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COMPUTATION AND APPLICATIONS OF DIRECTIONAL ECHOGRAMS IN ROOM AND CONCERT HALL ACOUSTICS

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ABSTRACT
Directional echograms give the temporal distribution of acoustical energy at the receiver, for one particular direction of incidence. They can be used to enhance the quality of auralization in room acoustics. In this paper, we study the possible applications of these diagrams in room acoustics projects. This research is based on computed (not measured) directional echograms, which are evaluated by a sound ray program. Their determination is not very different from traditional echograms, except that the receiver is surrounded by a "transparent" sphere divided into 26 solid angles. Each of them acts as a directional microphone, collecting the sound rays in a particular direction, which leads to 26 directional echograms at each receiver position. Directional echograms have been computed in several rooms. These applications show that these diagrams are particularly useful in the detection of potential flutter echoes, lack of diffusivity and asymmetrical distribution of absorption. They explain significant differences between T30 and EDT, as a result of non-linear energy decays, and they can suggest optimal placement of absorbing and/or diffusing material to attenuate reverberation.

INTRODUCTION
In rooms and concert halls, spatial impression, listener envelopment and sound localization are created by the spatial distribution of the sound field around the listener. Some room acoustics parameters have already been defined to characterize these impressions, like IACC or Lateral Energy Fraction [1].

Originally, directional echograms have been defined to enhance the quality of the sound field reproduction in auralization cues, especially concerning the spatial distribution of the acoustical energy around the listener's head [2]. A directional echogram is simply defined as the time evolution of acoustical energy at the receiver (when an impulse signal is emitted by the source), but for one particular direction of incidence only (figure 1). The "traditional" echogram (or "omnidirectional" echogram) would therefore be retrieved by the integration of the directional echogram over all possible directions of incidences.

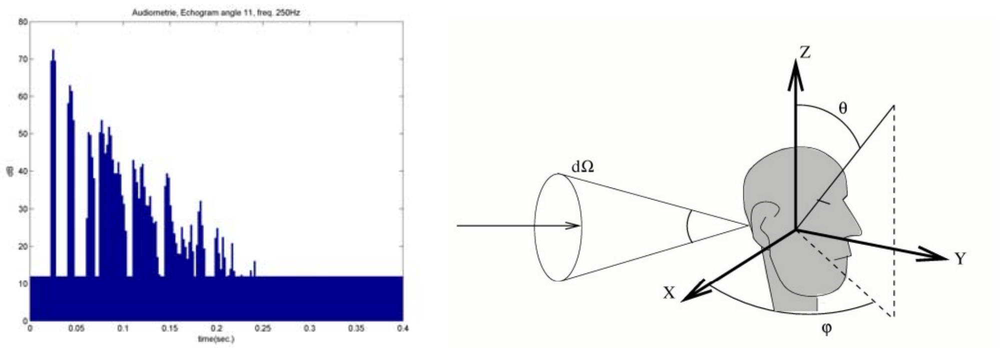


Figure 1.-A directional echogram gives the distribution of acoustical energy at the receiver (dB) contained in the solid angle dΩ, versus time arrival (s).

Apart from this application in auralization, directional echograms can also contain useful information for the design of acoustical spaces, like concert halls. In this paper, some examples of applications will be described to illustrate which kind of information, and which types of rooms are concerned.

COMPUTATION OF DIRECTIONAL ECHOGRAMS

The directional echograms could be measured with a directional microphone. Our research work is rather based on computed directional echograms, which are evaluated by a sound ray program [3,4]. Their determination is not very different from traditional echograms, except that the receiver is surrounded by a "transparent" sphere divided into 26 solid angles (fig. 2). Each of them has an extent of 45 degrees in azimuth and elevation (except the one at the “north pole” and the one at the “south pole”, which both have a conical shape with an aperture of 45 degrees) and acts as a directional microphone, collecting the sound rays in a particular direction, which leads to 26 directional echograms at each receiver position.

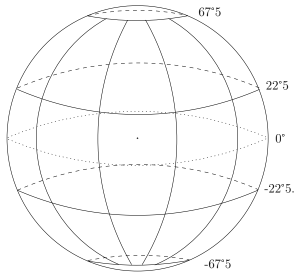


Figure 2.-Definition of the 26 solid angles around the listener’s head (the azimuth discretization angle is 45 degrees).

The contributions of the collected sound rays are added to give the squared-pressure (Pa^2) time-distribution, for each direction of incidence (i.e. for each solid angle). A discussion about the number of solid angles can be found in [2].

APPLICATION IN TWO “ACADEMIC” ROOM ACOUSTICS PROBLEMS

We first compute the directional echograms in two “academic” rooms, which have been used by Hodgson in his early experiments on diffusion effects in room acoustics [5].

The first one (Room A) is a cubic room (side length : 27.5m, absorption coefficient of all faces : 0.068, scattering coefficient : d=0 or 1). The point source is at mid-height, at 4m from one of the vertical face. The receiver is also at mid-height, and at 5m from the source.

Figure 3 shows the directional echograms (filtered in the 1 kHz octave band) computed at the receiver, for six directions of incidence. These are indicated as “up”, “front”, “left”, ...and so on, referring to the virtual listener who is situated at the receiver position, looking horizontally to the source: “front” therefore indicates the source-to-receiver direction of incidence. Specular reflection is assumed for all surfaces (d=0) in that case.

It is first observed that, in this room, the directional echograms are quite similar (except in their early part). The energy decay is approximately linear, indicating a diffuse sound field (even if the reflections are specular). In the “front” echogram, the direct sound contribution clearly appears. Moreover, the early part of this echogram is clearly dominated by the first-orders image sources created by the specular reflections on the “front” and “back” walls. This regular structure of the early part of the “front” echogram is also visible on the “rear” echogram and, in a less extent, on the “up” and “down” ones : it clearly indicates the presence of a flutter echo in those directions. After some reflections, the regular structure disappears, because the corresponding solid angle is so large that it now includes image sources not representative of this flutter echo.

When all reflections are diffuse (d=1 for all surfaces), the directional echograms are similar to those presented in figure 3, except that there's no flutter echo anymore (not shown). All directional echograms have the same linear structure, except the direct sound contribution which is still present in the "front" echogram.

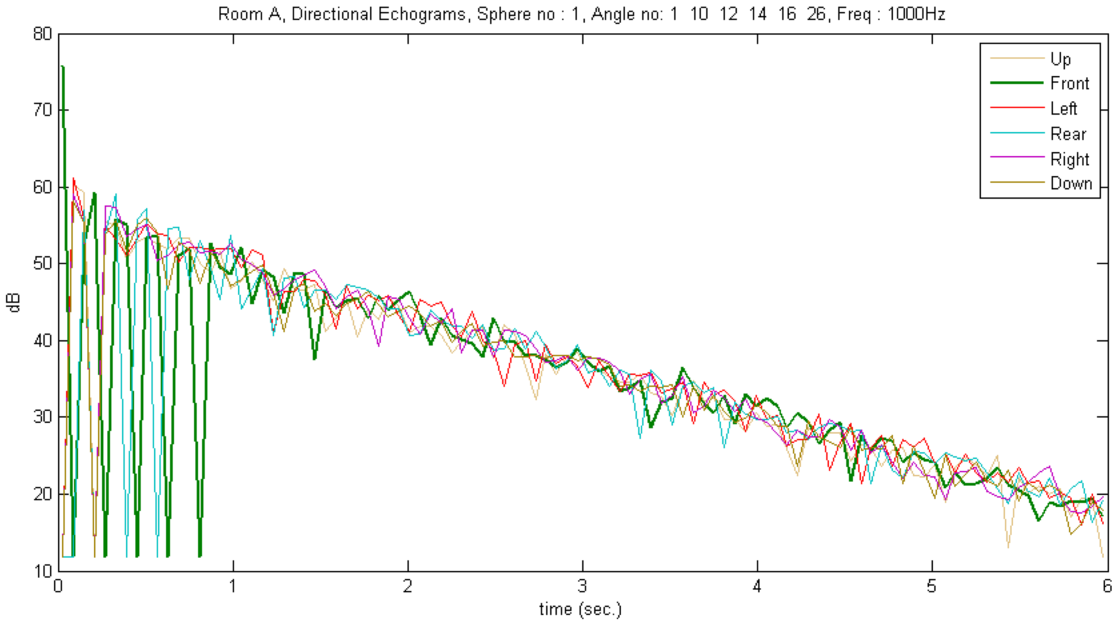


Figure 3.-Directional echograms computed in Room A (1 kHz), for six particular directions of incidence. All reflections are specular (d=0).

The second room (Room B) is a long disproportionate room (55m x 110m x 5.5m, absorption coefficient of all faces : 0.068, scattering coefficient : d=0 or 1). The point source is at mid-height, situated on the long axis of the room, and at 10m from the closest vertical surface. The receiver is also at mid height, on the same axis, and at 5m from the source.

Figure 4 shows the directional echograms (filtered in the 500 Hz octave band) computed at the receiver, for six directions of incidence. The virtual listener who is situated at the receiver position is still looking horizontally to the source.

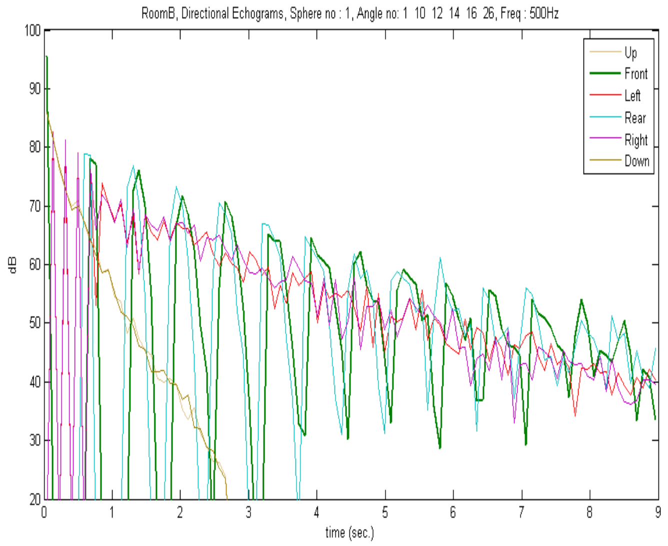
In this room, the directional echograms are clearly different, if specular reflection is assumed for all surfaces (d=0). The "up" and "down" echograms decrease more rapidly than the others, since their decay is mostly governed by the sound rays travelling in non-horizontal directions, which statistically have a much shorter mean free path. Also, the decay seems somewhat longer in the front-back direction, than in the left-right one. The consequence of this is that the corresponding "omnidirectional" echogram is obviously non-linear, with a steeper energy decay at the beginning (figure 4), leading to a much shorter Early Decay Time (EDT) than the reverberation time T30 at 500 Hz.

If a reduction of the reverberation time is required, it is therefore suggested to increase the acoustical absorption of the vertical walls, preferably. Another solution would be to increase their surface diffusion. Indeed, with d=1 for all surfaces, the directional echograms perfectly coincide after their initial part (not shown), and the corresponding reverberation time drops from 16.4s (d=0) to 4.3s (d=1) at 500 Hz, without changing the absorption coefficients.

We can also observe on the figure 4 :

- the contribution of the direct sound, on the "front" echogram only (the receiver is quite close to the source, so this contribution is still visible);
- the regular structure of the "front-back" flutter echo, as in Room A;

- the similarity between the "left" and "right" echograms, and between the "up" and "down" ones, by symmetry. If they perfectly coincide in their initial part, more significant differences appear in their mid- and late parts, due to the statistical errors inherent to the sound ray process. These statistical errors are discussed in [2].



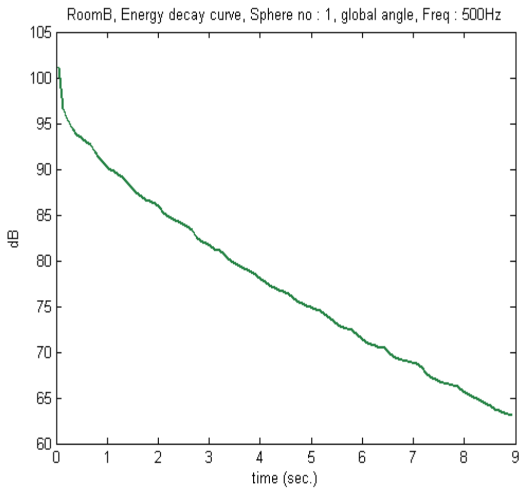
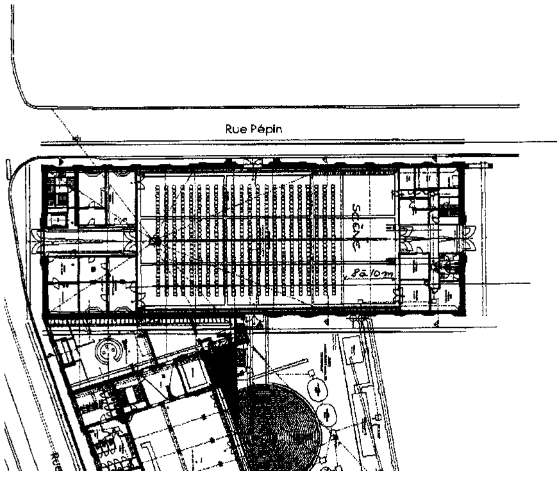


Figure 4.-Left : Directional echograms computed in Room B (500 Hz), for six particular directions of incidence. All reflections are specular (d=0).
Right : Corresponding omnidirectional (traditional) energy decay curve.

As a conclusion of these "academic" room acoustics problems, it can be said that directional echograms can afford interesting additional information (compared to "traditional" echograms), especially for disproportionate rooms, with rather few surface diffusion and asymmetrical distribution of acoustical absorption. All these conditions are supposed to create non-diffuse acoustical fields.

APPLICATION IN A REAL ROOM ACOUSTICS PROJECT

The project is the renovation of an ancient horse-riding school into a concert hall. The main hall is shown in figure 5, the scene is on the right of the figure. The dimensions are 21.5m x 37.6m x 15m (height). The audience is tilted (14°), and the seats can be removed to transform the concert hall into an exhibition hall.



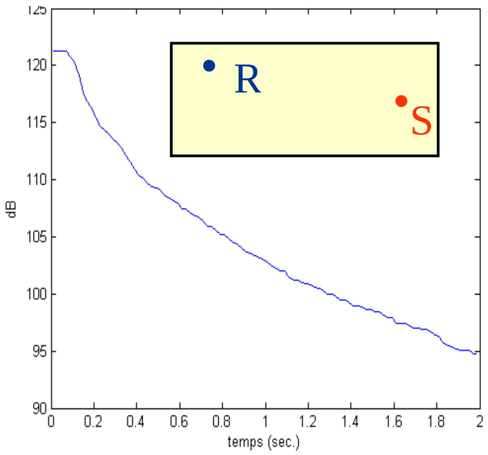


Figure 5.-Left : Renovation of an ancient horse-riding school into a concert hall
(*by courtesy of "Architecture & Urbanisme Francis HAULOT sprl"*).
Right : Energy decay curve computed at 1 kHz, at receiver position (R), the source being in (S).

In the initial project, the architect proposed to place absorbing panels on the ceiling, the vertical walls being reflecting. The first simulations revealed a very different EDT value (1.4s at 1kHz) from the reverberation time T30 (5.6s at 1kHz). This is also apparent on the energy decay curve, obtained by backward integration of the "omnidirectional" echogram, which shows a significant non-linear character.

The question was then to identify the origin of this long reverberation time, and to find the most efficient solution to reduce it. The directional echograms are shown in figure 6. They clearly show that the late part of the reverberation is dominated by the left-right reflections, the front-back modes being attenuated by the absorption of the tilted audience (seats' absorption), and the up-down reflections by the absorption of the ceiling. This is also clearly illustrated by the corresponding "directional" energy decay curves in figure 7, and by the reverberation times computed from the directional echograms in the directions of the horizontal plane (fig. 7, right).

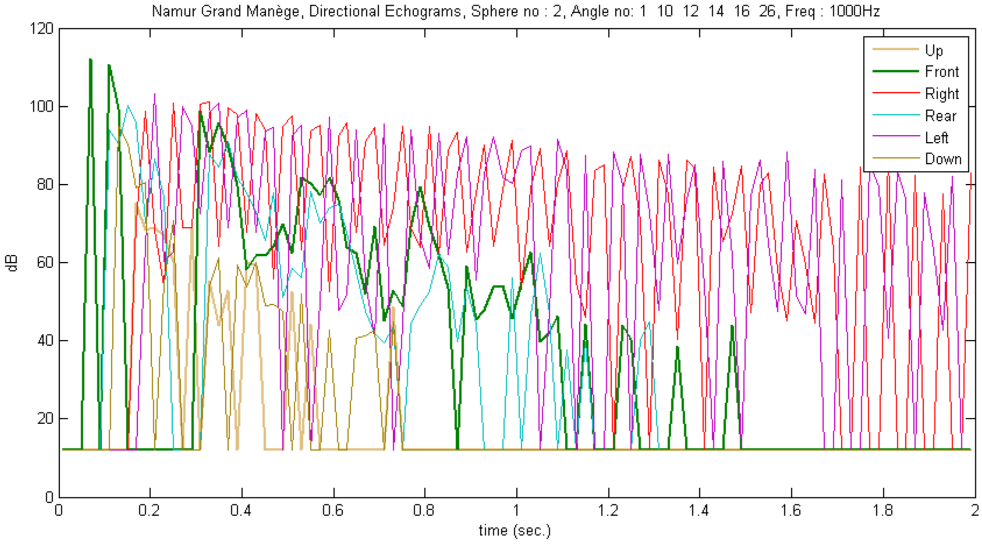


Figure 6.-Directional echograms computed in the concert hall (1 kHz), for six particular directions of incidence (same receiver position as in figure 5).

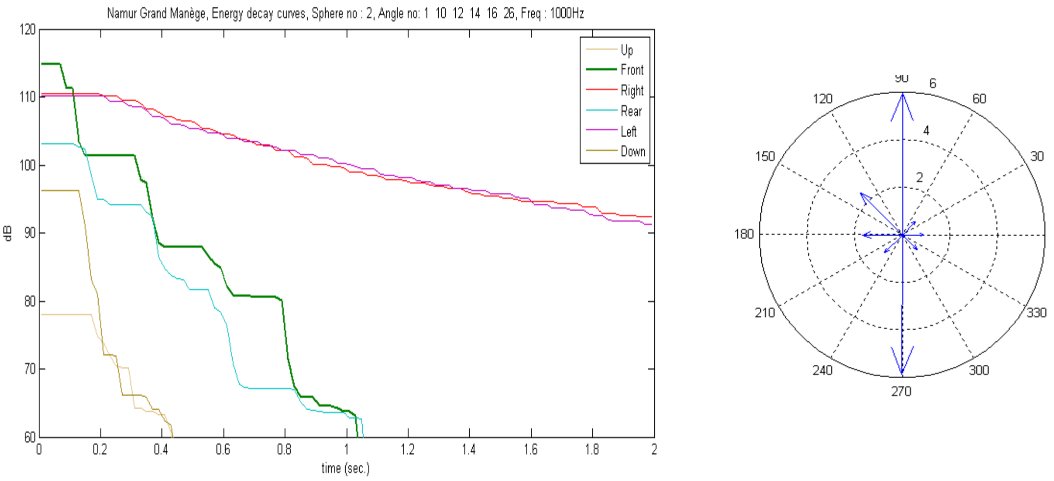


Figure 7.-Left : Directional energy decay curves (1 kHz), corresponding to figure 6.
Right : Reverberation times T30 computed in the horizontal plane (0 degree is the "front" direction, 90 degree is the "left" one, ...).

We can also observe in figure 6 the characteristic structure of the “left” and “right” echograms, identifying a flutter echo in the left-right direction.

All this analysis suggests that the priority to reduce the reverberation time is to attenuate the reflections in the left-right direction, which has been proposed as a first solution. More precisely, it has been suggested to place absorbing panels (20 m^2) and diffusers (45 m^2) on the right (when looking to the scene) wall. Diffusers are useful to break the flutter echo, which has been detected in figure 6. A new simulation has been performed with these data, and the calculated “directional” energy decay curves are shown in figure 8. Comparing with figure 7, it is clear that the left-right echograms have been drastically shortened, while the other directional echograms show less significant differences. The reverberation time T30 has dropped from 5.6s to 1.9s at 1kHz.

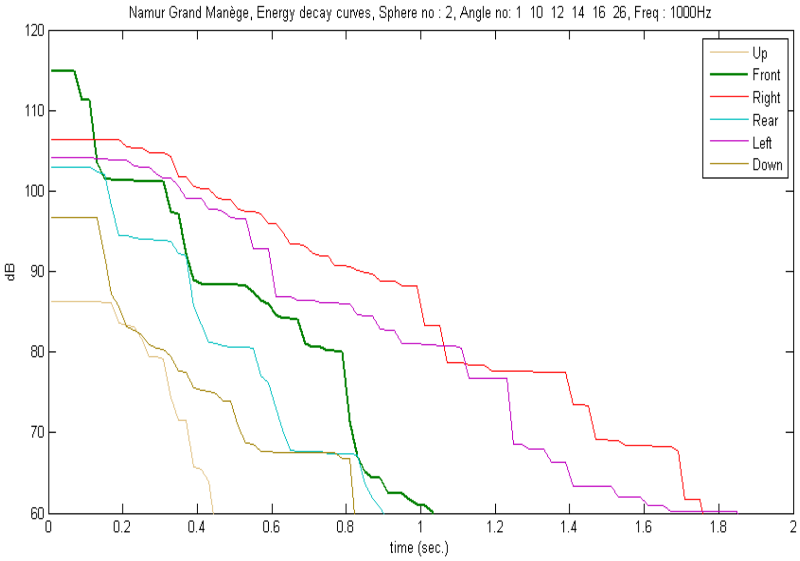


Figure 8.- Directional energy decay curves (1 kHz), computed in the concert hall with an acoustical treatment of the right wall (same receiver position as in figure 5).

The whole project will not be reported here, but this first step already illustrates which kind of information can be learned from the observation of directional echograms, and how this observation can suggest efficient actions to modify the acoustical parameters of the room.

CONCLUSIONS

Directional echograms can deliver original information in room and concert hall acoustics projects, especially in non-diffuse acoustical fields (disproportionate rooms, specular reflections, asymmetrical distribution of acoustical absorption). They are particularly useful in the detection of potential flutter echoes and lack of diffusivity. They explain the significant differences that can occur between EDT and T30 values, resulting from non-linear energy decays. Finally, they can suggest the optimal placement of absorbing and/or diffusing material to attenuate reverberation.

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