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Spatial Average Measurement Methods for Calibration of Immersive Sound in Small Rooms

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ABSTRACT

Immersive sound systems are increasingly used in the production of recorded music. Proper calibration of these systems is critically important to achieve a neutral reference where best translation can be achieved. With regards to final equalization, an accurate and sufficiently high-resolution measurement is required to properly adjust the system. Various methods of measurement in small rooms, including both static microphone and moving microphone methods are compared, and recommendations based on calibration requirements are made.

1 Introduction

While measurement methods for calibration of cinema rooms have some degree of standardization, there are no authoritative measurement standards for calibration of small rooms for music. Best practices guides call out the use of multi-microphone spatial averages [1], but the number and arrangement of microphones is not given. Perhaps as a result, there is a wide variety of spatial averaging methods used for calibration of these spaces.

2 Equalization

The scope of this paper will be limited to the measurement made for final system equalization and after the system is already set up and functioning properly. It is acknowledged that proper time-domain measurements are critical for such things as time alignment, polarity check, and determination of boundary or speaker anomalies. Also, the case for or against full-range calibration for immersive sound will not be discussed.

3 Static Microphone Measurements

Many measurements employed for the calibration of immersive sound systems use static microphone positions to analyze impulse response, reverberation time, etcetera. Using static microphone measurements to capture spatial averages for the purpose of equalization is a logical progression. There are various techniques used to capture this data. Measurement systems can use a multitude of microphones to simultaneously capture data, or a single microphone can be used to sequentially capture measurements. Each strategy has its own benefits and drawbacks. As an example, using multiple microphones might require a more elaborate set up and the management of many calibration files, but measurement iteration would be very rapid. Practically speaking, the number of measurement positions would be limited by required equipment and wiring. Conversely, using a single microphone with sequential measurements would require less equipment and configuration, but measurement iteration would take longer and individual measurement positions would be less repeatable. The number of positions captured would only be practically limited by the time required to gather sequential measurements, however. There are also various strategies as to the geometric properties of the space analyzed. Spatial averages might include a linear array of microphone positions, a two-dimensional plane, or a three-dimensional volume. By definition, spatial averages that do not include data from three dimensions do not apply spatial averaging in the dimension(s) that isn't/aren't measured.

In cinema applications, current standards call for the use of a planar average of static microphone positions. [2,3] In small rooms with a single mix position, a linear or planar array of measurement positions is commonly used. It should be noted that microphones are often placed in a single orientation (, for example pointing upwards,) regardless of the number of positions used or the geometric properties of the space analyzed.

4 Moving Microphone Average (MMA)

The use of a moving microphone to capture spatial averages may not be as common as static microphone measurements, but the technique has been used for some time in calibration of IMAX theatres. [4] The moving microphone technique involves moving a microphone throughout a three-dimensional volume of space while data is continuously captured by a real-time analyzer (RTA). The motion of the microphone may include the continuous change in orientation of the capsule axis so as to randomize the incidence of the sound being analyzed. Potential benefits of this technique include reduced equipment and setup time as well as the ability to capture high resolution spatial averages rapidly.

5 Measurement Technique Comparison

It is the purpose of this paper to compare various techniques and strategies of spatial averaging. The reference for all comparisons will be a high-resolution spatial average of static microphone measurements incorporating a three-dimensional volume of space. The number of microphone positions used in this average will be such that it would be impractical to implement in either a parallel or sequential capture strategy and thus form an upper limit to the resolution and accuracy that could be expected. This average will be comprised of individual time-domain measurements that will also be used for evaluation of different static microphone configurations and number of microphones.

6 Measurement Environment

Experiments were conducted in a variety of rooms with different geometric and reverberant characteristics. Not all experiments were conducted in all rooms, but rooms were chosen for experiments to provide variation in environment that could be relevant to a particular study. Table 1 lists reverberation time (RT60) and arrival time (t_{R1}) of first specular reflection for each room. (The source of this reflection is also noted.)

Room	RT60 (ms)	t_{R1} (ms)
VRD	230	0.62 (C)
EWA	550	0.60 (C)
EWB	142	0.66 (C)
VRM	1100	3.26 (F)
KA	300	1.92 (S)

Table 1. Room Characteristics. First reflection noted as (C) console, (S) side wall, or (F) floor.

Room "VRD" is an irregularly shaped room with a large console. Loudspeaker measured was placed on the console bridge. Room EWA is a medium sized rectangular room with a small table used as a mixing desk. Loudspeaker was placed on a stand behind the desk with a measurement distance of 2 meters. Room EWB is a small rectangular room with a small mixing console. Loudspeaker was placed on a stand immediately behind the console. Rooms measured with no desk or console were rooms VRM and KA. Room VRM is a very large rectangularly shaped space. Loudspeaker was placed on a stand and measured at a distance of 2 meters. Room KA is a small rectangular room with a moderate amount of acoustic treatment. Measurement distance was also 2 meters with loudspeaker placed on a stand.

7 Equipment Used

Microphone used for measurements was an Earthworks M23R. This omni-directional microphone has a 6.3mm capsule and is factory calibrated for free-field measurement. Its polar response is shown in figure 1.

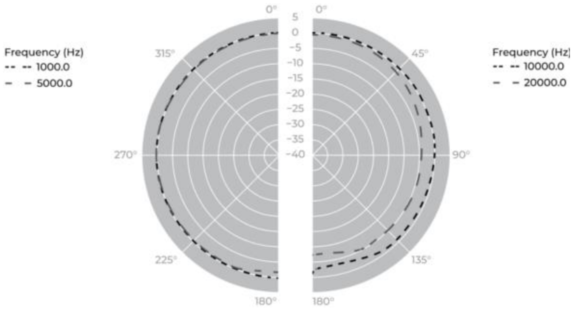

Figure 1. Polar Response of Earthworks M23R microphone. From product webpage.

Interface used was a FocusRite 2i2. Sampling rate was set at 48kHz for all measurements. Loopback on secondary channel was used for timing reference of static microphone measurements, and calibration for interface was performed by loopback of each channel. Measurement software used was Room EQ Wizard version 5.20.13. Software was operating on a PC running Windows 10.

8 Experimental Procedures

Static microphone spatial average measurements were captured in a three-dimensional grid. Five planes of thirty-six measurements each were taken, for a total of 180 measurements. Spacing between measurements in the horizontal planes was 90mm in both width and depth. Spacing between planes was 70mm. The total volume measured was 280 x 450 x 450 (H x W x D, mm). Microphone capsule axis was vertical for all static array measurements, and with the source at 90 degrees from that axis. Calibration for measurement at 90 degrees was derived from free-field microphone calibration by adjusting for polar response using ground plane measurements. Each static measurement used a sweep with length of 256k samples at a sample rate of 48kHz, with a total time of 5.3 seconds. A separate measurement at the center of the three-dimensional array was also made for the purpose of analyzing impulse response and reverberation time.

Static microphone polar response measurements were made at a distance of approximately 2m from the source. The microphone capsule axis was oriented at angles of 0, 45, and 90 degrees with respect to the source. Stimulus used was the same as for grid measurements.

Moving microphone measurements were made in the same volume of space as the static microphone measurements. The measurements were captured while holding the microphone by hand. The motion of the microphone capsule was that of a wide sideways figure-eight motion while keeping the position of the hand steady and rotating the wrist.

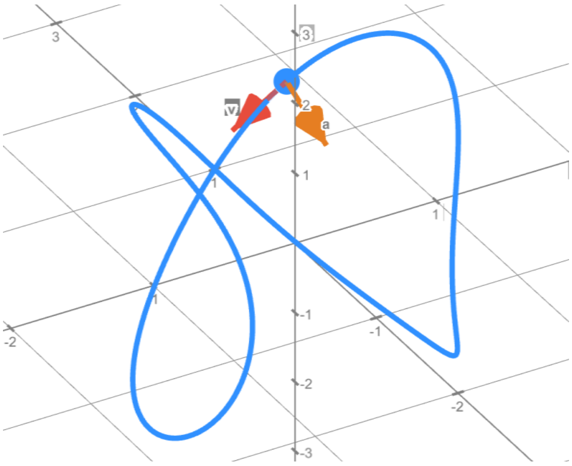

Figure 2. Moving microphone motion.

Geometrically, the motion of the capsule is similar to a lemniscate, but curved around a cylinder. As such, the microphone capsule axis is cycled through three-dimensions and incidence to the source is varied. Calibration for moving microphone measurements was derived from free-field calibration by determining the difference between moving microphone measurements made with the capsule oriented directly at the source and those made with the technique described above. RTA was configured for 1/24th octave resolution, 16k sample FFT length, and Hann window. “Forever” averaging was used with no smoothing.

Influence of microphone polar response on moving microphone measurements was investigated by positioning the experimenter at various orientations with respect to the source. All orientations were mutually perpendicular. In the first orientation, referred to as “forward”, the experimenter was directly facing the source. In the second orientation, referred to as “sideways”, the experimenter was facing 90 degrees from the source in the horizontal plane. In the third and final orientation, referred to as “upwards”, the experimenter was facing upwards and at a 90-degree angle relative to the source in the vertical plane. The measurement volume was the same for all orientations.

9 Experiments, Results, and Analysis

9.1 Static Measurements: Volume Average

The average of all 180 measurements are shown in figure 3 for room VRD (Red), EWB (Blue), and KA (Green). As previously mentioned, these measurements represent an upper limit to practically achievable resolution and accuracy. As such, these volume averages will be used as a normalization reference for comparison to all other measurement methods.

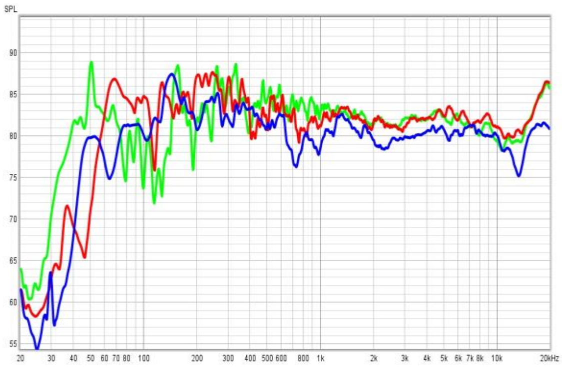

Figure 3. Volume average

9.2 Static Measurements: Planar Average

The average of thirty-six measurements in a horizontal plane was likewise determined for the three rooms measured and compared against the corresponding 180-position volume average. The averages in figure 4 were from the center plane of the three-dimensional grid in rooms VRD (Red), EWB (Blue), and KA (Green), and normalized to the corresponding volume average.

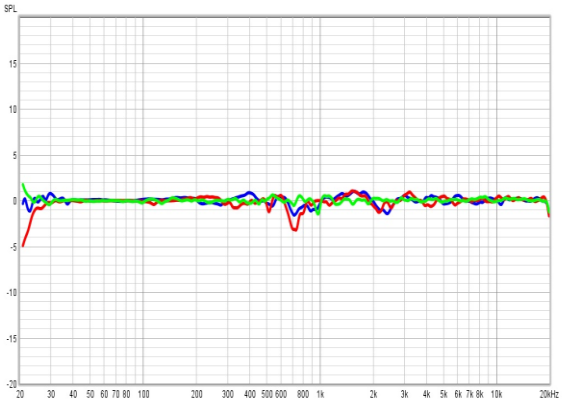

Figure 4. Planar averages

The measurements show that the response at low frequencies matches the volume average very well, as it also does at high frequencies. At middle frequencies, there is a periodic variation shown in measurements made with large horizontal surface such as a mixing desk or console. It is thought that the source of this variation may be a result of combing in the vertical plane with the first specular reflection from the horizontal surface, since the planar measurement has no averaging in the vertical dimension. Quantification of this effect and potential mitigating factors will be the subject of future work.

9.3 Static Measurements: Line Average

The average of six microphone positions in a horizontal line across the width of the measurement volume was determined for three rooms measured. The measurements of figure 5 were from room VRD (Red), EWB (Blue), and KA (Green) in the center plane of the three-dimensional directly forward of the plane center. Measurements are shown normalized to the 180-position volume average.

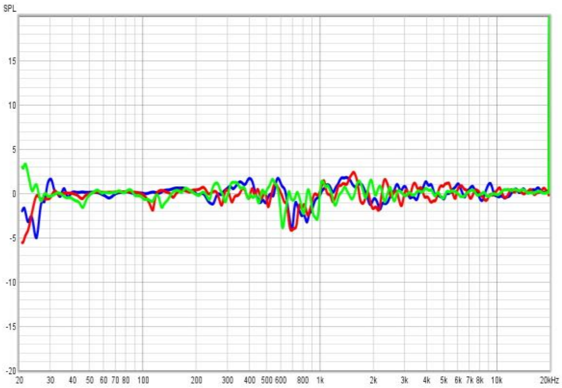

Figure 5. Line Average

It can be seen from figure 5 that like planar averages, the response matches the volume average better at high and low frequencies than in middle frequencies. Anomalies previously described are at the same frequencies but are more severe.

9.4 Static Measurements: Random Positions

Volume averages with various numbers of microphones were analyzed to determine expected variation from the 180-microphone volume average. Six averages each were made using four, eight, sixteen, and thirty-two microphones randomly selected from the entire three-dimensional volume. Measurements are shown in figures 6 through 9 normalized against the 180-position average of room KA.

As can reasonably be expected, fewer microphones resulted in greater variation, while greater number of positions converged to the full volume average.

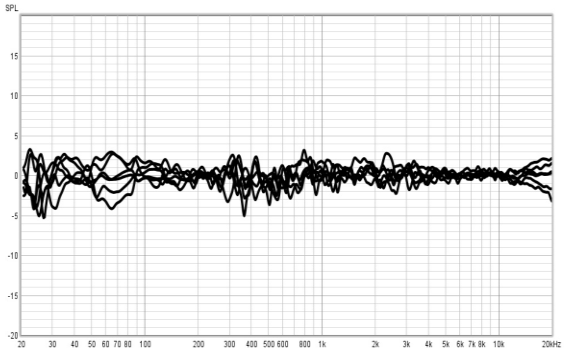

Figure 6. Four position volume averages.

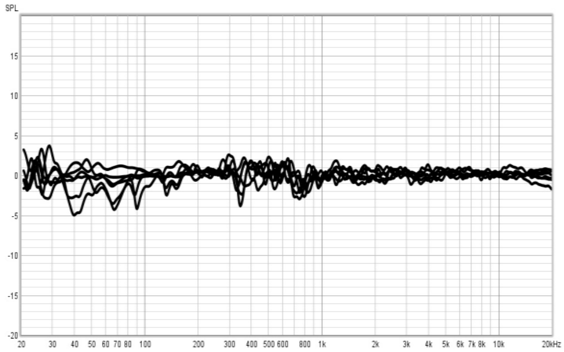

Figure 7. Eight position volume averages

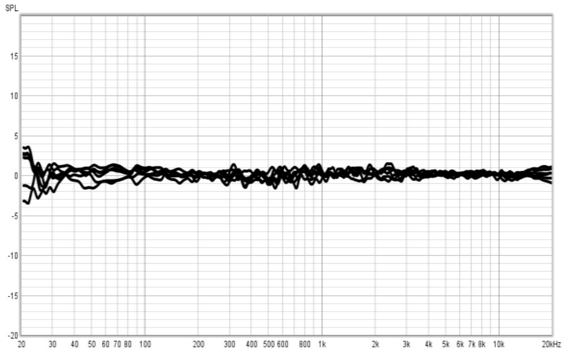

Figure 8. Sixteen position volume averages.

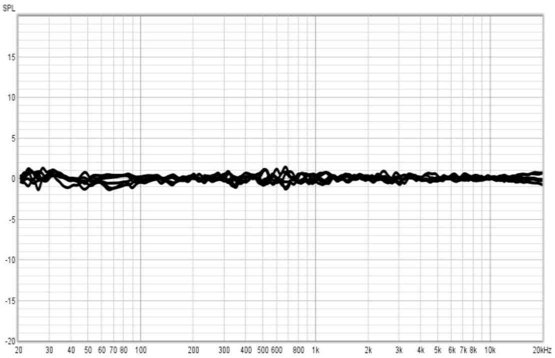

Figure 9. Thirty-two position volume averages.

9.5 Static Measurements: Polar Response

Static microphone measurements made at angles of 0 (Green), 45 (Blue), and 90 (Red) degrees are shown in figures 10 and 11 normalized to the 0-degree response.

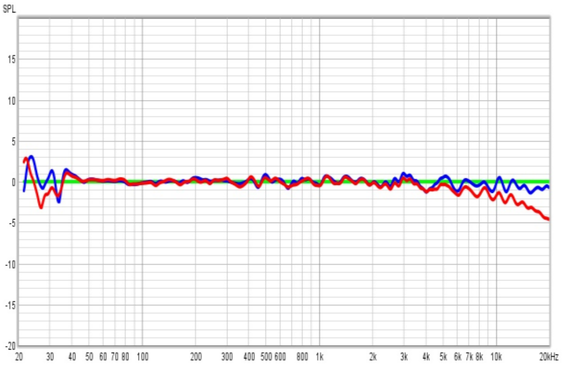

Figure 10. Static microphone polar influence.
(Room VRM)

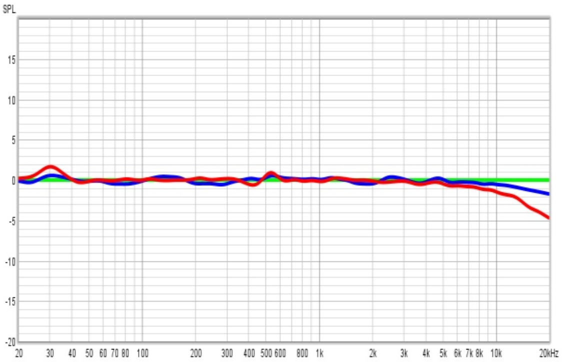

Figure 11. Static microphone polar influence.
(Room EWA)

Influence of microphone polar response can clearly be seen above 4 kHz. The amount of influence is similar in both rooms regardless of reverberation time.

9.6 Moving Microphone: Consistency

To test consistency of MMA measurements, six separate measurements from a single experimenter are compared as shown in figure 12 normalized to the average of all six measurements. Measurements were made in room KA.

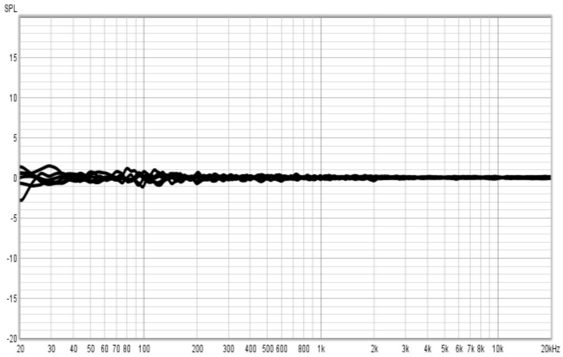

Figure 12. MMA measurement consistency.

Moving microphone method shows consistent response among all measurements made. Variation increases at lower frequencies, but is still comparable to static microphone measurements made with 16 or more measurement positions.

9.7 Moving Microphone: Accuracy

When normalized to the volume average of 180 static measurement positions, moving microphone measurements are likewise consistent. Figure 13. Shows moving microphone average from room VRD (Red), EWB (Blue), and KA (Green) normalized to the corresponding volume average. Variation at low frequencies is below the low-frequency cut-off of the loudspeaker.

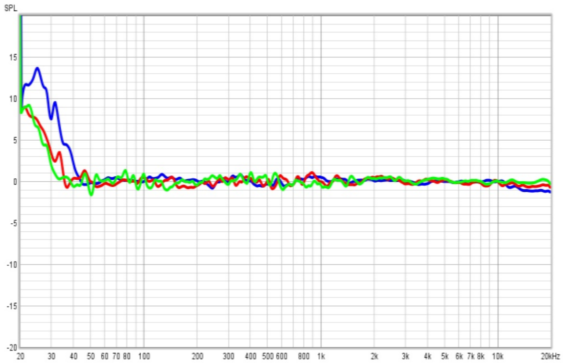

Figure 13. MMA vs. Volume Average

When compared to averages of randomly selected microphone positions, MMA measurements compare favorably. As shown in figures 14 and 15, moving microphone averages (black) are comparable to static microphone measurements (grey) made with between 16 and 32 microphone positions.

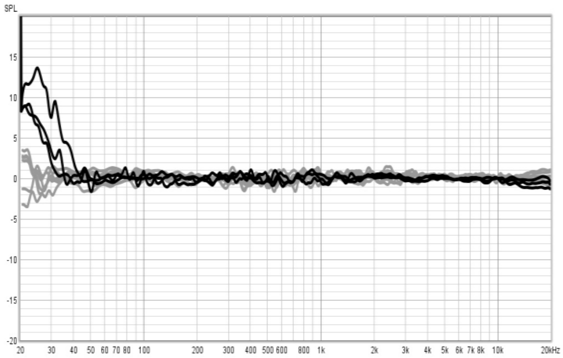

Figure 14. MMA measurements vs 16 positions.

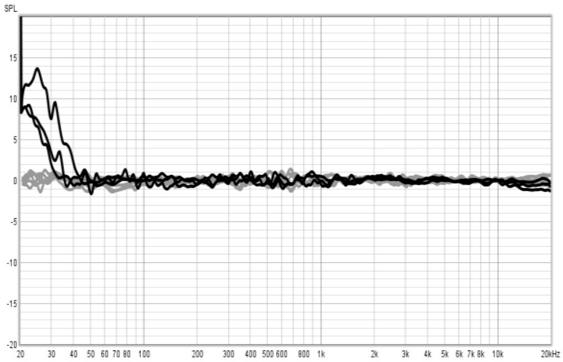

Figure 15. MMA measurements vs 32 positions.

9.8 Moving Microphone: Polar Response

Figures 16 and 17 show the influence of microphone polar response on moving microphone measurements. Measurements were made in forwards (Green), sideways (Red), and upwards (Blue) experimenter orientations. All measurements are normalized to the average of all three orientations.

When measured in the same space as previous measurements of polar influence on static microphone measurements, MMA measurements show substantially less effect.

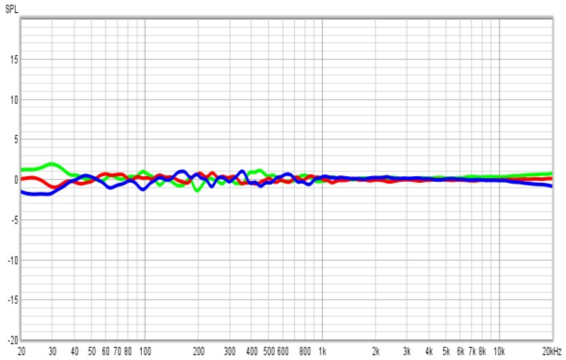

Figure 16. MMA Polar Influence (Room EWA).

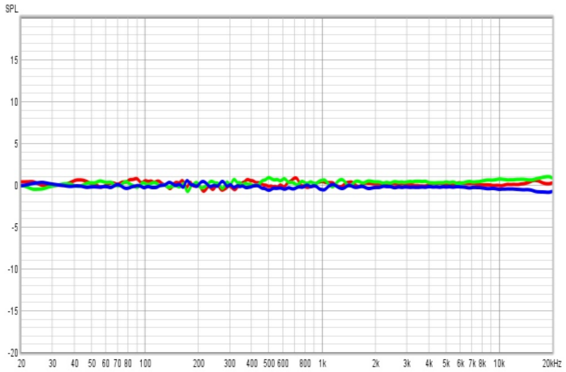

Figure 17. MMA Polar Influence (Room VRM).

10 Conclusions

Commonly used methods of spatial averaging using static microphone measurements have problems which are potentially troublesome for full-range immersive calibration. If the microphones are arranged in a single plane or line, they by definition do not have averaging in the dimension(s) not measured. This can be a problem in a situation where a specular reflection from a console or desk causes combing in the vertical plane with the direct sound, as an example. Secondly, since the loudspeakers in an immersive audio system are placed at various angles with reference to any particular orientation of the microphone capsule, the polar response of the microphone can be a confounding variable in full range calibration. Lastly, averages calculated from an insufficient number of microphones can increase variation in the measurement. There are mitigation strategies to deal with these potential issues, such as using a three-dimensional array with sufficient number of measurement positions. Polar response can potentially be addressed by using a vertical orientation of the capsule so as to have the same angle of incidence for all bed channels. Overhead channels could have a separate calibration. Of course, the challenges enumerated are not a significant issue for stereo calibration where equalization is typically applied only at low frequencies.

Moving microphone measurements provide a rapid, repeatable, and accurate method that does not suffer from the same drawbacks for full-range calibration. Because the method averages many positions in three-dimensional space and with varying microphone orientation, it is inherently robust in this regard.

Because of these reasons, the author is of the opinion that moving microphone method has compelling advantages for the full-range equalization of immersive sound systems.

Regardless of the method used, the results of this study have reminded the author that the precision of equalization applied should never exceed the confidence in measurements made.

Acknowledgements

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