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Spatial analysis of concert hall impulse responses

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ABSTRACT

Omni-directional measurements and parameters derived from them are not adequate to describe the details of concert hall acoustics. Inherently, spatial properties of the sound field are lost, and these spatial details are a major component of the musical presentation. Until relatively recently, spatial analysis of the sound field has been limited to simple microphone response patterns, such as omni, figure-of-eight, or cardioid. However, new microphone array analysis techniques allow high spatial resolution measurement and evaluation of concert hall sound fields. These measurements can be used for time-frequency and spatiotemporal analysis [Pätynen et al. 2013, JASA Vol.133, 2] to unravel the underlying physical phenomenon and perceptual consequences. This paper presents further results with the spatial analysis method. Detailed analysis results of two European concert halls are shown.

1 INTRODUCTION

Objective measurement of concert hall acoustics ideally describes the important subjective features of the acoustics. Recent research has questioned the standard objective measures[1,2], since they do not describe the subjective perception of the acoustics in an adequate manner[3].

Due to the inadequacy of the standard, we have recently developed spatiotemporal analysis methods for the detailed analysis of the acoustics. Instead of a few source positions, suggested by the standard, we use a loudspeaker orchestra that consists of 34 loudspeakers that simulate a symphony orchestra. A spatial room impulse response is measured for each source, and the spatial response is analyzed with respect to direction of arrival and energy at each time moment[4,5].

In this paper, these recently proposed techniques are further developed to analyze the spatial response also at different frequency bands. The proposed method is applied to the analysis of measurements of two unoccupied European concert halls. In detail, the early sound of the room impulse responses, the first 50 ms, is analyzed at octave bands.

2 METHODS

This section presents the spatial analysis of the sound field for frequency bands and the visualization of the results.

A spatial room impulse response $h_r(t)$ is captured with R microphones at locations $\mathbf{r}_r$. The microphone array, applied in this paper is shown in Fig. 1. For each time discrete moment n the direction of arrival of the sound field is estimated at discrete frequency band k as:

$$\bar{\mathbf{n}}_{n,k} = \mathbf{n}_{n,k}/\|\mathbf{n}_{n,k}\|, \;\; \mathbf{n}_{n,k} = V^{*} c \boldsymbol{\tau}_{n,k} \tag{1}$$

where c is the speed of sound, $(\cdot)^{*}$ denotes Moore-Penrose pseudo-inverse,

$$\mathbf{V} = [\mathbf{r}_1 - \mathbf{r}_2, \mathbf{r}_1 - \mathbf{r}_3, \ldots, \mathbf{r}_{R-1} - \mathbf{r}_R]^{\mathsf{T}} \tag{2}$$

is the sensor difference matrix, and

$$\hat{\boldsymbol{\tau}}_{n,k} = [\hat{\tau}_{1,2}^{(n,k)}, \hat{\tau}_{1,3}^{(n,k)}, \ldots, \hat{\tau}_{R-1,R}^{(n,k)}]^{\mathsf{T}}, \tag{3}$$

are the time delay of arrival (TDOA) estimates for microphone pairs $\{i, j\}$. For a certain frequency band the TDOA estimates are calculated directly from the cross correlation $R_{i,j}(\tau, f_c)$ between microphones i and j

$$\hat{\tau}_{i,j}^{(n,k)} = \arg\max_{\tau} R_{i,j}(\tau, f_c) \tag{4}$$

where f_c is the central frequency of the k^{th} octave band. The cross-correlation is obtained from short-time Fourier Transform, and the signals are band pass-filtered prior to calculating the TDOA estimates with octave band filters, implemented according to Antoni[6]. Moreover, we select the time window T to be 2 times the length of the central frequency f_c, i.e., $T = 2/f_c$ to ensure that more than one period of the analyzed frequencies is included in the analysis window.

The direction is estimated at each discrete time step $n/f_s, n \in \mathrm{N}^{+}$, where $f_s = 48$ kHz is the sampling frequency, and for octave bands $f_c = [63, 125, 250, 500, 1000, 2000, 4000]$ Hz. The energy arriving from azimuthal direction θ is inspected from the directional energy histogram $G(\theta, f_c)$, which is given as[5]

$$G(\theta, f_c) = \left[10 \log_{10} \frac{1}{L} \sum_{l=1}^{L} \int_{n=t_0^{(l)} f_s}^{(t_{50}+t_0^{l}) fs} H_l^2(n, f_c) \left| \cos(\phi_{n,f_c}^{(l)}) \right| dt \right]_{\theta_{n,f_c}^{(l)} = \theta} - G_{\mathrm{ref}}(f_c), \tag{5}$$

where $l = 1 \ldots L$ are the loudspeaker channels, $H_l(n, f_c)$ is the short time Fourier transform of one of the pressure signal in the microphone array for channel l, and $\theta_{n,f_c}^{(l)}$, and $\phi_{n,f_c}^{(l)}$ are the azimuth and elevation of the direction vector $\bar{\mathbf{n}}_{n,k}$, respectively. The term $\theta_{n,f_c}^{(l)} = \theta$ is a notation for indexing, and it should be interpreted as "histogram is evaluated when the estimated direction equals the direction under consideration". The directional resolution in this case is set to one degree, thus the estimates are rounded to their closes integer in degrees. Further, $t_0^{(l)}$ denotes the time of arrival of the direct sound for channel l and it is estimated from the first local maximum that exceeds 5 dB, and $t_{50} = 50$ ms. In this paper the number of channels is $L = 25$, but 34 loudspeakers are used. Thus, some of the loudspeakers are connected to the same channel.

In this paper, $G_{\mathrm{ref}}(f_c)$ is the maximum sound pressure level obtained in the measured halls. Previously[5] we have used the sound pressure level at 10 m in free-field conditions as the point of reference.

The directional energy histogram is presented for lateral and median plane, i.e., cross-section on the x-y and x-z planes.

3 EXPERIMENTS

Since 2009, we have measured 19 concert halls, listed in Table 1, with the proposed loudspeaker orchestra. A detailed description of the loudspeaker orchestra can be found for example in[7]. This

Table 1: Physical and acoustical parameters for the measured halls. The acoustic parameters are averaged over all measured source positions, 5 receiving positions, and 500 Hz and 1000 Hz octave bands. The results shown later on in this paper are for BK and BP.

Hall	Abbr.	T	V [m^3]	N	G [dB]	EDT [s]	Date
Amsterdam Concertgebouw	AC	S	18 780	2 040	2.8	2.4	Nov 13 2012
Wuppertal Stadthalle	WS	S	*17 000	1 500	3.6	2.6	Nov 14 2012
Vienna Musikverein	VM	S	15 000	1 680	4.1	3.1	Nov 17 2012
Berlin Konzerthaus	BK	S	15 000	1 580	2.7	2.1	Nov 18 2012
Munich Herkulessaal	MH	S	13 590	1 300	2.9	2.1	Nov 22 2012
Hämeenlinna Vanaja Hall	HV	S	9 500	700	2.6	1.7	Aug 10 2010
Lahti Sibelius Hall	LS	S	15 500	1 250	3.2	2.0	Aug 11 2010
Pori Promenadi Hall	PP	S	10 000	860	5.1	2.5	Aug 12 2010
Espoo Sello Hall	ES	S	5 200	400	2.8	1.8	Jun 4 2009
Helsinki Conservatory	HK	S	5 600	520	3.2	2.2	Jun 6 2009
Espoo Tapiola Hall	ET	S	*11 000	690	1.2	1.9	Jun 5 2009
Brussels Palais des beaux-arts	BB	C	12 520	2 150	3.6	1.6	Nov 15 2012
Stuttgart Beethovenhalle	SB	F	16 000	2 000	1.8	2.0	Nov 16 2012
Cologne Philharmonie	CP	F	*19 000	2 000	1.9	1.6	Nov 14 2012
Helsinki Culture House	HC	F	7 800	1 390	1.8	1.6	Aug 17 2010
Helsinki Finlandia Hall	HF	F	15 000	1 700	1.3	1.9	Aug 16 2010
Munich Gasteig	MG	F	29 700	2 400	1.2	2.1	Nov 21 2012
Berlin Philharmonie	BP	V	21 000	2 220	2.1	1.9	Nov 14 2012
Helsinki Music Centre	HM	V	25 000	1 700	2.4	2.0	Dec 28 2011

V: volume, N: number of seats, G: Strength, EDT: early decay time, Date: Measurement date, * estimated, T: Type, S: Shoebox, C: Curved shoebox, F: Fan, V: Vineyard,

paper shows results for two halls, Konzerthaus Berlin (BK) and Berlin Philharmonie (BP), with the directional energy histogram. The first one is a traditional shoebox hall, and the second one the first vineyard hall ever built. These halls were selected to illustrate the fundamental differences that these geometric designs have on the sound field.

The impulse responses were measured with the sine-sweep technique from 25 loudspeaker channels to a microphone array, which is of type G.R.A.S. vector intensity probe VI-50. More than 10 receiver positions for each hall were measured, but this paper only considers one receiver position which is at 19 m distance from the first row of loudspeakers. The array consists of 6 microphones on a regularly spaced open sphere, two on each Cartesian coordinate axis. The spacing between two microphones on an axis is 2.5 cm, instead of the 10 cm spacing shown in Fig. 1. The highest frequency that can be analyzed with the array is therefore $c/(2 \times 0.025\text{m}) \approx 6.9$ kHz. Thus the highest octave that can be correctly analyzed is the 4 kHz octave band.

4 RESULTS, ANALYSIS, AND DISCUSSION

The directional energy distributions for the two studied concert halls in one receiver positions, at 19 m distance from the first row of loudspeakers are shown in Figs. 2 - 4. The leftmost plot always illustrates the energy with respect to azimuth angle, and the rightmost to elevation angle. As explained above, for this paper the integration time is set to 50 ms, thus the early field of the halls is studied. The results are normalized for each octave band separately with the $G_{\text{ref}}(f_c)$, thus they are not in scale with respect to other octave bands. That is, they can only be compared to

Figure 1: The loudspeaker orchestra (left) and the microphone array (right). The results in this paper are obtained with 25 mm microphone spacing instead of the shown 100 mm spacing.

other halls with this normalization. Moreover, the radius 0 in the polar plot is set to -80 dB from $G_{\text{ref}}(f_c)$ for each octave band.

Octave bands 63, 125, and 250 Hz, shown in Fig. 2, reveal that most of the sound energy is arriving from the front of the hall, i.e., stage, as expected. BK has more sound energy from nearly all directions compared to BP, especiall from the sides. There are several large reflecting surfaces in BK within the 50 ms arrival time contributing to the low frequency energy, whereas in BP only few reflecting surfaces are within this time window. Since the analysis time window for octave bands 63 and 125 Hz are quite long, they include the direct sound and several reflections. Spatial separation between the acoustic events is therefore not achieved in the analysis, and the resulting direction is an average of the directions of the acoustic events in each analysis window. It is difficult to conclude anything about the direction of arrival of the sound for octave bands 63 and 125 Hz, because of the long window size.

At 500 and 1000 Hz octave bands, the sound energy from the frontal direction in BP is higher than in BK, as shown in Fig. 3. That is, it can be seen that a large amount of energy is arriving from about $(0°, -15°)$ in BP, in BK the amount of energy is not as high in the frontal direction. This is due to the floor and other reflections from the stage in BP. Since the audience area in BP is inclining the stage reflections are more prominent in BP than in BP. The contribution of the stage to the sound energy is already visible at 250 Hz in Fig. 2 for BP.

At 2 and 4 kHz octave bands, the sound energy from the sides is clearly higher in BK than in BP, as shown in Fig. 3. This is a result of the shoebox-shape, as the parallel walls provide early lateral reflections.

At 500 Hz and 1 kHz octave bands, BP receives energy from the top, which indicates a strong ceiling reflection. Namely, the ceiling in BP is concatenated, possibly to provide this ceiling reflection. The sound energy arriving from the ceiling is also visible at 2 and 4 kHz octave bands. As previously at 500 Hz and 1000 Hz octave bands, also here the sound energy from the direction of the stage is clearly higher for BP than for BK.

BK has more sound energy arriving from the back than BP from 500 Hz to 4 kHz octave bands. BK has a back wall, whereas the inclining audience area in BP blocks some of the sound from the back.

5 CONCLUSIONS

An analysis method to visualize spatial impulse responses measured from concert halls was applied to two concert halls. The method illustrates the sound energy distribution at octave bands in space. In this paper, the inspection of the sound field was limited to the first 50 ms after the direct sound.

From the observations in the paper it is noted that

- a stage structure and inclining audience area, increases the energy from the direction of the stage for 250 Hz and higher octave bands
- an inclining audience area blocks a large part of the sound energy arriving from the back for all frequency bands,
- in lateral plane, the shoebox-geometry provides strong early sound for octave bands higher than 125 Hz, and
- the ceiling reflection in Berlin Philharmonie is visible for octave bands higher than 250 Hz.

From earlier research we note that, ceiling reflections are less useful for compensating the seat-dip effect than side-wall reflections[5]. In addition, ceiling reflections increase the perceived distance of the sound source compared to an equally loud reflection from the lateral plane[8].

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REFERENCES

1 J.S. Bradley. Review of objective room acoustics measures and future needs. *Applied Acoustics*, 72:713--720, 2011.

2 L. Kirkegaard and T. Gulsrud. In search of a new paradigm: How do our parameters and measurement techniques constrain approaches to concert hall design? *Acoustics Today*, 7(1):7--14, 2011.

3 T. Lokki, J. Pätynen, A. Kuusinen, and S. Tervo. Disentangling preference ratings of concert hall acoustics using subjective sensory profiles. *Journal of the Acoustical Society of America*, 132(5), November 2012. 3148-3161.

4 S. Tervo, J. Pätynen, and T. Lokki. Spatial decomposition method for room impulse responses. *J. Audio Eng. Soc.*, 61(1/2):16--27, Mar. 2013.

5 J. Pätynen, S. Tervo, and T. Lokki. Analysis of concert hall acoustics via visualizations of time-frequency and spatio-temporal responses. *Journal of the Acoustical Society of America*, 133(2):842--857, February 2013.

6 J. Antoni. Orthogonal-like fractional-octave-band filters. *The Journal of the Acoustical Society of America*, 127(2):884--895, 2010.

7 J. Pätynen. *A virtual loudspeaker orchestra for studies on concert hall acoustics*. PhD dissertation, Aalto University School of Science, Espoo, Finland, 2011.

8 T. Lokki, J. Pätynen, S. Tervo, S. Siltanen, and L. Savioja. Engaging concert hall acoustics is made up of temporal envelope preserving reflections. *Journal of the Acoustical Society of America*, 129(6):EL223--EL228, June 2011.

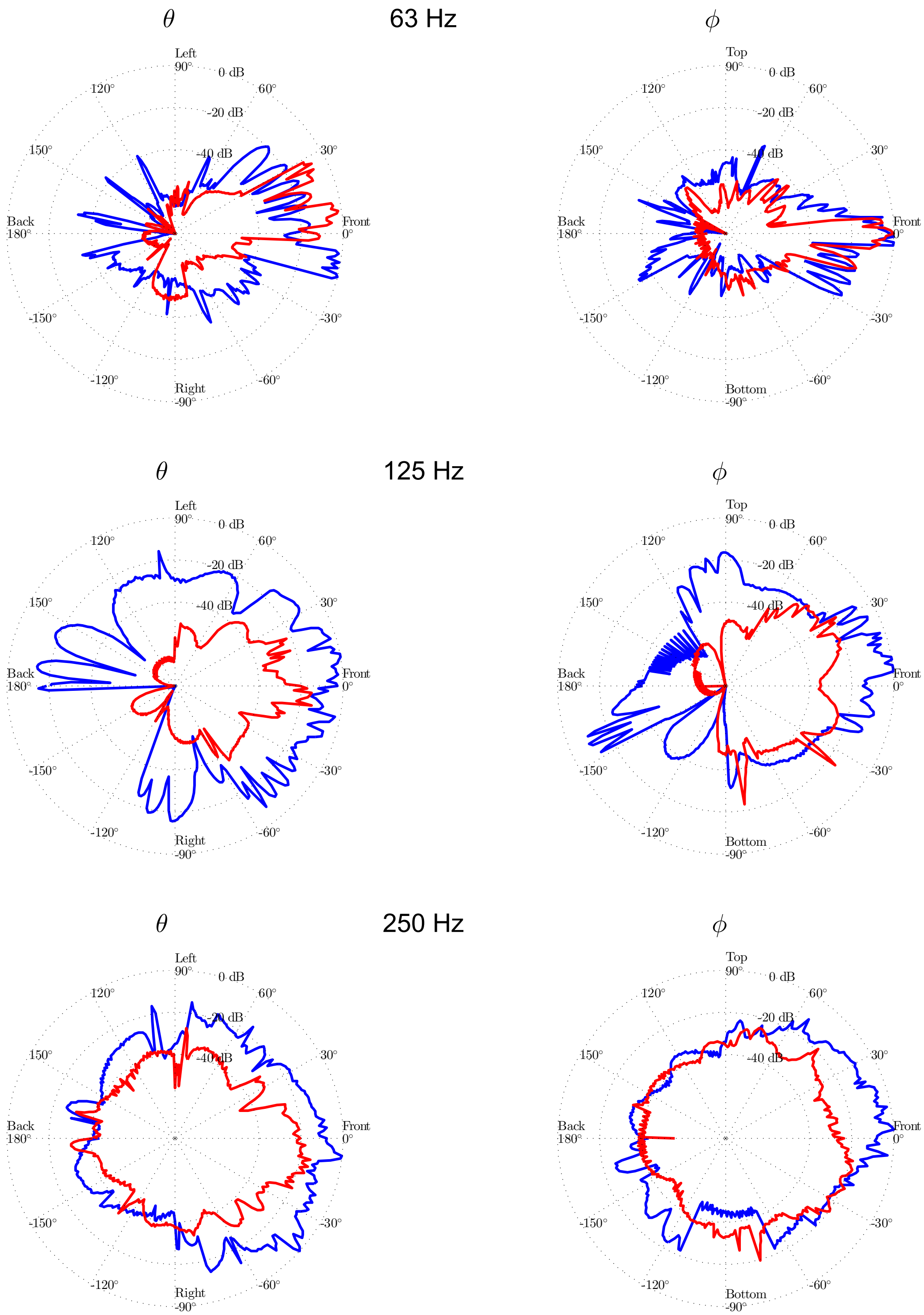

Figure 2: Directional energy distributions of Berlin Konzerthaus (–) and Berlin Philharmonie (–) at 63 Hz, 125 Hz, and 250 Hz octave bands for azimuth (θ) and elevation (ϕ) angles.

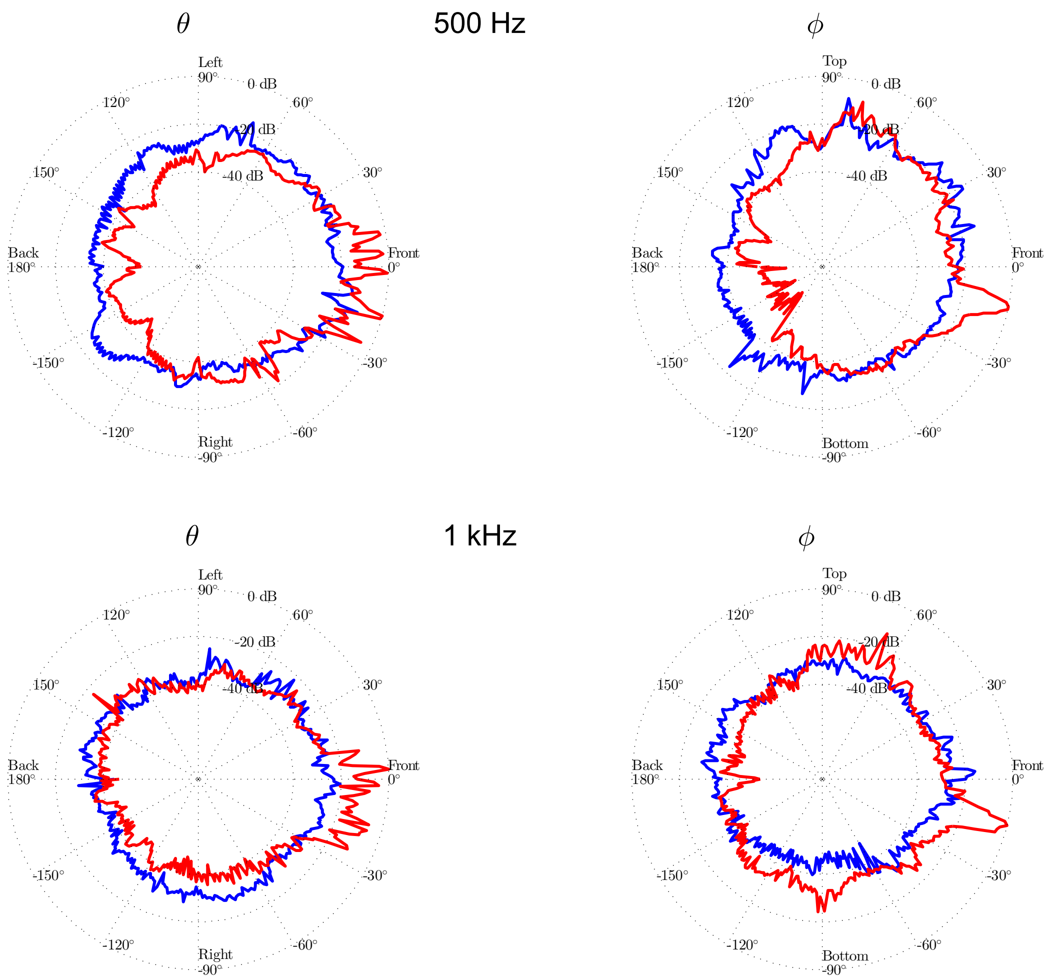

Figure 3: Directional energy distributions of Berlin Konzerthaus (–) and Berlin Philharmonie (–) at 500 Hz and 1000 Hz octave bands for azimuth (θ) and elevation (ϕ) angles.

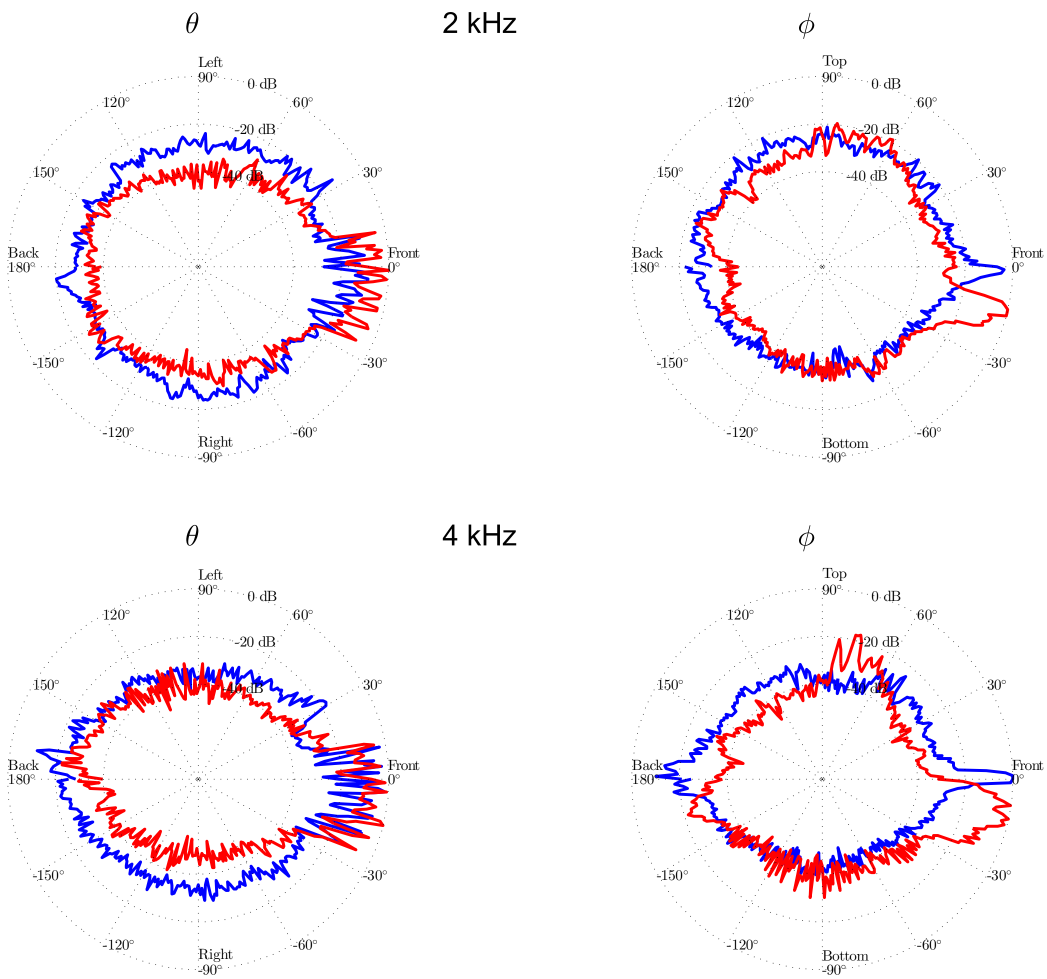

Figure 4: Directional energy distributions of Berlin Konzerthaus (–) and Berlin Philharmonie (–) at 2 kHz and 4 kHz octave bands for azimuth (θ) and elevation (ϕ) angles.