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METEO-BEM: A POWERFUL TOOL FOR COMPLEX OUTDOOR SOUND PROPAGATION

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ABSTRACT
This paper presents a model for complex atmospheric sound propagation problems above uneven absorbing grounds: Meteo-BEM [1-2]. This model is based on one hand on the Boundary Element Method, that allows the assessment of any kind of shape and absorption of the boundaries of the propagation-domain, and on the other hand on recent propagation models in inhomogeneous media accounting for meteorological effects. First, the theory of Meteo-BEM is briefly given and applied to the case of sound propagation with refraction (downward and upward) around a sound barrier. The results are then compared to experimental data obtained in controlled conditions with scale models (curved surfaces) using the TDS technique. The agreement shows that Meteo-BEM is a powerful tool for outdoor sound propagation prediction, which gives rise to many applications and developments.

1 - INTRODUCTION
In environmental acoustics there is today a need for models to predict long range sound propagation. In this case, meteorological effects become important. This work aimed to develop a model for complex atmospheric sound propagation above uneven absorbing grounds. On one hand, the Boundary Element Method is a powerful tool to assess for any kind of shape and absorption of the boundaries of the propagation domain, but this approach was restricted, up to now, to homogeneous media. On the other hand, recent propagation models above flat absorbing surfaces have been designed to account for meteorological effects. We have derived a new model: Meteo-BEM [1-2], based on the layer potentials formulation [3-4], and a) on the normal modes solution for downward refraction; b) in the case of upward refraction, on the residue series solution (shadow zone) and the geometrical theory (illuminated region) [5-6]. Section 2 presents briefly the model, applied to the case of sound propagation above an absorbing ground, around a thin rigid sound barrier, under various refracting conditions. Then a comparison between calculated and measured data is shown in section 3 and we conclude in section 4.

2 - THEORY
Consider the case of a rigid thin noise barrier on a flat ground of finite impedance Z (figure 1), in a refracting medium.
The scattered field by the screen can be represented by a double layer potential whose density is μ [3-4]. So, with $p_{0,inhom}$ the incident pressure due to the source S and G the Green's function of the problem considered, we can write for the acoustic pressure:

$$p\left(M\right) = p_0\left(M\right) + \int_\Gamma \mu_{inhom}\left(P\right)\partial_{n(P)}G\left(M,P\right)d\Gamma\left(P\right)\ ;\ \forall M\in\Omega \tag{1}$$

The acoustic pressure must verify the Neumann condition on the rigid screen, and we obtain the following Fredholm integral equation of the first kind:

$$-\partial_{n(M)}p_{0,inhom}\left(M\right) = PF\int_\Gamma \mu_{inhom}\left(P\right)\partial_{n(M)}\partial_{n(P)}G\left(M,P\right)d\Gamma\left(P\right)\ ;\ \forall M\in\Gamma \tag{2}$$

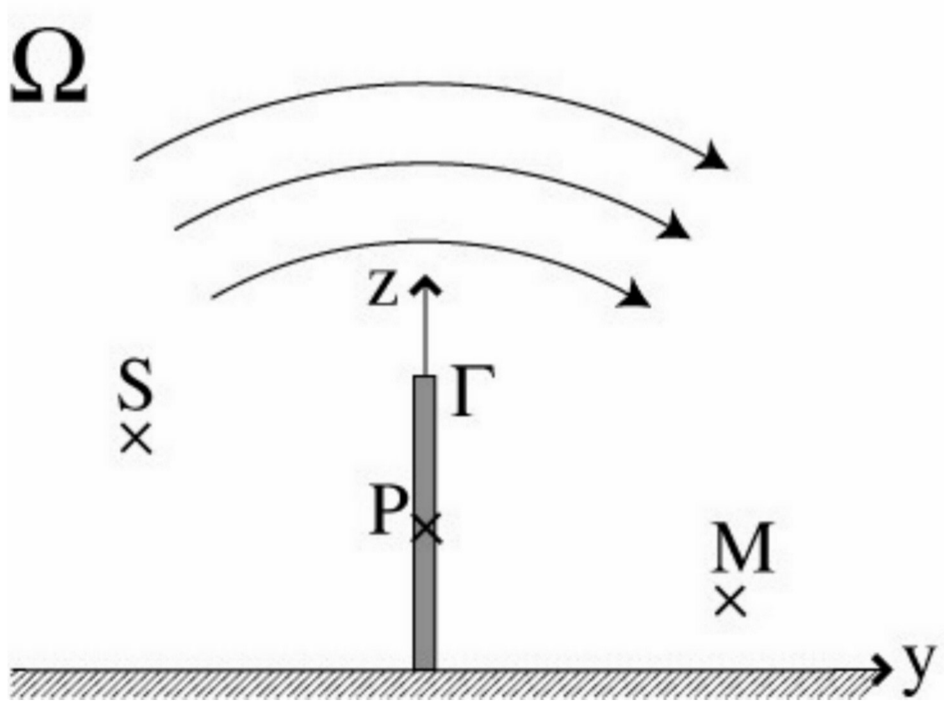

Figure 1: Thin noise barrier on a flat absorbing ground, under refracting conditions.

PF denotes the Hadamard finite part. It has to be emphasized here that ground and meteorological effects are included into the Green's function, so that the integration domain is reduced to the screen.
In the case of a downward refracting atmosphere, we can write the acoustic pressure in 2D (line source) for a linear sound speed profile as follows (normal modes solution):

$$G(S,M) = p_S(y_M, z_M) = \frac{i}{2l}\sum_n \frac{\exp(ik_n|y_M - y_S|)\, A_i(\tau_n + z_s/l)\, A_i(\tau_n + z_M/l)}{k_n\tau_n [A_i(\tau_n)]^2 - [A_i'(\tau_n)]^2} \tag{3}$$

where $\tau_n = \left(k_n^2 - k_0^2\right) l^2$ are the zeros of $A_i'(\tau_n) + qA_i(\tau_n) = 0$

$$k_0 = 2\pi f/c(0)\,, q = (ik_0 l\rho c)/Z, l = \left(R_c/2k_0^2\right)^{1/3}, R_c = c/(dc/dz)\, \tau = \left(k^2 - k_0^2\right) l^2 \tag{4}$$

R_c is the ray paths curvature radius, z_s is the source height and z_r the receiver height. k_n represents the horizontal wave number of the n^{th} mode (see [5]).
In the case of an upward refracting atmosphere, the acoustic pressure in 2D, for a linear sound speed profile, can then be written in the shadow zone (with the same notations as for downward refraction, cf [5]):

$$\begin{aligned} G(S,M) &= p_S(y_M, z_M) \\ &= \frac{e^{i\pi/6}}{2l}\sum_n \frac{\exp(ik_n|y_M - y_S|)\, A_i\left(b_n - (z_S/l)\, e^{2i\pi/3}\right) A_i\left(b_n + (z_M/l)\, e^{2i\pi/3}\right)}{k_n\left([A_i'(b_n)]^2 - b_n [A_i(b_n)]^2\right)} \end{aligned} \tag{5}$$

where $b_n = \left(k_n^2 - k_0^2\right) l^2 e^{2i\pi/3}$ are the zeros of $A_i'(b_n) + qe^{2i\pi/3}A_i(b_n) = 0$.
For propagation in the illuminated region, this residue series is divergent. Therefore, we have to use **(6)** for the Green's function, based on the geometrical theory and the analogy with propagation above a convex surface (see [6]).

$$G(S,M) = p_S(y_M, z_M) = -\frac{i}{4}H_0(kd) + Q\left[1 + \frac{d_2}{d_1} + \frac{2d_2}{R_c \mathrm{co\ s}\theta}\right]^{-1/2} - \frac{i}{4}H_0(kd_1)\, e^{ikd_2} \tag{6}$$

Here, Q is the 2D reflection coefficient. We can use for Q the 3D classical expression, which is a good approximation.

The integral equation **(2)** is solved using a collocation method. Note that for the right hand side of **(2)**, we can consider that vertical propagation is weakly affected by the refraction, so this term is at first approximated by the classical homogeneous term.
Once the layer density μ in an inhomogeneous medium is known, the acoustic pressure can be calculated at any receiver point with the integral formulation **(1)**.

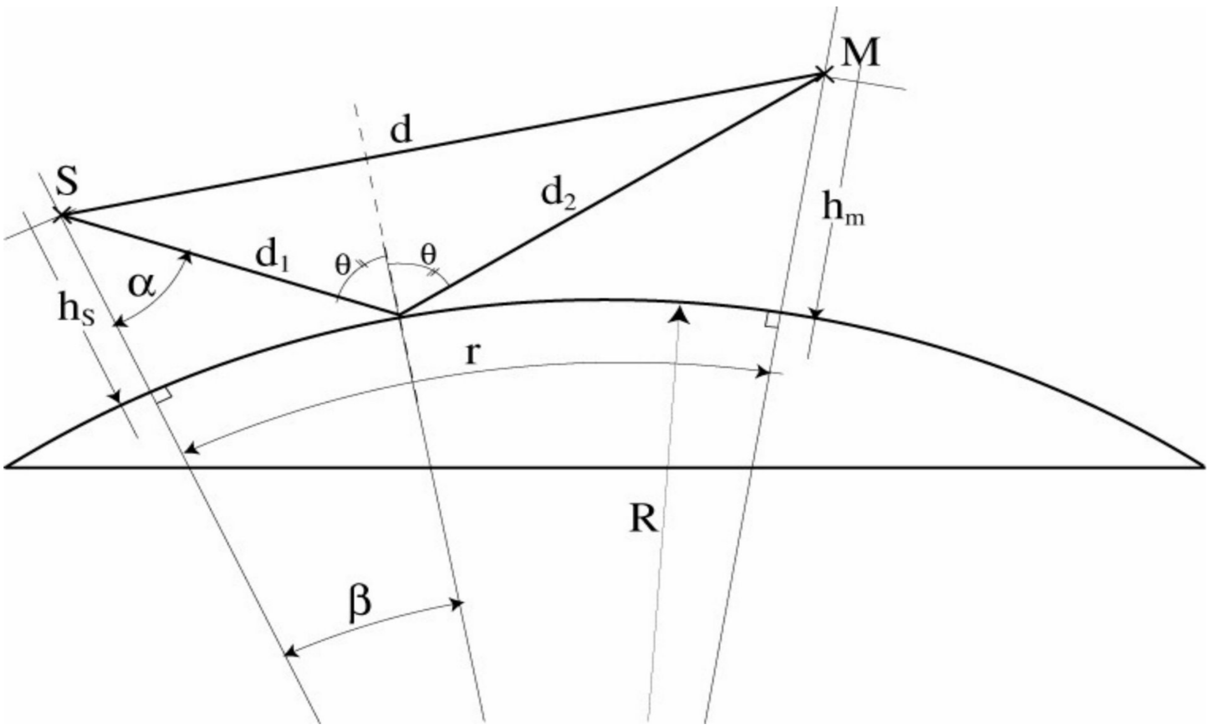

Figure 2: Notations for the geometrical model.

3 - COMPARISON WITH EXPERIMENTAL RESULTS

The results of Meteo-BEM are compared to experimental results obtained in controlled conditions, above rigid curved surfaces, in the scale model room of C.S.T.B. A rigid screen ($H = 0.1525$ m) can be set on the surfaces. We used the T.D.S. technique [6]. Figure 3 and figure 4 show the results in the case of a downward refracting atmosphere (concave surface, $R_c = 10.2$ m), respectively without and with a screen.
For figure 3 and figure 4, the source and receiver heights are $z_S = 0.04$ m and $z_R = 0.10$ m, the receiver and the screen are respectively at a distance of 2 m and 0.5 m from the source.
Figure 5 and figure 6 give the results for upward refraction (convex surface, $R_c = 5$ m), without and with a screen. The agreement between calculated and measured data is good and shows that meteorological effects can be included in a Boundary Element Method.
For figure 5 and figure 6, the source and receiver heights are $z_S = 0.007$ m and $z_R = 0.025$ m, the receiver and the screen are respectively at a distance of 2.05 m and 1.6 m from the source.

4 - CONCLUSION

The results prove that Meteo-BEM allows one to calculate accurately the sound field in a complex outdoor environment. Work is in progress in order to extend Meteo-BEM to a wide class of real cases (propagation above uneven grounds and above an impedance discontinuity e.g. in refracting conditions). Other investigations need to be pursued in order to study complex sound propagation problems in range dependent media.

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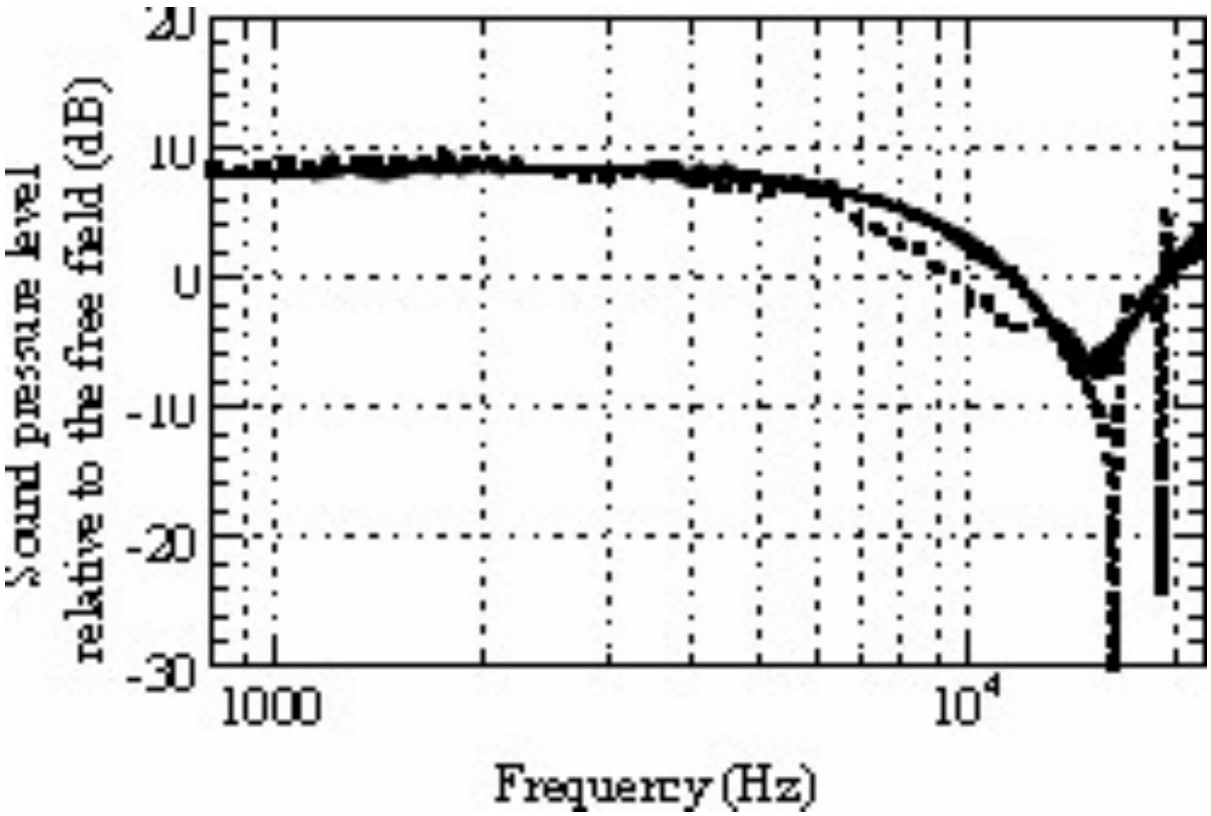

Figure 3: Comparison of the 2D normal modes solution with TDS measurements above a concave surface without any screen (solid line: calculated data; dashed line: measured data).

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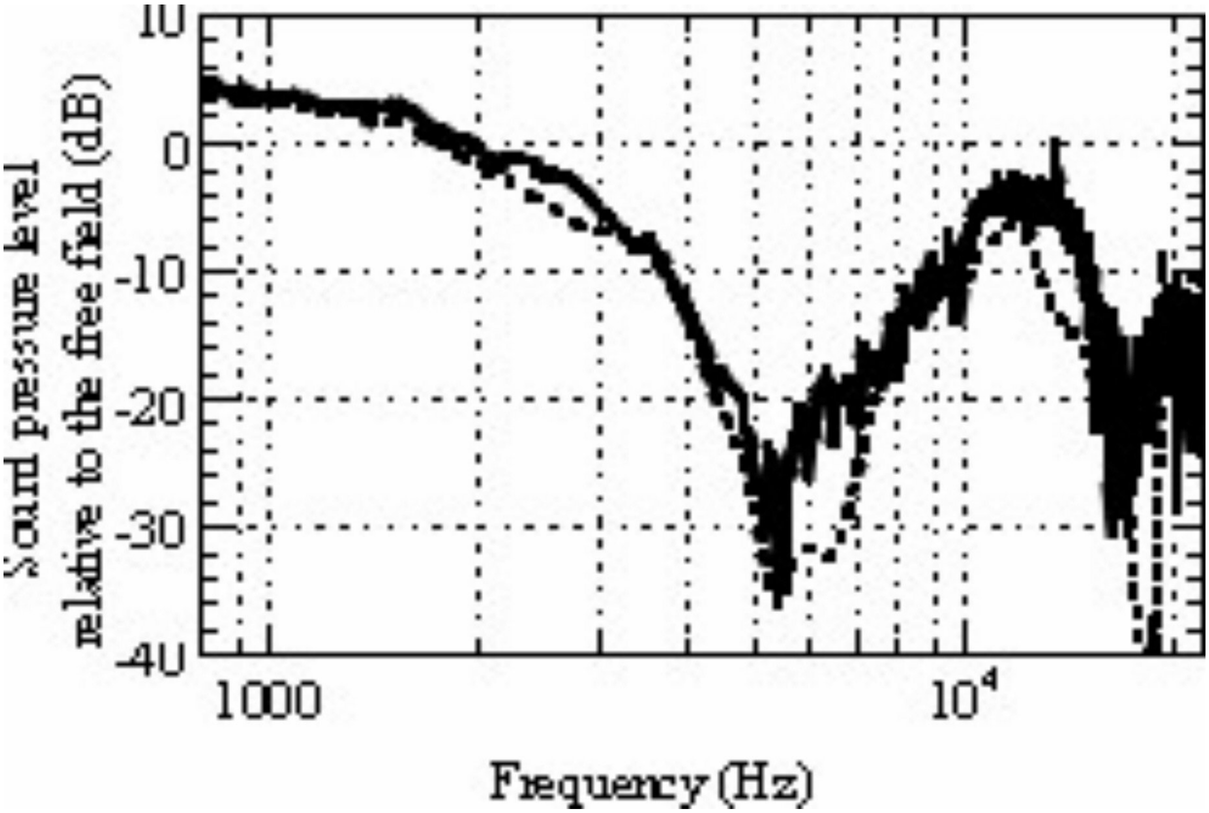

Figure 4: Comparison of Meteo-BEM with TDS measurements above a concave surface with a screen (solid line: calculated data; dashed line: measured data).

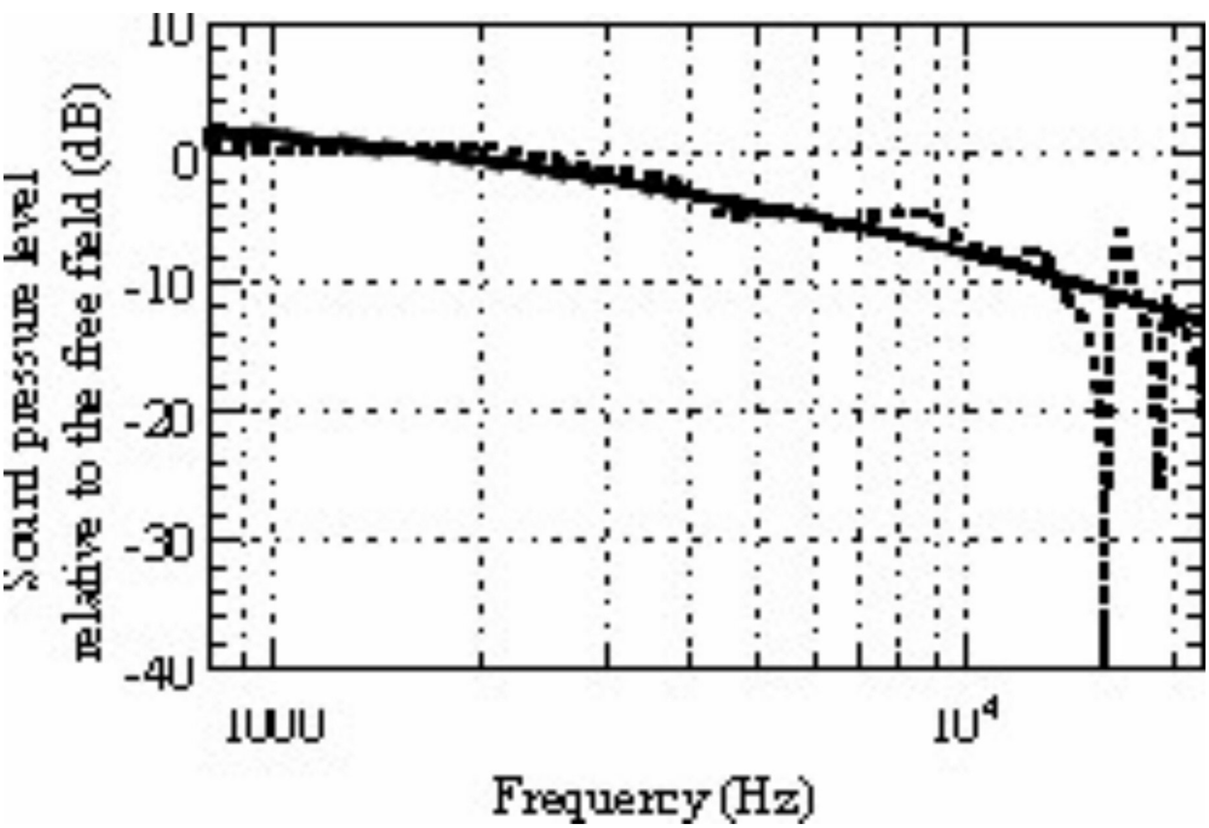

Figure 5: Comparison of the 2D model geometrical theory + residue series with TDS measurements above a convex surface without any screen (solid line: calculated data; dashed line: measured data).

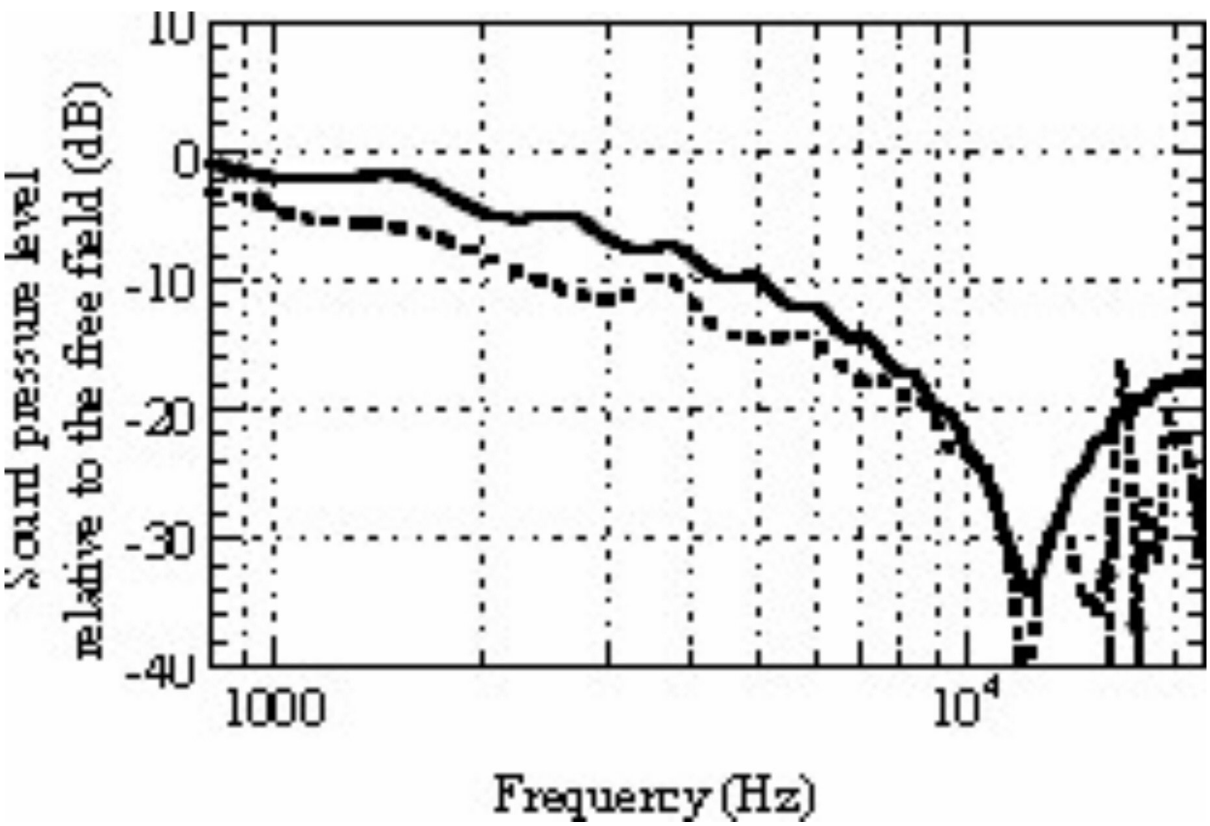

Figure 6: Comparison of Meteo-BEM with TDS measurements above a convex surface with a screen (solid line: calculated data; dashed line: measured data).