BACCH™ 3D Sound

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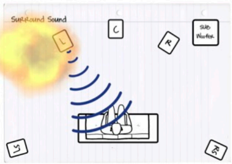
1 What is the invention?

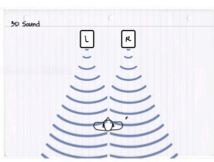
BACCH™ 3D Sound is a recent breakthrough in audio technology (licensed by Princeton University) that yields unprecedented spatial realism in loudspeakers-based audio playback allowing the listener to hear, through **only two loudspeakers**, a truly 3D reproduction of a recorded sound field with uncanny accuracy and detail, and with a level of high tonal and spatial fidelity that is simply unapproachable by even the most expensive and advanced existing audio systems.

2 How is it innovative?

BACCH™ 3D Sound is a vast improvement over Surround sound. Surround sound, which was originally conceived to make the sound of movies more spectacular, does not (and cannot) attempt to reproduce a 3D sound field and can only provide some degree of sound envelopment for the listener by surrounding the listener with five or seven loudspeakers.



5.1 Surround Sound (above) can portray far off sound effects, such an explosion at a distance but cannot place sounds near the listener. BACCH™ 3D Sound (below) can place a sound anywhere in 3D space such as a fly around the head of the listener, using only 2 loudspeakers.



In contrast, BACCH™ 3D Sound's primary goal is accurate 3D sound field reproduction. It gives the listener the same 3D audio perspective as that of the ideal listener in the original recording venue. For instance, if in the original sound field a fly circles the head of the listener during the recording, a listener of that recording played back through the two loudspeakers of a BACCH™ 3D Sound system will hear, simply and naturally, the same fly circling his or her own head (while a Surround sound system will reproduce the fly incorrectly near the speakers). Recorded applause in a concert hall, or laughter or chatter in a jazz club, will be reproduced through BACCH™ 3D Sound with uncanny accuracy, and would appear as near to the listener as they were in the original venue during recording.

The technology is completely compatible with all stereo recordings made since 1954, which become naturally 3D when played through the BACCH™ filter.

3 Applications

BACCH™ 3D Sound is ideal for many applications including home audio, car audio, 3D Movies, 3D TV, computer gaming, teleconferencing, music recording, live broadcasting, security, military, and medical (e.g. helping the hearing impaired).

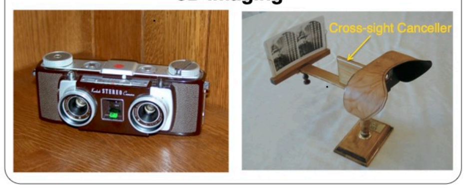
Demonstration of 3D audio teleconferencing using BACCH™ 3D Sound.

It has received wide media coverage in CNET, The Atlantic magazine, BBC Radio, NPR and the Discovery Channel.

4 How does it work?

BACCH™ 3D Sound is based on the same principles used in 3D imaging and video as explained in the panel below.

3D Imaging



Recording Playback

3D Audio

3D imaging (top panel) and 3D Audio through two loudspeakers (bottom panel) share the same *stereo* principles. In 3D Imaging (3D Audio) two lenses (microphones) of a camera (dummy head) separated by the typical human inter-ocular (inter-aural) distance are used to record two separate images (audio channels) intended for the left and right eyes (ears) separately. Such a stereoscopic (stereophonic) recording contains the visual (aural) 3D cues needed to see (hear) in 3D.

During viewing (listening) a physical barrier (BACCH™ filter) insures that the left image (channel) is seen (heard) by the left eye (ear) *only.* The same applies for the other eye (ear). This cross-sight (crosstalk) cancellation insures the proper transmittal of the stereo-coded 3D cues to the brain leading the viewer (listener) to perceive a realistic 3D image (sound field).

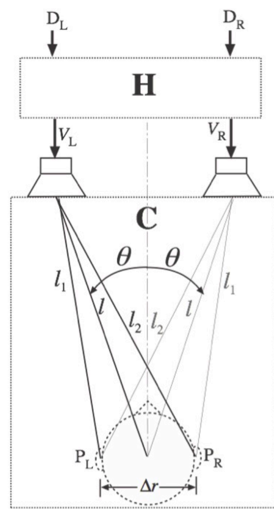
For viewing a 3D image the required *cross-sight cancellation* is done by placing a physical barrier between the two eyes (see the photo of the *circa* 1895 stereoscope in the panel above). Similarly, for 3D Audio playback, the BACCH™ digital filter causes ***crosstalk cancellation (XTC)*** by essentially placing an invisible sound "barrier" between the left and right ears of the listener. The BACCH™ digital filter creates this "barrier" by forcing the left and right speakers to emit positive and negative pressure waves appropriately timed to cancel the crosstalk at the ears of the listener.

XTC Filters existed before but inherently caused unacceptably high spectral (tonal) alteration to the sound. **The breakthrough behind the BACCH™ 3D Sound technology is a method for designing completely transparent XTC filters (i.e. with no tonal alteration to the sound).** This is described in Sections 5.1 and 5.2 of this poster.

5.1 Theory: Perfect XTC

A crosstalk cancellation (XTC) filter is a digital filter that allows the signals D_L and D_R (see schematic below) on the Left and Right channels of a stereo (or binaural) recording to be manifested as air pressure signals P_L and P_R at the left and right ears respectively, so that the left (right) ear hears only what is on the left (right) channel.

The perfect XTC filter, which has been known for some time, consists of simply inverting the transfer matrix (shown schematically and symbolically below for the idealized case of point sources in free space) that describes the wave propagation from two loudspeakers to two ears.



$$\begin{bmatrix} P_L \\ P_R \end{bmatrix} = \begin{bmatrix} 1 & ge^{-i\omega\tau_c} \\ ge^{-i\omega\tau_c} & 1 \end{bmatrix} \begin{bmatrix} V_L \\ V_R \end{bmatrix}$$

$$\boldsymbol{p} = \boldsymbol{C} \quad \boldsymbol{v}$$

$$\begin{bmatrix} V_L \\ V_R \end{bmatrix} = \begin{bmatrix} H_{LL} & H_{LR} \\ H_{RL} & H_{RR} \end{bmatrix} \begin{bmatrix} D_L \\ D_R \end{bmatrix}$$

$$\boldsymbol{v} = \boldsymbol{H} \quad \boldsymbol{d}$$

$$\boldsymbol{p} = \boldsymbol{C}\,\boldsymbol{H}\,\boldsymbol{d}$$

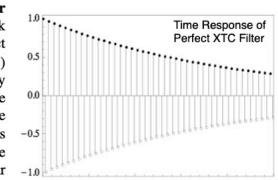
$$\boldsymbol{p} = \boldsymbol{d}$$

$$\boldsymbol{CH} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Perfect XTC Filter:

$$\boldsymbol{H}^{[P]} = \boldsymbol{C}^{-1} = \frac{1}{1 - g^2 e^{-2i\omega\tau_c}} \begin{bmatrix} 1 & -ge^{-i\omega\tau_c} \\ -ge^{-i\omega\tau_c} & 1 \end{bmatrix}$$

This perfect XTC filter yields infinite crosstalk cancellation (in a perfect world, with no reflections) at the ears of a perfectly aligned listener. It has the following intuitive time response, which shows how, for an impulse to be perceived at the left ear only, positive and negative impulses are emitted from each speaker with the proper delay and attenuation to cancel out the crosstalk perfectly, so that only the first impulse is heard and only at the left ear.

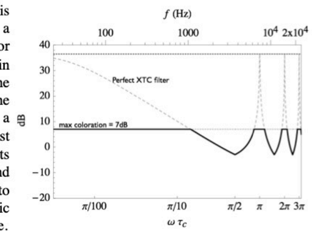


5.2 Theory: Introducing Imperfection

Imperfection sounds better: The frequency response of the perfect XTC filter at the loudspeakers has very large peaks, typically exceeding 37 dB, (in order to compensate for destructive interference) as shown by the dotted curve in the plot below.

While in a perfect world these peaks should not be audible at the sweet spot, in the real world the slightest head misalignment from the perfect head location will cause these peaks to be audible, resulting in severe and intolerable spectral (tonal) coloration to the sound.

To do away with this severe coloration, a frequency-dependent error is deliberately added in the inversion of the transfer function $\boldsymbol{C}$. The error is calculated in a way to minimize a cost function that represents both the coloration and the crosstalk level, and to meet a psychoacoustic target frequency response.



This results in an optimal XTC filter with an arbitrarily low coloration level. (e.g. a maximum 7 dB as shown by the hard curve in the figure).

Such an optimal XTC filter is called BACCH™ for Band-Assembled Crosstalk Cancellation Hierarchy, because the optimization process theoretically requires splitting the audio spectrum in finite bands, applying a hierarchy of XTC filters, then reassembling the bands.

6 Implementation and Multiple Sweet Spots

- BACCH™ Filters can be designed for any pair of loudspeakers to give 3D Audio in a single but large sweet spot.
- BACCH™ is implemented as a digital filter that is used to process (in real-time or offline) digital audio on a DSP chip or computer.
- DynaSonix™ is a combination of Princeton's BACCH™ 3D Sound technology with the unique phased array speaker technology developed by our strategic partner, Cambridge Mechatronics Ltd, (Cambridge, UK). It allows up to 6 listeners sitting anywhere in a room to get simultaneously a 3D audio image. The multiple sweet spots are adjusted dynamically by steering the 12 sound beams from the phased array to the ears of the listeners located with a head tracking camera.

DynaSonix™ implemented on a phased array mounted on top of a laptop computer being tested in the anechoic chamber of the 3D3A Lab. Up to 6 simultaneous 3D audio sweet spots can be produced.

More info at: www.princeton.edu/3D3A