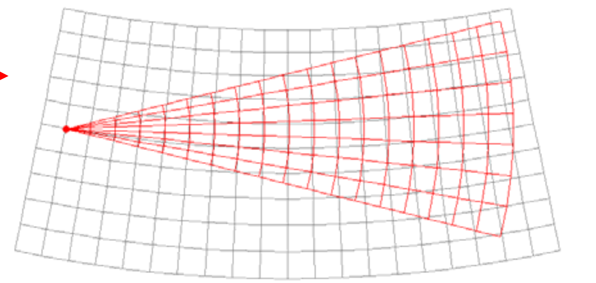
$$w = x + j\,y$$



$$c(z) = c_0\left(1 + \frac{y}{R}\right)$$

Poincarré metric !

$$w' = x' + j\,y' = \frac{2\,j\,R\,w}{w + 2\,jR}$$

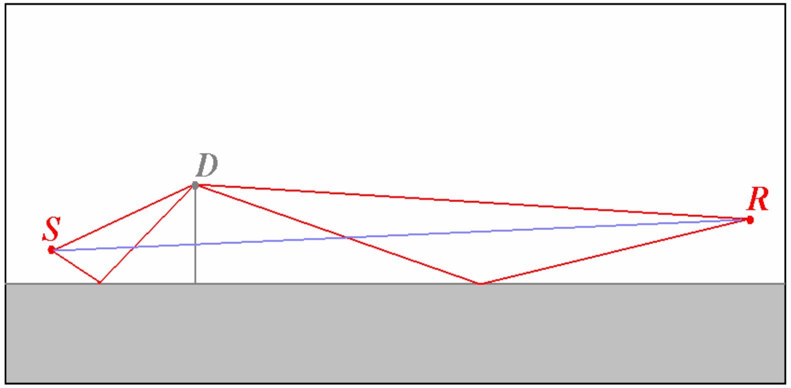


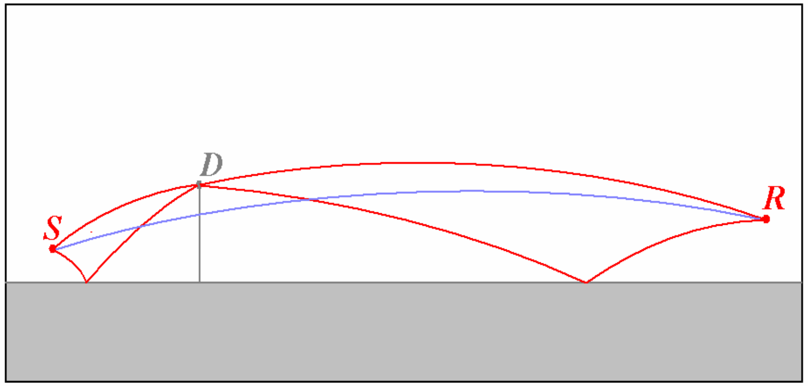
$$c(d) = c_0\left(1 + \left(\frac{d}{2R}\right)^2\right);$$

$$\text{...almost constant if } d \ll R$$

The Point-To-Point model

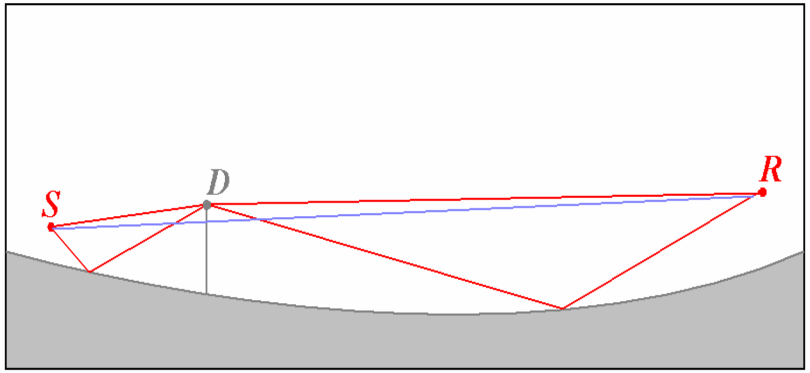
= DIFFRACTION + GROUND + METEOROLOGICAL REFRACTION





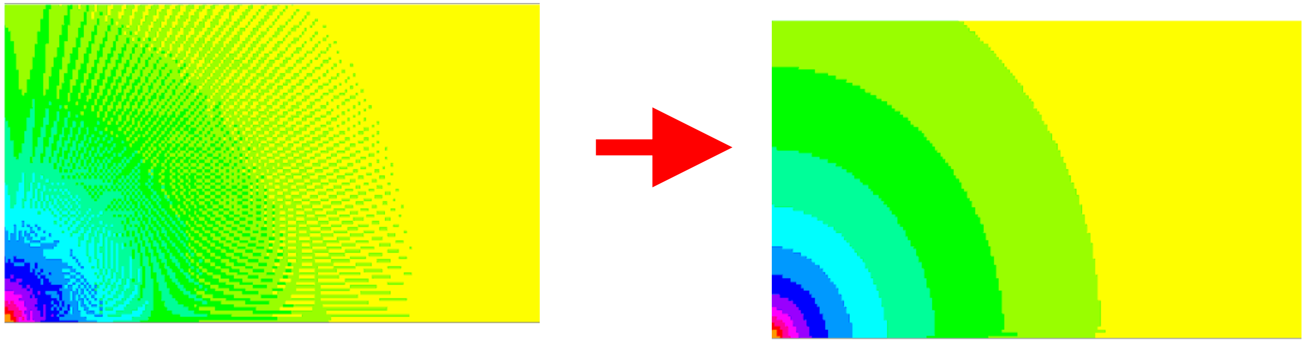
After conformal transformation…

use “straight ray” model over modified terrain model !



Fine-tuning the model & secondary effects…

☞ Loss of coherency

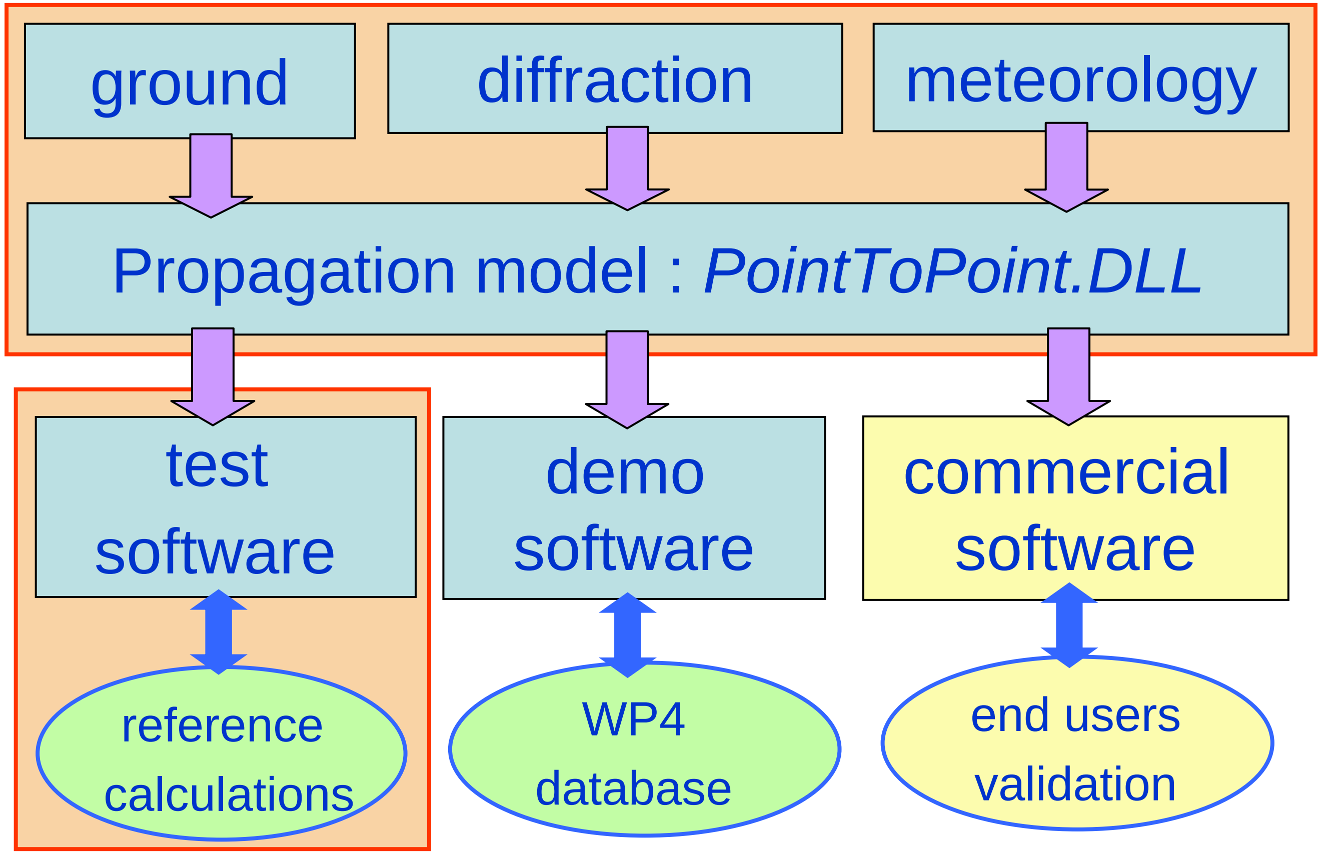


$$\left(\frac{\Delta\varphi}{\varphi}\right)^2 = \left(\frac{\Delta f}{f}\right)^2 + \left(\frac{\Delta c}{c}\right)^2 + \left(\frac{\Delta h_S}{h_S}\right)^2 + \left(\frac{\Delta h_R}{h_R}\right)^2$$

☞ Turbulence and scattering (simplified, one parameter)

$$\Delta L_{scat} = 25 + 10\log\gamma_T + 3\log\frac{f}{1000} + 10\log\frac{d}{100}$$

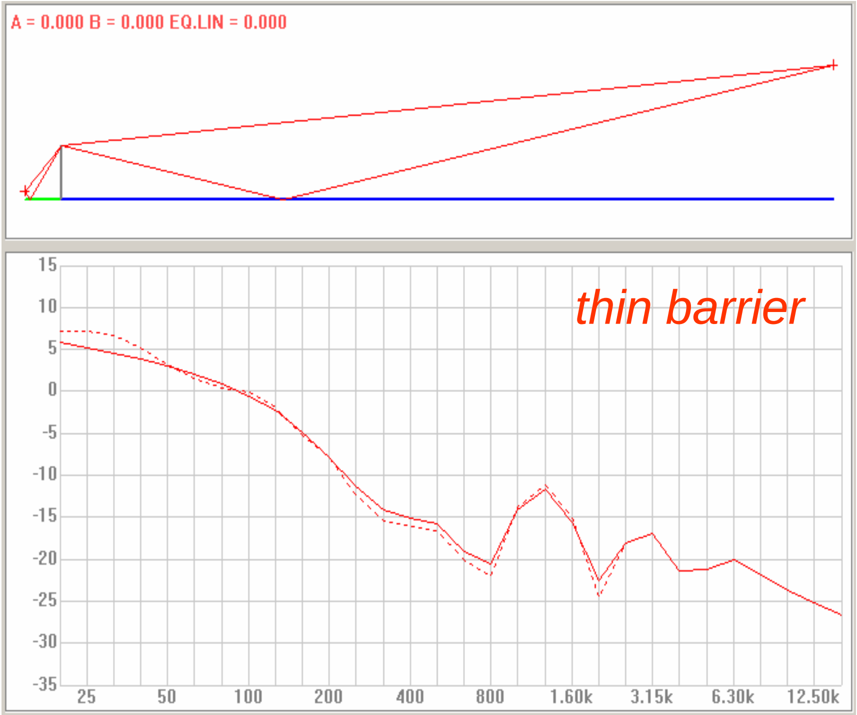
SOFTWARE IMPLEMENTATION & VALIDATION

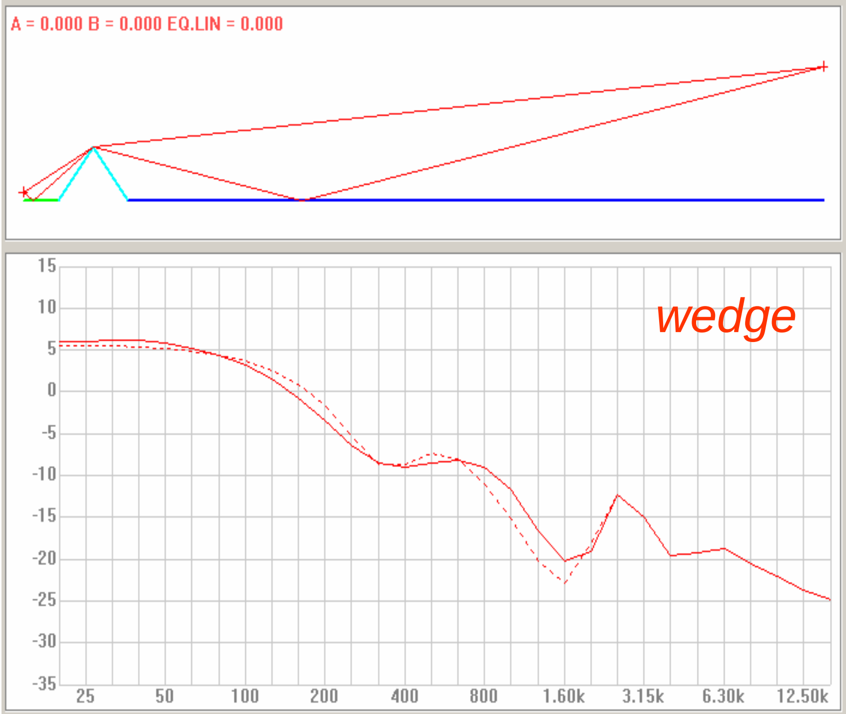


VALIDATION AGAINST BEM CALCULATIONS (no meteo)

h_S = 0.30 m ; h_R = 5.00 m ; d = 100.0 m

thin barrier / wedge , h = 2.00 m, d = 10.0 m





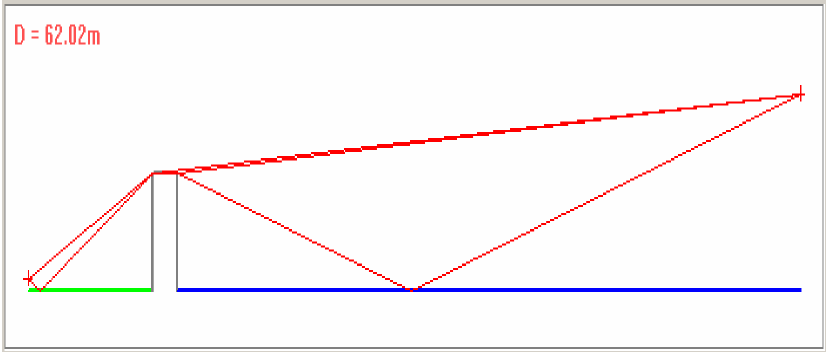
NUMERICAL VALIDATION (BEM)

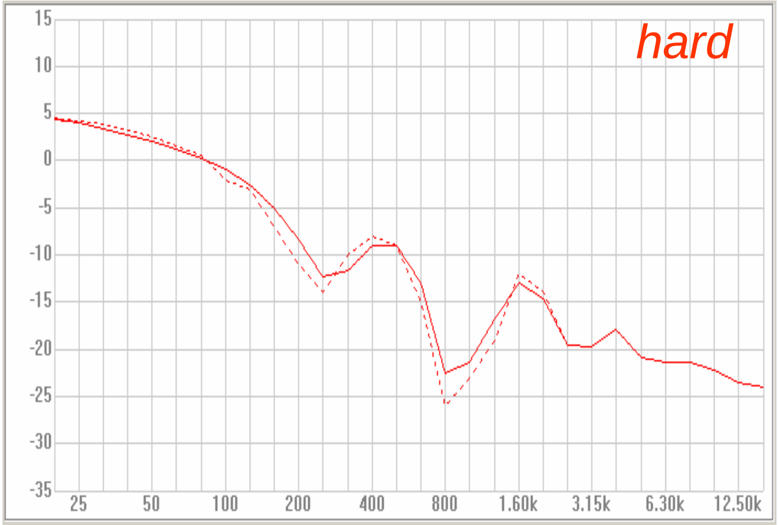
h_S = 0.30 m ; d_S = 10.0 m

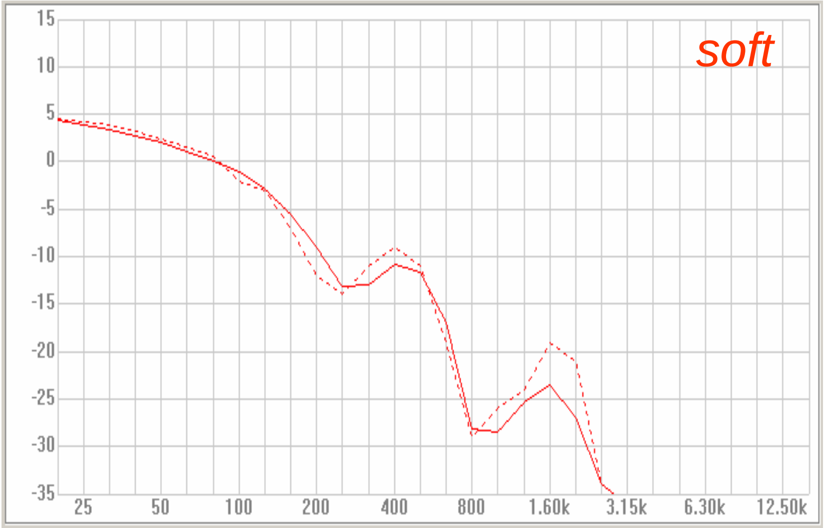
h_R = 5.00 m ; d_R = 50.0 m

h_B = 3.00 m; d_B = 2.00 m

σ_B = 50 or 2000 kNsm^{-4}

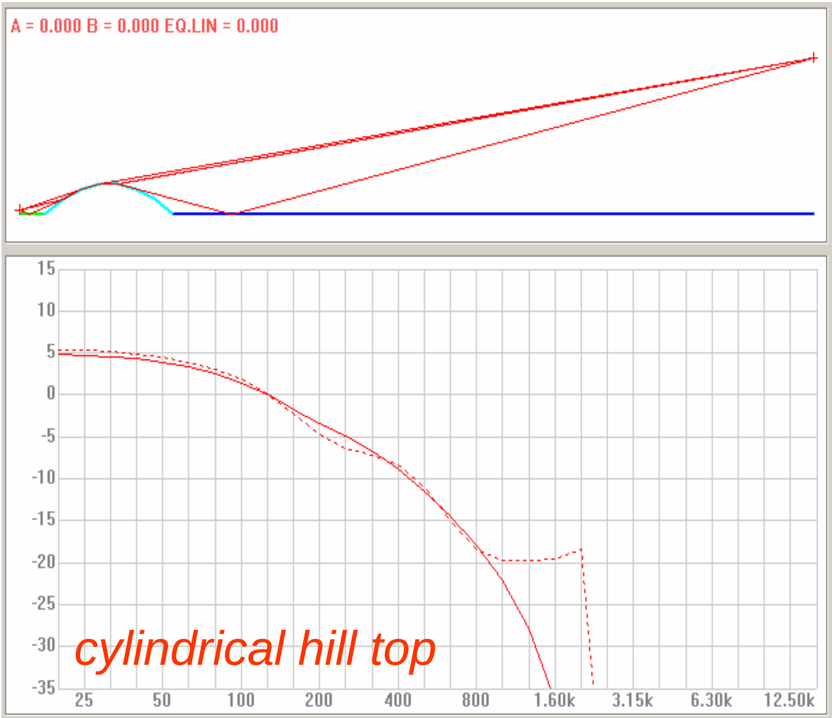




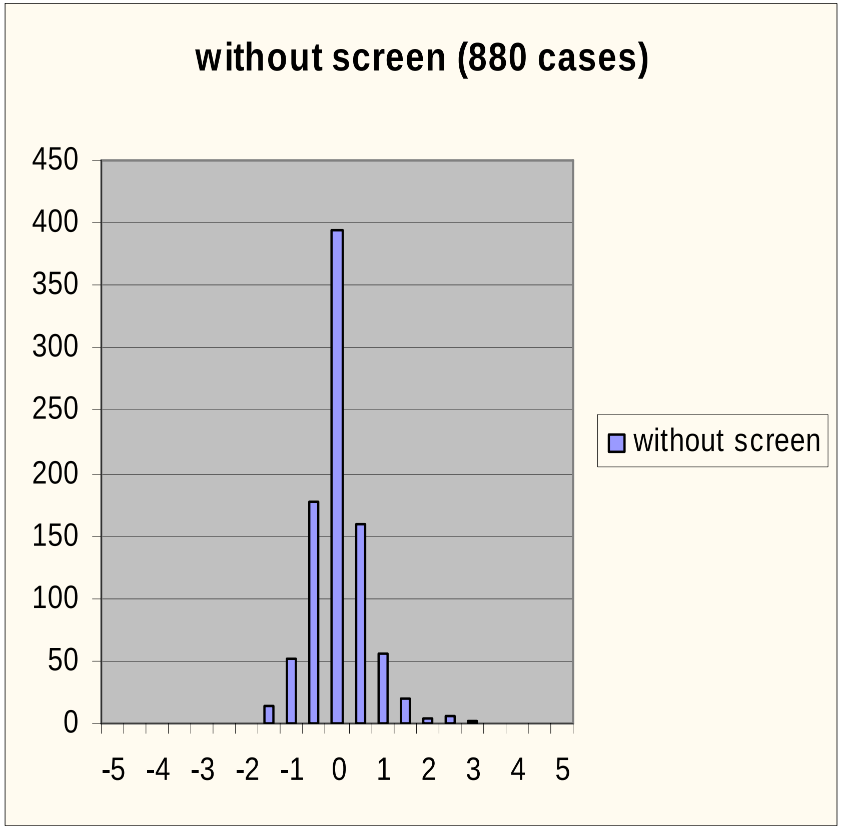


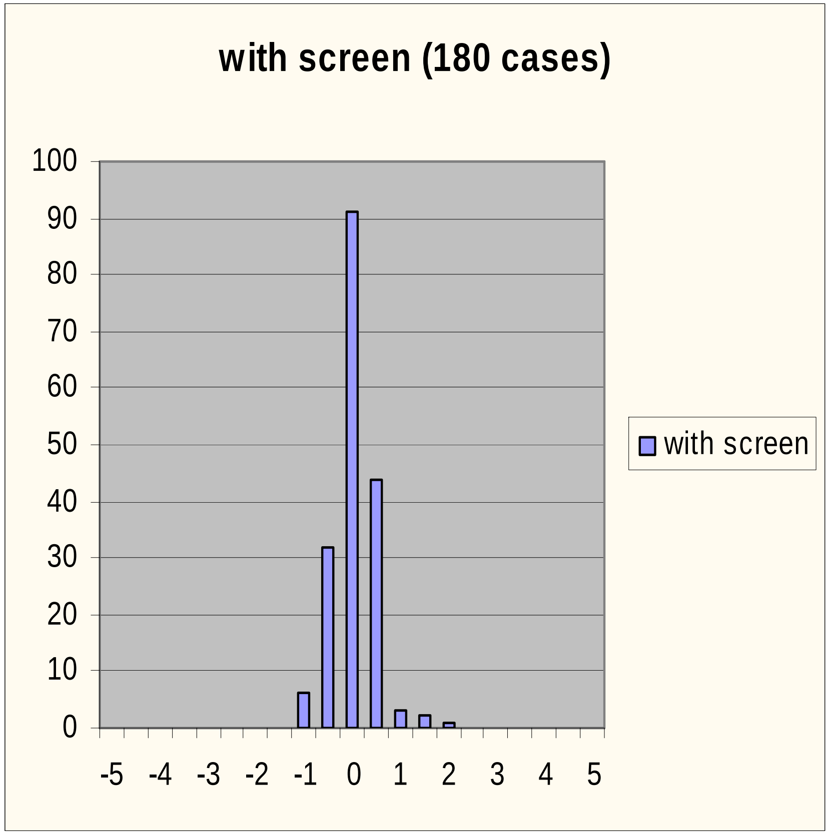
NUMERICAL VALIDATION (BEM)

- embankments, earth walls, round hill tops, ….
- receiver grids : d = 50 / 100 / 250 / 500 m , h = 1.25 / 2.5 / 5.0 / 10 m



NUMERICAL VALIDATION (BEM)





VALIDATION AGAINST GFPE CALCULATIONS (with meteo)

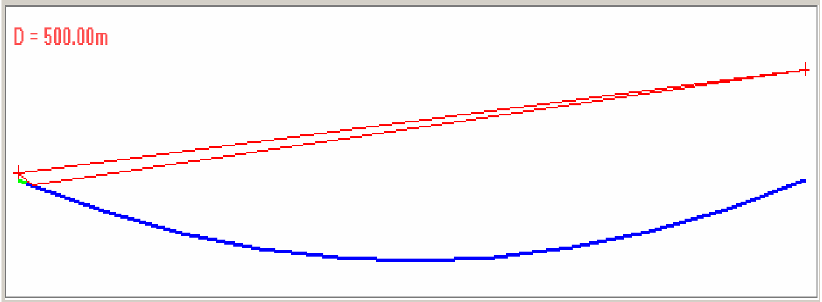
h_S = 0.30 m ; d = 500.0 m

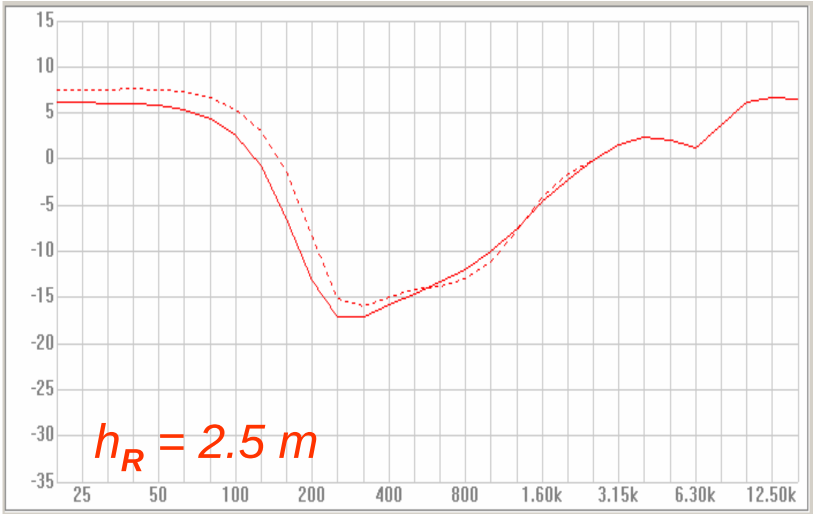
h_R = 2.50 / 10.0 m ;

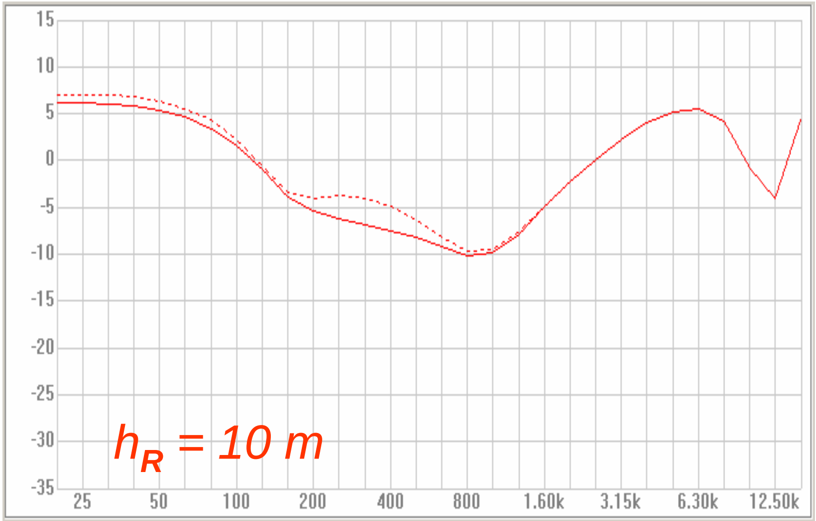
σ = 200 $kNsm^{-4}$

A_{lin}= 0.04 s^{-1} (R ~ 18 D)

weak linear gradient







NUMERICAL VALIDATION (GFPE)

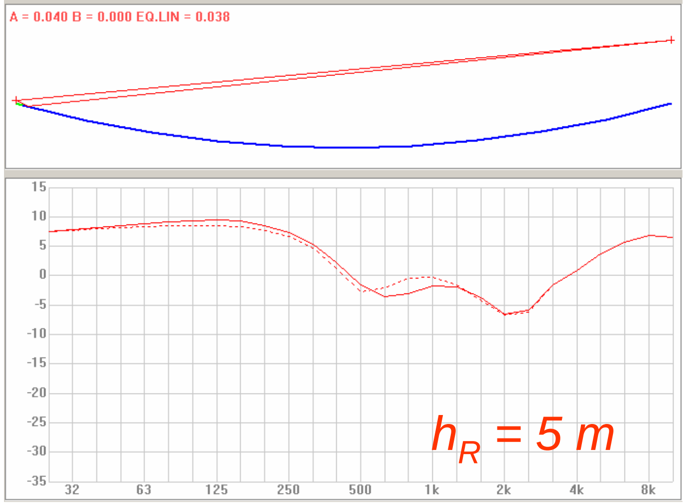
h_S = 0.30 m

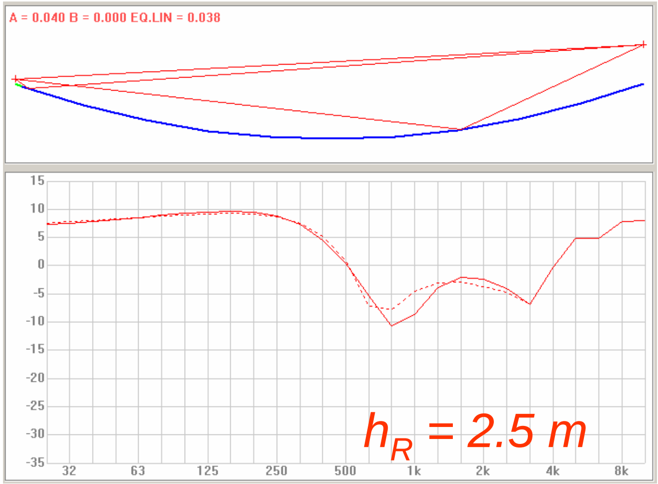
d = 500.0 m

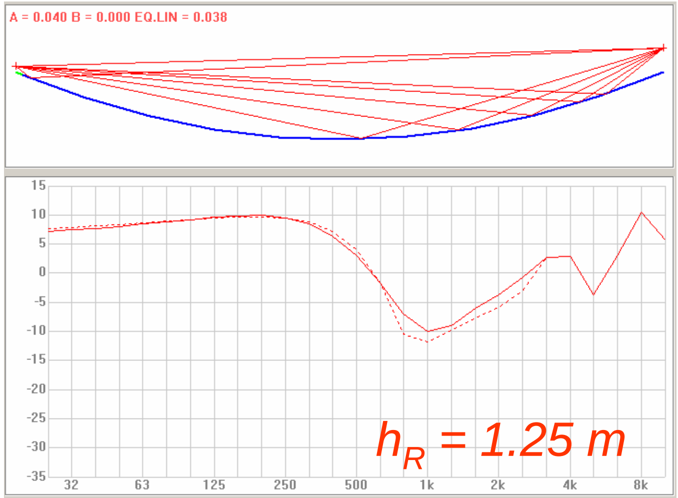
σ = 2000 kNsm^{-4}

A_{lin}= 0.04 s^{-1} (R ~ 18 D)

Low source / low receiver ?







NUMERICAL VALIDATION (GFPE)

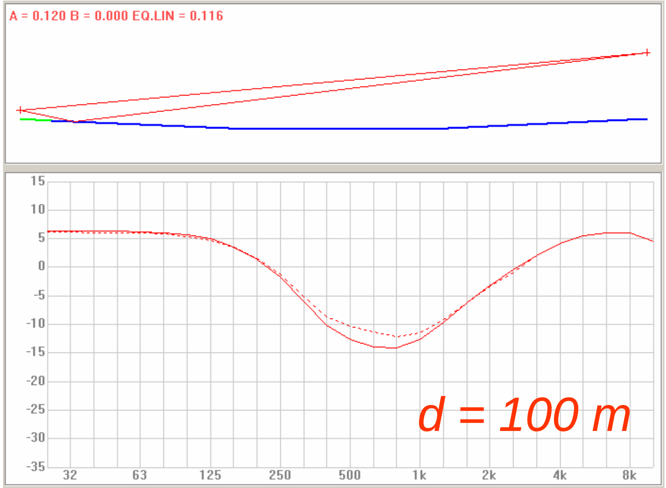
h_S = 0.30 m

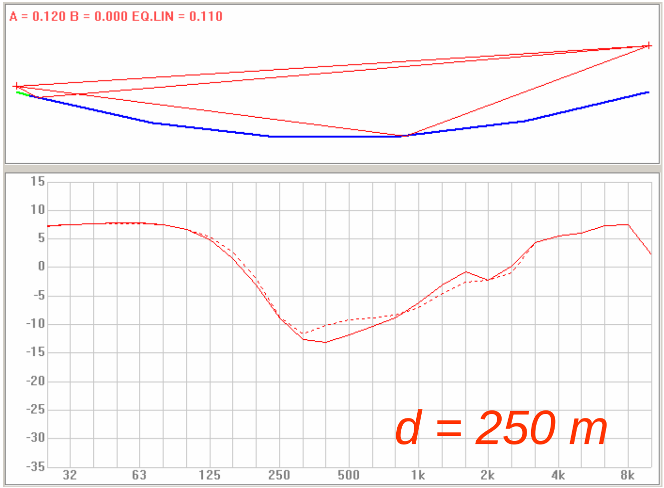
h_R = 2.50m

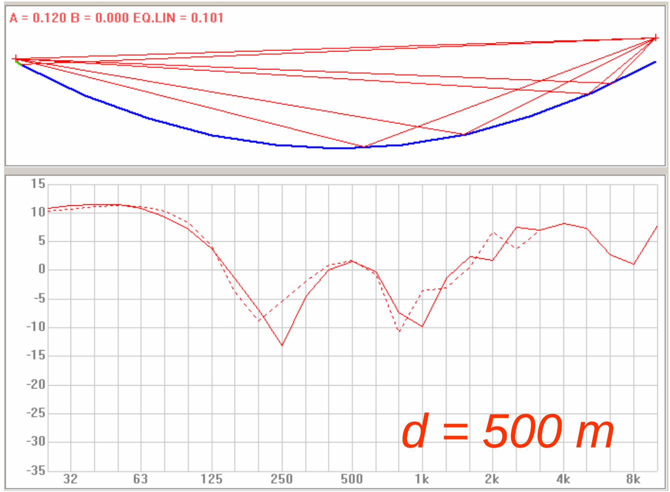
σ = 200 kNsm^{-4}

A_{lin}= 0.12 s^{-1} (R ~ 6 D)

Stronger gradients ?



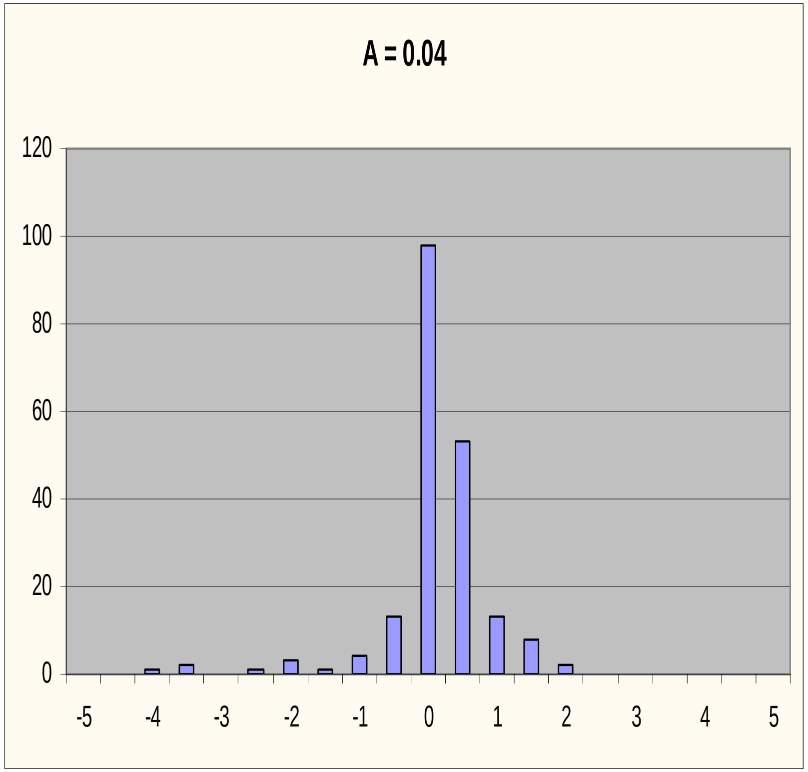


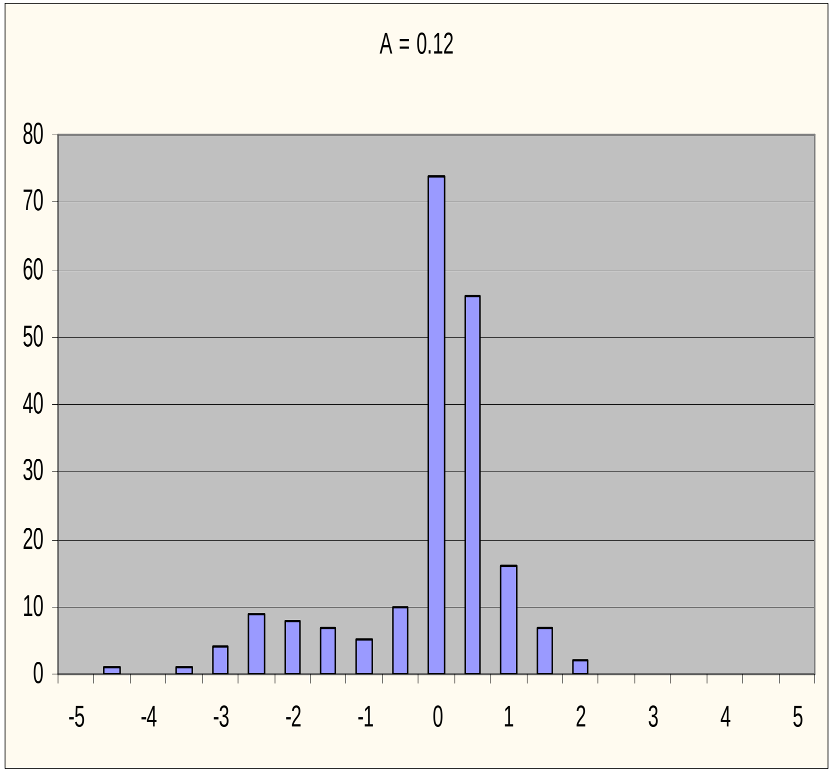


NUMERICAL VALIDATION (GFPE)

D = 25 / 50 / 100 / 250 / 500 m, , σ = 200, 2000 kNsm^{-4}

Hs = 0.30 / 1.0, 2.0, 5.0 m / Hr = 1.25 / 2.50 / 5.0 / 10 m





CSTB le futur en construction

HARMONOISE

METEOROLOGICAL EFFECTS ON SOUND PROPAGATION

1) the complexity of reality

$$\begin{cases} U(x,y,z,t) \\ T(x,y,z,t) \end{cases}$$

2) frozen atmosphere

+ turbulence

$$\begin{cases} U(x,y,z,t) = \overline{U}(x,y,z) + \Delta U(x,y,z,t) \\ T(x,y,z,t) = \overline{T}(x,y,z) + \Delta T(x,y,z,t) \end{cases}$$

3) stratified medium

$$\begin{cases} U(x,y,z,t) \approx \overline{U}(z) \\ T(x,y,z,t) \approx \overline{T}(z) \end{cases}$$

4) simplified wave equation

+ effective sound speed

$$c_{eff}(z) = c(\overline{T}(z)) + \overline{U}(z).\cos(\theta_u - \theta_{sr})$$

5) lin-log sound speed profiles

$$c_{eff}(z) \approx c_0 + A + B.\ln\left(\frac{z}{z_0}\right)$$

CHARACTERIZATION OF METEOROLOGICAL PROFILES

1) the simplified reality

$$\begin{cases} U(x,y,z,t) \approx \overline{U}(z) \\ T(x,y,z,t) \approx \overline{T}(z) \end{cases}$$

2) similarity theory

= standard profile functions

+ few parameters

$$\begin{cases} \overline{U}(z) = \dfrac{u^*}{k}\left(\ln\dfrac{z}{z_0} + \Psi_1\left(\dfrac{z}{L}\right)\right) \\ \overline{T}(z) = T_0 - \dfrac{g\,z}{c_P} + \dfrac{T^*}{k}\left(\ln\dfrac{z}{z_0} + \Psi_2\left(\dfrac{z}{L}\right)\right) \end{cases}$$

3) estimation of parameters

based on “surface” observations

Wind speed (at $z = z_{ref}$)

Wind direction

Cloud cover (in octants)

PROCESSING METEOROLOGICAL INPUT DATA

meteorological (surface) observations

Wind speed (3 to 5 classes)
Wind direction (in 10, 22.5 or 45° steps)
Stability class (3 day + 2 night classes)

wind and temperature profiles

Tables of U*, T* and 1/L

lin/log sound speed profile

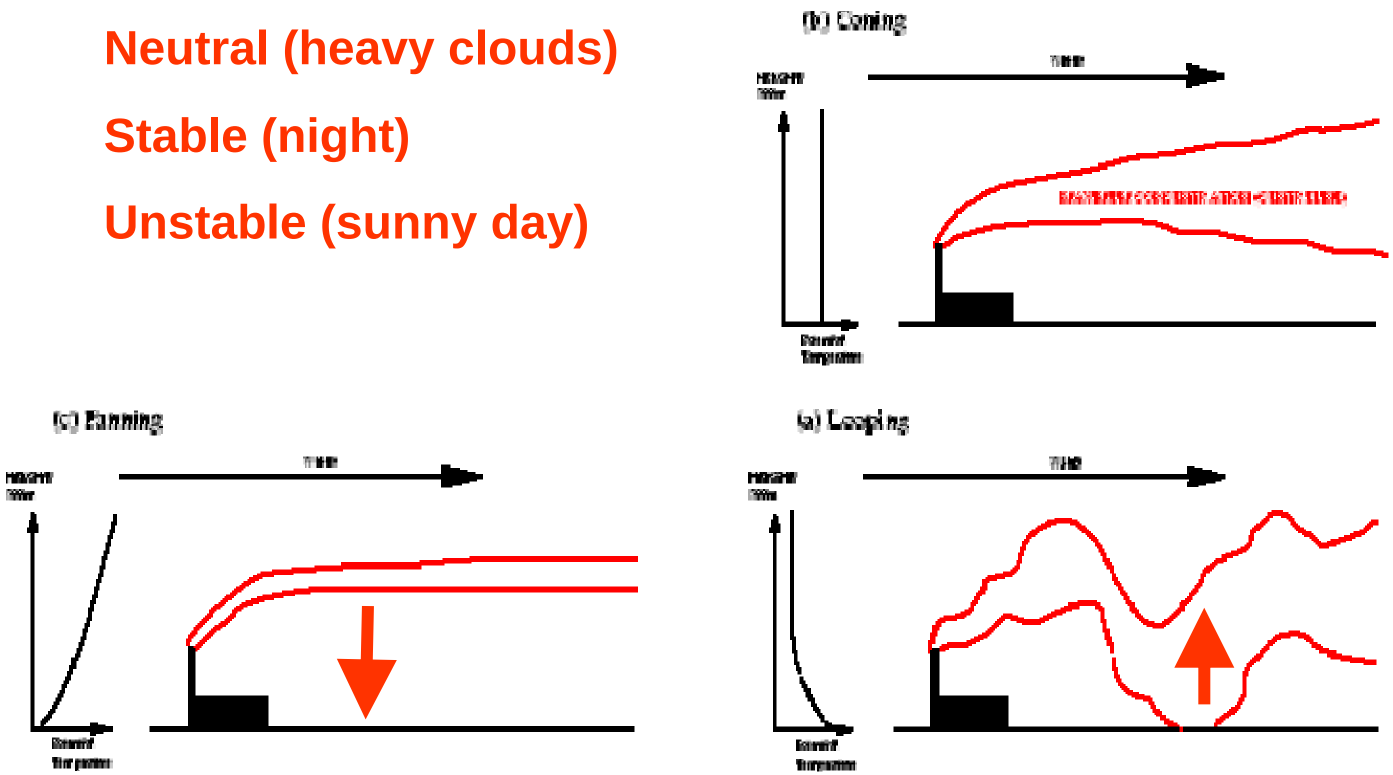
$$A = A_T + A_W \cos(\theta_U - \theta_{sr})$$
$$B = B_T + B_W \cos(\theta_U - \theta_{sr})$$

equivalent linear gradient

$$\frac{1}{R} = \frac{1}{R_A} + \frac{1}{R_B}$$

THE MONIN-OBUKHOV LENGTH SCALE

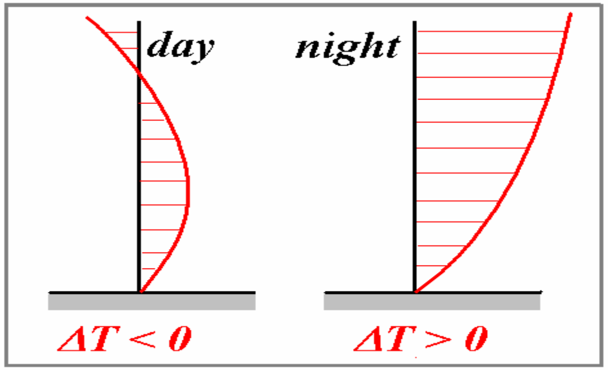
- $1/L = 0$ Neutral (heavy clouds)
- $1/L < 0$ Stable (night)
- $1/L > 0$ Unstable (sunny day)



COMBINED EFFECTS OF WIND AND TEMPERATURE GRADIENTS

Ratio D/R	Wind direction (2 m/s), D = 250 m					
Stability class	-90°	-45°	0°	45°	90°	
S1 : day, no clouds	-0.12	-0.11	-0.10	-0.10	-0.06	
S2 : days, clouds 50%	-0.10	-0.09	-0.07	-0.04	-0.02	
S3 : day, clouds 100%	-0.08	-0.06	-0.01	0.03	0.08	⇐ RMV-II
S4 : night, cloudy	-0.05	0.00	0.03	0.07	0.12	⇐ NMPB
S5 : night, clear sky	0.01	0.03	0.06	0.11	0.16	

Very favourable
Favourable
Neutral
Unfavourable
Very unfavourable

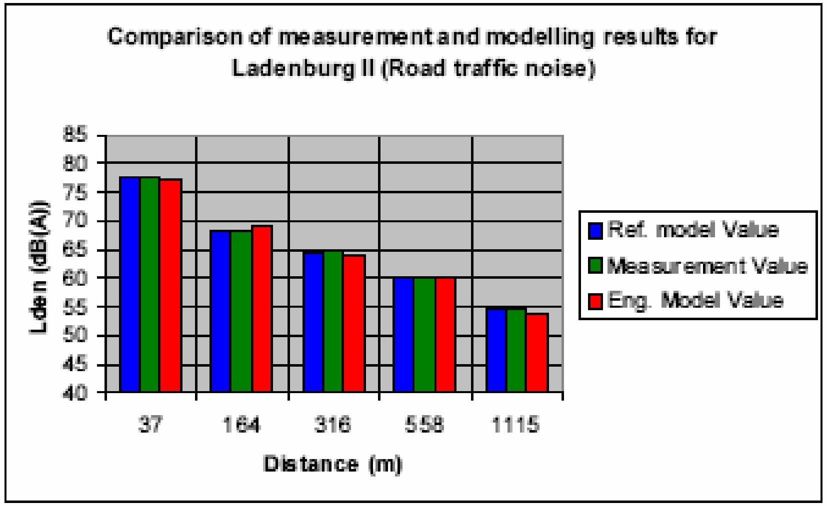


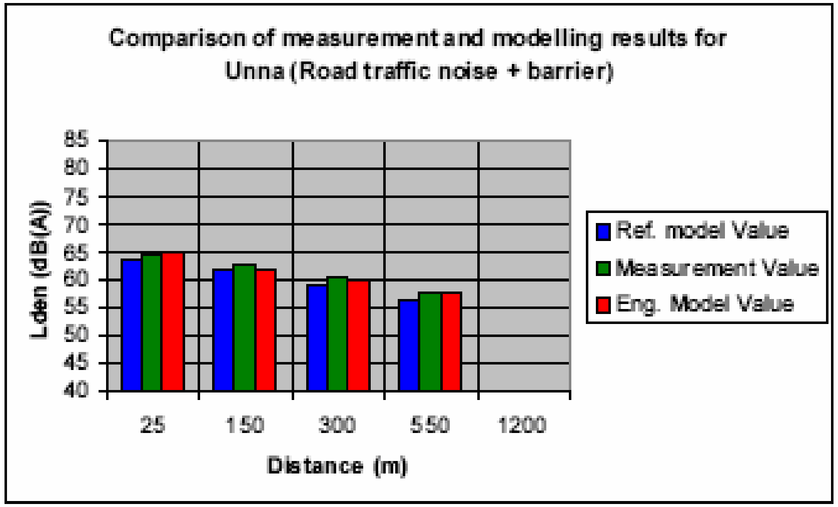
VALIDATION AGAINT EXPERIMENTAL RESULTS

Measurements: 2 to 10 weeks, records of sound levels and meteorological parameters (*W*, θ_W, *1/L*) in 30' steps

Reference models : lin/log sound speed profiles for each point source and for each time period

Engineering model : 8 wind directions, 3 wind speeds, 5 stability classes = 120 cases + frequency of occurrence





CONCLUSIONS :

- Multi-purpose, generic, propagation model based on “physical” principles
- Extended range of application (complex geometries, multiple screening,…)
- Accounts for “realistic” meteorological conditions
- Well adapted to be integrated in commercial noise mapping software
- Fast (enough ?) for all-day use in noise mapping
- On average, accuracy = 0.5 … 1.5 dB(A) compared to BEM & PE

NEXT STEPS :

- Integration in commercial noise mapping software
- More comparison with “real life” experimental data
- Feedback from end-users
- Fine-tuning & extensions

BUT :

A MODEL IS JUST A MODEL…