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Optimum measurement locations for large-scale loudspeaker system tuning based on first-order reflections analysis

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ABSTRACT

This paper investigates how first-order reflections impact the response of sound reinforcement systems over large audiences. On the field, only few acoustical measurements can be performed to drive tuning decisions. The challenge is then to select the right measurement locations so that it provides an accurate representation of the loudspeaker system response. Simulations of each first-order reflection (e.g. floor or side wall reflection) are performed to characterize the average frequency response and its variability over the target audience area. Then, the representativity of measurements performed at a reduced number of locations is investigated. Results indicate that a subset of eight measurements locations spread over the target audience area represents a rational solution to characterize the loudspeaker system response.

1 Introduction

1.1 Loudspeaker system tuning

In professional audio industry, loudspeaker systems such as line source arrays are usually designed using free-field simulation software. This allows to rapidly estimate the performance of such loudspeaker systems over a large area with reduced calculation time. Nevertheless, the on-site performances of a loudspeaker system also depend on the environment in which it is implemented. For instance, sound waves are reflected by surfaces such as the floor or side walls, which impacts the system response over a large audience.

Equalization can be used to correct some response irregularities during the tuning of the system. The tuning operator measures the response of the loudspeaker system at a few locations distributed over the audience area. The operator then performs a visual analysis of multiple magnitude responses and their average (see Figure 1). Smoothing is generally applied to make the responses more readable and account for the reduced frequency resolution of the auditory system [1]. The tuning decisions often consist in applying equalization filters to fit the average response to a target curve. A cautious operator may choose to give priority to frequency areas with low variability among the measurement locations and not compensate for deviations that show large spatial disparity (200-300Hz frequency range in Figure 1).

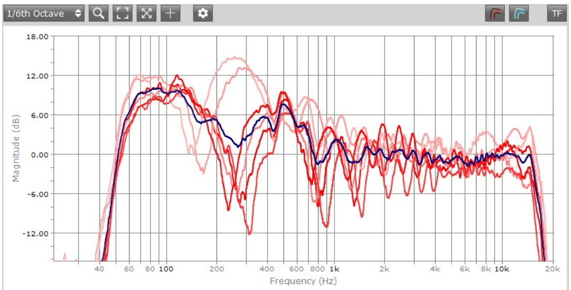

Figure 1. Snapshot of magnitude responses measured at different locations using M1 measurement software from L-Acoustics (1/6th octave smoothed). The blue curve is the average.

The number and the position of the measurement locations is therefore a critical parameter of the tuning process.

1.2 First-order reflections

In presence of a reflective surface such as the floor, the sound emitted by a source reaches the ears of a listener following two paths: the direct path going from the sound source straight to the listener, and the reflected path (one bounce on the floor for instance). As the direct path is shorter than the reflected path, the direct sound arrives before the reflection. The sum of these two sounds creates an interference pattern also called comb-filtering. The resulting frequency response displays a series of notches as illustrated on Figure 2. The frequency of the first notch is often referred to as comb frequency F_c in the literature and is given by:

$$F_c = \frac{1}{2\,\Delta t} \qquad (1)$$

where Δt is the time difference. The notches at higher frequencies correspond to the odd-order harmonics of F_c. The notch depth is determined by the relative level between the two sounds (similar levels create deeper notches as shown on Figure 2). The notch depth is constant if the surface is perfectly reflective and if no smoothing is applied. The attenuation of the comb-filtering pattern observed on Figure 2 is due to the 1/6th octave smoothing applied.

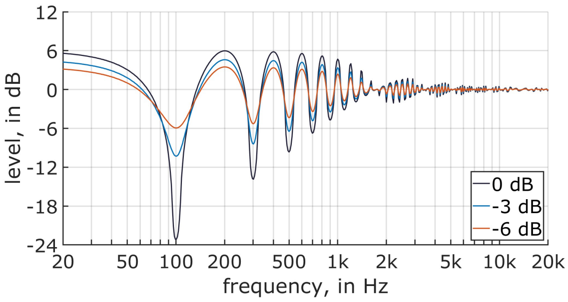

Figure 2. Example of comb-filtering patterns (1/6th octave smoothed) for different relative levels.

This type of smoothing is commonly used to analyze acoustical measurements[1] and typically smooths out ripples from a given harmonic order.

This paper focuses on the analysis of first-order reflections (sound that bounces off one time of a surface) over large audiences. First-order reflections are known to have a strong impact on sound perception [2, 3] and on acoustical measurements. Indeed, first-order reflections are usually energetic and cannot be dissociated from the direct sound in contrast to higher-order reflections and reverberation. This makes any time windowing method inefficient to remove them from the measurements. First-order reflections can be fully characterized by the first notch of the comb-filtering because of the harmonic relation between the notches. In addition, the depth of the first notch is marginally affected by the smoothing (see Figure 2 as an example). Consequently, the first-order reflections and especially the first notch caused by these reflections are considered as good indicators to study the influence of reflections on measured magnitude response over a large audience.

1.3 Goals of the study

The present study has two main objectives:

1. to investigate the variability of each first-order reflection over the audience area in terms of comb frequency F_c and notch depth.
2. to provide basic recommendations on the selection of a reduced number of measurement locations that ensure the best representativity of the first-order reflections in the area to optimize. The goal is to limit the risk of making inappropriate tuning decisions.

To do so, the evolution of the comb-filtering patterns caused by individual first-order reflections are first compared through mappings of the first notch frequency and depth.

In the second part of this study, different configurations of measurement locations are

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[1] Time windowing can also be applied.

considered. The representativity of each measurement configuration is compared to the average response observed over the target area (i.e. loudspeaker coverage area). Basic recommendations on the selection of measurement locations for large-scale loudspeaker system tuning are derived from this work.

Finally, the validity of the results in a more realistic scenario (directive sources, complex reflective surfaces) is discussed.

2 First-order reflections variability

2.1 Simulation framework

As a first step for studying the variability of first-order reflections, a simple image source model [4] is implemented using a monopole to represent the loudspeaker system. The virtual source is placed in two large-scale shoebox rooms that have perfectly reflective surfaces. The source is located on one side to simulate a single loudspeaker system of a Left/Right design which is the most common configuration. The dimensions of the rooms and placement of source relative to the walls are chosen to be representative of typical shoebox venues:

- the **Small room** has a total volume of 1.800 m^3 (20 x 15 x 6 meters) and a stage width of 8 meters. The source is placed at one side of the stage, at 2 meters from the front wall and at a height of 4 meters.

- the **Large room** has a total volume of 40.500 m^3 (60 x 45 x 15 meters) and a stage width of 16 meters. The source is placed at one side of the stage, at 3 meters from the front wall at a height of 8 meters.

For the two rooms, the first-order reflection caused by each reflective surface (i.e. floor, ceiling, side wall, rear wall and front wall) is simulated at a listener height of 1.2 m (typical seated audience height). The rear wall is defined as the wall behind the audience (i.e. at 60 meters from the source in the Large room). The level of the direct sound is normalized so that the responses are comparable over the entire area without being affected by geometrical attenuation. Only the relative level and time difference between the direct sound and the reflection due to propagation distance is considered.

2.2 Simulation results

First, the simulation results are compared based on the mapping of two types of data over the audience area: the first notch frequency of the comb-filtering pattern, and the notch depth. These results are presented in Section 2.2.1. Then, the average frequency responses calculated over the source coverage area are presented in Section 2.2.2.

2.2.1 Mappings over the audience area

As illustrated on Figure 3, the **side wall reflection** creates strong local variations close to the wall. In this region, the first notch frequency and depth increase drastically. Similarly, the **rear wall reflection** creates strong local variations of the first notch frequency and depth close to the wall (see Figure 4). The reflection is less energetic than for the side wall though and with a low first notch frequency for most of the audience (less than 10Hz in the Large room, 20Hz in the Small room for 75% for the audience area). This should limit the influence of the rear wall reflection providing that the measurement locations are not too close from the rear wall.

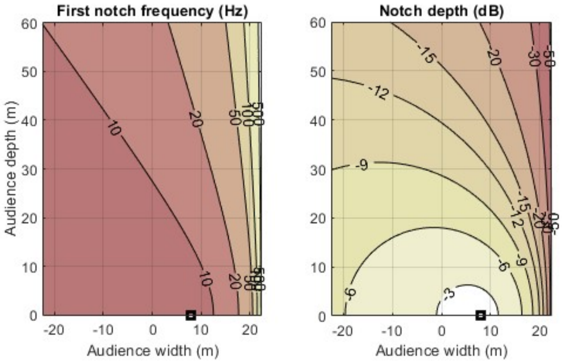

Figure 3. Mapping over the audience area of the first notch frequency (left) and notch depth (right) in the Large room, caused by the side wall reflection. The black square represents the source location.

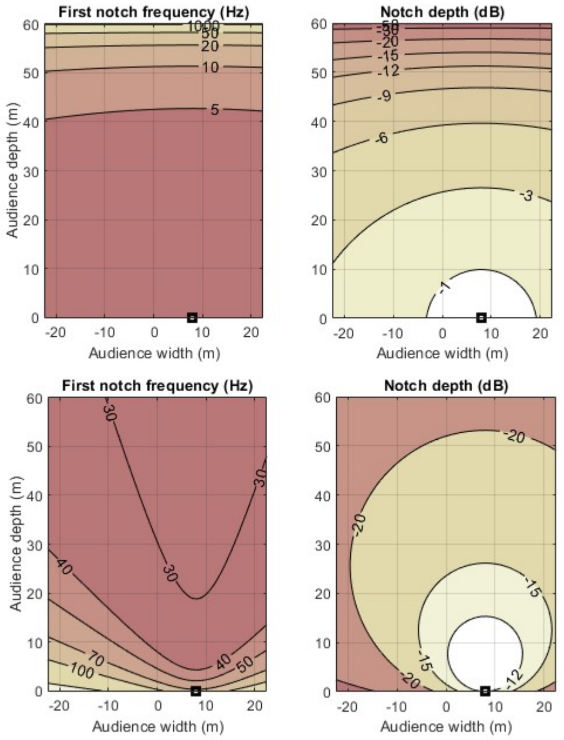

Figure 4. Mapping of the first notch frequency and depth caused by the rear wall (top) and front wall reflection (bottom).

The **front wall reflection** is energetic and shows a stable first notch frequency (Figure 4). This indicates that the tuning operator might want to correct its effect as it seems relatively stable over the audience.

The **floor reflection** shows large variations over the audience as the first notch frequency increases with the distance of the listener to the source (see Figure 5). This reflection is energetic with deep notches over the entire audience area which makes it potentially more visible on *in situ* measurements. As the floor reflection, the **ceiling reflection** varies over the audience and the first notch frequency increases with distance to the source (see Figure 5). The ceiling reflection is less energetic than the floor reflection though and lower in frequency due to the considered geometry (see Section 2.1). The increase of first notch frequency with distance is illustrated on Figure 6 for the floor reflection, where source heights are simulated between 2 and 12 m.

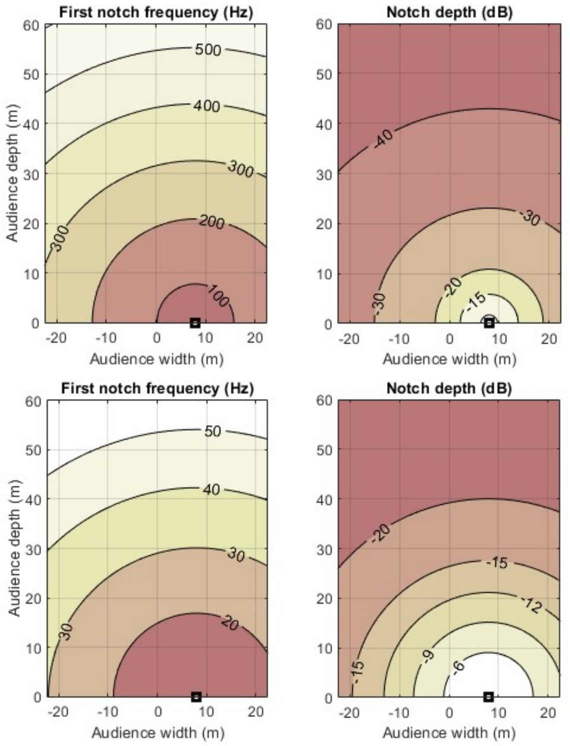

Figure 5. Mapping of the first notch frequency and depth caused by the floor (top) and ceiling reflection (bottom).

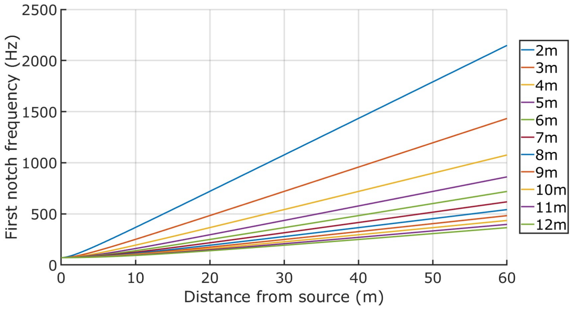

Figure 6. Evolution of the first notch frequency (floor reflection) measured on-axis of the source for different source heights (between 2 and 12 m).

Summary of the results

The results reveal that the floor and ceiling reflections are energetic over the entire audience with a first notch frequency that increases linearly[2]

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[2] asymptotic behaviour at large distance.

with the distance from the source. The side wall and rear wall reflections creates very local effects close to the walls and large variations are observed over the audience in terms of first notch frequency and depth. On the contrary, the front wall reflection creates a more stable interference pattern over the audience.

2.2.2 *Average response over the target area*

In this section, the average magnitude response of each reflection is studied as well as its standard deviation to illustrate how variable is the reflection response over the target area.

Definition of the target area

Most of the time, a loudspeaker system is designed to cover a specific area of the audience called target area. In this study, the target area of the simulated source is slightly larger than half of the audience width[3], to represent a typical L/R design.

Target responses

Measurement locations are distributed every meter to estimate the average magnitude responses over the target area and associated standard deviations as an indicator of variability (see Figure 7).

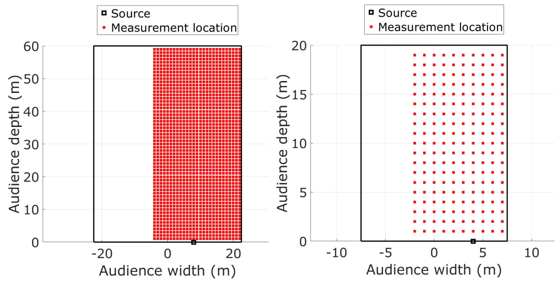

Figure 7. Distribution of the measurement locations in the target area for the Large room (left) and Small room (right).

The resulting target responses are shown for each reflection on Figure 8 (Large room with the source at 8 m high, and Small room with the source at 4 m). Figure 8 illustrates the low-frequency build-up created by the **floor reflection**, associated with a low variability in the target area. Indeed, the standard deviation values are low up to about 70-80 Hz in both rooms[4], meaning that the boost in this frequency range is stable over the target area and observed no matter the position in the audience. A tuning decision could be made to limit this build-up for the entire audience. On the contrary, the "bump" observed for the same reflection around 800 Hz (Large room) or 500 Hz (Small room) is associated with a high standard deviation (about 5 dB). This means that large variations are observed in this frequency range from one position to the other in the audience. Applying a corrective EQ would be inappropriate here, because it would favor some locations in the audience to the detriment of some others.

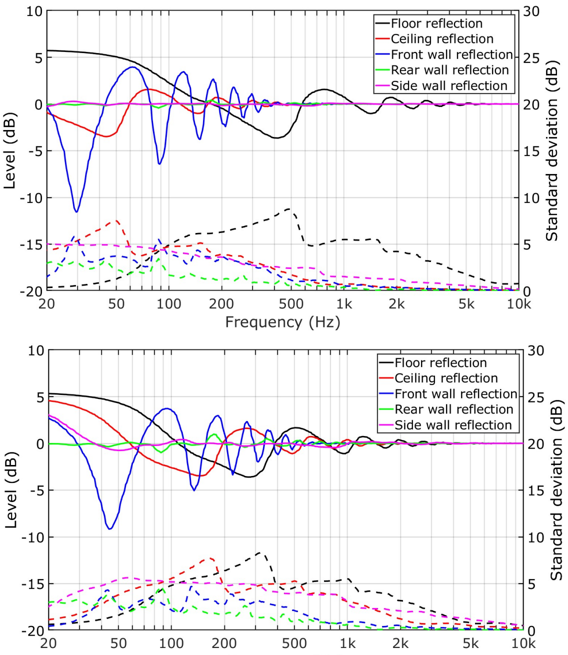

Figure 8. Average magnitude response over the target area for each reflection (solid line) and associated standard deviation (dashed line) in the Large room (top) and Small room (bottom). A 1/6th octave smoothing is applied.

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[3] A typical L/R design often include an overlap area between the Left and Right sources. In this study, the overlap is chosen to be of half of the stage width.

[4] It is anticipated that the bandwidth of the build-up depends on the source height (see Figure 6).

The **ceiling reflection** shows the same pattern as the floor reflection but lower in frequency. In the Large room, the standard deviation is high in low frequencies meaning that large variations are observed within the target area.

The **side wall** and **rear wall reflections** have a flat magnitude response on average over the target area, especially in the Large room. The flatness of the magnitude response is due to the large variations of the comb-filtering pattern of the side wall reflection over the target area (see standard deviations values), and the low energy of the rear wall reflection.

Finally, the **front wall reflection** is the only reflection that shows strong ripples on average over the target area for both rooms. It indicates that the comb-filtering pattern created by this reflection is stable over the target area. In this case, applying a corrective EQ may be appropriate.

3 Representativity of multilocation measurement configurations

On the field, it is impossible to measure the system response every meter and only few measurement locations are used for tuning the system. In this section, several configurations of measurements locations (number and spatial distribution) are studied. The goal is to identify the configurations that are the most representative of the target responses.

3.1 Definition of the measurement area

A measurement area is defined inside the target area considering some practical constraints that tuning operators face on site. It is for instance often that the first quarter of the venue is difficult to access because of on-going work close to the stage at the time of the system tuning. In addition, measurement locations should not be placed too close from the walls, where local effects occur and where the reflections are more energetic. Indeed, such variations would strongly affect measurement but cannot be optimized during the tuning process. Therefore, their contribution to the measured response should be reduced.

For these reasons, the proposed measurement area is limited to [1/4 – 3/4] of the audience depth, with no measurement locations closer than 2 meters from the side walls (see Figure 9).

3.2 Measurement configurations

The number and spatial distributions of the measurement locations tested are inspired from common practice in the field. The locations are often chosen to be on-axis of the source under consideration. Additionally, tuning operators also want to have a measurement location placed at or close to the mixing desk. This position is often considered as the reference measurement location used to align the main loudspeaker system with subwoofers during the tuning stage, and to monitor the sound during the show.
Three spatial distributions are tested based on these common practices (see Figure 9):

- **Line** corresponds to a distribution of the locations on a line, on-axis of the source and parallel to the side wall.
- **IntersecLines** is the combination of two lines; one on-axis and the other off-axis of the source toward the center of the audience area. The off-axis line is oriented toward the mixing desk, corresponding to an angle of 15 degrees in the Large room and 22 degrees in the Small room.
- **Zebra** corresponds to a wider distribution of the locations, spread in the measurement area with a total coverage angle between 30 and 35 degrees in both rooms. The coverage angle is defined by the difference between the location of the mixing desk on one side and the limit of the measurement area on the other side.

For each spatial distribution, 4, 6, 8, or 12 measurement locations are tested. This range seems rational when looking at on-the-field practices.

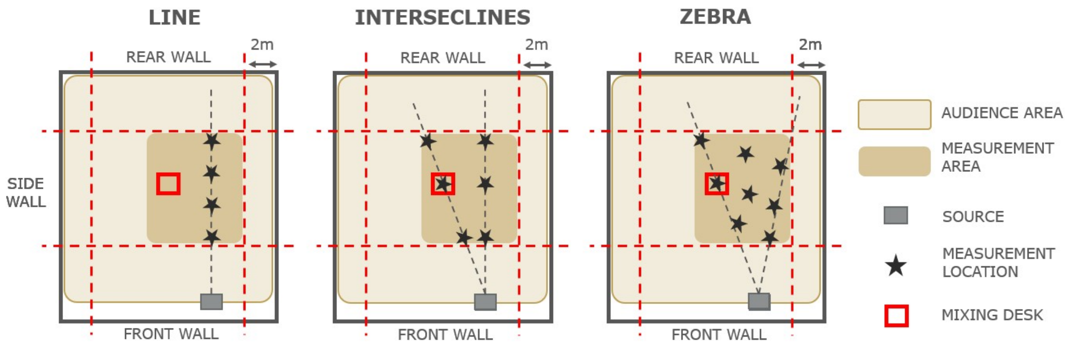

Figure 9. Illustration of spatial distribution of measurement locations tested in this study: *Line* with 4 locations, *IntersecLines* with 6 locations, and *Zebra* with 8 locations.

3.3 Results

3.3.1 General behavior

Many measurement configurations are tested for each first-order reflection. Two cases are chosen to illustrate the type of response and deviations that can be observed (see Figure 10).

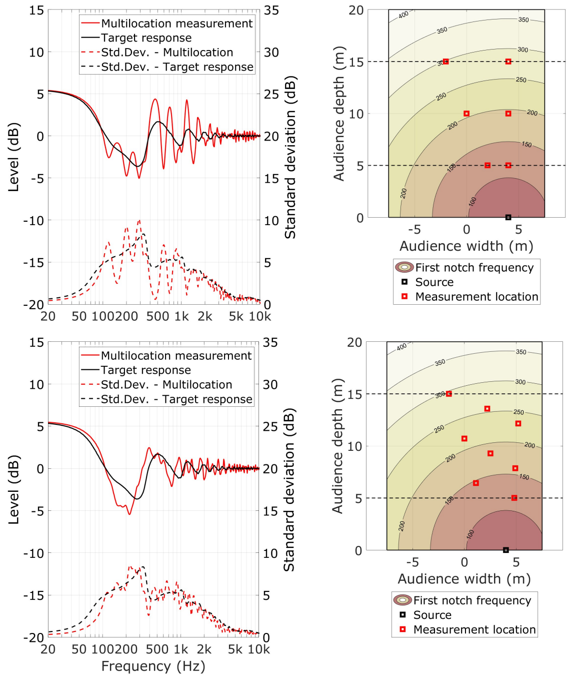

Figure 10. Example of deviation from the target response of the floor reflection in the Small room – *IntersecLines* with 6 locations (top) and *Zebra* with 8 measurement locations (bottom).

Figure 10 illustrates how the magnitude response and standard deviation can differ from the target response depending on the spatial distribution and number of measurement locations considered. In general, results show that more locations spread over the measurement area give smoother and more accurate responses. An objective metric is needed to be able to compare the configurations under test.

3.3.2 Evaluation metric

The average responses captured by a configuration under test is calculated for each reflection, in each room. The magnitude response error *MRE(f)* is defined as the difference between the average magnitude response of the configuration under test and the target, for each frequency of the [20 Hz – 1 kHz] frequency range. It is also important to account for the variability of the measured data as it gives crucial cues to the tuning operator. Indeed, tuning decisions are usually made when measurements show an area of low variability, indicating a stable effect over the space. This indication can be misleading in case the low variability between measurements is due to unfortunate measurement locations, therefore, not representative of the "true" variability of the phenomenon over the area. Such case is visible on Figure 10 for *IntersecLines,* where the standard deviation observed at 500 Hz is low in comparison to the target.

A **Risk Factor (*RF*)** is created to better illustrate the risk of making a bad tuning decision based on the measurement configuration under test. The *RF(f)* criteria is designed so that, at a given frequency *f*, a large magnitude response error *MRE(f)* associated with a low variability between measurements of the configuration under test $STD_{config}(f)$ gets a higher score. Indeed, this higher score better reflects a higher risk of making an inappropriate EQ decision based on the analysis of the reduced number of measurement locations. *RF(f)* is defined as follow:

$$RF(f) = MRE(f)\,.\frac{1}{1 + STD_{config}(f)} \qquad (2)$$

The RF_{95} is the 95th percentile of *RF(f)* and is considered as the maximum Risk Factor value.

3.3.3 Focus on key reflections

Results from previous sections showed that the rear reflection has a limited impact on the measurements (low energy and low frequency); that the ceiling reflection has globally the same behavior as the floor reflection (only a shift in frequency); and that the front wall reflection is stable over the target area and therefore captured no matter the choice of the measurement configuration. Consequently, the floor and the side wall reflections are considered as the most relevant to focus on.

For the **floor reflection**, the RF_{95} values are slightly higher in the Large room than in the Small room for all spatial distributions (see Figure 11). In addition, the risk of error is relatively high when less than 8 measurement locations are used in the *IntersecLines* distribution. This is probably due to insufficient discretization of the audience depth. When the audience depth is discretized with 4 points or more, the Risk Factor is drastically reduced.

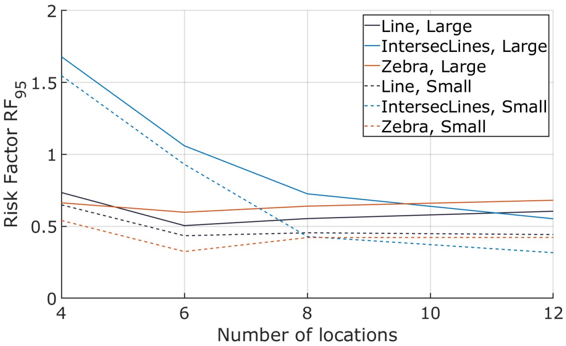

Figure 11. RF_{95} values obtained for the floor reflection in Small and Large rooms.

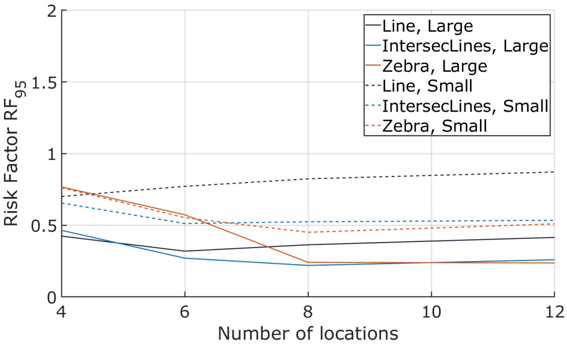

Figure 12. RF_{95} values obtained for the side wall reflection in Small and Large rooms.

For the **side wall reflection**, results show that the RF_{95} values are generally higher in the Small room than in the Large room (see Figure 12). This is explained by the fact that the first notch frequencies are low in the Large room with relatively high variability in comparison to the Small room. The risk factor is particularly high with the *Line* distribution, which indicates that such distribution should be avoided in Small rectangular rooms.

Figure 13 gives an overview of the results for each reflection averaged over the three spatial distributions and the two rooms. The front wall reflection is deliberately removed from this plot because it is stable over the measurement area and captured no matter the measurement configuration.

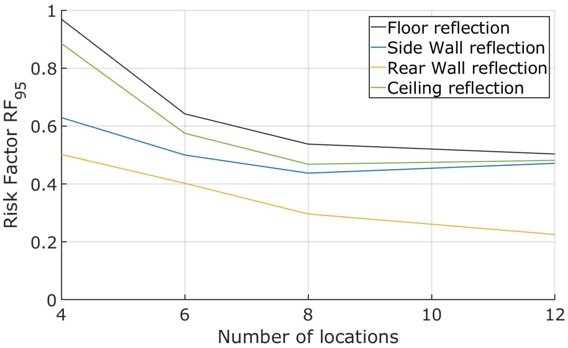

Figure 13. RF_{95} values for each reflection averaged on the rooms and spatial distributions.

This figure shows that the Risk Factor generally decreases when the number of locations increases. This figure also shows that the floor and ceiling reflections are the ones that lead to more risk of error. In general, a number of 8 locations seems to represent a rational solution to ensure a good representativity of each reflection.

3.3.4 Recommendations on measurement configuration

Basic recommendations on the selection of measurement locations for large-scale loudspeaker system tuning can be derived from this work. Results show that it seems appropriate to use 8 locations spread in the depth and width of the measurement area. Indeed, the spread in depth reduces error for the floor and ceiling reflections, whereas the spread in width (i.e. *IntersecLines* and *Zebra* distributions) gives better results for the side wall reflection, especially in the Small room. Increasing the number of locations minimizes the risk of making bad tuning decisions for all the reflections that are not stable in the target area. It also improves the smoothing of the average response. Finally, it might be that the first notch frequency of one location coincide with the second notch of another location. This would have a strong impact on the average measurement. The only way to limit the influence of such unfortunate placement is to increase the number of measurement locations.

4 Discussions

This study is based on simple simulations and it seems important to put the conclusions of this work in perspective with more realistic scenario.

4.1 Effect of a more realistic source

4.1.1 Typical source in the Small room

The audience area of the Small room could be covered thanks to a combination of coaxial loudspeakers placed in a L/R configuration. Figure 14 illustrates the directivity pattern of such loudspeaker system in the Small room (one X15 loudspeaker from L-Acoustics placed at 4 m high). SPL mapping are presented in the vertical plane (side views) and the horizontal plane at the audience height (top views), for two frequency ranges: sub-low frequencies [20 Hz - 250 Hz] and low-mid frequencies [250 Hz - 1000 Hz]. Figure 14 shows that a typical coaxial loudspeaker system is relatively omnidirectional, especially in the sub-low frequencies. It becomes more directive as the frequency increases. Based on these observations, the simple model implemented in this study with an omnidirectional source seems reasonably realistic.

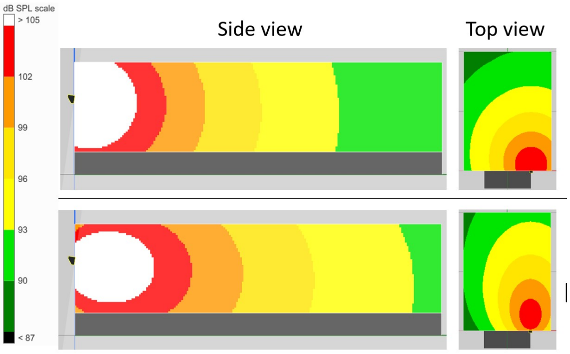

Figure 14. SPL mappings of a typical loudspeaker system designed for the Small room calculated on the [20Hz - 250 Hz] frequency range (top) and the [250Hz - 1000 Hz] frequency range (bottom).

4.1.2 Typical source in the Large room

Line source arrays are typically used to cover large-scale audiences (both indoor and outdoor). The directivity of a line source array is not omnidirectional and can be described by the Fresnel approach [5, 6, 7]. The increased directivity of this type of loudspeaker system has a direct impact on the energy sent to the different walls. Figure 15 illustrates the distribution of the SPL of a line array source (12 K2 loudspeakers from L-Acoustics at 10.2 m high[5]) in the sub-low frequency range [20 Hz –250 Hz] and the low-mid frequency range [250 Hz –1000 Hz]. Figure 15 shows that even at sub-low frequencies, the array is designed to send more acoustic energy toward the audience (i.e. toward the floor) than toward the ceiling or the front wall. At higher frequencies (low-mid frequency range), the acoustic energy sent to the rear wall is also reduced. This would naturally limit the influence of the first-order reflections caused by these surfaces. It is anticipated though that side wall

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[5] The trim height of the source is determined so that the middle of the line array is placed at 8 m high to be consistent with the parameters used in the image source model (see Section 2.1).

reflections are energetic depending on the placement of the source relative to the walls and the aperture of the loudspeaker system in the horizontal plane.

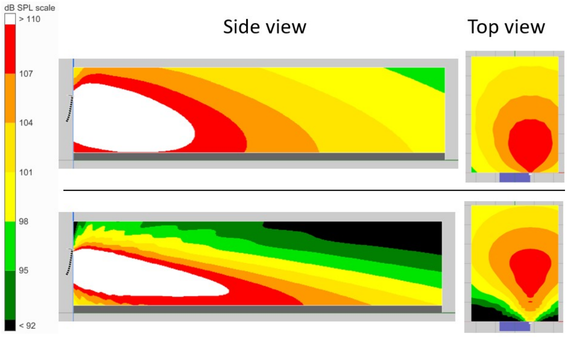

Figure 15. SPL mappings of a typical loudspeaker system designed for the Large room calculated on the [20Hz - 250 Hz] frequency range (top) and the [250Hz - 1000 Hz] frequency range (bottom).

4.2 Effect of more realistic materials

The image source model used in this study considers perfectly reflective surfaces. One could argue that typical venues are often equipped with acoustical materials on walls. Such absorptive materials mainly impact the high frequencies and would reduce the strength of the reflections at these frequencies. Even if not realistic, perfectly reflective materials represent the worst-case scenario where interferences due to first-order reflections are considered as potentially critical up to a higher frequency than it would be in a realistic case.

Finally, the audience itself could be considered as an absorptive material that has a strong influence on the floor reflection. This is regarded as out of the scope of this study because the audience is not present during the tuning phase. Nevertheless, the tuning operator must be aware that the tuning decisions made during the calibration (i.e. without the audience) might need to be adapted during the show simply because of the presence of the audience.

4.3 Relevance of the model used

The model used in this work is simple but can be considered as the worst-case scenario. Indeed, when looking at more directive sound sources, and more realistic acoustic environments, it seems that the strength of most first-order reflections decreases, especially in high frequencies. This would limit the impact of reflections on *in situ* measurements. For this reason, giving basic recommendations based on the worst-case scenario (i.e. based on the simple model used in this study) can be considered as a conservative and safe approach.

5 Conclusions

This paper investigates how a reduced number of measurement locations can be representative of the loudspeaker system response over a large audience area. First, the variability of first-order reflections is studied in large-scale shoebox shaped rooms through simple simulations. Results show that the comb-filtering due to the front wall reflection is stable over the target area, so as the low-frequency build-up created by the floor reflection.

On the contrary, some first-order reflections such as the side wall reflection strongly depend on the position in the audience. Then, different configurations of measurement locations are compared. Results indicate that spatial distributions spread in the depth and width of the measurement area give a more representative characterization of the first-order reflections over the target area. In addition, 8 measurement locations appear as a rational solution to provide a representative characterization of the loudspeaker system response over the target area.

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