Measurement of Spatial Impulse Responses with a Soundfield Microphone

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Abstract

As concert hall designers we have a keen interest in measuring the spatial evolution of sound fields. So far, 3D impulse responses have been measured with sound intensity methods, with tetrahedral microphone arrays and with large microphone arrays. These methods are very sensitive to phase, and therefore to particulars of microphone construction and analysis bandwidth.

In this paper a method is proposed for capturing the spatial impulse response of a room by means of orthogonal cosine directivity microphones. Tests have been done with a simple figure-8 / omni microphone pair oriented in three directions, one after the other, as well as with a purpose-built Soundfield Microphone. Impulse responses are captured for each of the X, Y, Z and omni (Soundfield B-format) channels. The directional impulse responses are then cross-correlated with the omni impulse response to construct "direction cosines" of strength with respect to the listener position, over time. Data can be mapped graphically in 3D space to visualize the evolution of the sound field; the degree of scatter in the data represents diffuseness. In addition to graphics, convincing 3-dimensional auralizations have been performed with soundfield impulse responses.

Introduction

Most architectural acoustics situations of interest to us include at least three elements: at least one source, the room as a sound propagation channel, and at least one listener. In the real world all three of these have characteristics that are not uniform in space; in concert halls and theatres their spatial characteristics are relevant to the output, the perception by the listener.

The source has an directivity function that varies with frequency and time. The room geometry governs how sound behaves in the space. The listener has a perception function that depends on the temporal *and spatial* characteristics of the sound field.

Jens Blauert and many others have made significant process over the past couple of decades in our understanding of what Blauert calls “spatial hearing”. Through controlled laboratory experiments researchers are refining our knowledge of psychoacoustics to the degree that we can now link, or at least postulate, some of what and how we hear to physical and psychological processes; for example diffraction by the ear pinna and binaural processing. It is clear now that spatial aspects of a sound field determine a great deal about what it sounds like to listeners. What is NOT yet clear are the complete details of the physical to psychological transformation.

In analysis of concert hall and theatre acoustics, and other spaces as well, we consider progress of sound in time, and increasingly, the 3D spatial aspects. But, until recently, spatial sound measurements have been given far more high-tech attention in underwater acoustics and medical imaging than in architectural acoustics.

In recent years we as a community have developed an interest spatial characteristics of the sound field. Early work was done with directional mics and parabolic reflectors. When the importance of lateral energy surfaced (through the work of Barron, Marshall and others), many of us began using a pressure gradient microphone to measure lateral or frontal sound. More specifically, a gradient mic and an omni mic pair, placed as close to coincidence as possible.

For concert hall and theatre designers information on the spatial aspects of the sound field is helpful in relating the sound to the architecture, to help us understand which surfaces ultimately reflect the sound to the listener. Moreover, we need to study the directional attributes of sound fields in halls and correlate them with perceptual attributes.

Our goals for 3D measurements include the following:
- Development of a library of 3D measurements made in many facilities
- Appropriate as a diagnostic tool to help understand the directional behavior of the sound field in time
- Full 3D spatial impulse response, including pressure as a function of time, direction
- Ability to slice data across time and space
- Motivate / develop new approaches to visualization / animation
- Auralization – independent of specific ears used in recording

Large arrays for high directional resolution have been developed by others
- Steerable, trainable, directional array – Elko
- Synthesized 3d cube, sparse array -- Broadhurst
- Synthesized 4-sphere array: Hanyu and Kimura
  4 mics to synthesize 128 points on each of 4 spheres

These incorporate many transducers and much electronics, or alternatively, much time for measurement with a synthetic array. These systems are critical with respect to transducer spacing, calibration and alignment. We were looking for something a bit more forgiving, a lot less expensive and a bit easier to use, yet still an open system.

We can recognize that four channels of information is sufficient in principle to fully describe the 3D spatial sound field, though at a price of lower spatial resolution. The four channels are three orthogonal directional vectors and a total pressure.

Recently, several groups have developed room acoustics measurement systems based on 4 omni mics in a tetrahedral array:

- Yamasaki and Itow
- Sekiguchi, Kimura & Hanyu
- Korenaga

and a 3D Intensity Method:

- Abdou and Guy

These, too, require critical alignment and/or extensive postprocessing.

Soundfield microphone and Ambisonics

In the 1970's a different 4-channel approach to recording and playback was pioneered Duane Cooper and Michael Gerzon, who called it "Ambisonic" or "Soundfield" recording. This was envisioned as a way to recreate the sound pressure at a point in space. The Soundfield microphone, as it is now known, is a very closely spaced tetrahedral array of cardioid microphones, time aligned to measure the sound at a point at the center of the array. The four signals can be combined in a certain way to give pressure gradient (fig-8) response in X, Y, Z directions and the pressure response W; this set of outputs has been called "B-format".

These four channels can be captured in principle with an omni and pressure gradient microphone pair, oriented in three directions one after the other. They can be captured on a 2-channel recorder, which can be a portable DAT or a portable computer. The question was could we develop an analysis procedure that would not be critically reliant on phase (and therefore location). In principle, we wanted to use just the amplitude and polarity information inherent in the 4 signals.

Directional Fractions

We had been using an omni/fig-8 microphone pair for lateral energy fraction measurements, and along the way, developed an approach to show the instantaneous lateral or frontal fraction. The process is a cross correlation of the pressure and gradient channels, normalized by the autocorrelation of the pressure channel, for a short time window that, ideally, would be chosen according to perceptual relevance.

$$F_x(t) = \frac{\sum_{\tau = t-\delta/2}^{\tau = t+\delta/2} x(\tau)\, w(\tau)}{\sum_{\tau = t-\delta/2}^{\tau = t+\delta/2} w(\tau)\, w(\tau)}$$

Directional Fractions – for x, y, z

Since the Soundfield microphone B-format outputs are equivalent to the cosine directivity pressure gradient microphone, we can use the same process on each X, Y, Z with the common W pressure response.

3D Display

The x, y, z fractions constitute the amplitude shading in each direction according to the cosine weighting of the microphone. We can therefore consider the three directional fractions to be "directional cosines" to establish the general direction of sound at a particular instant with respect to the receiver (listener). Time can be mapped to radius form the listener, and pressure amplitude to intensity, color, dot size, or any number of scalars. We calculate the smoothed pressure from the short-time autocorrelation of the omni (w) signal, and map amplitude to both color and dot size.

Coordinates

$r = c\, t$
$x = r\, F_x(t)$
$y = r\, F_y(t)$
$z = r\, F_z(t)$

Amplitude

$$P(x,y,z,t) = \left[\sum_{\tau = t-\delta/2}^{\tau = t+\delta/2} w(\tau)\, w(\tau) \right]^{1/2}$$

3D Plot of direction cosines

Source

The analysis principle is independent of source. One criterion is fundamental to the method: the source should be repeatable, especially for 2-channel measurements, where three separate acquisitions are required. Also, as for most measurements, the transducer should have low distortion. We wish to use this technique in occupied halls, where there are additional criteria: easy on the ears, speed of setup and capture, and portability. Trials have been carried out with the following:

- Sweep (2-part) through omni dodecahedron loudspeaker
- MLS through PA system
- Balloon Bursts

Recording System

We have used two different systems:

<u>More costly, less portable system:</u>

- Soundfield microphone -- Ambisonic
- Record 4-channels in parallel -- Digital multitrack, ADAT
- 4-channel A/D board in PC
- Acquisition Software - 4 channels

<u>Less costly, more portable system:</u>

- Omni-fig8 microphone pair, used serially in 3 orientations
- Portable DAT – battery powered
- 2-channel A/D board in PC
- Acquisition Software - 2 channels

Analysis/Display

The goal for initial processing and display is to show directional information in a perceptually relevant way. The approach is an extension of instantaneous lateral fraction. The process is as follows:

1. Deconvolve each channel (MLS, Sweep) to retrieve Impulse Response

2. Compute partial fractions with respect to all 3 axes from amplitude of short time cross correlation w/ omni channel

3. Use partial fractions as "direction cosines" to plot on 3D axis,
   with time -> radius,
   amplitude -> color and/or size

4. Animated rotation helps visualization

Field Experience

Large, dry recording studio (Soundfield microphone)

Boston Symphony Hall (Soundfield microphone)

Radio City Music Hall (Omni, Fig-8 pair)

Other concert halls, opera houses (Omni, Fig-8 pair)

CAPTIONS

Dry Studio
Directional Fractions: 10ms sliding window
0-500ms

Dry Studio
Directional Fractions: 30ms sliding window
0-500ms

Dry Studio
3D Plot: 10ms sliding window
0-500ms

Dry Studio
3D Plot: 30ms sliding window
0-500ms

Boston Symphony Hall
3D Plot: 30ms sliding window
0-1300ms

Boston Symphony Hall
Directional Fractions: 30ms sliding window
0-1300ms

Radio City Music Hall
Directional Fractions: 30ms sliding window
0-700ms 1kHz octave

Radio City Music Hall
Directional Fractions: 60ms sliding window
0-700ms 125 Hz octave

Radio City Music Hall
Directional Fractions: 30ms sliding window
0-700ms Unfiltered

Radio City Music Hall
3D Plot: 60ms sliding window
0-700ms 125 Hz octave

Radio City Music Hall
3D Plot: 30ms sliding window
0-700ms 1kHz octave

Boston Symphony Hall Images Model
X directivity

Boston Symphony Hall Images Model
Y directivity

Boston Symphony Hall Images Model
Z directivity

Boston Symphony Hall Images Model
W directivity (omni)