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Patrick Chevret, Jacques Chatillon

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Sound level prediction in open-spaces: implementation of diffraction in RAYPLUS software

P. Chevret and J. Chatillon

INRS, Rue du Morvan, CS 60027, 54519 Vandoeuvre Les Nancy, France
patrick.chevret@inrs.fr

This study addresses the problem of diffraction by screens in open-plan offices. A numerical model, based on a ray-tracing method, was implemented. The initial model used was a piece of software whose purpose was to predict sound levels in industrial premises. Diffraction was introduced into the model via the Uniform Theory of Diffraction (UTD). For the purposes of validation, a campaign of tests was conducted in a semi-anechoic chamber. A first series of measurements of diffraction by a single screen and by a low-divider partition on a double desk made it possible to validate the experimental conditions through comparisons with the UTD. In the same experimental context, the predictions of the octave band spectra with the modified model were of good accuracy. In a second series of measurements, a removable ceiling was suspended above the double desk. The acoustic field behind the low divider was then made up of a mixture of the field diffracted by the low divider and of the field reflected by the ceiling. The results of the comparisons between calculations and measurements in this unitary configuration show that the modified model can be an excellent tool for predicting sound levels in an open-plan office.

1 Introduction

Since several decades, the rise of the open-plan office, combined with the growth of the tertiary sector, has shifted our focus on the problem of noise in this type of workplace. In open-plan offices, noise sources (speech of the occupants, ventilation, computer equipment, *etc.*) are often very numerous but their levels are lower than the prescribed values and in any event non-lesional. However, noise is the cause of numerous complaints from people working in such open-space offices: indisposition, fatigue, *etc.* The interior layout is often designed to facilitate movement and visibility while also isolating people partially. There are therefore a large number of separating partitions that are supposed to insulate and protect people from noise. However, the presence of such partitions gives rise to particularly complex acoustic phenomena such as diffraction by the edges of the separating elements. This diffraction behaves as a secondary source that adds noise to the shadow zone initially created by the partition.

In order to predict ambient sound accurately in this type of environment, the major families of acoustics modeling thus had to adapt, in particular they had to take account of the diffraction phenomena. This was done through the diffuse-field theory [1], the volume or surface integral methods [2], the geometrical methods [3-5]. The limitation of these approaches is either the reduction of the frequency domain or the increase of the computation times for complex environments.

In this paper, we present an advanced model perfectly relevant for predicting diffraction in complex spaces. The model, which is based on a ray-tracing method, known as RAYPLUS software, consists in sending from the source a set of acoustic particles into the three-dimensional space, determining their paths, and calculating energy loss suffered on collision with the walls of the room and with the interior elements. Thanks to this approach, all the main acoustic phenomena can be modeled: specular reflection off the walls and off the interior elements (screens, volume, section members), atmospheric absorption, absorption by the walls and by the elements inside the room, diffusion by the same elements which is based on the concept of mean free path defined by a law of probability, transmission through the walls, and diffraction, which constitutes the central point of this paper. The model thus makes it possible to accommodate complex situations, a priori without any limitation on the dimensions, shape, or layout of the rooms.

After a brief description of the theoretical background, the paper presents some comparisons of insertion loss between measurements done in our own semi-anechoic

chamber and calculations performed with the model. It is articulated in 2 sections: comparisons without a ceiling and comparisons with a ceiling suspended over a double-desk equipped with a low-divider partition. This study is also a contribution to the setup of a new standard (NFS 31 199) dedicated to open-plan offices, by the S30D commission of the French national organization for standardization (AFNOR).

2 Theoretical background

Diffraction by an edge is implemented in RAYPLUS software with the help of the Uniform Theory of Diffraction [6]. Each time a particle collides with an edge its energy is modified according to the diffraction coefficient which is calculated from the equations of the UTD [7]. Therefore, the energy of a diffracted acoustic particle e_{dif}^i can be written as a function of the incident particle energy e_{inc}^i as:

$$e_{dif}^i = e_{inc}^i \times |D|^2 \times \frac{r \times (r + s)}{n' \times s^2} = e_{inc}^i \times \frac{\alpha_d(s, \varphi, \varphi')}{n'}, \quad (1)$$

where D is the spherical diffraction coefficient obtained from Kouyoumjian and Pathak [8],

$$D(k, R, S) = -\frac{\exp(-i\pi/4)}{2 \times \sin \beta \times \sqrt{2\pi k}} \times \sqrt{\frac{s}{r \times (r + s)}} \times \left[\frac{F(kLa(\varphi' - \varphi))}{\cos\left(\frac{\varphi' - \varphi}{2}\right)} + \frac{F(kLa(\varphi' + \varphi))}{\cos\left(\frac{\varphi' + \varphi}{2}\right)} \right]. \quad (2)$$

F is the transition function which is equal to:

$$F(X) = 2i\sqrt{X} \exp(iX) \int_{\sqrt{X}}^{\infty} \exp(-iu^2) du.$$

The geometrical variables in Eq. 1 are identified on figure 1. r and s are respectively the distance from the receiver to the edge and the distance from the source to the same edge. φ and φ' are respectively the angle of the incident and diffracted rays with the plane of diffraction. β is the angle of the incident and diffracted rays with the edge. n' is the

number of particles diffracted at each collision and α_d is the particle diffraction coefficient which equals to:

$$\alpha_d(s, \varphi, \varphi') = \frac{1}{\sin^2 \beta \times 8\pi s k} \left| \frac{F(kLa(\varphi - \varphi'))}{\cos\left(\frac{\varphi - \varphi'}{2}\right)} + \frac{F(kLa(\varphi + \varphi'))}{\cos\left(\frac{\varphi + \varphi'}{2}\right)} \right|^2. \quad (3)$$

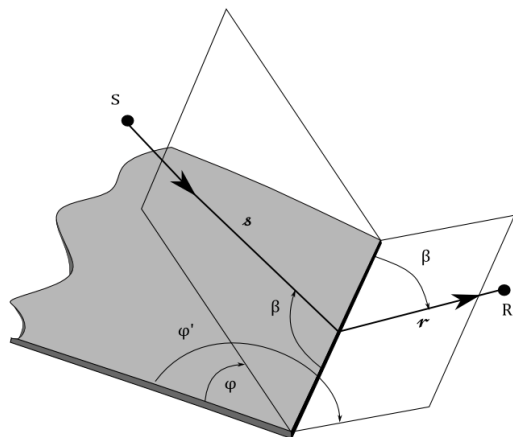
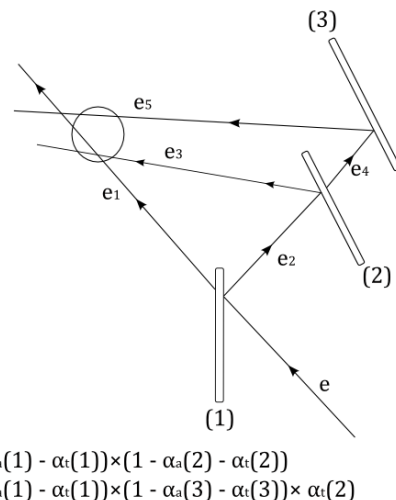


Figure 1: Representations of the diffraction by the edge of an infinitely thin panel

Taking in account all the particles which pass through a receiver sphere surrounding the receiver position, the total energy is equal to:

$$\mathcal{E} = \frac{\wp}{nn'} \sum_{i=1}^m \left(\ell_i \times \prod_{j=1}^{p_i} (1 - \alpha_a(P_j) - \alpha_t(P_j)) \times \prod_{j=1}^{q_i} \alpha_t(P_j) \times \prod_{j=1}^{w_i} \alpha_d(P_j) \right), \quad (4)$$

where \wp is the source power, n is the number of particles sent from the source, ℓ_i is the length of the ray i inside the reception cell, p_i is the number of collisions for which the ray has been reflected, q_i is the number of collisions for which the ray has been transmitted and w_i is the number of diffractions that the particle i has undergone all the way along its path. $\alpha_a(P_j)$ and $\alpha_t(P_j)$ are the values for the coefficients of absorption and of transmission of the plane P_j at the collision j . See figure 2 for an illustrative example of the calculation.



$$\begin{aligned} e_1 &= e \times \alpha_t(1) \\ e_3 &= e \times (1 - \alpha_a(1) - \alpha_t(1)) \times (1 - \alpha_a(2) - \alpha_t(2)) \\ e_5 &= e \times (1 - \alpha_a(1) - \alpha_t(1)) \times (1 - \alpha_a(3) - \alpha_t(3)) \times \alpha_t(2) \end{aligned}$$

Figure 2: Example of paths for an acoustic particle. Illustration of the reflection and of the transmission by screens.

3 Diffraction by a desktop low-divider partition

In open-plan offices, the tendency is to have multi-workstation desks (double, triple, or even sextuple desks), on which each workstation is separated by a low-divider partition whose height depends on the requirements of the interior designer. The quality of the component materials of the low-divider also varies considerably. The low-divider has various purposes, one of which is an acoustic function for reducing transmission of the wave between the various workstations. It thus acts as an incident wave reflector, as a sound energy absorber, and also as an energy diffuser via its own edges.

3.1 Prediction without a ceiling

Firstly, the case of a double desk separated by a rigid low divider is considered. This desk, whose dimensions are shown in Figure 3, was placed in a semi-anechoic room. Figure 4, is a comparison between the measurements, a classical UTD calculation and RAYPLUS.

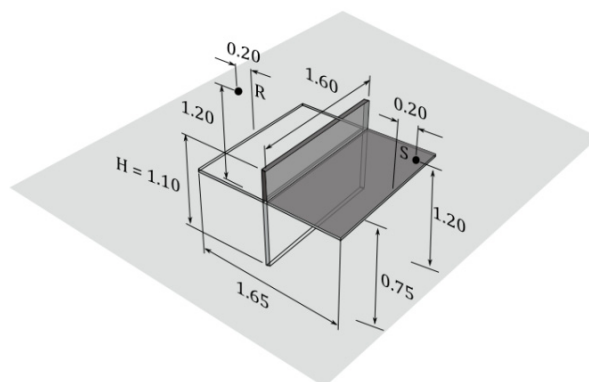


Figure 3: Dimensions of the double desk

The general behavior of the two models matches that of the measurements: a slight increase in insertion loss as a function of frequency is observed for small low-divider heights. This is due to the fact that the receiver is in the line of sight of the source. For large low-divider heights,

diffraction predominates over direct and reflected paths, resulting in a large increase in insertion loss as a function of frequency. Differences can be noted between the coherent results (measurements and UTD) and the incoherent results (model and incoherent UTD), in particular at medium frequencies. This is particularly apparent in the 500 Hz octave with an underestimation by RAYPLUS for the height of 35 cm and an overestimation for a height of 75 cm. Finally, the insertion loss is underestimated in the 8000 Hz octave. This phenomenon, which is particularly apparent when the low divider is tall (Figure 4, bottom), is due to the narrowing of the source directivity at high frequency that is not taken into account by our model. This results in a reduction in the level of incident energy on the horizontal edge of the low divider compared with the level obtained with an omnidirectional source, and thus in a reduction in the energy contributed by diffraction at the receiver. The real insertion loss for this directive source at high frequency is therefore higher than for a theoretical omnidirectional source.

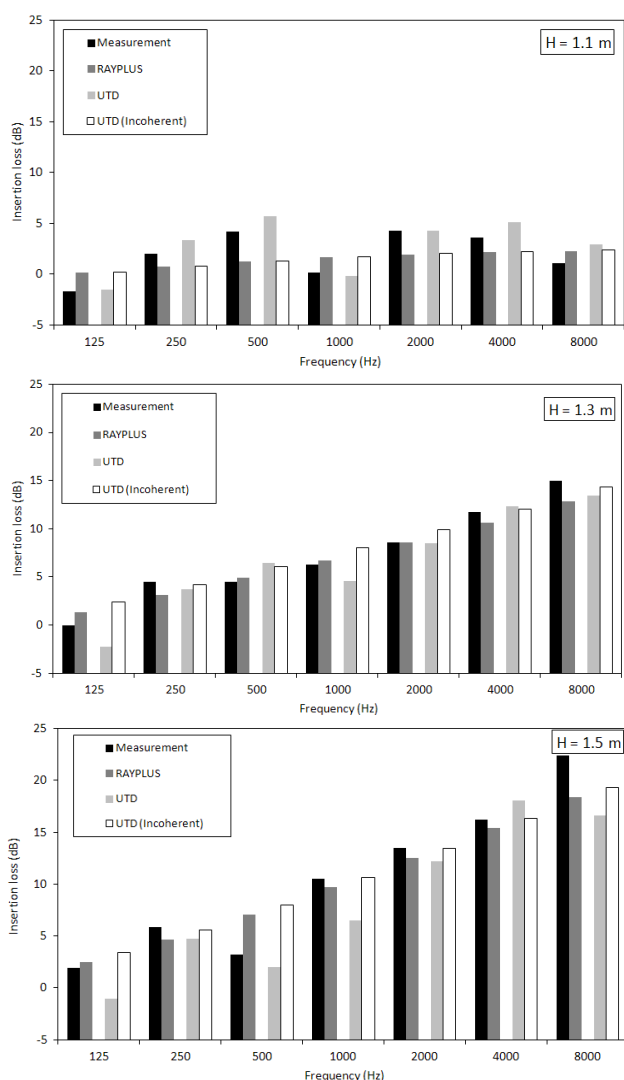


Figure 4: Octave band spectra of insertion loss for a double desk in a semi-infinite field. Comparison between measurements, RAYPLUS and UTD. (a) low divider having a height of 35 cm (top edge at 1.1 m above the floor); (b) low divider having a height of 55 cm (top edge at 1.3 m above the floor); (c) low divider having a height of 75 cm (top edge at 1.5 m above the floor)

3.2 Prediction with a ceiling

In an open-plan office, the ceiling generally plays a major role in the ambient sound at the workstation. So that, although workspace designers commonly require absorbent materials to be used to cover the concrete ceiling slabs, the contribution to the sound field from reflections off the ceiling is often non-negligible. The object of this paragraph is to show the capacity of our model to predict the acoustic field for the case of a double desk separated by a low divider in the presence of a ceiling.

In order to enable reflections off a ceiling to be taken into account, the semi-anechoic chamber has been equipped with a removable aluminum structure. This structure is suspended above the floor by means of a hoist enabling its height to be adjusted. The structure is made up of a grid of tensioned cables for supporting boards that are easy to put in place as the tests require. Absorbent structures can also be suspended from the cables so as to represent conditions close to a real environment (e.g. when a plenum space is present). In this paper, a reflective structure was chosen, with plaster boards being installed on the grid of cables. 6 boards having a thickness of 13 mm were juxtaposed to form a total area of 18 m² (3.6 m x 5 m) above the desk. The reflection coefficient was measured in situ. An illustration of the installation is provided, with the dimensions, on figure 5.

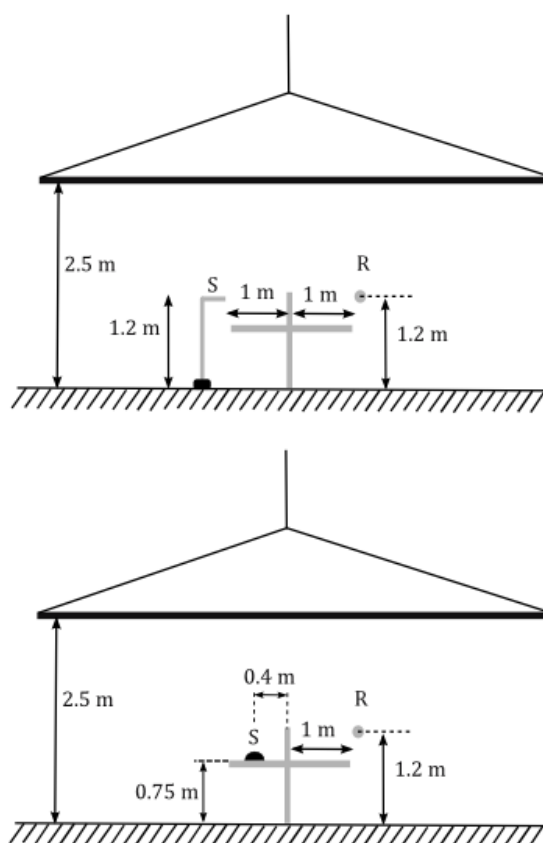


Figure 5: Picture of the installation in the semi-anechoic chamber: double desk with a removable ceiling

The insertion loss induced by the low divider separating the two workstations was measured for two source positions, as shown in the diagrams of Figure 5.

The first source was the source used for the preceding tests without any ceiling: a modified compression chamber

whose mouth was placed 1 m from the low divider, and 1.2 m above the floor, this position being representative of a person at their workstation. The second source, the hemispherical Norsonic Nor275, was placed in the center of the horizontal top of the desk. It was representative of noise-generating electronic equipment such as a telephone, a PC, etc.

Once again, the measurements were taken successively without the low divider and with the low divider for various heights. The insertion loss was deduced from the two measurements. The octave band spectra results are presented in Figures 6 and 7, respectively for the modified compression chamber and for the source Nor275.

A. WITH THE MODIFIED COMPRESSION CHAMBER

When the separation lies below the height of the source and of the receiver ($H = 110$ cm, Figure 6, top), the measured insertion loss varies over a range of small amplitude [-2.9 dB; 3.2 dB]. The low divider thus plays a very limited role in that case. It can even contribute to an increase in level (-2.9 dB at 1000 Hz) due to the fact that it suppresses the area of destructive interference between the direct path and the reflected paths (desktop/ceiling) while also adding a diffraction contribution mainly via its top edge. As regards the comparison between the measurements and the model, the same observations as above are to be noted, namely the estimation of the sound level is a fair one (maximum of 2 dB over the entire octave band) except at 1000 Hz, where a difference of about 4 dB is to be noted, largely attributable to the incoherent computation. Comparison of the computations with and without diffraction shows that diffraction plays a small part compared with the direct and reflected paths.

When the low divider masks the source and the receiver ($H = 130/150$ cm, Figure 6, middle and bottom), the various effects are amplified by the fact that the separation cuts across the direct path. Thus, the differences between measurement and modeling (RAYPLUS with diffraction) can reach 4.5 dB at low frequency (125/250 Hz), due to interference not described by our model, and 6.5 dB at 8000 Hz because of the flattening of the directivity of the source that we mentioned earlier. Conversely, at medium and high frequencies (except for 8000 Hz for the reason mentioned earlier), where the interference density is high, prediction is excellent. Unlike in the preceding case ($H = 110$ cm), diffraction plays a decisive part because differences of about 8 dB are to be observed between the computations with and without diffraction.

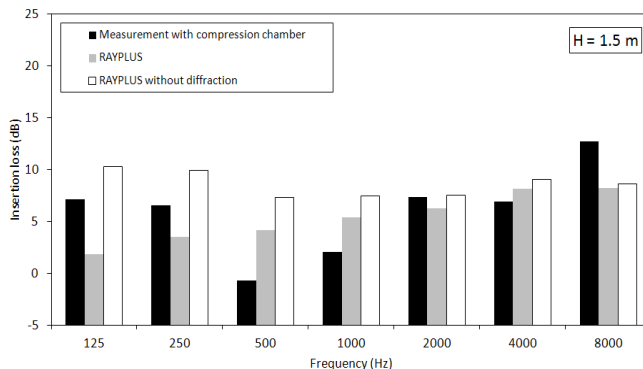
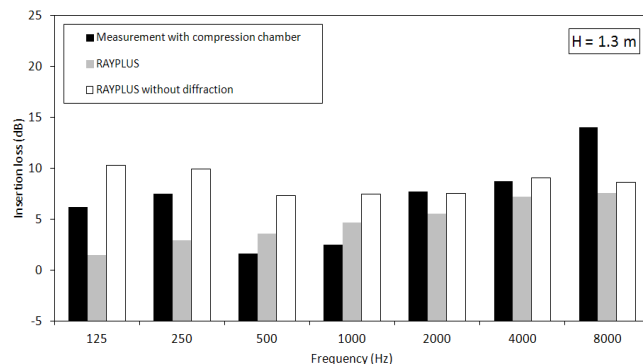
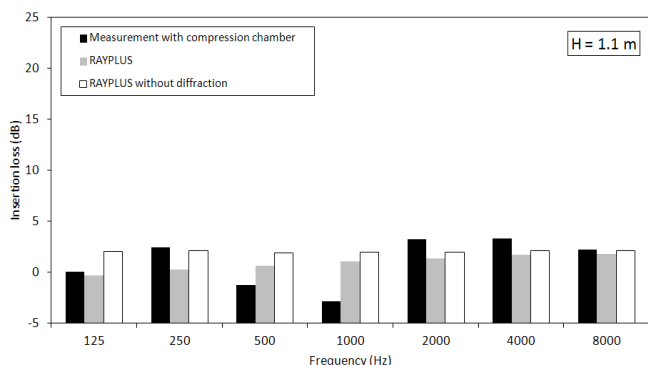
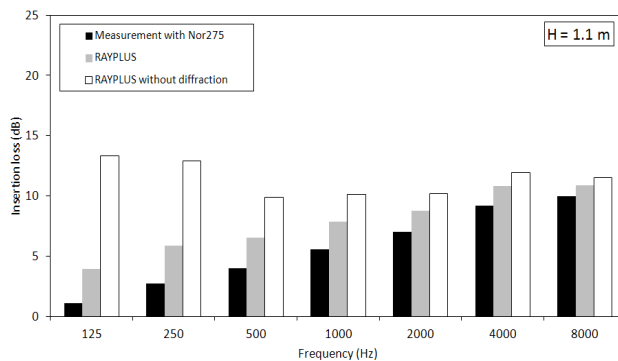


Figure 6: Octave band spectra of insertion loss for a double desk in a free field. Comparison between measurements with the modified compression chamber, RAYPLUS and UTD. (a) low divider having a height of 35 cm (top edge at 1.1 m above the floor); (b) low divider having a height of 55 cm (top edge at 1.3 m above the floor); (c) low divider having a height of 75 cm (top edge at 1.5 m above the floor)

B. WITH THE NOR275 SOURCE

The results obtained when the Nor275 source is placed on the desktop (Figure 7), confirms the preceding analysis. In this case, the direct path is suppressed by the low divider regardless of the height studied. Thus, the contribution from diffraction to the insertion loss is determined at low frequency (comparing computations with and without diffraction). The differences of a few dB (< 5 dB) due to interference are still present. Conversely, since the Nor275 source is omnidirectional, the modeling at high frequency is excellent for all low divider heights.



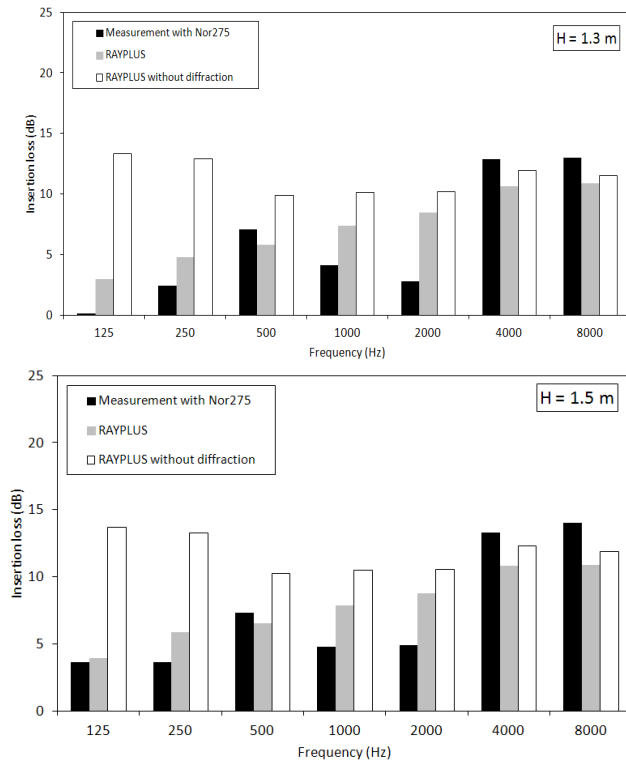


Figure 7: Octave band spectra of insertion loss for a double desk in a free field. Comparison between measurements with the Nor275 source, RAYPLUS and UTD. (a) Low divider having a height of 35 cm (top edge at 1.1 m above the floor); (b) low divider having a height of 55 cm (top edge at 1.3 m above the floor); (c) low divider having a height of 75 cm (top edge at 1.5 m above the floor)

4 Conclusion

All The comparisons presented in this paper emphasize the fact that the software is a very good acoustic predictor, even when diffraction phenomena are important. The only slight reservation to be mentioned lies in the concept of incoherent summation in the receiver cell that does not take account of the interference phenomena due to the difference in path length between the various paths. This assumption of incoherent summation is particularly penalizing when the number of possible paths between source and receiver is small, as it is for the configurations addressed herein. It is highly probable that the real situations are more favorable to method assumptions because of the number of obstacles that are often present in the room and whose effect is to decorrelate the paths.

The prospects for this work are considerable as regards both modeling and also measurements. From the prediction standpoint, the model will, for complex cases, procure fast access to the input data necessary for estimating intelligibility (except for the impulse response of the room), which is, today, the main indicator for evaluating inconvenience. As regards experimental prospects, novel test resources are now available, by means of the removable ceiling installed in our semi-anechoic chamber, making it possible to evaluate the performance levels of various absorbent solutions in the presence or in the absence of furniture. These novel test resources form a bridge between

measurements of absorption in a reverberant chamber that delivers merely a value for Sabine absorption, and overall measurements of linear decay in situ.

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