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Objective study of spatial attributes in the room impulse response's late part and their relevance for auralization

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ABSTRACT

The addition of directivity in the early part of the room impulse response improves the quality of auralization. Its effect is twofold as both source localisation and source width are more accurately simulated. However, for the late part of the impulse response, the contribution of the sound field spatial attributes to the auralization's quality must be investigated. Briefly stated, is the evaluation of the omnidirectional response sufficient or do directional impulse responses represent an improvement? In this paper, the listener envelopment is objectively studied through the spatially balanced center time and the late part lateral energy fraction. Those criteria are evaluated in some test situations by the ray-tracing program Salrev. In this program, the spherical sound receptors are divided in a variable number of solid angles (here 26) allowing the evaluation of the directional impulse responses. So, objective comparisons between directional and omnidirectional impulses are carried out for different rooms' geometries and reflection laws.

1. INTRODUCTION

In rooms and concert halls, the spatial structure of the reverberated sound field, the incidence angle of the acoustic energy, is responsible of the room's spatial impression[1]. This impression is related to two subjective dimensions: the apparent source width[2] and listener envelopment[3] (LEV). The apparent source width is related to the spatial structure of the early part of the room impulse response[4-5] (RIR) whereas the LEV is linked to the spatial structure of the late part of the RIR[2,6-7].

Auralization systems[8] (sound rendering of RIRs) try to recreate the spatial dimension of the sound fields. While recreating the spatial structure of the early part of the RIR improves considerably the realism of the obtained auralization (mainly by improving the localisation cues), spatial attributes of the RIR's late part are seldom considered. To the authors' knowledge, only

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two systems consider the directionality of the RIR's late part through directionnal echograms: VirKopf via the program RAVEN[9] and Auralias[10] via the program Salrev[11-12]. For both systems, a convolution is carried out for each directional echogram. Auralization systems tend towards real-time capabilities and this convolution stage is very time consuming. So, the question about the relevance of such thorough modelling to auralization can be arisen.

In this paper, this question is addressed through the objective study of spatial attributes of the echograms late part (no subjective tests have been carried out). It is recalled that RIRs late part is obtained after the calculation of the directional echograms. These spatial echograms obtained with the geometrical-acoustics program Salrev will be investigated. Three kinds of results will be compared: the omnidirectional echogram, this omnidirectional echogram with image sources up to the third order and the directional echograms.

Firstly, two objective criteria describing the spatial and temporal contents of the RIR will be presented. Then, Salrev will be briefly described. In section 4, three geometrical configurations typical of room-acoustics (a proportionate room, a flat room and a long room) will be studied for various diffusion and absorption coefficients values. An application to a more realistic case, the HELMIA hall[13], will be carried out in section 5 and then, conclusions will be drawn.

2. LISTENER ENVELOPMENT CRITERIA

To measure the listener envelopment (LEV), Beranek[6] suggested the utilization of $IACC_{\mathrm{L3}}$ which the mean of the interaural cross-correlation late part over the 500 Hz to 2000 Hz octave bands. On the other hand, Bradley and Soulodre[7] obtained a better correlation with subjective tests using the late part of the lateral energy fraction averaged over the octave bands from 125 Hz to 1000 Hz. This criterion, late lateral energy strength (GLL), can be defined by[3]:

$$\mathrm{GLL} = 10\log\frac{\int_{0.08}^{\infty} p_F^2(t)\,dt}{\int_{0}^{\infty} p_A^2(t)\,dt} \text{ in dB,} \tag{1}$$

where $p_F(t)$ is the RIR measured using a figure-of-height microphone with its null pointing toward the location of the source and $p_A(t)$ is the response of the same source at 10 m in free field. The drawback of this criterion is the occurrence of abrupt jumps due to acoustical energy arriving in the vicinity of the 80 ms threshold.

To consider both the temporal and spatial aspects of reverberation, Hanyu and Kimura[15] suggested a modification of the central time (T_s), the spatially balanced center time (SBT_s). T_s is an indicator of the intelligity[16]: the shorter the T_s, the better the intelligibility. For energy arriving from direction i, T_{si} can be evaluated through[15]:

$$T_{Si} = \frac{\int_{0}^{\infty} t\times p_i^2(t)\,dt}{\int_{0}^{\infty} p^2(t)\,dt}, \tag{2}$$

where $p_i(t)$ is the RIR limited to the i incidence direction and $p(t)$ omnidirectional RIR measured at the same location. This T_{si} is weighted by its incoming angle θ_{Li} from binaural axis (Figure 1):

$$a_i = T_{Si} \times \left(1 + \left|\cos\theta_{Li}\right|\right)/2\,, \tag{3}$$

where θ_{Li} varies between 0 and 2π. a_i reaches a maximum in the binaural axis and is different to zero in the front/back direction. The interaction of the reflections coming from other directions is evaluated with[15]:

$$b_i = a_i \sum_{j=0}^{n} \left| a_j \sin\left(\theta_{ij}/2\right) \right|\,, \tag{4}$$

where a_j is the contribution from the reflections coming from direction j and θ_{ij} the angle between the direction of arrival i et j (also varying between 0 and 2π, see Figure 1). In the original paper[15], the absolute value in relations (3) and (4) doesn't appear. However, the authors found that its presence is necessary to ensure the coherence of the results. Finally, the b_i of every reflection are integrated:

$$SBT_S = \sqrt{\sum_{i=0}^{n} b_i} = \sqrt{\sum_{i=0}^{n} a_i \sum_{j=0}^{n} a_j \sin\left(\theta_{ij}/2\right)}\,. \tag{5}$$

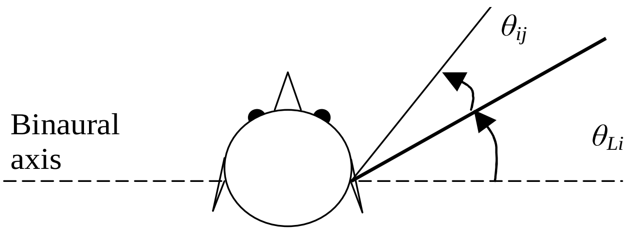

Figure 1: Angles defining the direction of sound incidence at the listener's head.

3. SALREV

Salrev is a geometrical-acoustics program associating the ray-tracing method and the image sources method. The visible images sources are found using the hybrid method developed by Vorländer[17]. The visible images are detected via the specularly reflected rays; these rays do not then contribute to the echogram. These images model more accurately the specular reflections up to a user-defined order (3 in this study) and reinforce the localization cues to the listener.

For the ray-tracing part, the program uses the splitting coefficient method[12]. Instead of a sequential succession of ray-launchings, one for every frequency, one launching is employed for all the frequency bands. Computation time is thus reduced at the expense of a loss of the statistical accuracy[12]. The receiver is a sphere with variable diameter which permits to obtain omnidirectional echogram. To compute the directional echograms, this sphere is divided into 26 solid angles[11] (Figure 2): 24 with 45° azimuth and elevation angl es and 2 conical for the top and bottom. Each angular sector acts as a directional microphone, collecting the incoming rays depending of their incidence direction, which lead to 26 directional echograms at each receiver position. Besides improving the spatial definition of the computed acoustic field[11], these directional echograms can help to detect acoustic flaws[14] like flutter echoes, lack of diffusivity and asymmetrical distribution of absorption.

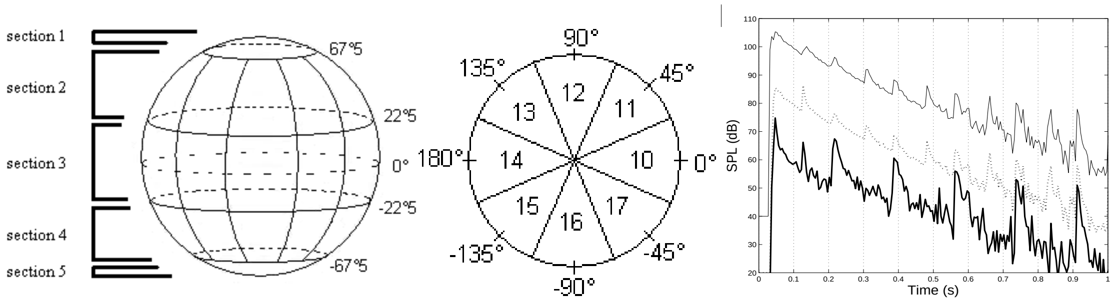

Figure 2: Definition of the 26 solid angles (left), top view of section 3 (middle) and echograms of sector 10 for the long room for s=0.10: (**—**) directional echograms, (—) omnidirectional echograms shifted of 40 dB, (▪▪▪) omnidirectional echograms with image sources shifted of 20 dB.

At each receiver position, a list of image sources with their characteristics, an omnidirectional echogram and 26 directional echograms are obtained with Salrev. In this study, three spatial models will be compared. For the first one, the simplest, the image sources are added to the omnidirectional echogram and the resulting echogram is divided into the 26 angular sectors. In the second model, the energy of the omnidirectional echogram is first distributed over the angular sectors and the image sources are then added in accordance with their incidence angle. The third model is composed of the directional echograms including the image sources according to their incidence angle. An example of the obtained echogram is shown in Figure 2. Finally, the GLL is computed via relation (1) and the SBT_s is evaluated using (5) at ears height.

4. TYPICAL ROOM-ACSOUTICS GEOMETRIES

A. Numerical parameters

Three geometries typical of room-acoustics are inquired (Figure 3): a room with proportionnate dimensions (5x4x3) m^3, a long room (30x2x3) m^3 and a flat room (30x30x3) m^3. The sources are located at (1;2;1) m, (1;1;1) m and (1;14;1) m and the sound receivers at (4;2;1) m, (14;1;1) m and (14;14;1) m, respectively. Each sound receiver is directed towards the source (the 0° azimuth and elevation angles are in the source direction). This direction has been chosen because, most of the time, the listener gaze is directed towards the sound source. The sound receivers' diameter is 0.5 m. For the long and proportion rooms, 1 000 000 rays are emitted and, for the flat room, 5 000 000. The echograms are computed over 400 time steps of 5ms.

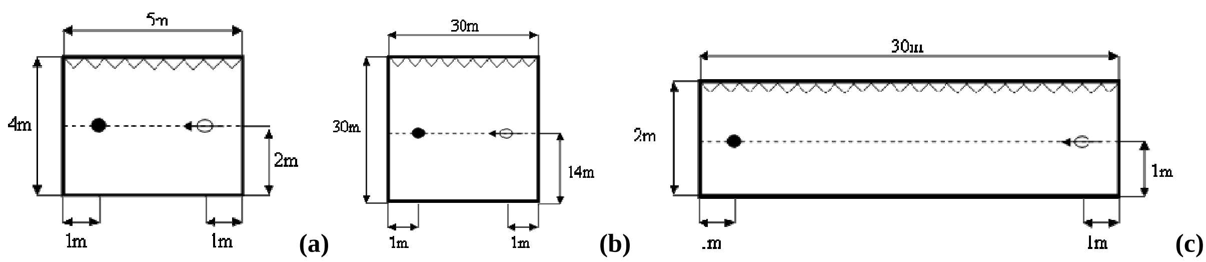

Figure 3: Sketches of the studied geometries, (a) proportionate room, (b) flat room and (c) long room: (●) source, (o) receiver and (\/) wall with modifiable absorption. The arrow indicates the receiver orientation.

Two acoustics parameters are studied. Firstly, the scattering coefficient value, s, is varied from 0.05 (specular reflection law) to 1 (pure Lambert diffuse reflection) at every wall. The absorption value is homogeneous and set to 0.1. Secondly, the absorption coefficient of the right hand wall (in the sound receiver's basis) is varied from 0.1 to 1 (Figure 3) with s set to 0.4.

B. Diffusion coefficient

Apart from the SBT_s value in the long room, the LEV decreases with increasing scattering coefficient value (figure 4). It implies that the LEV is more related to strong discrete reflections (caused by specular reflecting walls) than to a homogenous reverberated sound field (due to scattering at walls). The noticeable exception is the evolution of the SBTs in the long room which increases from a minimum reached at 0.2.

The evolution of the T_s around the sound receiver for the long room is plotted in Figure 5, 0° being the direction of the sound source. For both specular configurations (s=0.05 and 0.2), the evolutions are characterised with two maxima occurring at 0° and 180°, along the room's length. The increasing of scattering, from 0.05 to 0.2, implies that the T_s value for the 0° and 360° sectors is reduced from 20 ms to 11 ms. On the other hand, the T_s of the other sectors does not increase significantly. This result is responsible of the decrease of SBT_s observed in Figure 4.

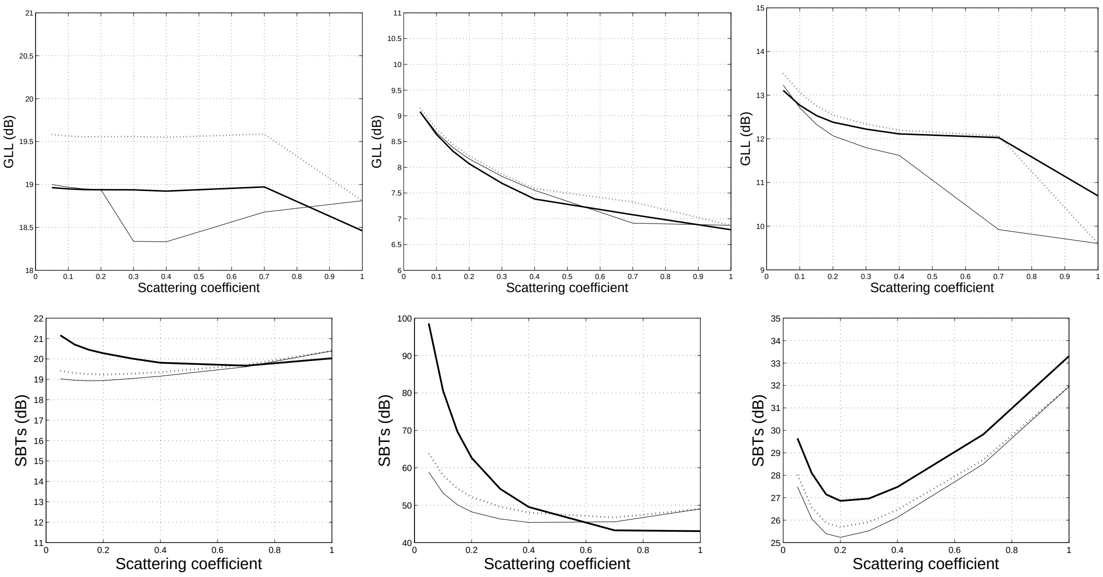

Figure 4: LEV as a function of the scattering coefficient value; (left) proportionate room, (middle) flat room and (right) long room; (top) GLL, (bottom) SBT_s: (▬) directional echograms, (—) omnidirectional echograms, (▪▪▪) omnidirectional echograms with image sources.

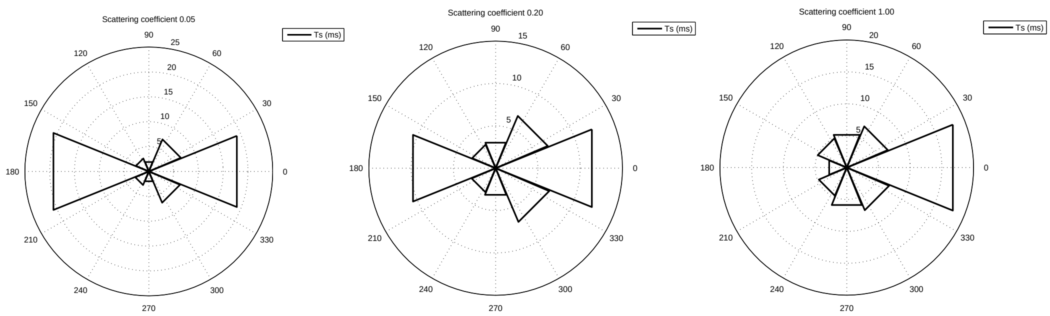

Figure 5: Angular distribution of T_s around the sound receiver in the long room obtained with the directional echograms; (left) s=0.05, (middle) s =0.20 and (right) s =1.00.

Concerning the diffuse case (s=1.0), the value of the 180° sector decreases steeply to 2 ms due to the vanishing of specular reflections from the back wall whereas the T_s values of for angular sectors, 90°, 135°, 225° and 270°, rise up to 5 ms. The increase of SBT_s observed in Figure 4 is then due to increasing energy coming towards the lateral directions.

If the three echogram's models are compared, the obtained results are very similar apart for the SBT_s in the flat room when specular reflections are dominant. This case departs the most from a diffuse sound field. Nevertheless, it can be stated that the directional echograms do not seem to noticeably increase the LEV even for non diffuse sound field as in flat and long rooms.

B. Absorption coefficient

When the absorption coefficient of the right hand side wall is increased (Figure 3), the LEV decreases in every configuration. While the GLL shows no difference between the tested models, the STB_s reveals different behaviours (Figure 6). Figure 7 shows the T_s angular distribution for the three models. With the omnidirectional echogram, this distribution is, as expected, homogeneous whereas the other two models present maxima along the room's length. For the directional echograms, the T_s for is almost negligible the lateral sectors. Due to the absorbent wall, the sound decay in the transverse direction is very quick resulting into a decrease of the LEV.

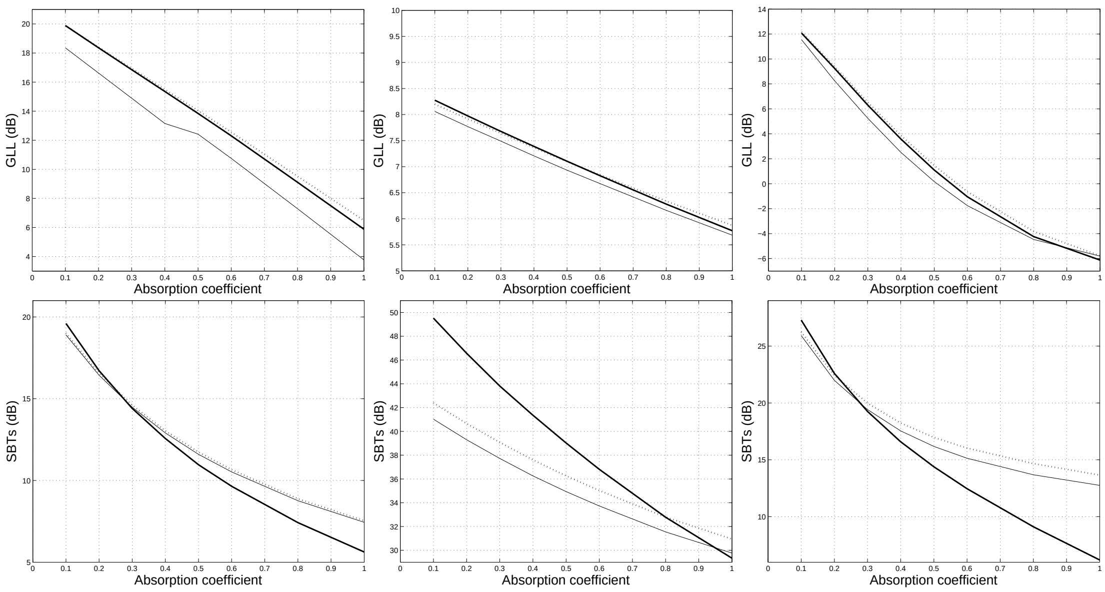

Figure 6: LEV as a function of the absorption coefficient value; (left) proportionate room, (middle) flat room and (right) long room; (top) GLL, (bottom) SBT_s: (▬) directional echograms, (—) omnidirectional echograms, (▪▪▪) omnidirectional echograms with image sources.

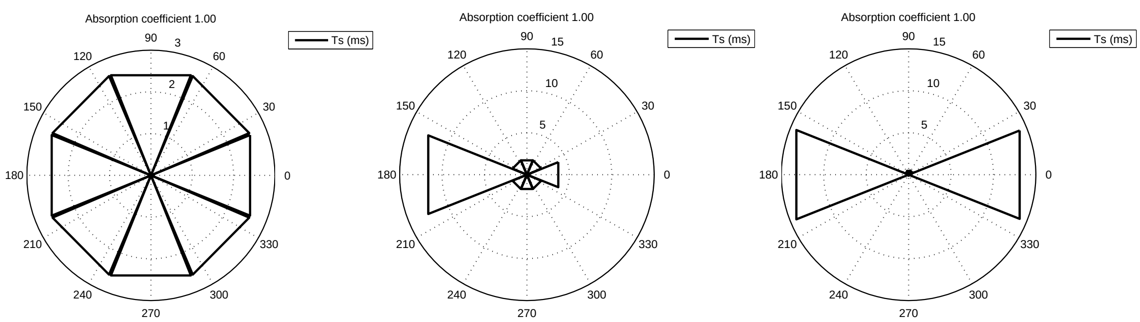

Figure 7: Angular distribution T_s in the long room for an absorption equal to 1.00; (left) omnidirectional echogram, (middle) omnidirectional echogram with image sources and (right) directional echograms.

In the studied configuration, the three models cannot be distinguished using the *GLL*. On the other hand, the T_s shows a notable difference between the models. The directional echograms are more affected by the increase of the wall's absorption. The lack of lateral reflections leads to a more realistic diminution of the LEV.

5. APPLCATION TO A MULTIPURPOSE HALL

The configuration modelled is the HELMIA hall, a multipurpose hall in Jönköping Sweden. This hall was used to conduct a benchmark of room-acoustic programs[13]. Measurements of several acoustic parameters have been carried out[13]. Unfortunately, *GLL* was not one of those criteria. The volume of the hall is 11 000 m3 and it has 1 100 seats (details can be found in reference 11). Figure 8 presents a sketch of the hall. The sound source is located at (2;8.5;3) m and the 0.5 m diameter receiver at (0;15,2.3) m directed towards the source (the 0° azimuth and elevation angles are in the source direction). 5 000 000 rays are emitted and the echograms are computed over 400 time steps of 5 ms.

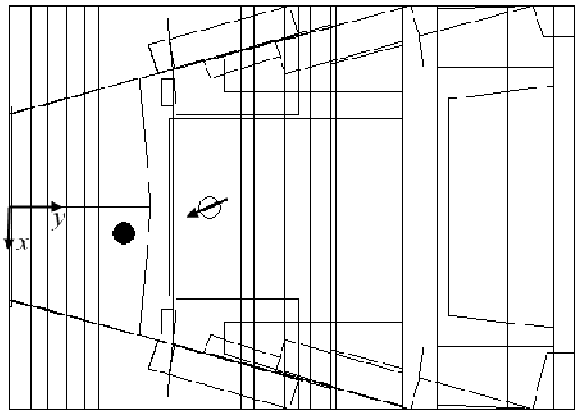

Figure 8: Sketch of the ELMIA hall: (●) source and (o) receiver. The arrow indicates the receiver orientation.

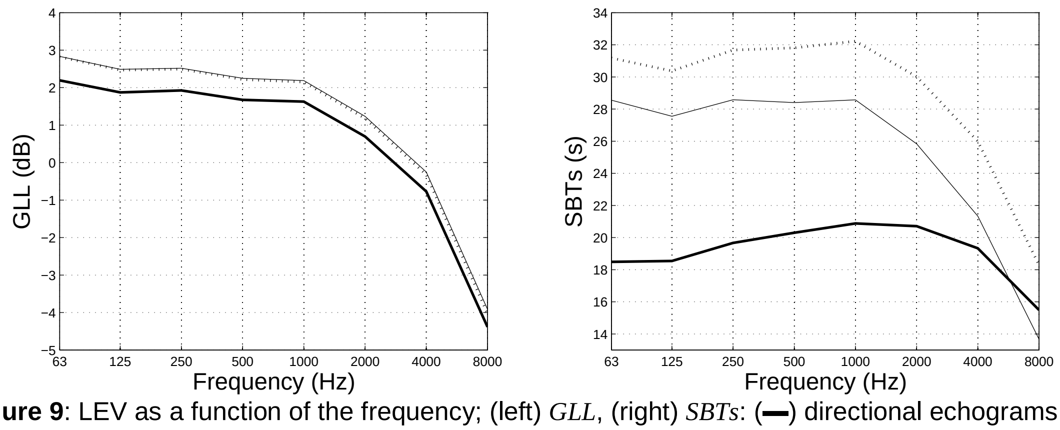

Figure 9: LEV as a function of the frequency; (left) *GLL*, (right) *SBTs*: (▬) directional echograms, (—) omnidirectional echograms, (▪▪▪) omnidirectional echograms with image sources.

The predicted LEV is lower than in the preceding sections due to the shape of the hall (Figure 9). The fan shape tends to decrease the spatial impression compare to a parallelepiped[18]. The evolution of the LEV follows the trend of the measured reverberation time[13], decreasing 2.3 s at 125 Hz to 1.9 s at 4000 Hz. The *GLL* results are very similar for the different models. The SBT_s

shows a lower LEV for the directional echograms. The model consisting of the omnidirectional echogram with the image sources presents a rather homogeneous distribution whereas the omnidirectional echograms show a strong component in the front back direction (Figure 10). The lateral components are almost negligible explaining the lower value of SBT_s observed in Figure 9.

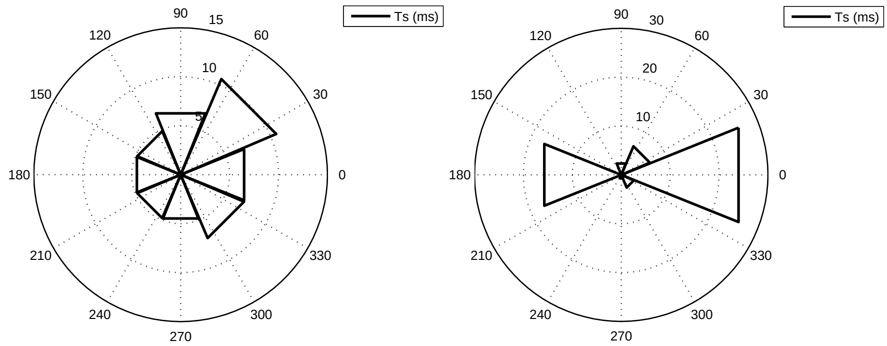

Figure 10: Angular distribution T_s at 125 Hz; (left) omnidirectional echogram with image sources and (right) directional echograms.

6. CONCLUSIONS

Comparison between three different methods to obtain echograms presenting spatial components has been carried out in terms of listener envelopment. The first model is the omnidirectional echogram. The second one is the omnidirectional together with image sources up to the third order and the last one is the result of the division of the receiver into 26 angular sectors in order to rigorously obtain directional echograms. The objective criteria used were the late part lateral energy fraction and the spatially balanced center time. Three canonical room shapes (a proportionate, a long and a flat rooms) and a real hall were tested. The criteria were in good agreement. Despite the different angular energy distributions observed, the three models present almost similar results in terms of envelopment. Differences can be noticed only when the reverberant sound field is very heterogeneous like a disproportionate room shape with very specular reflective walls or a strongly heterogeneous absorption distribution. In these cases, the acoustic field presents a strong directional component (the sound decay is much slower in the lengthwise direction than in the other directions) and the directional echograms seem to show a more realistic image of the sound field. Further work must be done as only receivers directed towards the sound source have been considered here and also, subjective tests must be carried out to confirm the conclusions of this objective study.

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