A COMPARISON OF LATE LATERAL ENERGY (GLL) AND LATERAL ENERGY FRACTION (LF) MEASUREMENTS USING A SPHERICAL MICROPHONE ARRAY AND CONVENTIONAL METHODS

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ABSTRACT

Late Lateral Energy Level (GLL) and Lateral Energy Fraction (LF) are two room acoustics measures that have both been shown to correlate with certain aspects of the spatial impression of a listening space. In order to obtain these quantities, the lateral energy must be measured, which is typically carried out using microphones with a figure-of-eight (figure-8) polar pickup pattern. However, most commercially available figure-8 microphones are intended for use in audio recording applications, and are not laboratory-grade or designed for room acoustics impulse response (IR) measurements. Such microphones may suffer from non-ideal frequency response and/or directivity patterns. This study compares measurements that were taken in a 2500 seat auditorium using an omni-directional and studio-grade figure-8 microphone pair versus the omni-directional and dipole components extracted from a 32 element spherical microphone array. The results show that the two measurement methods agree in the 500 Hz and higher octave bands, but differ at low frequencies due to differences in the directivity patterns. The difference of the LF average from 125 Hz to 1 kHz for the two methods was between 0.59 and 1.81 just noticeable differences (JNDs) at the six receiver locations. The difference of the GLL average from 125 Hz to 1 kHz for the two methods was between 0.02 and 0.48 JNDs (applying the JND for strength of 1 dB). It was also found that repeatability error was present at one of the six receiver locations for the LF measurements, but was very small for the GLL measurements.

1. INTRODUCTION

To quantify certain spatial parameters in rooms, a measurement of the lateral sound field is required, which is typically acquired using microphones with a figure-8 polar pickup pattern. The focus of this study was to compare the measurement of spatial measures by obtaining the figure-of-eight (figure-8) room impulse response (IR) in two different ways: using a microphone with a figure-8 directivity pattern, and by using a spherical microphone array and obtaining the figure-8 pattern by beamforming the dipole response.

It should be noted that while the spherical microphone array used in this study is capable of a third order spherical harmonic expansion, only the first order dipole is required for these measurements. While the full capability of the microphone array isn't needed for this work, this study serves as a verification that spherical microphone arrays, which are now being used for advanced analysis of room IRs, can also be used to measure the metrics commonly used in the architectural acoustics community which are outlined in the room acoustics measurement standard, ISO 3382 [12].

1.1. Spatial Measures

There is ongoing research to find objective metrics that correlate with the subjective perceptions of the quality of concert hall acoustics. Spatial impression is one characteristic that has been shown to be related to overall quality [1]. This concept was explored in terms of early lateral reflections by Barron [2], and low frequencies were also found to be an important component of spatial impression [3]-[5]. Further research proposed that spatial impression should be formally divided into two distinct components [5], with the particular details established by Bradley and Soulodre who defined: the apparent source width (ASW) as being associated with the early lateral reflections, and listener envelopment (LEV), which is related to late lateral reflections [6].

A number of objective measures have been proposed to predict both ASW and LEV, but only two were the focus of this study. Lateral energy fraction (LF) is a commonly used parameter to predict the perception of ASW, which is the ratio of early lateral energy to total early energy [2]:

$$LF = \frac{\int_{5\,ms}^{80\,ms} p_f^2(t)dt}{\int_0^{80\,ms} p_O^2(t)dt} \tag{1}$$

where $p_f(t)$ is the room IR measured with a figure-8 microphone, and $p_o(t)$ is the room IR measured with an omnidirectional microphone. Late lateral energy level (GLL) has been used to predict LEV, which is the ratio of the late lateral energy to the normalized source energy [6]:

$$GLL = 10log\left[\frac{\int_{80ms}^{\infty} p_f^2(t)dt}{\int_0^{\infty} p_a^2(t)dt}\right] \text{ [dB]} \tag{2}$$

where $p_f(t)$ is the room IR measured with a figure-8 microphone, and $p_a(t)$ is the IR of the sound source normalized at a distance of 10 meters away in a free field.

1.2. Measurement Uncertainty of Spatial Measures

Only a handful of studies have been published that evaluate measurement uncertainty of spatial measures and the results from the majority of the studies show a high degree of uncertainty [7] - [10]. One of the earliest studies showed that the standard deviation across the results from four measurement teams for LF measurements was up to 0.20 at 1 kHz which each used a different figure-8 microphone [7]. A second study compared the results of LF and GLL measurements from a figure-8 and omni-directional microphone pair and a custom intensity probe, and reported significant differences in the results likely due to variations in the microphone directivity patterns [8]. The first phase of the third room acoustics simulation programs round robin study was to collect measurement data on the space that was to be modeled. The results for the typical parameters, e.g. reverberation time (T30), early decay time (EDT), etc. were very similar across the four measurement teams [9]. However, significant differences in LF were found, which were on the order of 3 just noticeable differences (JNDs), where the JND for LF is 0.05. Some follow-up measurements using three figure-8 microphones of the same make and model (Neumann KM86) revealed significant differences in measurements taken with the microphones at different orientations. One possible source of this measurement error was hypothesized to be due to changes in the microphone sensitivity of each diaphragm due to aging.

A more recent case study was conducted to further evaluate the measurement uncertainty of spatial measures in terms of microphone orientation, spacing between the microphone pair, and microphone type [10]. A total of five different makes and models of figure-8 microphones were evaluated by taking measurements in a small lecture hall with about 100 seats. The average differences due to microphone spacing, which varied between 64 to 152 mm, and microphone orientation, were found to be relatively small for GLL, which were on the order of 0.2 dB, but were slightly higher for LF, on the order of 3 JNDs. On the other hand, the effect of microphone type was more significant for GLL, with variations on the order of 1.5 dB, and similar variation of about 3 JNDs for LF.

1.3. Microphone Limitations

For this experiment, three different microphones were used to measure room IRs: a Brüel & Kjær (B&K) Type 4192 omni-directional microphone, a Sennheiser MKH 30 Figure-8 microphone, and an mh Acoustics em32 Eigenmike® spherical microphone array. The Sennheiser microphone and the Eigenmike both have their own distinct disadvantages in measuring the lateral energy component of the IR. The Sennheiser microphone is not a laboratory-grade instrument, and the frequency response is not flat broad-band. In addition, the linearity of the microphone is not known, and was not measured as a part of this study. The Eigenmike has a high frequency limit of approximately 8 kHz due to spatial aliasing. Below approximately 150 Hz, the Eigenmike begins to veer away from an ideal dipole shape due to white noise gain constraints. Below this frequency, the null shifts in angle, and the main lobes are no longer symmetric [11].

2. MEASUREMENT PROCEDURE

2.1. Measurement Equipment

A B&K Type 4292-L OmniPower Sound Source dodecahedron loudspeaker was used for the source, driven with a Crown K2 amplifier. An RME Babyface was used for the audio interface with the computer for the B&K and Sennheiser pair. For the Eigenmike configuration, the Eigenmike Interface Box (EMIB) was used as the audio interface, and the RME Babyface was used as a D/A converter to send the output signals from the Eigenmike Interface Box to the amplifier. EASERA room acoustics software running on a MacBook Pro was used to measure the IRs. The EMIB connects to the MacBook via FireWire interface to send the 32 channels of data from the Eigenmike to the computer.

A custom microphone stand was built that could be used for both microphone configurations, the Eigenmike, and the omni and figure-8 pair (see Figure 1). The omni and figure-8 microphones were placed 7.6 cm apart from each other. This spacing was used to allow for the microphones to be adequately far enough apart so as to minimize the effects on the other microphone [10], but close enough so that they were measuring approximately the same point in space.

During the measurements, the base of the microphone stand was positioned in front of the seat, and the adjustable arm was used to place the microphone in the location of a listener's head. The microphone stand is adjustable in each dimension separately to allow for accurate and precise positioning of the microphone. For these measurements, the center of each microphone array (either the center of the Eigenmike array or the center of the two discrete microphones) was placed in the halfway across the width of the chair, 20 cm from the seat back, and 70 cm above the seat bottom.

Figure 1: *The two microphone arrays in the custom microphone stand.*

2.2. Anechoic Chamber Measurements

In order to calculate GLL, the free field sound pressure level of the sound source at 10 meters must be obtained to use in the denominator in equation (2), which is typically done using an anechoic chamber. An IR measurement was taken every 12.5 degrees around the dodecahedron loudspeaker at a distance of 3.55 meters away according to ISO 3382 [10] using a B&K 4191 free field microphone. The stimulus was a swept sine signal with a pink-weighted spectrum, which was played at the same level that was used for the IR measurements in the hall. The resulting 29 measurements were energy-averaged to account for the directivity of the source, and normalized to a distance of 10 meters away.

Since standard calibrators are not available for either the Eigenmike or the Sennheiser MKH 30, the microphones had to be calibrated using a loudspeaker playing a calibration tone in an anechoic chamber. A 1 kHz tone was played over the dodecahedron loudspeaker, and the sound level was measured using a calibrated sound level analyzer, B&K type 2250. These levels were entered into the measurement program, which used these quantities to calculate the microphone sensitivities. The Eigenmike includes a PC application which controls programmable gain amplifiers to correct for magnitude differences between the individual microphone capsules.

To verify the directivity of the Sennheiser and Eigenmike, the frequency response of each microphone was measured in an anechoic chamber as a function of angle in the horizontal plane. The microphone was placed on a turntable two meters away from a stationary loudspeaker, and the frequency response function was measured with each microphone rotated every three degrees.

2.3. Room Impulse Response Measurements

IR measurements were taken in the Eisenhower Auditorium located on The Pennsylvania State University campus in University Park, PA in the United States. The source was placed in the center of the stage for all measurements. Six receiver locations were chosen in the hall: two on the main floor (R1 and R2), two on the grand tier level (R3 and R4), and two on the balcony level (R5 and R6), as shown in Figure 2.

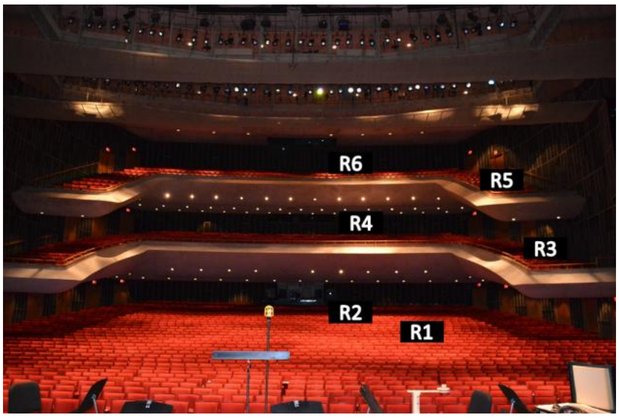

Figure 2: *Receiver positions in Eisenhower Auditorium.*

At each receiver position, the IR was measured using the measurement software EASERA. The stimulus was a swept sine signal with a pink-weighted spectrum. Each measurement was done using 10 sweep averages, and an additional pre-sweep. Measurements were taken using both microphone arrays: the Eigenmike and the omni and figure-8 pair. In terms of aligning the microphones with the sound source, the front of the Eigenmike array was pointed at the loudspeaker, while for the microphone pair, it was aligned with the null plane of the Sennheiser microphone oriented vertically toward the loudspeaker. The aligning of microphones toward the source was done by eye, which became increasingly more difficult for the receiver locations were towards the back of the hall.

To check for measurement repeatability, two additional sets of measurements were taken. In between sets, the custom microphone stand was removed and the various adjustment points were loosened and randomly repositioned. The stand was then replaced in the same spot to re-measure the IRs for each microphone. A total of three IR measurements were taken for each microphone array, at each of the six receiver locations for a total of 36 measurements.

3. DATA PROCESSING

3.1. Frequency Response Correction Filter

The raw frequency response of the Sennheiser MKH 30 microphone and Eigenmike array varied as much as ± 6 dB at certain frequencies, and this was deemed unacceptable for the measurements of LF and GLL. Filters were generated to compensate for the frequency response of both the Eigenmike array and the Sennheiser MKH 30 based on free field measurements.

A target for the filter magnitude as a function of frequency was generated by taking the difference between the on-axis magnitude of the Sennheiser MKH 30 frequency response and the on-axis magnitude of a B&K 4191 free field measurement microphone in dB. The difference was taken with one-third octave band logarithmic-energy-smoothing applied to both the figure-8 response and the measurement microphone response. The target was then fit to a minimum-phase FIR filter. A minimum-phase filter was used to keep the filter's IR compact in time and to avoid pre-ringing of the IR, which would occur in linear-phase or zero-phase filtering techniques. The same procedure was applied to the dipole pattern generated from the Eigenmike, although since the magnitude of each lobe on the figure-8 differs at low and high frequencies, an energy average of the magnitude of both lobes were used to create the target.

A similar method was used to create a filter for the omni-directional response of the Eigenmike. Instead of free-field measurements, the filter target was created by using the energy averaged (over receiver position) difference in dB between the B&K 4192 and the Eigenmike frequency responses in the hall.

3.2. Beamforming

To calculate LF and GLL from the Eigenmike measurements, the omni-directional response and dipole response must be extracted. These responses were generated using EigenStudio, a computer application by mh Acoustics for the Eigenmike, which performs the beamforming operation on the 32 channels of data. The 32-channel IRs recorded in EASERA were loaded into EigenStudio, which outputs both the omni-directional and dipole IRs, with the null plane oriented vertically toward the source. EigenStudio uses a two stage beamforming process [13]. In the first stage, the 32 channels are transformed into orthonormal beam patterns referred to as eigenbeams via a transformation to spherical harmonics. The second stage is a modal beamformer where each beam is weighted by a factor and the beams are summed to achieve the desired directivity.

3.3. Spatial Parameter Calculation

EASERA was used to calculate the spatial parameters LF and GLL. Using equation (1), LF was calculated for each octave band for the Eigenmike using the beamformed omni-directional IR and beamformed dipole IR for each of the three repetitions at each receiver location. In addition, LF was calculated for the omni and figure-8 pair using the IRs from the B&K 4192 and the Sennheiser MKH 30. The LF in the octave bands from 125 Hz to 1 kHz were arithmetically averaged together to obtain a single number for LF according to ISO 3382 [12]. Differences for LF are given in JNDs, where one JND is 0.05.

EASERA does not have a built in function to calculate GLL, so as an alternative, the Strength (G) function was adapted. In order to use this function, the figure-8 IR was used for the numerator of the strength calculation, with the first 80 milliseconds of the IR multiplied by zero. This modification was done using both the Eigenmike beamformed dipole IR and the Sennheiser MKH 30 IR. In both cases, the denominator for the GLL calculation was the anechoic response of the omni-directional source discussed in section 2.2. The GLL in the octave bands from 125 Hz to 1 kHz were energy-averaged together to obtain a single number for GLL according to ISO 3382 [12]. Differences for GLL are given in JNDs. The JND for GLL is not known, but for the purposes of this study the JND is assumed to be 1 dB, which is the JND for Strength (G).

4. RESULTS

4.1. Directivity

The frequency response function was measured every three degrees in the horizontal plane for each microphone. The magnitude was one-third octave band energy smoothed at each angle. For each microphone, polar plots of the magnitude were generated at each octave band. The Sennheiser MKH 30 directivity is very good broadband. As shown in Figure 3, the response is a consistent dipole over the entire frequency range of interest (125-4k Hz). The beamformed dipole response measured with the Eigenmike was very good for the 500 Hz to 4 kHz octave bands as shown in Figure 4. At 125 Hz, the response was not an ideal dipole. The magnitude of one of the lobes was smaller than the other lobe, and the nulls shifted in angle. This change occurs because at low frequencies EigenStudio sums in a portion of the zeroth order spherical harmonic, and the response approaches a cardioid pattern. While this technique is helpful in mitigating issues relating to white noise gain in certain applications, it is not ideal for measurements of LF and GLL.

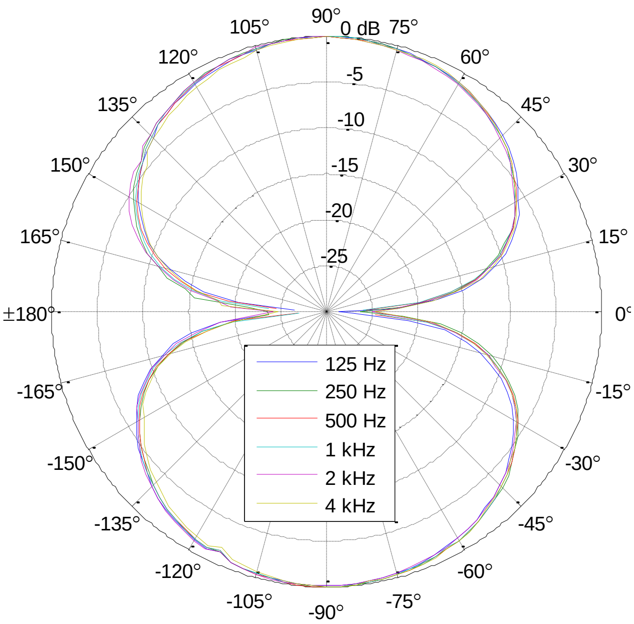

Figure 3: *Measured directivity pattern of the Sennheiser MKH 30.*

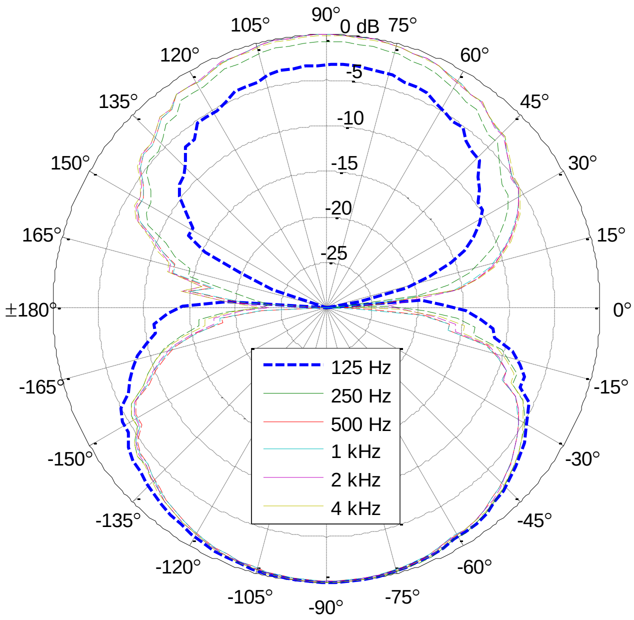

Figure 4: *Measured directivity of the Eigenmike dipole beamformed in Eigenstudio.*

4.2. Repeatability

The repeatability of the LF and GLL measurements for both the Eigenmike and omni-directional and figure-8 pair was assessed using the standard deviation of the three separate measurements taken at each of the six receiver locations. Since the number of measurements at each location was small, statistical tests were not performed. In terms of LF, repeatability was found to be good for R1 through R5 measured with the Eigenmike, which had standard deviations of 0.20 or less JNDs (see Table 1 for the average and Table 2 for the standard deviation). However, there was significantly more variation at R6, which had a standard deviation of 0.86 JNDs. This receiver position was in the back of the auditorium on the balcony, which was approximately 35 meters away from the stage, and was the most difficult to align the rotation of the microphone array. The repeatability was similar for the Sennheiser and B&K pair with lower variation at R2, R5, and R6, and slightly higher variation at R1, R3, and R4 (see Table 3 for the average and Table 4 for the standard deviation).

Table 1: *Average LF measured with Eigenmike.*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	0.26	0.21	0.10	0.10	0.17
R2	0.12	0.15	0.08	0.09	0.11
R3	0.34	0.38	0.16	0.11	0.25
R4	0.19	0.16	0.11	0.15	0.15
R5	0.45	0.29	0.18	0.17	0.27
R6	0.16	0.16	0.28	0.28	0.22

Table 2: *Standard deviation of Eigenmike LF measurements in # of JNDs, where one JND is 0.05.*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	0.04	0.07	0.03	0.05	0.05
R2	0.10	0.52	0.06	0.07	0.19
R3	0.15	0.07	0.10	0.01	0.08
R4	0.06	0.02	0.04	0.02	0.03
R5	0.18	0.23	0.20	0.16	0.20
R6	0.34	1.13	1.07	0.91	0.86

Table 3: *Average LF measured with Sennheiser and B&K pair.*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	0.13	0.15	0.09	0.08	0.11
R2	0.05	0.10	0.07	0.09	0.08
R3	0.13	0.26	0.15	0.08	0.16
R4	0.12	0.13	0.10	0.14	0.12
R5	0.26	0.20	0.14	0.14	0.18
R6	0.12	0.24	0.19	0.19	0.18

Table 4: *Standard Deviation of Sennheiser and B&K pair LF measurements in # of JNDs, where one JND is 0.05.*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	0.09	0.04	0.04	0.09	0.07
R2	0.13	0.07	0.05	0.07	0.08
R3	0.13	0.08	0.17	0.05	0.11
R4	0.08	0.07	0.02	0.07	0.06
R5	0.13	0.21	0.09	0.02	0.11
R6	0.20	1.52	0.15	0.11	0.50

The repeatability was found to be better for GLL than for LF in all receiver locations for the Eigenmike (see Table 5 for average GLL and Table 6 for standard deviation). This finding was true even in cases where the LF repeatability was relatively poor. These results indicate that GLL measurements are less sensitive to small spatial misalignments than LF measurements. The repeatability of the GLL measurements made using the Sennheiser and B&K pair were also similar to repeatability of the Eigenmike measurements (see Table 7 for average GLL and Table 8 for standard deviation).

Table 5: *Average GLL measured with Eigenmike [dB].*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	-2.07	-0.93	-2.70	-4.03	-2.29
R2	-1.60	-3.03	-5.63	-5.27	-3.57
R3	-3.17	-2.67	-5.63	-4.40	-3.82
R4	-4.00	-3.93	-5.00	-4.53	-4.35
R5	-0.50	-1.53	-3.53	-3.67	-2.10
R6	-2.50	-1.93	-3.43	-3.87	-2.87

Table 6: *Standard deviation of Eigenmike GLL measurements in # of JNDs, where one JND is 1 dB.*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	0.12	0.09	0.00	0.09	0.08
R2	0.22	0.12	0.12	0.12	0.15
R3	0.19	0.05	0.05	0.00	0.07
R4	0.08	0.05	0.00	0.05	0.04
R5	0.00	0.12	0.12	0.09	0.09
R6	0.16	0.05	0.09	0.05	0.09

Table 7: *Average GLL measured with Sennheiser and B&K pair [dB].*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	-2.00	-0.90	-2.70	-4.20	-2.29
R2	-3.23	-3.23	-5.40	-5.33	-4.17
R3	-3.50	-2.20	-5.17	-4.33	-3.66
R4	-5.50	-3.63	-4.70	-4.53	-4.54
R5	-0.67	-1.47	-3.27	-3.50	-2.06
R6	-3.27	-2.00	-3.23	-3.93	-3.05

Table 8: *Standard Deviation of Sennheiser and B&K pair GLL measurements in # of JNDs, where one JND is 1 dB.*

	125 Hz	250 Hz	500 Hz	1 kHz	Avg. 125-1k
R1	0.00	0.00	0.00	0.00	0.00
R2	0.05	0.12	0.08	0.05	0.08
R3	0.08	0.08	0.05	0.05	0.06
R4	0.08	0.05	0.00	0.05	0.04
R5	0.05	0.05	0.09	0.00	0.05
R6	0.12	0.00	0.05	0.05	0.05

In IR measurements where repeatability was found to be poor for LF, the GLL measurements were largely unaffected. LF is calculated by integrating the lateral energy from 5 ms to 80 ms, which can be seen in equation (1). In this region, the microphone picks up energy from the direct arrival and early reflections. Ideally, the figure-8 microphone should reject both the direct sound and early reflections which are coming from directly in front of the microphone. Small angular misalignments will allow some of the direct sound in the measurement, and since the direct sound is high in level compared to later reflections, these misalignments could have a significant impact on the measurement. This effect can be seen in the figure-8 IRs measured at R6. Figure 5 shows the three repetitions of the 250 Hz octave band measured with the Sennheiser microphone, which was the worst case for measurement repeatability. One of the measurements has more energy in the first 20 ms of the IR than the other two measurements, after which the IRs seem to agree more closely. Conversely, the GLL calculation involves integration of the lateral energy from 80 ms to infinity as seen in equation (2), and is less susceptible to small misalignments because there are no longer strong components which are directly on-axis in the late sound field.

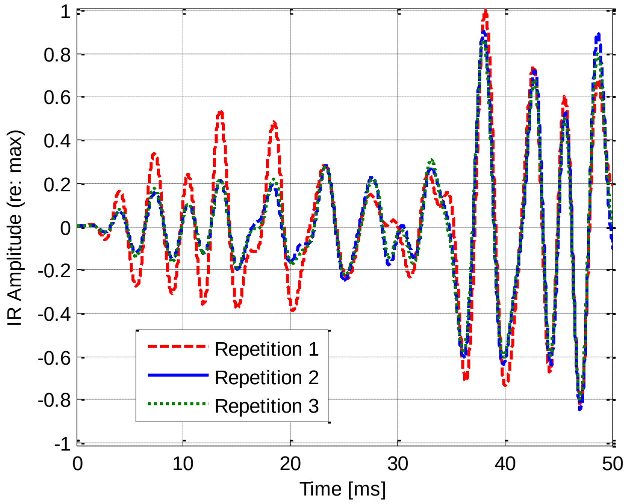

Figure 5: *Three repetitions of the Sennheiser IR measurement at R6 filtered at 250 Hz octave band.*

4.3. Two microphone comparison

The LF and GLL measurements made with the Eigenmike and Sennheiser MKH 30 were compared by subtracting one value from the other and then converted into the number of JNDS. The largest differences in LF between the two microphone configurations were found in the 125 Hz octave band, and to a lesser extent the 250 Hz octave band (see Table 9), where the LF measured with the Eigenmike is substantially higher than the LF measured with the Sennheiser MKH 30 in all receiver locations. This discrepancy is likely due to the fact that the null in the Eigenmike's dipole response beamformed in Eigenstudio has shifted in angle from the ideal dipole pattern. For these measurements, the null is pointed at the sound source on the stage. Since the null is shifted, the microphone is picking up portions of the direct sound and early reflections which are rejected in the Sennheiser measurement. An example of this effect can be seen in Figure 6, which shows the first 80 ms of the 125 Hz IRs for both the Eigenmike and Sennheiser microphones. Agreement between the Eigenmike and the Sennheiser is much better from 500 Hz to 4 kHz where the Eigenmike's directivity pattern is closer to an ideal dipole, with the exception of R6 where agreement was poor from 500 Hz to 4 kHz, which is also where there was relatively poor repeatability.

Table 9: *Difference in LF between Sennheiser and B&K pair and Eigenmike in # of JNDs, where one JND is 0.05.*

	125 Hz	**250 Hz**	**500 Hz**	**1 kHz**	**Avg. 125-1k**
R1	2.61	1.16	0.26	0.48	1.13
R2	1.49	1.09	0.19	0.07	0.71
R3	4.08	2.43	0.30	0.44	1.81
R4	1.52	0.57	0.24	0.02	0.59
R5	3.78	1.72	0.77	0.71	1.75
R6	0.85	1.57	1.93	1.82	0.76

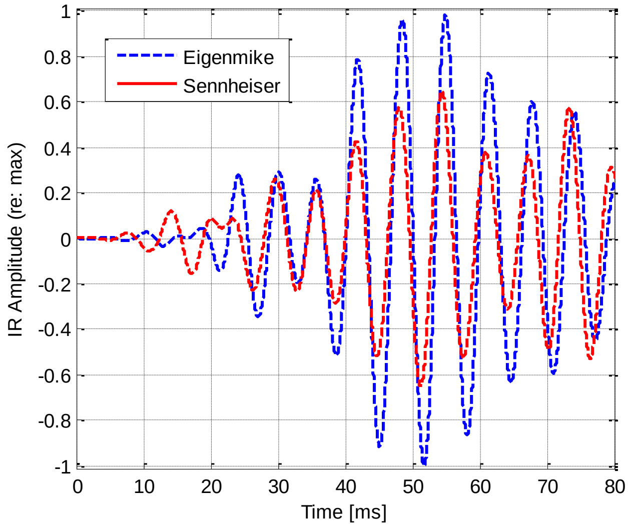

Figure 6: *Sennheiser and Eigenmike beamformed dipole IR measurements at R3 filtered at 125 Hz octave band.*

The measurement of GLL between the two microphones had better agreement than the measurement of LF. The largest variation is again seen in the 125 Hz octave band due to the non-ideal directivity of the beamformed dipole (see Table 10).

Table 10: *Difference in GLL between Sennheiser and B&K pair and Eigenmike in # of JNDs, where one JND is 1 dB.*

	125 Hz	**250 Hz**	**500 Hz**	**1 kHz**	**Avg. 125-1k**
R1	0.07	0.03	0.00	0.17	0.02
R2	1.63	0.20	0.23	0.07	0.48
R3	0.33	0.47	0.47	0.07	0.15
R4	1.50	0.30	0.30	0.00	0.29
R5	0.17	0.07	0.27	0.17	0.08
R6	0.77	0.07	0.20	0.07	0.19

5. CONCLUSIONS

The lateral energy component that is used to calculate the spatial parameters LF and GLL was measured using two different microphone configurations: a conventional figure-8 microphone (Sennheiser MKH 30), and a spherical microphone array (mh Acoustics em32 Eigenmike). Using the two methods, room impulse responses were measured in a 2500 seat auditorium and three repeatability measurements were taken in all six of the receiver locations.

The repeatability was evaluated for the spatial measures of LF and GLL. The LF measurement repeatability was found to be poor at R6, which was the location farthest from the stage. The low frequency standard deviation was more than one JND in some octave bands at R6. A likely cause for the repeatability error was misalignment in the rotation of the microphone, which would allow the figure-8 microphone to pick up a portion of the direct sound and early on-axis reflections, skewing the measurement of LF The measurements of GLL were much more consistent than the measurements of LF.

The averages of the three measurements at each receiver location were compared for each method. The difference of the LF average from the 125 Hz to 1 kHz octave bands for the two microphone configurations was between 0.59 and 1.81 JNDs at the six receiver locations. The largest differences were found in the 125 Hz and 250 Hz octave bands where the Eigenmike's dipole directivity is not ideal, while the differences were relatively small from 500 Hz to 4 kHz. The difference of the GLL average from 125 Hz to 1 kHz for the two methods was between 0.02 and 0.48 JNDs, with the largest variation in the 125 Hz octave band, which is most likely caused by the Eigenmike's low frequency non-ideal directivity pattern.

Future work will include manually calculating the spherical harmonic expansion of the Eigenmike's impulse responses to compare to the results from the included software, Eigenstudio. Since the LF and GLL agreement between the two methods was better at frequencies where the Eigenmike had an optimal directivity pattern, it is very likely that a manual calculation of the dipole component will yield better agreement with the Sennheiser microphone. Future work could also include simulations of changes in LF and GLL with variations in receiver directivity pattern and small spatial misalignments.

6. ACKNOWLEDGMENTS

The authors wish to express their thanks to Mr. Tom Hesketh, for allowing the authors access to the auditorium for taking the measurements. The authors also wish to acknowledge Matthew Neal, Matt Kamrath, Martin Lawless, and Acadia Kocher for their assistance with the measurements. The authors would also like to thank Bose Corporation in Framingham, MA for use of their anechoic chamber.

This work was sponsored by NSF award #1302741.

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