BACCH® 3D SOUND

A Revolutionary Technology for Audiophile-Grade 3D Sound

An Introduction through Questions and Answers

3D3A Lab.
Princeton University
http://www.princeton.edu/3D3A

1 What is BACCH®3D Sound?

BACCH®3D Sound (previously called "Pure Stereo 3D Audio®") 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 soundfield 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 high-end audio systems.

BACCH®3D Sound can be implemented in any hi-fi system by adding a single component: a dedicated hi-end quality high-resolution (96 kHz, or 192 kHz, at 24 bits) digital processor that applies, in real time, a individualized (see Question 11) digital filter (called a i-BACCH®filter) to any stereo sound input. The processor (also called BACCH®Stereo purifier) filters out a fundamental impurity (thus the epithet "pure") that occurs whenever stereo sound is played through loudspeakers, thus allowing the 3D cues which the brain needs to hear in 3D, and which exist in abundance in practically all well-made stereo recordings, to naturally reach the brain of the listener.

One of the greatest advantages of BACCH®3D Sound is that **it is fully compatible with all existing stereo recordings** and does not require any additional playback hardware aside from the single digital processor. Pure Setreo (like standard stereo) requires only a single pair of loudspeakers.

Not only does BACCH®3D Sound provide a shocking improvement to the spatial realism of sound reproduction, but the same digital filter used in BACCH®3D Sound also corrects, in both the frequency and time domains, most non-idealities in the playback chain (including loudspeaker coloration and resonances, listening room modes, spatial comb filtering, balance differences between channels, etc. . .) so that the frequency and impulse responses at the listener's ears are as close to ideal as possible for a given listening room and hi-fi system. This corrective property of BACCH®3D Sound, which by itself is a highly desirable enhancement to the fidelity of any audio system, is only the secondary feature of BACCH®3D Sound – the primary feature being 3D sound.

BACCH®3D Sound is the brainchild of Professor Edgar Choueiri (see bio at the end of this document), who is a professor of applied physics at Princeton University. The method is described[1] in detail in a technical paper appended to this document.

2 How Does BACCH®3D Sound differ from surround sound?

BACCH®3D Sound has nothing to do with 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 soundfield. What 5.1 or 7.1 surround sound aims to do is provide some degree of sound envelopment for the listener by surrounding the listener with five or seven loudspeakers. For serious music listening of music recorded in real acoustic spaces, audio played through a surround sound system can at best give a sense of simulated hall ambiance but cannot offer an accurate 3D representation of the soundfield.

In contrast, BACCH®3D Sound's primary goal is accurate 3D soundfield reproduction. It gives the listener the same 3D audio perspective as that of the ideal listener in the original recording venue[2]. Soundstage "depth" and "width", concepts often used liberally in hi-end audio literature to describe an essentially flat image (relative to that in BACCH®3D Sound), become literal

[1] The paper can also be downloaded from the 3D3A Lab website of Princeton University http://www.princeton.edu/3D3A. It describes the mathematical theory behind the method. For proprietary reasons, it does not describe in detail the art of how filter is implemented in an actual h-fi system.

[2] By the "ideal listener in the recoding venue" we mean the actual main stereo recording microphones, or the left and right channels of the stereo master recording, which represent the left and right ear of the ideal listener in the original soundfield.

terms in BACCH®3D Sound. **If, for instance, in the original soundfield a fly cicrles the head of the ideal 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**. If, in contrast, the same recording is played through standard stereo or surround sound systems the fly will be perceived to be inside the loudspeakers or, through the artifice of the phantom image, in the limited vertical plane between the loudspeakers.

Fortunately (and perhaps to some, unfortunately) flies do not generally buzz around during the recording of great musical events[3]. However, an acoustically recorded real soundfield is replete with the 3D cues, if not buzzing insects, that give the brain of the listener the proper information it needs to correctly perceive true depth and width of a sound image, locate sound sources in 3D space, and hear the reflections of sound and the reverbation that occur naturally in the space where the recording was made. For instance, recorded applause in a concert hall, or laughter or chatter in a jazz club, will be reproduced with uncanny accuracy, and would appear as near to the listener as they were in the original venue during recording.

BACCH®3D Sound allows the transmission of these recorded cues (which are critical for the perception of a realistic 3D space) by removing an artifice that occurs during playback through loudspeakers (see Q&A 10) and which would otherwise corrupt the natural reception of these important cues by the listener.

Surround sound does not even attempt to do that. Furthermore, surround sound, like standard stereo, is inherently plagued by so-called comb filtering problems, which are caused by the mixing of the sound waves emanating from the loudspeakers and arriving at the ears of the listener[4], even if the listener is sitting in the "sweet spot". BACCH®3D Sound, in addition to its primary role of reproducing the 3D soundfield, automatically corrects these comb filtering problems and flattens the frequency response at the ears of the listeners, as well as other (spectral and temporal) non-idealities of the loudspeakers, the playback hardware, the listening room (see Q&A 19). It even compensates for the individual features of the listeners outer ears, head shape, and torso (see Q&A 11 on individualized BACCH®3D Sound filters), which affect the spatial fidelity of the reproduced sound.

[3]Recordings of natural sounds such as insects, birds, crowds, moving vehicles and sound sources are often used, along with music recordings, to demonstrate the shocking realism of BACCH®3D Sound.

[4]This is the well-known phenomenon of constructive and destructive interference, which causes the frequency response at the ears to be far from flat due to the creation of frequency-dependent peaks and valleys in sound pressure that severely color the sound.

3 Does BACCH®3D Sound meet the highest audiophile standards?

BACCH®3D Sound does not add anything to the sound. It simply subtracts an artifice that exists during playback through loudspeakers. This artifice, called crosstalk (see Q&A 10), corrupts the natural transmission to the brain of of the 3D cues that exist in all stereo recordings. The main breakthrough that led to BACCH®3D Sound was the development of a mathematical algorithm that allows, for the first time, this removal of artifice to be done, in the case of two loudspeakers, *without adding artificial coloration to the sound*.

BACCH®3D Sound was developed by a scientist-audiophile and recordist of classical music, whose prime concerns are the realism and fidelity of recorded music. Consequently, the digital processor and the software used to apply the BACCH®3D Sound filter (called BACCH filter) to an input stereo signal yield pristine audio. The audio performance exceeds the most stringent audio standards. The processor operates at the high-resolution frequency of 96 kHz and carries out all needed digital processing calculations at full 64 bits (followed by D/A conversion at 24 bits) in order to avoid degradation to the sound quality and dynamic range[5]. This far exceeds the quality of CD recordings (44.1 kHz, 16 bits) and equals the purity of audio in professional master processing.

The processor is essentially a high-quality digital audio unit, containing a dedicated and quiet Linux computer, with a highly-stable specialized operating system, coupled to an audio stage consisting of audiophile-grade (D/D, D/A, and A/D) converters and components. It is designed to be the purest and most transparent digital component of any hi-fi chain in which it is embedded. Its operation is very simple - only two controls are needed: 1) an on/off button and 2) a button to switch between various individualized BACCH®3D Sound filters (corresponding to various listeners, and/or listening positions).

4 How can I add BACCH®3D Sound to my Hi-Fi system?

BACCH®3D Sound is a recent breakthrough and while it has been perfected and made ready for home use, it is not yet widely available on the audio market because it requires a high-level of *in-situ* customization. A working prototype for a standalone processor called the BACCH®-SP (for "BACCH Stereo Purifier") has been built by Prof. Choueiri and will be commercialized in 2013. It allows any listener to quickly design and apply his or her individual i-BACCH®filters.

Until then, the only options for audiophiles to have individualized BACCH®filters are the bespoke services offered by Audtech Associates (US) and Elpine Technologies (Hong Kong), which are the two companies licensed so far by Princeton University to apply individualized BACCH®filters (i-BACCH®) in audio

[5] An Implementation of a BACCH®3D Sound system running at 192 kHz can be readily done.

installations[6].

For BACCH®3D Sound to work most effectively, detailed acoustic measurements of the listener's audio system, loudspeakers, listening room, and individual characteristics (ears, head, torso), must be conducted by an expert acoustician, in the audiophile's listening room, using advanced hardware and software especially developed for the design of individualized BACCH®3D Sound filters.

The acoustician comes on site and hooks up a rig of instruments to the audiophile's hi-fi chain. He then asks the audiophile to sit in his favorite listening seat and places special miniature microphones in the audiophile's ears. The instrument rig then emits a set of test tones through the audiophile's hi-fi chain and loudspeakers, and the signal captured by the in-ears microphones is recorded in high definition on a computer. The signal contains all the relevant acoustic information about the audiophile's hi-fi chain, loudspeakers, listening room, head, torso and ears, and is used by the filter design software to design, on the spot, the individualized BACCH®filter needed to implement BACCH®3D Sound for that set-up and listener.

The filter (which is essentially a file of 32-bit numbers) is then loaded in the digital processor unit, which is installed seamlessly and transparently in the audiophile's hi-fi chain. Many filters can be loaded in the processor, corresponding to various listening positions, and various listeners (e.g. the audiophile's spouse and family members). A few universal filters (called i-BACCH®filters) will also be loaded in the unit. These universal filters are designed using, in place of the audiophile's own head, a special dummy head with microphones in its ears. When these filters are selected instead of the individualized versions, they allow anyone to listen to the 3-D audio of BACCH®3D Sound, albeit with a slightly decreased spatial fidelity than the audiophile hears with the individualized filters.

5 Does BACCH®3D Sound require special loudspeakers?

BACCH®3D Sound will greatly enhance the spatial fidelity of sound reproduction through any loudspeakers. Loudspeakers that have high sound directivity[7] will give the best and most accurate 3D imaging in a room with little or no sound treatment, as room reflections, which degrade the imaging, are minimized by such loudspeakers.

However, even loudspeakers with low directivity (i.e. omni-directional loudspeakers) will give a spectacularly wide soundstage with BACCH®3D Sound in a typical listening room. With increasing loudspeaker directivity the image's

[6] Audtech Associates (US) and Elpine Tecnologies Ltd (Hong Kong) (http://www.elpinetech.com/masis/) are licensed to use BACCH 3D Sound technology only for customized audiophile installations.Inquiries should be sent to Audtech Associates via email to: mailto:j5652c@alumni.Princeton.EDU or to Elpine Technologies to mailto:info@elpinetech.com.

[7] Sound directivity is the extent to which loudspeakers beam the sound towards the listener instead of broadcasting it in all directions around the room.

depth and 3D imaging approach the depth and spatial characteristics of the original soundfield.

An ongoing investigation of speakers directivity at the 3D3A Lab[8], has shown that dipole speaker designs, electrostatic speakers, as well as speakers with horns and waveguides offer significant advantages in 3D imaging with BACCH 3D Sound as they reduce the ratio of reflected to direct sound.

6 Does BACCH®3D Sound require special room treatment?

Abating room reflections with physical room treatment (i.e. using sound absorbers on sound-refeective surfaces) in a listening room is always beneficial to any audiophile-grade sound system. For BACCH®3D Sound the effect of sound treatment is equivalent to using loudspeakers with high directivity. The more directive the loudspeakers are, the less sound treatment is needed for BACCH®3D Sound to produce a full and accurate 3D sound image.

Therefore, in a reflective untreated listening room, directive loudspeakers are more desirable. In a well treated listening room with sound-absorbing surfaces, any loudspeakers, even omnidirectional ones, will produce an excellent 3D image.

7 Does BACCH®3D Sound require sitting in a sweet spot?

Like for standard stereo, where serious listening requires the audiophile to sit in an optimal location called the sweet spot, BACCH®3D Sound also has a sweet spot. However, unlike standard stereo, where the sweet spot must be at a given location and in a vertical plane that is exactly equidistant from the two loudspeakers, **the sweet spot of BACCH®3D Sound can be designed to be anywhere in the listening room**[9], because the BACCH®3D Sound filter can compensate for any asymmetries in the listening configuration (like it does for non-idealities in the loudspeakers and the hi-fi system).

During the filter design session the audiophile chooses the various locations in which he likes to have a BACCH®3D Sound sweet spot. A filter is then designed for each location and the filters are loaded in the processor. The audiophile can then switch between these filters using a simple button on the processor and a display that shows the name of the sweet spot location (e.g. "Main Listening Chair," "Reading Side Chair," "Family Couch," etc. . .)

[8] http://www.princeton.edu/3D3A/Directivity.html

[9] It should ideally be located at a close enough distance form the loudpseakers to minimize the ratio of reflected to direct sound, since early sound reflections, i.e. those arriving 20 ms or earlier at the ears after the arrival of the direct sound, are the most detrimental to stereo imaging. This minimal distance depends on the directivity of the loudspeakers and the sound reflectivity of the listening room. In practice, the minimal distance is more than 1.5 meters.

When sitting in the sweet spot, the listener will not sense that sounds are emanating from the loudspeakers[10]. The loudspeakers completely disappear acoustically.

The BACCH®3D Sound sweet spot is large and robust enough so that a listener sitting in it perceives a high-fidelity 3D image without having to strain to keep his head in a fixed position. It does not require any more precision in sitting then standard stereo requires for serious listening. In fact, BACCH®3D Sound imaging is so robust that more than one listener can experience most features of the 3D image as long as they sit near the sweet spot, ideally in front or behind it. Moving a few feet *to the side* of the sweet spot, however, will cause the 3D image to collapse and the sound to be perceived to emanate from the loudspeakers. Therefore, listeners sitting well outside the sweet spot, will hear the sound clearly but it will lack the 3D imaging and sound equalization that the BACCH®3D Sound system produces.

8 Does BACCH®3D Sound require special positioning of the loudspeakers?

While BACCH®3D Sound filters can be readily designed for a pair loudspeakers and a sweet spot in an any geometric configuration (including the standard stereo triangle configuration[11]), it is highly recommended that the loudspeakers be positioned in the so-called "stereo dipole" configuration, which typically has the loudspeakers about 50 cm apart only.

While this configuration may initially look odd or surprising, it is in fact a superior configuration for 3D imaging - the 3D image is more robust and less sensitive to listener head movements. It is very unlikely that audiophiles who experience BACCH®3D Sound with this loudspeaker configuration would ever wish to switch back to the standard stereo triangle loudspeaker configuration (although that could easily be done by moving the loudspeakers apart and switching to the corresponding BACCH®3D Sound filter).

9 What does BACCH®3D Sound require from a hi-fi system?

BACCH®3D Sound enhances the capability of any hi-fi system. There is simply not a single component that could be added to a hi-fi chain that would bring, even remotely, as much improvement to the realism of sound reproduction as the BACCH®3D Sound processor.

[10] Except for the rare cases where the sound source in the original soundfield happens to coincide with the location of one of the loudspeakers. In that case, the sound source will be imaged, correctly, at the location of that loudspeaker.

[11] i.e. a loudspeaker half-span of 60 degrees.

The BACCH®3D Sound processor is an audiophile-grade audio unit that accepts digital and analog inputs and has digital an analog outputs[12]. It can be integrated into any hi-fi chain.

10 How does BACCH®3D Sound work?

Imagine a musician who stands on the extreme right of the stage of a concert hall and plays a single note. A listener sitting in the audience in front of stage center perceives the sound source to be at the correct location because his brain can quickly process certain audio cues received by the ears. The sound is heard by the right ear first and after a short time delay (called ITD) is heard by the left ear. Furthermore there is a difference in sound level between the two ears (called ILD) due to the sound having travelled a little longer to reach the right ear, and the presence of the listener's head in the way. The ILD and ITD are the two most important types of cues for locating sound in 3D and are to a good extent preserved by most stereophonic technique[13].

When the stereo recording is played through the two loudspeakers of a standard stereo system, the ILD and ITD cues are largely corrupted because of an important and fundamental problem: the sound recorded on the left channel, which is *intended only for the left ear*, is heard by *both* ears. The same applies to the sound on the right channel. Consequently, an audiophile listening to that recording on standard stereo system will not correctly perceive the musician to be standing on the extreme right of the stage but rather at the location of the right speaker.

Consequently the perceived soundstage is mostly confined to an essentially flat and relatively limited region between the two loudspeakers irrespective of the quality and cost of the hardware in the standard stereo system - the 3D image is greatly compromised[14].

In order to insure the correct transmission of the ILD and ITD cues to the brain of the audiophile, the sound from the left loudspeaker to the right ear, and that reaching the left ear from the right loudspeaker (called "crosstalk") should be cancelled.

The technique of crosstalk cancellation (XTC) has been known for some time and can be applied by filtering the recorded sound through an XTC filter before feeding it to the speaker. This can easily be done digitally. However, until recently, XTC filters have had a detrimental effect on the sound as they inherently add a strong spectral coloration to the processed signal (i.e. they severely change the tonal character of the sound). This is why XTC had not

[12] The processor can be configured to handle both balanced and unbalanced analog I/O's.

[13] They are most accurately preserved if the recording is made with a dummy head (see Q&A 13).

[14] Aside from greatly compromising the 3D image, standard stereo (and even more, surround sound), inherently suffers from the problem of comb filtering, which significantly alters the tonal content of sound, and which is due to the interference of sound waves emanating from more than one speaker.

been widely adopted by stereo manufacturers and audiophiles. (See the detailed discussion on XTC-induced sound coloration in the technical paper).

BACCH®3D Sound is based on a breakthrough in XTC filter design, that allows producing *optimized* XTC filters, called BACCH®[15] filters, that add no coloration to the sound for a listener in the sweet spot . Not only do BACCH®filters *purify* the sound from crosstalk, but they also purify it from aberrations by the playback hardware in both the frequency and time domains.

The result is a 3D soundstage with a striking level of spatial and tonal fidelity never experienced before by audiophiles[16].

11 What are individualizedl BACCH®Filters?

There are two types of BACCH®filters. The individualized BACCH®filter (called i-BACCH®) is custom-made using *in-situ* acoustic measurements of the audiophile's entire listening chain, including his hi-fi hardware, loudspeakers, head, torso and ears. It is designed by sending special test tones through the hi-fi chain and recording the sound with miniature microphones placed at the entrance of the audiophile's ear canals as he is sitting in a sweet spot of his choice. It takes about one minute to do this measurement.

The universal BACCH®filter (called u-BACCH®) is the same as i-BACCH® except a special dummy head, having microphones in its ears, is used to make the measurements instead of the audiophile's own head and ears. A u-BACCH®filter yields a slightly less accurate 3D image then i-BACCH®when used by the audiophile himself to listen to his hi-fi system, but is more compatible with other listeners (who do not have i-BACCH®filters designed for them). Since the dummy head was designed to represent the sound diffraction characteristics of an "average" human head, the difference between the sound through the two types of filters is subtle but perceivable by a discerning audiophile.

As described in Q&A 7, the listener can easily switch between the two types of filters (as well as filters for different sweet spots and listeners) using a button on the processor.

12 Is BACCH®3D Sound compatible with existing stereo recordings?

Yes. Unlike other 3D audio techniques (see Q&A 18), all of which require non-stereophonic recording techniques and coding, and many more than two loudspeakers for playback, BACCH®3D Sound is fully compatible with all existing stereo recordings, and requires a single pair of loudspeakers.

[15] BACCH®stands for "Band-Assembled Crosstalk Cancellation Hierarchy" - a name that represents the mathematical filter design method and pays tribute to the great composer with a similar sounding name.

[16] See the video Ref [1] made by the Star Ledger newspaper of an audiophile from the NJ audio society experiencing BACCH®3D Sound for the first time.

In fact, virtually all stereo recordings contain 3D cues that are corrupted by standard stereo playback (see discussion in Q&A 10). BACCH®3D Sound simply allows these 3D cues to reach the brain of the listener. Therefore an audiophile can delight in re-listening to his existing collection of recordings through BACCH®3D Sound and discover the striking spatial and tonal fidelity that was missing or marred by standard stereo playback.

13 Is the 3D realism of BACCH®3D Sound the same with all types of stereo recordings?

The stereophonic recording technique that is most accurate at spatially representing an acoustic sound field is, incontestably, the so-called "binaural" recording method[17], which uses a dummy head with high-quality microphone in its ears[18]. Until the recent advent of BACCH®3D Sound, the only way for an audiophile to experience the spectacular 3D realism of binaural audio was through headphones. Many such recordings exist commercially, and more have recently been made thanks to the iPod revolution.

BACCH®3D Sound shines at reproducing binaural recordings through two loudspeakers and gives an uncannily accurate 3D reproduction that is far more stable and realistic than that obtained by playing binaural recordings through headphones[19].

All other stereophonic recordings fall on a spectrum ranging from recordings that highly preserve natural ILD and ITD cues (these include most well-made recordings of "acoustic music" such as most classical and jazz music recordings) to recordings that contain artificially constructed sounds with extreme and unnatural ILD and ITD cues (such as the pan-potted sounds on recordings from the early days of stereo). For stereo recordings that are at or near the first end of this spectrum, BACCH®3D Sound offers the same uncanny 3D realism as for binaural recordings[20]. At the other end of the spectrum, the sound image would be an artificial one and the presence of extreme ILD and ITD values

[17]The accuracy is due to the fact that binaural audio preserves not only the correct ILD and ITD cues discussed in Q&A10, but also contains so-called "spectral cues," which are the effects the torso, head and ears have on the frequency response and which the brain uses, in addition to ILD and ITD cues, to locate sound, especially at higher frequencies.

[18]The spatial accuracy of dummy head recording is only surpassed by recordings made with microphones placed in the listener's own ears - alas, a rare commodity that would have benefits upon playback for only that listener.

[19]This is because binaural playback through headphones or earphones is very prone to head internalization of sound (which means that the sound is perceived to be inside the head) and requires, in order to avoid this problem, an excellent match between the geometric features of the head of the listener and those of the dummy head with which the recording was made (this problem has been recently surmounted by the Smyth headphones technology http://www.smyth-research.com/). BACCH®3D Sound does not suffer from this problem as the sound is played back though loudspeakers far from the listener's ears.

[20]The 3D realism is the same although the ability of reproducing a sound source at a location that accurately corresponds to the original location is relatively decreased due to the absence of spectral cues.

would, not surprisingly, lead to often spectacular sound images perceived to be located in extreme right or left stage, very near the ears of the listener or even sometimes inside of his head (whereas with standard stereo the same extreme recording would yield a mostly flat image restricted to a portion of the vertical plane between the two loudspeakers).

Many of well-made popular music recordings over the past two decades have been recorded and mastered by engineers who understand natural sound localization and construct mostly natural-like stereo images, albeit artificially, using realistic ILD and ITD values. Such recordings would give a rich and highly enjoyable 3D soundstage when reproduced through BACCH®3D Sound.

14 Is BACCH®3D Sound compatible with analog audio?

Yes. The BACCH®3D Sound processor accomodates (balanced or unbalanced) stereo analog inputs and outputs. Since the BACCH®filter is a digital one and must be applied in the digital domain, the input analog signal is converted to a high-resolution using audiophile-grade A/D converters inside the processor. The processed digital signal can then be sent out as a digital signal (e.g. for an outboard converter or a digital speaker) or converted to analog using an audiophile-grade D/A converter inside the processor[21].

15 Why call this "BACCH®3D Sound"?

The word "stereo" was always associated with three-dimensional objects or effects until its later use, in the 1950s, in the word stereophony, which, ironically, is now a term that does not invoke true three-dimensional sound in the popular mind[22]. In fact, the earliest use of "stereo", which comes from the word Greek $\sigma\tau\epsilon\rho\epsilon\acute{o}\varsigma$, (stereos) which means solid, goes back to the 16^{th} century when the term stereometry was coined to denote the measurement of solid or three-dimensional objects. This was followed by stereographic (17th c.), stereotype (18th c.), stereoscope (19th c.) (a viewer for producing 3D images), and stereophonic (circa 1950). Stereophonic sound, alas, remained a poor approximation of 3D audio until the recent advent of BACCH®3D Sound, which restores to the word stereo it original 16th century 3D connotation.

The epithet "pure" in "BACCH®Stereo Purifier" (which is the other name for the BACCH®processor) refers to the purifying action of the BACCH®filters, which are at the heart of BACCH®3D Sound. A BACCH®filter "purifies" the sound from crosstalk for playback on loudspeakers, without adding coloration,

[21]The analog i/o of the BACCH®3D Sound Processor has the following technical specifications: SNR (Unwtd): 104 dB; THD+N (Unwtd): -94 dB; Frequency Response: 20Hz to 20kHz±0.1dB.

[22]Despite the tendency of some audiophiles and audio reviewers for describing the sound from certain hi-fi components as "three-dimensional" or "holographic".

and purifies it also from the detrimental effects of spatial comb filtering and non-idealities of the listening room, the loudspeakers and the playback chain.

16 I have heard of binaural audio and crosstalk cancellation. Are they related to BACCH®3D Sound?

As discussed in Q&A 13, Binaural audio, which usually refers to recordings made with a dummy head[23] is intended to be played back through headphones or earphones in order for the listener to perceive a 3D sound image. However, BACCH®3D Sound, allows the audiophile, for the first time, to reproduce the excellent 3D audio image (that is coded in binaural recordings) through a pair of standard loudspeakers. In fact, as discussed in Q&A 13, binaural recordings played through BACCH®3D Sound are far more realistic and stable than when played through headphones or earphones.

Crosstalk cancellation (XTC) is the general technique that allows playing binaural recordings through loudspeakers by eliminating the crosstalk (i.e. the sound path between the left loudspeaker and the right ear, and the path between the left loudspeaker and the right ear) which corrupts the transmission of the 3D cues needed to perceive a 3D audio image. The BACCH®filter is indeed a crosstalk cancellation filter but differs from previous XTC filters in that it is *optimized* to deliver maximum XTC at the lowest sound coloration, as described in the technical paper. In other words, **unlike other two-loudspeaker XTC filters, the BACCH®filters of BACCH®3D Sound do not tonally alter the recorded sound.**

17 How does BACCH®3D Sound differ from Ambiophonics?

Ambiophonics (not to be confused with Ambisonics, mentioned in the next Q&A), is a method advocated by Ralph Glasgal of the Ambiophonics Institute, and which relies on using (non-optimized) crosstalk cancellation filters on two front and two back loudspeakers to produce a wide stereo image, and a number of additional surrounding loudspeakers to give a sense of hall ambiance by emitting the sound that results from convolving the stereo signal with the impulse response of a concert hall (most often a different hall than that in which the recording was originally made).

Ambiophonics uses non-optimized XTC filters (called RACE filters) that are designed in the time domain and that do not attempt to maximize XTC level while minimizing spectral coloration. Since a low level of XTC often results in

[23] Or sound convolved with the HRTF (sound diffraction characteristics) of a human, or human-like, head.

an exaggerated wide soundstage (especially for solo instruments or small ensembles) and a reduced 3D sense of depth and proximity[24], RACE filters cannot reproduce proximity effects and the same 3D sense of depth as BACCH® filters. They are better suited for the playback of recordings of large ensembles, where the perception of a large soundstage is not jarring.

Furthermore, due to the significantly higher XTC levels achieved by the optimized BACCH® filters, BACCH® 3D Sound does not require additional loudspeakers and extraneous convolutions with hall impulse responses to give a realistic sense of hall reverb and ambiance. BACCH® 3D Sound naturally reproduces the hall reverb that exists in the recording. In fact, one of the striking features of BACCH® 3D Sound is the realistic reproduction of hall reverb and ambiance, which, if it exists in the recording, would, under high enough XTC levels, envelop the listener as realistically as it did the main stereo microphones during the recording.

18 How does BACCH® 3D Sound differ from other 3D audio techniques?

High order ambisonics (HOA) and wavefield synthesis (WFS) are two other techniques for 3D audio over loudspeakers. They are presently being developed by a number of research groups and can, in principle, reconstruct an approximation of a recorded 3D soundfield over a relatively large area (larger than the sweet spot of crosstalk cancellation techniques). However, unlike BACCH® 3D Sound, they require a large number of loudspeakers for playback.

Moreover, unlike BACCH® 3D Sound, both HOA and WFS are incompatible with stereo recordings as they require highly specialized recording techniques involving a large number of microphones.

[24] To understand this psychoaoustic effect, consider an impulse fed into the left channel only of a playback system equipped with an XTC filter with variable XTC level. If the the XTC level is infinite or very high, the impulse will be perceived by the listener to originate very close to his or her left ear. As the XTC level is decreased, the impulse will be perceived to move away forward from the left ear towards the left side well beyond the left loudspeaker. With further decrease of the XTC level, the impulse will appear to be emanating from behind the loudspeakers and well to the left of the left loudspeaker. When the XTC level is brought down to vanishing levels, the sound will appear to emanate from the left loudspeaker. Therefore a decreasing XTC level will lead to a decrease in the depth and 3D feel of the audio image and to an overly wide and exaggerated soundstage. For instance, a good (or binaural) acoustic recording of a solo piano in a real hall will sound 3-dimensional when played back through a filter that can yield a high XTC level, such as the BACCH® filter, but will sound dimensionally flat and much wider than in real life when the XTC filter cannot yield a high enough XTC level.

19 How does BACCH®3D Sound correct problems in audio playback?

While the foremost goal of BACCH®3D Sound is 3D audio imaging, the BACCH®filters at the heart of BACCH®3D Sound have the additional advantage of correcting, in both the time and frequency domains, many non-idealities in the playback chain, including loudspeaker coloration and resonances, listening room modes, spatial comb filtering, balance differences between channels, etc...

This capability, often called "room correction" (even though it corrects more than just the effects of the listening room), is inherent to the nature of BACCH®filters, whose design is made under the requirement that a perfect impulse response fed into, say, the left channel (only) of the playback system, should appear as close to a perfect impulse response at the left ear of a listener sitting in the sweet spot.

Therefore a BACCH®3D Sound processor functions also as a state-of-the-art and individualized digital room correction unit.

20 Can BACCH®3D Sound be experienced without the the BACCH®3D Sound Processor?

Yes. If a stereo signal is filtered through a BACCH®3D Sound processor and recorded it becomes a BACCH®3D Sound recording and does not require playback through a BACCH®3D Sound Processor. It can then be played back on any normal stereo system and can be heard in 3D with no special hardware or processing. (Such pre-processed BACCH®3D Sound recordings are generally made with non-individualized (universal) u-BACCH®filters in order to make them compatible with all stereo playback systems.)

This feature is piquing the interest of a number of leading recording and mixing engineers, and recording labels, who are interested in making new audio recordings in 3D or reissuing existing stereo recordings in 3D. The consumer can play these recordings in 3D on a regular stereo system without any specialized equipment.

For the audiophile, however, the *individualized* BACCH®3D Sound processor would remain indispensable as it 1) allows real-time processing of existing stereo recordings and 2) offers levels of spatial and tonal fidelity that are only possible with individualized/individualized filters.

21 Biography of Professor Edgar Choueiri

Professor Edgar Choueiri, is a professor of applied physics at the Mechanical and Aerospace Engineering Department of Princeton University, and Associated Faculty at the Department of Astrophysical Sciences, Program in Plasma

Physics. He is also Director of Princeton University's Engineering Physics Program and Chief Scientist at the university's Electric Propulsion and Plasma Dynamics Lab, a recognized center of excellence in research in the field of advanced spacecraft propulsion. He is also the director of Princeton's 3D Sound and Applied Acoustics (3D3A) Lab.

Professor Choueiri is a world-renown leader in the field of plasma physics and plasma propulsion for spacecraft. He is the author of more than 145 scientific publications, and encyclopedia articles on plasma rockets, plasma physics, instabilities and turbulence in collisional plasmas, plasma accelerator modeling, space physics and applied mathematics. He has been the Principle Investigator (PI) ion more than 25 competitively selected research projects (including two space experiments), funded by NASA, the US Air Force, the National Science Foundation, and other governmental and private institutions. He is Fellow of the American Institute of Aeronautics and Astronautics and the recipient of many awards and honors including a knighthood.

An avid audiophile, acoustician and classical music recordist, his decades-long passion for perfecting the realism of music reproduction has led him to work on the the difficult fundamental problem of designing advanced digital filters that allow the natural 3D audio to be extracted from stereo sound played through two loudspeakers, without adding any spectral coloration to the sound (i.e. without changing its tonal character). He was able to solve this problem mathematically by applying analytical and mathematical tools he uses in his plasma physics research.

22 Media Coverage

http://www.princeton.edu/3D3A/MediaCoverage.html

23 Technical Paper on BACCH®Filters

http://www.princeton.edu/3D3A/Publications/BACCHPaperV4d.pdf