

# 3D Impulse Response measurements on S.Maria del Fiore Church, Florence, Italy

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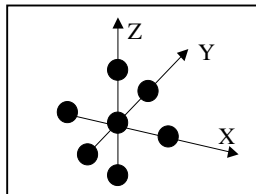
**Abstract:** A new technique for measuring three-dimensional impulse response has been applied for the first time in the S.Maria del Fiore church, in Florence, along with traditional binaural technique. Although 3D microphones already exist for B-format recordings, in this case a novel approach has been developed: it makes use simply of a single omnidirectional microphone, subsequently placed in 7 closely spaced positions located on a 3D crux. A proper software routine makes it possible to recover the 4-channels B-format impulse response by processing the 7 omnidirectional impulse responses measured at these locations. A comparison with traditional binaural impulse response was made for checking the suitability of the new technique for auralization purposes.

## INTRODUCTION AND MATHEMATICAL FORMULATION

A three-dimensional sound field can be described by spherical harmonics of the first order, following the well known Ambisonics approach (1). At the recording point, it is required to record the omnidirectional sound pressure signal ( $W$ ), plus three first-order pressure gradient components, along the three Cartesian axes ( $X, Y, Z$ ); these 4 channels of information are called a B-format signal. This task can be accomplished with a special 4-channel microphone, called Soundfield, which is widely used as a recording unit for the production of surround music.

In this paper the same technique is employed for a quite different goal: B-format impulse responses are first measured, with MLS excitation, in the hall to be characterized. After this, these B-format impulse responses are employed as filters, applied by convolution to anechoic music signals: this makes it possible to recreate the complete three-dimensional information of the room with any kind of source signal. Furthermore, the analysis of the B-format impulse responses makes it easy to see from where the single reflections or echoes are coming; this is a powerful diagnostic tool for analyzing the acoustical defects of the room and for gathering information about the surfaces which have to be treated.

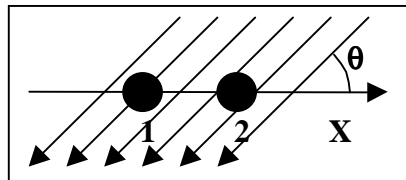
The above technique can be easily implemented making use of the Soundfield microphone, which anyway is quite expensive. So a new numerical technique has been developed, making use of a single omnidirectional



microphone: 7 impulse response measurements are made, moving the microphone from the reference position ( $R$ ) to other 6 closely spaced positions, placed along the three Cartesian axes in both directions ( $X+$ ,  $X-$ ,  $Y+$ ,  $Y-$ ,  $Z+$ ,  $Z-$ ), as shown in the picture on the left.

This way, the pressure gradients along the three axes can be computed with a numerical technique quite similar to the one implemented in pressure-difference sound intensity probes.

In the following, the mathematical theory for making this computation is first described, and an application example is presented.



Let us look at a single pair of microphone positions placed along the  $X$ -axis at a relative distance  $d$ , as in the picture on the left. Assume that the sound wave, travelling at speed  $c$ , is coming with an angle  $\theta$  with the  $X$ -axis. Following the well-known theory of Sound Intensity probes, the required first-order pressure gradient at the microphone #1 is given by:

$$p_1(\tau) \cdot \cos(\theta) = \int \left[ \frac{p_1(t) - p_2(t)}{d} \cdot c \right] \cdot dt \quad (1)$$

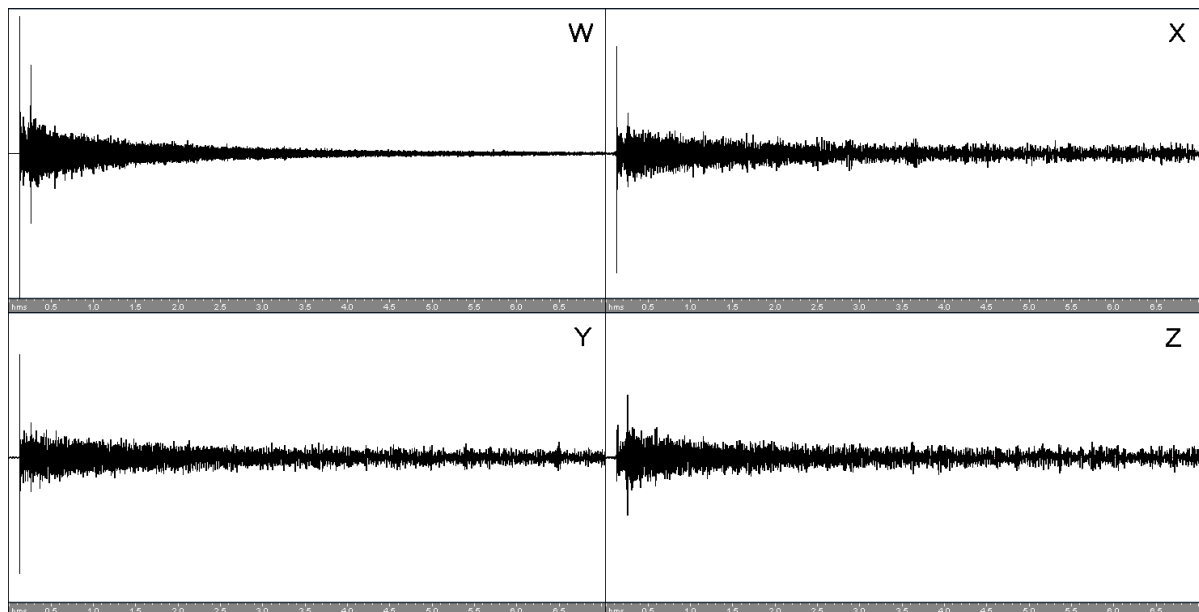
This computation is easier in the frequency domain. So the two pressure impulse responses measured at the two microphones are first FFT-transformed, then eqn. 1 is applied. Finally, the result is backward transformed to time domain through an inverse FFT. The process is repeated for each pair of microphone positions: along each axis, three pairs can be considered, two with spacing  $d$  and one with spacing  $2 \cdot d$ . The average of the first two is employed for estimating properly the higher frequencies, and the third one is better for low frequencies. The three computations are merged together in the frequency domain, through proper cross-over filters, and a single IFFT is then performed.

The above computation was implemented in a dedicated program, which reads the 7 impulse responses, and writes directly the 4 B-format impulse responses. The results are thus 4 separate mono .WAV files, because a proper flag for identifying 4-channels B-format .WAV file has not been standardized yet and most waveform editing programs cannot manage properly 4-channels files.

## EXPERIMENTAL MEASUREMENTS

The measurements were made in a highly reverberant church (rev. time is more than 8s). A full-duplex soundboard was employed for generating an MLS signal of order 21, at a sampling rate of 44.1 kHz. The microphone response was sampled in one of the recording channels, while the excitation signal was sampled in the other: this made it possible to re-align temporally the deconvolved impulse responses and to ensure that they were scaled uniformly to the same excitation magnitude. A microphone spacing  $d$  of 20 mm was employed, ensuring a correct estimate of the pressure gradient in the frequency range between 100 and 4000 Hz. 6 complete MLS sequences were averaged for improving the signal-to-noise ratio.

The following picture reports the 4-channels, B-format impulse response obtained in one of the measurement positions. This does not give evident information about the three-dimensional properties of the sound field.



A more evident information is obtained making ratios between the time-integrated energies. For example, the well known LE parameter can be computed easily from the ratio between the Y-axis pressure gradient and the omnidirectional response at the reference position. Furthermore, the sound intensity components can be computed from the product of each pressure gradient with the omnidirectional pressure. Thus a polar representation of the single energy arrivals at the receiver can be plotted on the 3 coordinate planes.

## REFERENCES

1. Gerzon M., *Journal of Audio Engineering Society*, Vol. 33, Number 11 pp. 859 (1985).