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The CHORDatabase: a twenty-one concert hall spherical microphone and loudspeaker array measurement database

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ABSTRACT

Repeatability and realism are both highly important goals in concert hall perceptual studies, but it is hard to satisfy both simultaneously. Auralization from room impulse response (RIR) measurements allows for repeatable listening conditions between halls, but typical measurement loudspeakers do not realistically represent an orchestra. To support both goals, the Concert Hall Orchestral Research Database (CHORDatabase) has been generated. This database consists of 32-channel spherical microphone array measurements in 15 North American and 6 European concert halls. First, measurements were made at 7 to 15 seats in each hall using a three-part omnidirectional loudspeaker, maintaining omnidirectionality up to 5 kHz. These measurements enable standard room acoustic parameter calculations and higher-order spherical array beamforming techniques, and the overall variety of the database will be demonstrated using both objective analyses. Also, a compact 20-element spherical loudspeaker array was used to provide realistic source directivities for RIR measurements. This array can accurately represent the frequency-dependent radiation patterns of different instruments up to 3-4 kHz. Measurements were made at 20 orchestral source positions and one seat in each hall, 15 meters from stage. Full-orchestra auralization techniques will be presented, and the future potential of this database will be discussed. [Work supported by NSF Award #1302741.]

Keywords: concert hall, spherical, microphone, array, beamforming, directivity, measurements, auralization

1. INTRODUCTION

The central goal of concert hall design is to generate a room that enhances the music, providing the most pleasing listening experience to all individuals in the audience. This preference is a complex function of the spectral, temporal, and spatial character of the room impulse response (RIR), let alone the complex and unique distribution of sources across the stage. The study of this topic is not new, originating from Sabine's early work on reverberation time (RT).[1] After that work, many believed that RT alone did not fully explain preference in a concert hall, so studies were initiated to more fully explain concert hall preference. These efforts have spanned from the 1950s to the present, including interview- and survey-based approaches,[2-3] live-listening surveys,[4-7] simplified laboratory studies,[8-9] measurement-based auralizations,[10-16] and simulation-based auralizations.[17] From all of this work, suggestions exist as to which might be important regarding preference in concert halls, but still much disagreement exists regarding which perceptions are most important. Some limitations could be linked to differences between measurement setups, auralization techniques, or the use of simulated data.[18]

2. THE CONCERT HALL ORCHESTRAL MEASUREMENT DATABASE

A new room impulse response (RIR) measurement database of 21 concert halls has been generated using a spherical microphone array, compact spherical loudspeaker array, and a three-part omnidirectional sound source. The halls included in the database were selected from an online survey, where researchers and consultants in concert hall acoustics provided suggestions of halls with both excellent and lower reputations. The final database included 15 halls located in North America and 6 halls located in Europe, having a large variety in shape, size, and RT, as shown in Table 1. In the table,

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a hall shape category of either historic shoebox (H.Sh.), modern shoebox (M.Sh.), fan, vineyard (Vnyd.), or other shapes outside these four categories (other) are provided along with the mid-frequency average T30, EDT, and C80 across all measured seat locations in each hall. For halls with variable acoustics, a letter is assigned to represent the variable acoustic setting (VAS) with "A" always corresponding to the setting used for unamplified orchestral performance. To maintain anonymity, hall volumes are provided in ranges for various size designations: extra small (XS: 15,000 – 17,500 m^3), small (S: 17,500 – 20,000 m^3), medium (M: 20,000 – 22,500 m^3), large (L: 22,500 – 25,000 m^3), or extra-large (XL: 25,000 – 27,500 m^3).

Table 1 – Summary data of the shape, size, variable acoustic setting (VAS), and mid-frequency averaged T30, EDT, and C80 across all measured seats. The Orch. column indicates whether the full-orchestra source measurements were made in each hall / setting, and the Rec. column specifies the number of seats measured using the omnidirectional source. Hall sizes are given in broad categories of XXS to XXL.

Hall	Shape	Size	VAS	T30 (s)	EDT (s)	C80 (s)	Rec.	Orch.?
1	H. Sh.	S	–	2.50	2.55	-2.76	11	Yes
2	H. Sh.	XS	–	2.17	2.13	-2.51	9	Yes
3	H. Sh.	S	–	2.51	2.43	-3.25	12	Yes
4	H. Sh.	M	A	2.56	2.92	-2.53	11	Yes
			B	1.97	2.38	–	3	No
5	H. Sh.	XXS	A	2.27	2.27	-3.21	5	No
			B	2.37	2.43	–	3	No
6	M. Sh.	S	A	1.61	1.62	0.41	4	Yes
			B	1.71	1.64	–	1	No
7	M. Sh.	L	A	2.73	2.54	-2.79	12	Yes
			B	1.54	1.74	–	1	No
8	M. Sh.	L	A	2.86	2.09	-1.33	7	Yes
			B	2.38	1.93	-0.76	6	Yes
			C	2.80	2.11	–	1	No
			D	2.74	2.12	–	1	No
			E	2.62	2.07	–	1	No
			F	2.65	2.05	–	1	No
9	M. Sh.	S	–	2.12	2.07	-3.15	14	Yes
10	M. Sh.	L	A	2.81	2.35	-1.80	7	Yes
			B	1.78	1.57	-0.28	6	Yes
11	Fan	XL	–	1.58	1.71	-0.35	7	No
12	Fan	S	–	1.79	1.75	0.81	14	Yes
13	Fan	XXL	–	2.29	2.21	-2.76	10	Yes
14	Fan	S	–	1.78	1.76	-0.53	10	Yes
15	Vnyd.	M	–	2.09	2.06	-0.59	13	Yes
16	Vnyd.	XS	–	2.09	1.85	-2.34	5	Yes
17	Vnyd.	S	–	2.21	2.09	-0.40	15	Yes
18	Vnyd.	XXL	–	3.28	2.80	-1.32	12	Yes
19	Other	XL	–	1.73	1.44	0.71	12	Yes
20	Other	M	–	2.41	2.40	-3.84	11	Yes
21	Other	L	A	2.09	2.00	-2.22	11	Yes
			B	1.75	1.76	–	3	No
			C	1.58	1.68	–	3	No
	Totals:		**33**	**–**	**–**	**–**	**242**	**21**

2.1 Objectively-motivated omnidirectional source measurements

The first goal of the database was to provide repeatable, objective measurements for sound field analysis that could be reproduced by other research teams. A three-part omnidirectional sound source was used for this objective measurement protocol to provide a wide-bandwidth omnidirectional measurement up through 5 kHz, with adequate signal-to-noise at low frequencies.[19] Single dodecahedron omnidirectional loudspeakers are common, since they provide adequate low-frequency power, but deviations from omnidirectional radiation are quite significant above 1 kHz when constructed using 10 cm (4-inch) driver elements. RIRs were captured with a 32-channel spherical microphone array, the Eigenmike em32, by mh Acoustics (4.2 cm radius). Measurements using this array can be processed using spatial beamforming techniques up to a high-frequency aliasing at 8 kHz. From this measurement, omnidirectional and figure-of-eight RIRs can also be extracted for standard metric calculation.[20]

These measurements were made in a number of seats, with the purpose of obtaining a representative sample of all seating areas in each hall. First, a standard grid of receiver locations was developed, to provide consistency between halls in terms of source-receiver distance, shown in Figure 1.[21] Four central hall receivers, R1 – R4, were placed at 10, 15, 20, and 25 m from the 'conductor' location of an orchestra, placed 1 m from the front of the stage. These four receivers were measured in each hall for setting A, and sometimes fully in other VAS. Three additional receivers were placed 5 m off-center, located in the same rows as R2 – R4. Once these receivers were completed, additional receivers were placed around each hall, contributing to a mostly uniform sampling throughout the hall, time permitting. The total number of receivers in setting A varied from 5 to 15, largely a function of the seating design and the measurement time limitations in each hall. In total, 242 individual seats were measured, the largest database with this degree of accuracy and repeatability created to date.

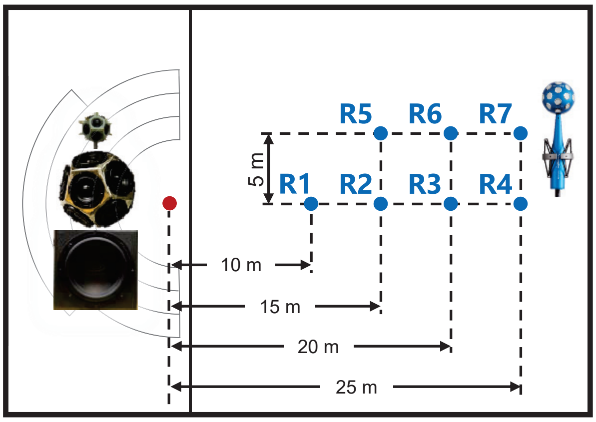


Figure 1 – The standard receivers, R1 – R7, with a constant source-receiver distance in all halls.

2.2 Subjectively-motivated compact spherical loudspeaker array (CSLA) measurements

Although the measurements described in section 2.1 employed a more standard and accessible technique, they are not directly related to the reality of a full orchestral performance. A full orchestra is made of many sources distributed across the stage with unique radiation patterns, changing significantly for the same instrument at different frequencies.[22] A compact spherical loudspeaker array (CSLA) was constructed to reconstruct the directional radiation patterns of different orchestral instruments.[21] This array consisted of 20 compact 40-mm drivers with an extended 200 Hz low-frequency resonance for drivers of this size, shown in Fig. 2. The array's overall size was 15.2 cm in diameter, compact enough to limit high frequency aliasing to frequencies above 3000 Hz.

A measurement database of instrument directivities represented in the spherical harmonic domain was used to reconstruct the frequency-dependent radiation patterns of each orchestral instrument.[23] Full-frequency filters were designed to build-in directional radiation patterns for specific orchestral instruments into a measurement signal. The use of built-in radiation patterns allowed for time-efficient measurements of many orchestral positions across the stage. This single source was capable of flexibly recreating any orchestral instrument, not requiring an extensive multi-loudspeaker setup. To validate the directional control of the array, full-3D impulse response measurements were made using a turntable in an anechoic chamber. The radiation pattern targets for an oboe, shown in the upper half

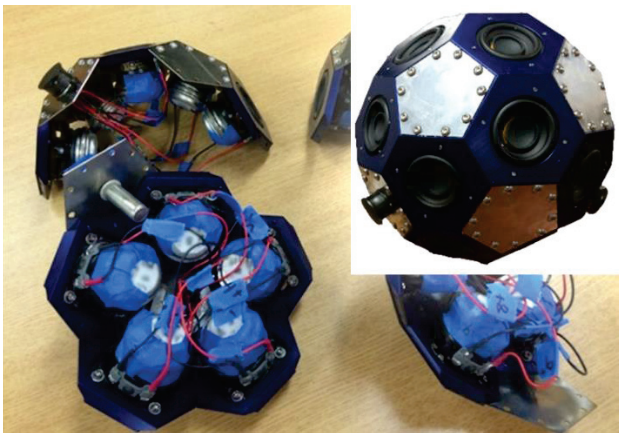
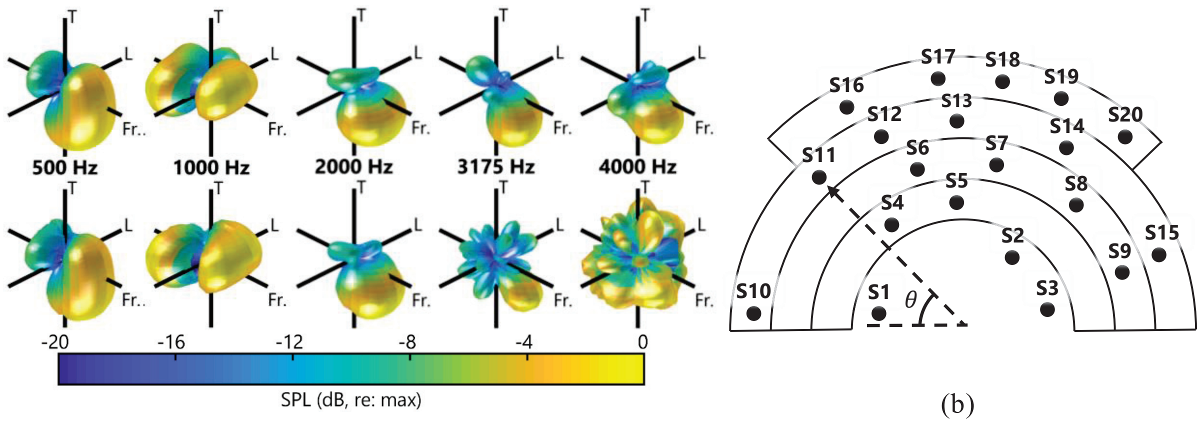


Figure 2 – The compact spherical loudspeaker array (CSLA) used for directional source radiation control.

of Fig. 3 (a), are compared against the reconstructed sound pressure levels as a function of direction in the bottom half of Fig. 3 (a). By comparing the upper target and lower reconstructed plots, high agreement is found between the target and reconstructed directional radiation patterns. This performance is maintained from low frequencies up to a spatial aliasing limit for the array around 3 – 4 kHz. Above that limit, incoherence due to driver spacing causes accuracy to degrade.

To provide a consistent measurement between halls, a receiver gird of 20 source locations was developed where each location was placed at a specific radius and angle from a central 'conductor' location, shown in Fig. 3 (b). Each position was assigned to a particular instrument, as radiation patterns were built-into each measurement. This layout provided a consistent source representation between halls, allowing for repeatability, while still ensuring a realistic presentation of a full orchestra. To achieve better low-frequency signal to noise for auralizations, an additional measurement was taken at each instrument position with the subwoofer component of the omnidirectional sound source. Full orchestral auralizations were generated using anechoic recording of Beethoven's 8th symphony, separately recorded for a 61-piece orchestra.[24] Full details on the 20-source measurement setup and the extension to a 61-piece orchestral for the auralizations are provided chapters 4 and 5 of Ref. [21].



(a) (b)

Figure 3 – Directional radiation pattern reconstruction results of an oboe's directivity using the CSLA. Results are shown at discrete one-third octave band center frequencies. In general, frequencies below 3000 Hz demonstrate accurate reconstruction and accuracy is fully degraded above 4000 Hz.

3. RESULTS

3.1 Standard Metric Distributions and Correlations

First, standard room acoustics metrics, as provided in ISO 3382, were calculated for all 242 seat positions across the entire database. The full processing details can be found in chapter 5 of Ref. [21]. To calculate each metric, the following steps in the calculation procedure were used:

Step 1: Individual microphone capsule differences were removed, correcting for broadband sensitivity differences across the thirty-two 12.7 mm (½") microphone capsules.

Step 2: A spherical Fourier transform using the SoFIA Toolbox was used to translate from a spatially sampled microphone RIR (MicRIR) to a spherical harmonic RIR (ShRIR) in the complex-orthonormal normalization format.[25-26]

Step 3: Steps 1 and 2 were repeated for each of the three parts of the omnidirectional source, where each was filtered to correct for diffuse-field equalization and overall gain differences from both driver sensitivity and power amplifier gain settings.

Step 4: A linear-phase three-band crossover filter was applied to combine all three separate measured ShRIRs into a single, broadband source-omnidirectional ShRIR. This step also included a small adjustment for time delays between the direct sound of the first channel of the ShRIR, due to changing computer latency between measurements.

Step 5: Radial filtering was used to correct for the effect of the size of the microphone array and scattered pressure term due to the presence of a rigid boundary condition in the sound field.[25]

Step 6: Diffuse-field equalization was used to correct for the non-flat response of the Eigenmike's measured omnidirectional RIR.

Step 7: The ShRIR was rotated in the spherical harmonic (SH) domain using a toolbox developed by Archontis Politis, such that the microphone was oriented directly at the omnidirectional sound source.[27]

Step 8: The RIR was cleaned using a RIR slope-fitting technique based upon nonlinear least squares regression of the backwards integrated RIR.[21] Since SH functions are orthogonal, cleaning was performed in the ShRIR, replacing the noise floor with uncorrelated decaying noise in each SH channel. This fit was done separately in each octave band, using the same slope across all ShRIR channels for a given frequency band.

Step 9: The ShRIR was transformed from the complex-valued orthonormal SH format to the ambiX format, based upon real-valued spherical harmonics. This representation allows for the direct extraction of the omnidirectional (W) and laterally oriented dipole response (Y) from ShRIR channels 1 and 2, respectively. This conversion was also performed using the toolbox develop by Politis, with modifications.[27]

Once the cleaned omnidirectional and figure-of-eight RIRs were extracted from the ShRIR, parameters from ISO 3382 could be calculated for each octave band.[28] The metrics for reverberation time (T30 and EDT) along with metrics for clarity (C80 and center time, Ts) were calculated from 63 Hz to 4000 Hz. Since the source maintained omnidirectionality over this range, the parameters were found to be reproducible over this frequency range. The distribution of the parameters for low- (63 – 250 Hz), mid- (500 – 1000 Hz), and high-frequency (2000 – 4000 Hz) averages are shown as overlapping histograms in Fig. 4. ISO 3382 lists the typical ranges for each of these parameters as: 1.0 to 3.0 s for T30 / EDT, -5.0 to 5.0 dB for C80, and 60 to 260 ms for Ts. All of these ranges are specifically given for mid-frequency average values, shown in green in Fig. 4.

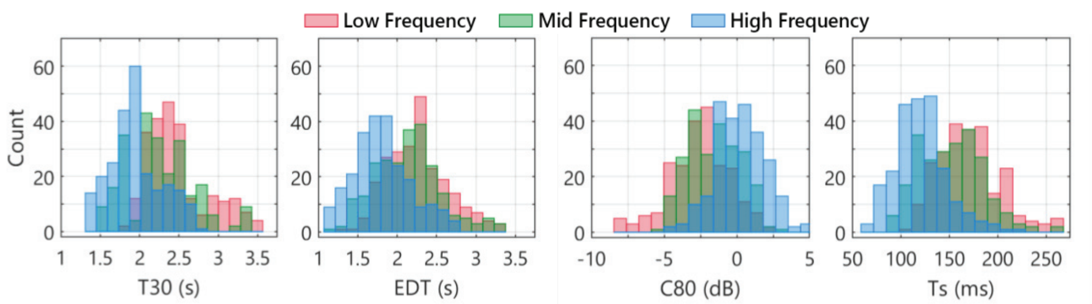


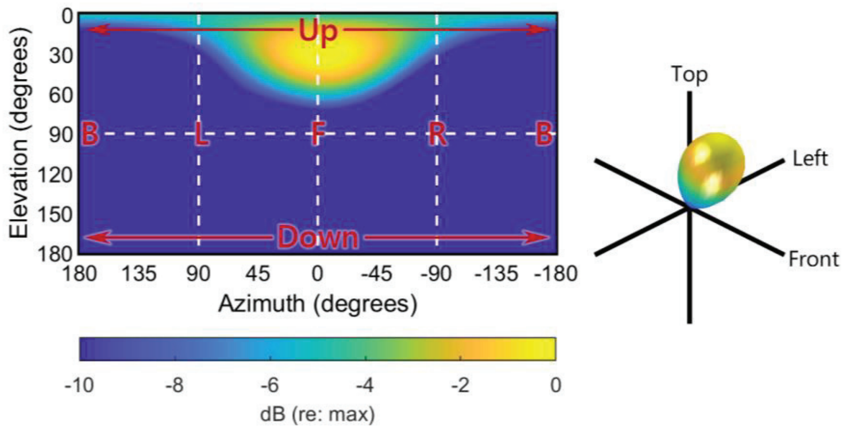
Figure 4 – Histogram of low- (63 – 250 Hz), mid- (500 – 1000 Hz), and high-frequency (2000 – 4000 Hz) distributions for T30, EDT, C80, and Ts as defined in ISO 3382.

The range is well covered for T30 and EDT, except for no metric results close to 1.0 s for T30. This limited range is due to the requirement of stages that could accommodate a full orchestra, as large rooms tend to have longer RTs. The range exceeds the upper 3.0 s limit, as two rooms had quite high values of T30. For C80, the range is well sampled down to -5 dB, with slightly reduced coverage at the upper limit, around 2 – 3 dB. This upper limitation is due to the same reason as the limited RT range. Finally, Ts covered the expected range from 60 to 260 ms, having distribution ends right at these end points. These distributions illustrate the large coverage of the CHORDatabase.

3.2 Visualizations using Spherical Array Beamforming

Once RIRs have been represented as a ShRIR, spherical array beamforming techniques can be used to decompose a RIR into individual spatial maps. These maps represent the energy given in a specific time and frequency region of a RIR, plotted as a function of azimuth and elevation. An example of one of these maps is shown in Fig. 5. For the ShRIR, plane-wave decomposition (PWD) was used to generate a set of directional RIRs (DirRIRs), each representing the response of the microphone array having a beam-like directivity pattern in a particular direction.[25-26] This beam directivity pattern is then rotated in full-3D space around the sphere, and each of these RIRs can be time-windowed, band-pass filtered, and then energy integrated. Specifically, these plots were generated using a -25 dB side lobe level Dolph-Chebyshev beam pattern, designed to reduce side lobe artifacts.[25]

Each point in the map below represents the energy integration for a DirRIR from a beam oriented in the specific direction of the selected point, generating a spatial “heat map” of the RIR. The example below is for a 1 ms time window of the RIR, isolating a single strong reflection arriving from 55 to 56 ms following the direct sound. The upper rectangular grid had artifacts that are similar to those associated with unwrapping a 3D globe onto a 2D rectangular map. The top and bottom of the globe are stretched across the top and bottom of the plots. The key directions are identified below as front (F), left (L), right (R), back (B), top (Up), and bottom (Down). The more natural representation of this data is shown as a balloon-style plot, with color and radius indicating energy amplitude, shown in the lower portion of Fig. 5. Both plots are normalized to the maximum spatial energy in the specific time-frequency region.



(a) (b)

Figure 5 – Examples of a rectangular spatial energy “heat map” for a reflection occurring between 35 and 35 ms following the direct sound (a). A more visually-intuitive balloon-style plot is also provided in (b).

3.2.1 Spatial Beamforming Maps

The spatial energy in a RIR can be analyzed over different time regions. To demonstrate this style of analysis, the early energy (10 – 100 ms) has been isolated in a single RIR from eight different halls in the CHORDatabase, shown in Fig. 6. For each hall, a time domain RIR is provided, highlighting the current energy window in red, and both the 2D map and 3D balloon plot of the spatial energy are visualized. Halls shown consist of fan-shaped halls (a & b), vineyard halls (c & d), historic shoebox halls (e & f), a modern shoebox hall (g), and a theatrically-inspired hall geometry, categorized as other-shaped (h).

First, certain halls emerge as having a narrow early reflection character, including the fan-shaped halls (a & b) and the other-shaped hall (h). The historic shoebox halls (e & f) both have strong, laterally-focused early energy, and a similar property is found in the second vineyard hall (d). This observation matches with the general wisdom that shoebox halls are more enveloping than fan shaped halls. The first vineyard hall, shown in (b), appears to have less lateral energy (c), but this conclusion is mostly due to the very strong rear-upward reflection arriving quickly following the direct sound. It is clear from the time-domain RIRs that this single reflection was stronger than any other single reflection in any of the halls. If normalized to the same absolute reference, and not the maximum

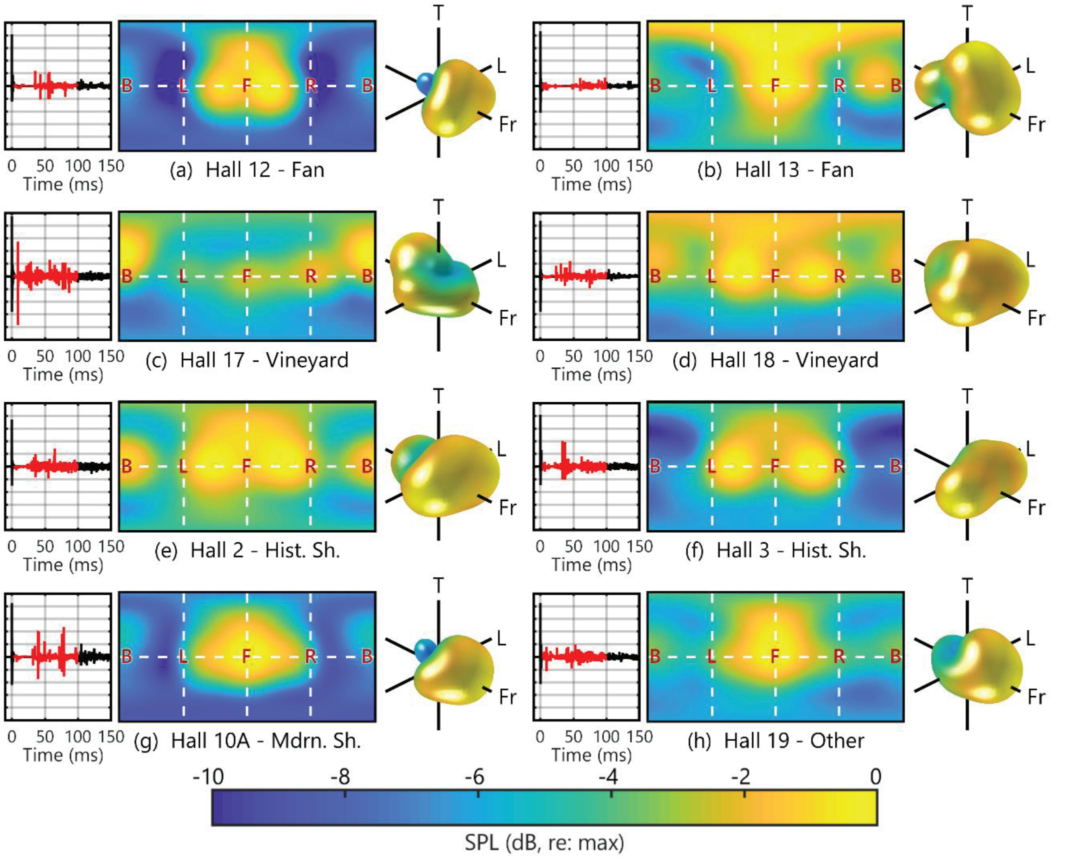


Figure 6 – Spatial energy maps of the early reflections (10 – 100 ms) for eight different halls in the CHORDatabase from the 1 – 4 kHz bands. Plots are normalized to the maximum energy in each map.

value, the plots would highlight such differences. These visualizations are intuitive when inspecting each hall, knowing their geometric properties. Such analysis methods provide clear advantages for assessing the spatial character of a RIR, difficult to assess with other techniques.

4. CONCLUSIONS

A concert hall RIR measurement database, the CHORDatabase, has been created using state-of-the-art spherical array processing techniques. Objectively-motivated measurements with a wide-bandwidth omnidirectional sound source was used to allow for the repeatable calculation of standard room acoustic metrics. These spherical microphone array measurements also allow for high-resolution beamforming of the RIR. Beamforming techniques were applied to the early portion of the RIR for eight different rooms. Clear and intuitive comparisons were made between halls, highlighting the classical lack of lateral, enveloping energy in fan-shaped halls as compared to shoebox-style halls. Measurements using the compact spherical loudspeaker array (CSLA) and the subwoofer component of the omnidirectional sound source were made at 20 source locations on stage. These RIRs were auralized and superimposed to generate a full-orchestral concert hall auralization, comparable across all halls. These measurements can form the basis of future subjective testing, providing highly realistic auralizations to study perception in a wide variety of halls. This testing can be rendered from the spherical harmonics domain to dedicated surrounding loudspeaker arrays or to headphones using average or individually tailored binaural techniques.

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