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Investigating Room Acoustics Using a 16-Channel, 2nd-Order Ambisonic Microphone

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ABSTRACT

Most room acoustic parameters are calculated with data from omni-directional or figure-of-eight microphones. Using an ambisonic microphone to record room impulse responses can open up several new areas of inquiry. It can yield much more information about the spatial characteristics of the sound field at the points of interest, including the diffuseness of the sound field and the directions of individual reflections. This method can also be used to produce high quality auralizations through ambisonic reproduction techniques. In this research, room impulse responses are measured in reverberant rooms used for music from stage and audience positions using a 16-channel, second-order ambisonic microphone and a dummy head. The results are analyzed using beamforming techniques and compared to those produced by acoustics models.

INTRODUCTION

Our current approach to measuring the acoustics of enclosed spaces is essentially a transfer function approach. Rooms are treated like two-port elements, with an omnidirectional source and a one- or two-channel receiver: an omnidirectional or figure-of-eight microphone or a dummy head. While this method allows for relatively easy signal processing and characterization of rooms, it greatly simplifies the very complex ways in which sound travels about a room. By measuring room impulse responses with a multi-channel receiver, it is possible to gain much more information about the the three-dimensional characteristics of the soundfield.

Some work has previously been done in this area by B. N. Gover, et. al. [1, 2, 3]. Two 32-channel acoustically transparent spherical microphone arrays were constructed to measure directional properties of the soundfield in several different rooms, with the microphones arranged as the vertices of a geodesic dome. (The two arrays were different sizes in order to cover different frequency ranges.) Using beamforming techniques, this team was able to determine the direction of individual reflections, as well as quantify the diffuseness of the soundfield.

In this research, a 16-channel ambisonic microphone was constructed, with omnidirectional capsules embedded in the surface of a rigid sphere. This microphone is designed to decompose the soundfield into spherical harmonics. Beamforming may then be accomplished by different combinations of spherical harmonics (eigenbeams). Another advantage to this system is that it is suited for playback via multi-channel loudspeaker array. This will allow us to create ambisonic auralizations and allow us to study whether or not this reproduction technique provides listeners with a better platform with which to make subjective judgments of performance halls. Of particular interest is whether ambisonic reproduction provides listeners with a noticeable advantage in judging spaciousness, envelopment, and apparent source width, subjective parameters correlated to the the way in which the sound energy arrives at the listener from different directions. Currently, the most accurate, readily available method we have for presenting auralizations to a listener is through binaural playback. The main disadvantage to this method is that many of the spatial characteristics of the auditory scene break down if the subject moves his or her head. Therefore, ambisonic reproduction potentially provides the opportunity to present listeners with a spatially complex auditory scene in a more natural way, leading to more accurate judgments about of the spatial attributes of the soundfield.

Guastavino et. al. have done several studies of listener preference for different forms of multi-channel audio playback, including ambisonics, stereo and transaural [4, 5]. Among their findings was that ambisonic playback provided for a strong sense of immersion and envelopment, but poor localization, while stereo and transaural playback offer the opposite advantages and disadvantages. This bodes well for using ambisonics as a tool for subjective judgments of concert halls, as immersion and envelopment are more relevant than sound source localization.

AMBISONIC MICROPHONE DESIGN

The mathematical basis of ambisonics comes from solving the wave equation in spherical coordinates [6, 7]. The set of solutions to this equation are known as the spherical harmonics [7]:

$$Y_n^m(\theta,\phi) \equiv \sqrt{\frac{(2n+1)}{4\pi}\frac{(n-m)!}{(n+m)!}}P_n^m(\cos\theta)e^{im\phi} \quad [1]$$

The pressure field on the surface of a sphere can thus be written as a weighted sum of these spherical harmonics, which are orthonormal:

$$\int_0^{2\pi} d\phi \int_0^{\pi} Y_n^m(\theta,\phi) Y_{n'}^{m'}(\theta,\phi)^* \sin\theta d\theta = \delta_{nn'}\delta_{mm'} \quad [2]$$

In theory, we would take measurements using a continuously transductive spherical surface. However, in practice, we must resort to spatial sampling, measuring the pressure on the surface of the sphere with a finite number of sensors. As mentioned previously, our microphone has a total of 16 sensors. In designing the microphone, one wants the sensors to be spaced as evenly as possible over the surface of the sphere. However, there are only five exact solutions to this particular problem, which correspond to the vertices of the platonic solids (tetrahedron: 4; octahedron: 6; cube: 8; icosahedron: 12; dodecahedron: 20). For any number of sensors that is not 4, 6, 8, 12, or 20, one can arrange them according to a scheme known as nearly-uniform sampling, and then apply a weighting to each sensor so that when one performs cubature of the unit sphere, the result is (very close to) unity [8]. Table 1 shows the 16 sensor positions and their weights.

Table 1. Sensor positions and weights

Sensor	*Azimuth*	*Elevation*	*Weight*
1	0	90.0	0.76
2	0	41.1	0.76
3	-81.3	35.3	0.87
4	-160.6	37.5	0.76
5	131.6	37.5	0.76
6	66.2	28.2	0.87
7	64.2	-26.4	0.76
8	15.5	-9.5	0.76
9	-36.4	0.1	0.76
10	-79.1	-26.4	0.76
11	-126.3	0.1	0.76
12	172.5	-11.0	0.87
13	116.9	-9.5	0.76
14	-14.5	-59.3	0.87
15	-141.4	-50.8	0.76
16	123.5	-61.8	0.76

(Source: Fliege)

The individual sensors essentially come in three groups that together cover the entiretry of the sphere: sensor 1 is on the top of the microphone, with sensors 2-6 encircling it; sensors 7-13 form a belt around the middle of the microphone; and sensors 14-16 are near the bottom.

The shell of the microphone was created with a 3-D rapid prototyping printer. A photo is shown below.

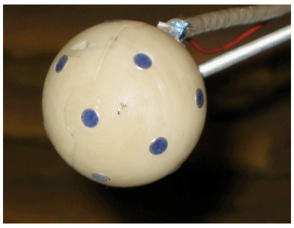

Figure 1. The ambisonic microphone

MEASUREMENTS

Room Impulse Response measurements were taken in a wide variety of small, medium and large halls throughout Upstate and Western New York. The halls are:

- West Hall Auditorium, a 700-seat auditorium and lecture hall at Rensselaer Polytechnic Institute in Troy
- The Concert Hall, a 1,200-seat concert hall, and the Theater, a 400-seat drama theater, of the Experimental Media and Performing Arts Center, also at Rensselaer Polytechnic Institute in Troy
- Helen Filene Ladd Concert Hall, a 600-seat shoebox-style concert hall with an orchestra pit and a glass rear wall, at Skidmore College in Saratoga Springs
- Sosnoff Theater, a 900-seat theater with an orchestra pit, used for opera, orchestral, and chamber music performances, at Bard College in Annandale-on-Hudson
- Mary Anna Fox Martel Recital Hall, a 500-seat recital hall at Vassar College in Poughkeepsie
- Eastman Theatre, a 3,100-seat hall used for opera and orchestral performances and the home of the Rochester Philharmonic Orchestra, at the Eastman School of Music in Rochester
- Lippes Concert Hall, a 670-seat hall for orchestral and chamber music at The State University of New York at Buffalo
- Picotte Recital Hall, a 400-seat hall for orchestral and chamber music with custom-designed diffusive panels by Peter D'Antonio of RPG Diffusor Systems, at The College of St. Rose in Albany
- The Main Theatre, a 500-seat drama theater with continental-style seating, and the Recital Hall, a circular 242-seat recital and lecture hall, at The State University of New York at Albany

Figure 2. The Concert Hall of EMPAC, Rensselaer Polytechnic Institute, Troy

Figure 3. Picotte Recital Hall, The College of St. Rose, Albany

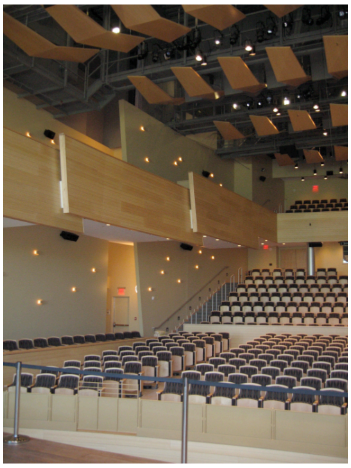

Figure 4. Helen Filene Ladd Concert Hall, Skidmore College, Saratoga Springs

An omnidirectional source was used, consisting of a sub-woofer and two dodecahedral loudspeakers radiating a logarithmic swept sine signal. In each hall the source was positioned in the center of the stage, near the front, where a musician would most likely be positioned when giving a recital.

In each hall, at least two and frequently three receiver positions were used. Typically, these were: in the center of the first row; two or three rows back, far off-center, near a side wall; and six to ten rows back, in an aisle seat in the center section. At each receiver position, measurements were taken with both the 16-channel ambisonic microphone and a dummy head.

The microphone was calibrated in the free field to determine the frequency response of each individual channel. The source was single mid-range loudspeaker driver mounted in a PVC tube, driven with a logarithmic swept sine signal. Two laser pointers were used to ensure that each microphone capsule was at the exact same position for each measurement. All of the channels remained connected to the interface for each measurement so that mutual interactions between the channels might be taken into account for calibration purposes. To measure the absolute level of each microphone, a pistonphone was used, along with a special attachment created with a laser cutter to isolate each channel on the surface of the sphere. Additionally, the mutual interactions between the channels were examined by making a brief recording and gently scratching each individual capsule in turn. No significant crosstalk effects were observed.

DATA ANALYSIS

The expression for the sound pressure on a rigid sphere due to a point source is known [9]:

$$P_s(r,a,f,\theta) = \frac{\rho c U_0}{2\pi a^2}\{\sum_{m=0}^{\infty}(m+\frac{1}{2})P_m(\cos\theta)\frac{h_m(kr)}{h'_m(ka)}\}e^{i(2\pi f t-\frac{\pi}{2})} \quad [3]$$

where ρ = the density of air, c = the speed of sound in air, f = the frequency of the point source vibration, k = the wave number, a = the radius of the sphere, r = the distance from the center of the sphere to the source, θ = angle between the ray from the center of the sphere to the source and the ray from the center of the sphere to the measurement point on the surface of the sphere, U_0 = volume velocity of the source, P_m = the Legendre polynomial, and h_m = the Spherical Hankel function. To find the transfer function at the measurement point, divide by the previous equation by the expression for the pressure due to a point source in the free field:

$$P_{ff}(r,f) = \frac{\rho c k U_0}{4\pi r}e^{i(2\pi f t-kr+\frac{\pi}{2})} \quad [4]$$

By considering the geometry of our microphone to determine the azimuthal angles (and using a source facing sensor 1), the following transfer functions were calculated for each sensor (Figure 5).

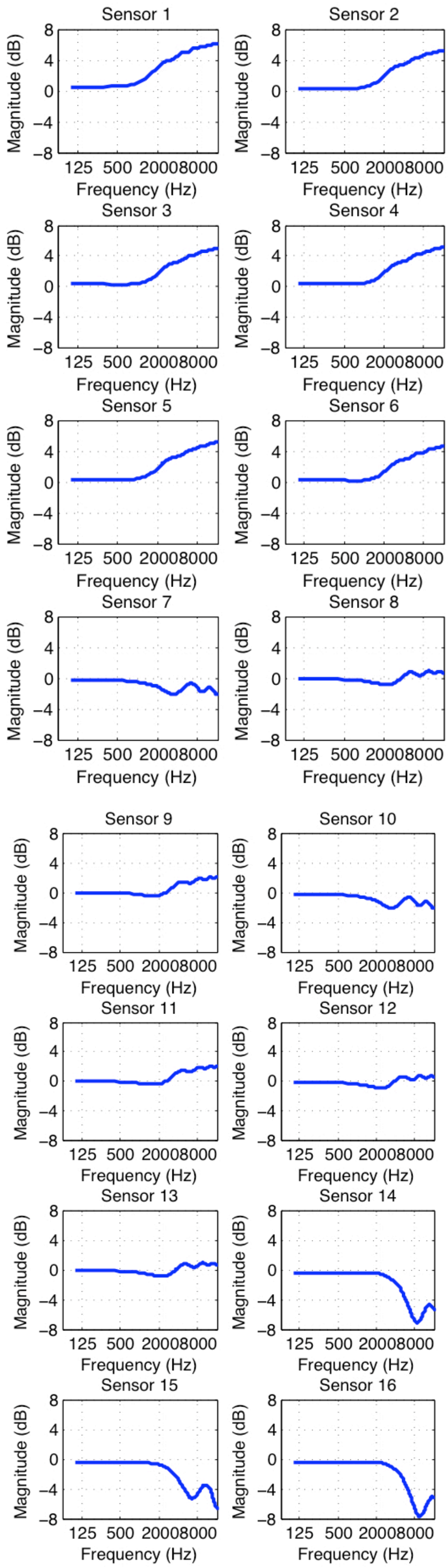

Figure 5. Theoretical Transfer Functions for each sensor of the ambisonic microphone due to a source facing sensor 1

These results are in line with what one would expect. The sensors closest to the source exhibit the highest magnitude at high frequencies, while those on the back of the microphone are more shadowed at high frequencies.

Moving on to the impulse response data collected at the various halls, we can use the data from the ambisonic microphone to calculate all of the traditional room acoustics parameters, such as reverberation time, early decay time, clarity, and lateral fraction. These parameters are normally calculated using omnidirectional and figure-of-eight microphones. As an ambisonic microphone is designed to decompose the soundfield into spherical harmonics, we can use these to extract the signal from a hypothetical omnidirectional or figure-of-eight microphone at the measurement point. The zeroth order spherical harmonic represents an omnidirectional pattern, while choosing the correct first order spherical harmonic yields a figure-of-eight microphone with the lobes aimed at the sidewalls (as the three first order spherical harmonics are figure-of-eight patterns directed along the x-, y-, and z-axes.) Moreau et. al. [10, 11] describe in detail the mathematical fundamentals of decomposing individual sensor signals into the spherical harmonics. This is done in the frequency domain, and once converted back into the time domain, these spherical harmonics may be used to calculate familiar acoustic parameters, such as early decay time, reverberation time, clarity, lateral energy fraction, etc. Some of these calculated parameters are shown below (with the dummy head impulse responses being used to calculate the interaural cross-correlation coefficient).

Table 2. Selected acoustic paramteters calculated from 16-channel ambisonic microphone impulse responses

Hall	*Seat*	*T30 (s)*	*C80 (dB)*	*IACC*
EMPAC-CH	Front	2.47	2.6	0.25
	Side	2.49	-1.8	0.29
	Aisle	2.49	-1.7	0.26
EMPAC-T	Front	0.96	6.9	0.29
	Aisle	1.20	4.7	0.18
	Balcony	1.27	5.2	0.14
Ladd	Aisle	2.25	-0.5	0.20
	Side	2.41	-2.2	0.27
Sosnoff	Front	1.77	0.8	0.19
	Side	1.80	0.3	0.23
	Aisle	1.76	-0.3	0.17
Martel	Front	1.19	4.0	0.35
	Side	1.53	1.6	0.19
	Aisle	1.63	0.0	0.28
Eastman	Front	2.34	1.9	0.24
	Side	2.45	-2.4	0.16
	Aisle	2.45	-3.0	0.28
Picotte	Front	1.85	3.1	0.18
	Side	1.85	1.4	0.19
	Aisle	1.81	0.0	0.16
Albany-RH	Front	1.31	3.9	0.23
	Side	1.33	1.6	0.27

DISCUSSION AND FURTHER STUDY

A large amount of data has been collected using this second-order ambisonic microphone, and the calculated parameters shown in Table 2 represent only the beginning of the many uses of these data. The calculated parameters correlate well with the authors' subjective impressions of the measured halls, but further experiments will be done to directly compare impulse response measurements taken in the simultaneously in the same hall on the same day to determine how closely the ambisonic measurements agree with those taken in a conventional 2-channel (omnidirectional and figure-of-eight) format.

Another application for this data is spatial soundfield analysis using beamforming techniques. Elko et. al. [12] have developed some beamforming algorithms involving combinations of the different spherical harmonics (also known as eigenbeams), which are readily applicable to this microphone design.

As impulse response measurements were taken with both the ambisonic microphone and a dummy head at all audience measurement positions, auralizations will be created using these data and used for psychoacoustic tests to determine how listener's subjective judgments of different halls are effected by ambisonic versus binaural playback.

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