Compatible PanAmbiophonic 4.1 and PerAmbiophonic 6.1 Surround Sound for Advanced Television – Beyond ITU 5.1

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Abstract: ITU 5.1 – the multichannel speaker standard for Advanced Television and home cinema – is not extensible to periphony – the entire, spherical wavefield of natural human hearing. Psychoacoustic theory and experimental recordings explore future-proof capturing, critical monitoring, and compatible production to help sound engineers today achieve more realistic multichannel television and cinema.

Introduction

Since the late 1920s when Al Jolson sang first in the cinema and Pres. Hoover spoke in the first demonstration of television, the moving picture media – film or electronic – have been a sum that, in impact, is more than its parts, which individually compare to silent movies or radio. The evolution, rather than joined, has been alternating – optical sound, then color film, then multichannel cinema sound, color television, stereo television (and matrix surround), etc. In the evolution now in progress, advanced television has increased the scale of both picture *and sound* to more fully engage our senses.

Multichannel sound for television delivers surround sound for television broadcast and DVD to increasing numbers of home theaters. Now, TV producers have the same creative tool filmmakers have had since 1939 when *Fantasia* introduced multichannel sound to the cinema. In addition to fidelity approaching transparency, multichannel surround, because it is all around the viewer, is a tool to exploit "imagery" *outside* the frame boundaries of the picture. This writing describes surround sound's place in advanced television and explores the potential for further advancement in psychoacoustics.

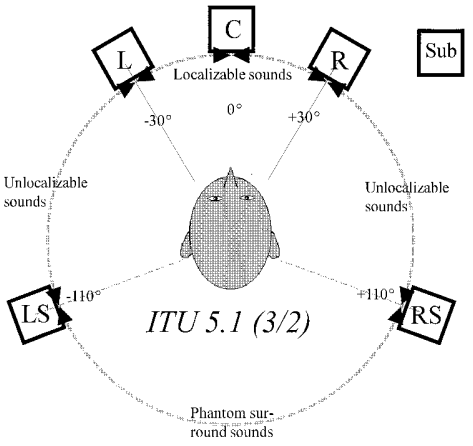

Fig. 1. ITU 5.1 (3/2) standard speaker placement creates five sets of phantom images, one between each pair of transducers, that surround the listener and makes it superior to stereo in "realism."

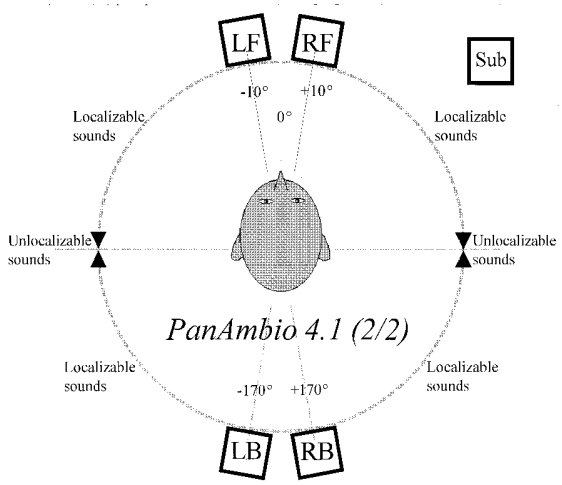

Fig. 2. PanorAmbiophonic 4.1 (2/2) speaker placement turns stereo "inside out," creating accurate images outside pairs of transducers. It can serve as a benchmark of quality for, or alternative to, ITU 5.1.

Background: cinema v. advanced television sound

Multichannel mixes for cinema presentation typically include five main channels, L, C, R, LS, RS, and on occasion an SPL-elevated LFE (the ".1" channel). A back channel is matrixed center of the

two surround channels. The front channels are typically contained within the width of (hidden behind) the projection screen, which, along with the moviegoer's choice of distance from the screen, determines the speaker angle to his/her head. For a typical multiplex theater screen 10x20ft (3x6m) and a viewer sitting at the recommended minimum distance of 2 times screen height, the L/R included angle will be approx. 60° – the same as the conventional 60° stereo (equilateral) triangle and ITU-R BS.775.1 [1] for 5.1 speaker layout, as shown in Fig.1.

However, most viewers sit further from the cinema screen, up to a recommended maximum of seven times screen height, where the L/R included angle is just 16° – a quarter the 60° arc-width of conventional stereo. So for most cinemagoers, the sound "image" is limited to the picture image width, so that sounds intended to be off-screen must be panned to surround channels, which in the cinema are distributed around the sides and in back of the audience.

Television stereo and matrix surround

Since implementation in the 1980s, a typical stereo television broadcast can be just stereo music with monaural dialogue (including location reverberation) and "nat-sound" panned to a phantom center. More complex mixes add stereo ambience and sound effects with images as wide as 60° if L/R speakers are placed according to the standard. These placements are typically wider than the screen, so passing automobiles and off-screen door slams seem indeed to be off-screen, not around back. However with 2-speaker stereo, more than a foot or two (0.5m) off the central plane, phantom center images "toggle" to the nearer L or R speaker, shifting dialogue far from center, and reducing image width mostly to sounds panned hard to the far side. This toggle-effect, along with pinna confusion about sounds that are supposedly central actually coming from speakers at the sides – both endemic to stereo since its invention in 1931 – were addressed in 4-2-4 matrix stereo (Dolby Surround, Pro Logic, and Pro Logic II), as they were in the cinema, by steering dialog and would-be centered phantoms to a center speaker. ITU 5.1 improves on the process using a dedicated C channel.

Home Theater 5.1

Home theater installations have been driven mostly by availability of theatrical movie releases on DVD-video and often include a 5.1 DD or DTS surround. However, this mix, intended for the cinema, is often not remixed for the home [2]. So sounds which have been panned to match cinema screen action (where L, C, & R speakers are contained within the screen width) are exaggeratedly reproduced as off-screen sounds in homes with screens narrower than the 60° L/R speaker angle. Further, off-screen sounds mixed for the cinema to surround channels are reproduced discretely at ±110° or more to the sides and back. For example, a passing car's sound will beat its image to the side of the screen; then very quickly pan around back in an unnatural way that may become distracting as viewers become more discerning.

One solution is to contain front speakers within the width of the screen, as in the cinema, using a large display or projection. However, early adopters will likely have narrower direct-view displays for some time. For novice home theater owners, this super-positioning of screen sounds may actually *add* to the perceived value of their purchase, much as ping-pong recordings of the 1950s did for new stereo owners. But as home theater matures and viewers become more discriminating, these errors may become distracting, then objectionable. If not newly mixed for home theater – paying particular attention to hard-panning moving SFX – a standardized translation matrix may be a possible solution, where speaker-feed parameters convert the mix from cinema layout to home layout.[1] If one standard (the original) mix were delivered on DVD media, this conversion would be best implemented in the consumer's system, unless two mixes are included on the DVD for the consumer to select during viewing.

[1] Similar to "ReEQ" on many multichannel receivers that removes pre-emphasis of high frequencies for the cinema.

Wider, more accurate imaging – *Ambiophonics*

Phantom-based stereo (including 5.1 that ignores the center channel) has the inherent psycho-acoustic problems of narrow stage, pinna confusion, and off-median plane toggling of important central sounds, as said above. Binaural reproduction and its derivatives for loudspeakers, by taking HRTFs into consideration, have long offered superior localization along with spaciousness – two qualities that in practice are nearly mutually exclusive in conventional loudspeaker stereo. Ambiophonics [3], or *Ambio* for short, championed by Ralph Glasgal of the Ambiophonics Institute (www.ambiophonics.org), uses two closely spaced speakers (a "stereo dipole" or "ambiopole") and crosstalk cancellation to simulate headphone isolation – one-speaker-per-ear – and can accurately localize images 120° to 150° wide without any toggling or pinna confusion of central sounds, as the speakers are in front. Add a second "ambiopole" pair in back – dubbed PanorAmbiophonic [4], or *PanAmbio* for short (Fig. 2) – and an accurate recreation around 360° envelops the listener.

An online demonstration of Ambio 2.0 can be heard at www.filmaker.com/surround.htm, where also is described the 2-channel music CD for professional education titled *Ambiophonic Demonstration: Bavaria 2001* demonstrated at AES 19th International Conference, Schloss Elmau, Germany, June 2001. 15 tests and musical excerpts compare main microphone approaches, including the Ambiophone – a baffled, pinnaless sphere microphone – and requiring either mechanical barrier or electronic crosstalk-cancellation for replay. As with stereo, Ambiophonics works precisely only in one listening position – which for serious music lovers, listening alone or with a second listener, is an acceptable compromise. Note that 5.1 deals with the so-called "sweet-spot" as the cinema did – with a hard center channel and speaker. However, with Ambio, the sweet spot seems confined because, perhaps for the first time, the listener is aware of a precisely focused image previously not perceivable – similar to the attention to detail in production that HDTV requires now that details are not hidden, as with standard definition.

PanAmbio 4.0 for Music-only

To form a basis for possible use of ambiophonic techniques for advanced television, we consider first the reproduction of natural sounds and music – also the goal of record producers for multichannel music-only (an evolving market delivered via DVD-audio, SACD, DTS-CD etc.). PanAmbio is nearly isotropic in the horizontal plane – capable of reproducing direct sources behind the listener just as in front, as shown in Fig.2. It exhibits fuzzy imaging and pinna confusion only at ±90° each side, where it is most acceptable, as it occurs within the human "cone of confusion" (because we don't have ears on the front and back of our heads to triangulate side incidence). Fig. 5 illustrates the layout during recording, and compares well with Fig. 3, which shows the accuracy within ±5° with which (based on azimuth tests, below) listeners are able to localize both the quintet in front and fans around sides and back. This contrasts in Fig. 4 with the angular distortion [5, 6] of ITU 5.1 using C (3-channel OCT microphone).

The author has reported on experiments [4] in several genres of music and natural sounds typical of cinema and multichannel television production, and made comparison 2-channel [7] and multichannel [8] CDs available for professional education and evaluation. Note that music-only rarely requires an LFE channel (an exception might be cannon in Tchaikovsky's *1812 Overture)*, hence the 4.0 and 5.0 designations. Simultaneous recordings contrast PanAmbio 4.0 with ITU 5.0, using twin-sphere and OCT (Optimized Cardioid Triangle) [9, 10, 11, 12] microphone arrays, respectively, shown in Fig.5 & Fig.6. A "Walkabout" azimuth test, played in informal listening tests using consumer-grade equipment, results in localization perceived with ±5° accuracy, plotted in Fig.7, exceeding that of coincident microphones, but with spaciousness usually associated with spaced microphones, plus surround envelopment. Central sounds (important dialogue voices and solo instruments) are uncolored using Ambio/PanAmbio reproduction techniques, imparting a "natural" quality, as proclaimed by listeners in tests to date.

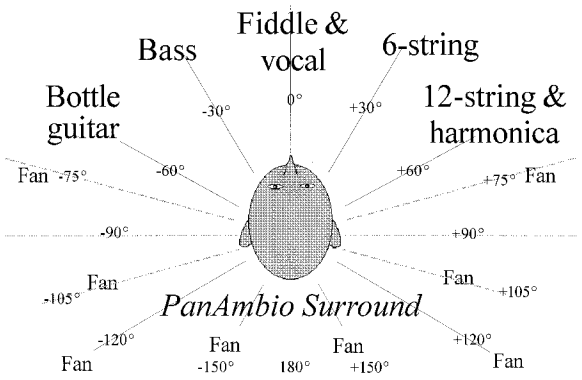

Fig. 3. PanAmbio 4.1 (2/2) reproduction localizes sources accurately within ±5°, virtually duplicating the recording session directions in Fig. 5 below. Guitar quintet and fans are placed as shown for experiments that contrast two 360° reproduction methods. Multi-channel surround sound is more "realistic" by localizing both front stage instruments and sounds from around and behind, including antiphonal voices, audience participation, and ambience.

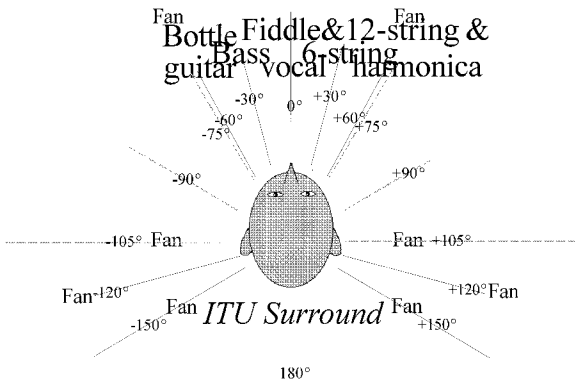

Fig. 4. Contrasted with PanAmbio, ITU 5.1 "relocates" quintet+fans by angular distortion (although less than two-speaker stereo). Original angles indicate sounds recorded at ±75° are heard at ±30° and are superimposed within the band. If precision localization is not essential to a recording, ITU 5.1 may be quite acceptable.

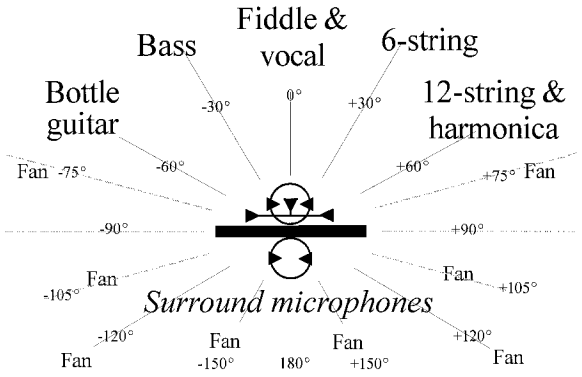

Fig. 5. Microphone arrays contrast two 360° reproduction methods. PanAmbio uses twin spheres with baffle. For ITU 5.1, OCT uses two supercardioids facing ±90° and cardioid facing front. Simultaneous recordings of guitar quintet + fans, opera, brass quintet, string quartet, marching bands, and "Perambiolating 360°" azimuth test were authored to companion DTS-encoded CDs for evaluation [8].

Fig. 6. Hoisting OCT and prototype Ambiophone microphones in the 1,000-seat opera house. Microphones are Schoeps CCM-series.

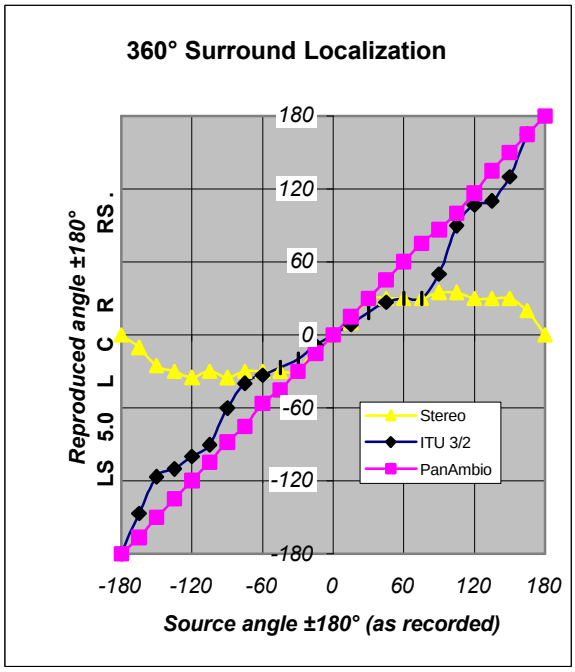

Fig. 7. Perceived localization around entire 360° horizontal plane – ITU 5.0 vs. PanAmbio 4.0. Listeners reported to the nearest 5° that ITU 5.1 (3/2) is "ambiguous" at ±90°, ±105°, ±120°, and ±150°. PanAmbio 4.0 approaches the ideal straight line but is "fuzzy" nearing ±90°, coinciding with the "cone of confusion" of human hearing.

PanAmbio 4.1 for "Advanced Home Theater"

Similar to staged music-only, in the case of surround sound "with accompanying picture" the "story" is up front. Cinema and television sound is psycho-acoustically interpreted in relation to the visual channel of information. If not on-screen, it is perceived as related to what we have seen (or anticipate we will see) even if the sound source is now off-screen. So surround sound completes the "picture." We have reviewed that, with conventional cinema, screen-related sounds are often panned L/C/R to match horizontally their position on screen. For multichannel television, this cinema panning is often over-wide for displays narrower than the ITU-recommended 60° speaker layout.

Wouldn't screen-related panning be even more exaggerated for PanAmbio, where front channels can even more accurately conjure up images 150°-wide? It can and does, and can be even more objectionable for critical listeners because higher image localization accuracy allows angular errors to be revealed and therefore more obvious. However, this increased range and accuracy implies a tool for mixers to pan wider yet subtler placement of sounds. As explored above, the "layout width" could, in future home theater systems, be user-selected on replay; the higher accuracy would not be lost and could add subtle enjoyment.

Ralph Glasgal at the Ambiophonics Institute and the author have demonstrated advanced television reproduction of broadcast and DVD-V material over PanAmbio speaker layouts simply by selecting on the multichannel decoder "no center." This matrixes the center sounds ordinarily to a L/R phantom, but the difference in PanAmbio is that the most important (center) voices reproduce without coloration from pinna confusion. Surround channels reproduce over the back ambiopole, where human perception creates left-back to right-back images, although not as acutely as in front – and with occasional ambiguity directly back. The result is surround envelopment, with sources imaging evenly all around 360° (fuzzy at ±90° each side) and have been tested informally, such as by many of the more than 100 attendees of the Audiophile Society of New York City meeting June 8, 2002. As indicated, this level of result was achieved for two listeners at a time – the most that can be seated within the Ambiophonic focus. (This group also critically compared PanAmbio reproduction of a vocal trio to the trio singing live, with the consensus that both coloration and placement of the vocalists was preserved amazingly well.)

Ambio 2.0 / PanAmbio 4.0 with surround by *convolution*

Stereo was slow to gain acceptance in the home until the 45/45 groove of the vinyl LP in the 1950s, FM stereo in the 1960s, compact cassette of the 70s, and CD and stereo broadcast television in the 1980s. Meanwhile, purists experimented with binaural (headphone) and other techniques in attempts to solve stereo's problems of inaccurate imaging, described above, whenever two spaced speakers were laid out in the "stereo triangle." But precise *localization* was by deemed by record producers as less important to a public they felt didn't know that violins were on the left and cellos on the right – *spaciousness* was thought more marketable, and that a satisfying wash of phasey sound would occur even with one speaker in the living room and the other in the dining room, far from the prescribed triangle!

Another of stereo's problems is that all sound, even room reverberation and applause, comes from the front, between two speakers only 60° apart (one-sixth of the panorama). "Verisimilitude," as termed by Glasgal, is far from achieved. Fortunately, these errors are functions of the speakers upon playback, not the microphones upon recording. However, mix decisions influenced by monitoring over speakers builds in errors that might not be correctable, such as compensating for the mid frequency dip in central voices caused by spaced stereo speakers. So if we improve replay techniques, a legacy of stereo recordings made over the last half-century would have new life! Glasgal has championed a way that

stereo (especially binaural) recordings can be played over loudspeakers using Ambiophonic cross-talk cancellation – first using an awkward acoustic barrier, then using DSP. Further, the acoustic imprint of the hall need not be recorded – it could be added during replay by DSP "convolution" using the hall's Impulse Response [13]. It could be reproduced in surround speakers or even in 3-space (see Periphonics, below), originating with just the 2 media channels of existing LPs, CDs, and broadcasts. When there are no direct sources other than frontal, hall convolution by the user economizes on surround channels.

In informal listening tests, conventional stereo sounds better to most listeners when played Ambiophonically. Users can convolve hall sounds according to taste (applies to relatively dry music-only). Recordings, movie soundtracks, and broadcasts made especially using Ambiophonic principles can sound better still, as can be evaluated in the author's demonstration CDs described below. (A convenient demonstration of Ambio's width and accuracy using a PC is at www.filmmaker.com/surround.htm.) Ambio and PanAmbio offer benefits not just to music purists, but also to producers of multichannel ATV, cinema surround, and Periphonic full–sphere surround reproduction with height, explored below.

Evaluation multichannel 4.0 & 5.0 CDs

For professional recording and broadcast engineers to evaluate 4.1 v. 5.1 systems and their compatibility, the author has prepared a 2-channel music CD [7] entitled *Ambiophonic Demonstration (AES Bavaria 2001)* and two DTS-encoded audio CDs [8] entitled *PerAmbiolating 360°* (pun intended): ITU 5.0 and companion PanorAmbiophonic 4.0 [13]. A ".1" LFE channel was considered unnecessary for these excerpts. Selection numbers in parenthesis ( ) below indicate pre-crosstalk-cancelled versions on the PanorAmbiophonic disc, so no special hardware is needed for evaluation – just temporarily moving four speakers (C unused) of a 5.1 layout. Except *Parade*, comparison PanAmbio 4.0 and ITU 5.0 recordings were made simultaneously with Ambiophone and OCT microphones described above. Brief descriptions of the recording setup and comparison of audible effects upon replay follow:

1 (&7) Barber of Seville *Sitzprobe* – 1:58
Recording Angle 120° front, hall back

The first rehearsal with soloists, chorus, and orchestra of a mixed professional/student production. Hall is 9,200 m³ with RT=2.1s and 3.77m (calculated) room radius. Room microphones are side-facing figure-8s back 10m. A spot microphone for soloists is mixed according to Room-Related Balancing [9].

In the benchmark PanAmbio 2/2 playback, individual instruments and voices are distinctly localizable and widely spread, nearly equal to the 120° recording angle. The spatial impression is "natural-sounding" with front and rear stage seamlessly integrated. In contrast, the ITU 3/2 playback over five identical speakers – 2-way with 10in (250mm) woofer – exhibits "commercially acceptable" spatial impression and envelopment with plausible localization, albeit across a compressed front stage, 60° L-to-R, but over a larger stable listening area than either PanAmbio or two-speaker stereo.

2 (&8) Lunchbreak at Martin Guitar Blues – 1:59
Quintet 0°, ±30°, ±60°, fans sides & back

Simulating a jazz club (or "unplugged" telecast) with bluegrass quintet and audience, the studio is 500m³, RT=0.31s (controllable, chosen to mimic a performance space) and with players in a 120° arc of approx. the measured 3.2m critical distance (room radius). Instruments from left to right are bottle (slide) guitar, acoustic bass guitar, fiddle & vocal, 6-string rhythm guitar, and 12-string guitar & harmonica. Eight fans, positioned as shown in Figure 5 hoot, clap, and clink glasses.

The benchmark PanAmbio 2/2 playback has the effect, astonishing at first, of replacing the listening environment with the recording environment, achieving a remarkably natural "you are there"

result – see Figure 3. In ITU 3/2 playback, the listener is enveloped in a quite plausible club atmosphere, notwithstanding the less precise localization, as shown in Figure 4.

3 (&9) Mozart Wrap-a-Rondo in F – 1:42
Flute quartet ±20°, ±60°, room back

A chamber quartet in the 500m³ studio, RT=0.31s (controllable, chosen to mimic a recital hall) and with players in a 120° arc the measured 3.2m critical distance (room radius) – from left: violin, viola, cello, and flute.

The benchmark PanAmbio 2/2 playback is a bit unsatisfying in its unequal representation of directional (string) and omni-directional (flute) in the live studio, possibly because the system's capability has created higher expectations. In contrast, the ITU 3/2 seems more acceptable in this regard, although the author feels that, in a commercial recording situation, a retake should be indicated with adjustments to acoustics and positioning. It is included on the evaluation CDs to study these error conditions.

4 (&10) Sousa's Fairest Brass – 2:37
Brass quintet 0°, ±30°, ±60°, room back

Recorded April, 2001, for AES 19th International Surround Conference, June, 2001, in the 500m³ studio, RT=0.31s (controllable, chosen to mimic concert stage-house) and with players in a 120° arc of approx. the measured 3.2m critical distance (room radius) but with ORTF room microphone. Instruments from left: 1st Trumpet, French horn, Tuba, Trombone, and 2nd Trumpet.

In benchmark PanAmbio 2/2 replay, the more directional instruments are slightly narrower than their recorded positions across the total 120° stage due to an earlier prototype Ambiophone (larger diameter sphere). The rearward-speaking French horn, as might be expected, is only vaguely correct. In contrast, the ITU 3/2 replay is "commercially present," although images are confined to the 60° front L/C/R speakers. Both envelop the listener with room ambience.

5 (&11) SPL Setup & *PerAmbiolating* 360° – 4:36
Voice ea 15°; quartet ±45°, ±135°

The "Walkabout" was recorded in the 500m³ studio, RT=0.31s and with the announcer *perambiolating* (pun intended) the twin baffled sphere microphone array at a radius of 2.5m. To parallel real-world conditions and the recordings above, studio acoustics were adjusted to replicate the stage house of a concert hall, with early reflections <15ms limited to those from horizontal planes (the floor), so their virtual "images" arrive at the same horizontal angle as their direct sound [14].

The benchmark PanAmbio 2/2 replay localizes announcements to the nearest 5° around all 360° with some "fuzziness" near 90° on each side. Accompanying bursts of filtered pink noise are more difficult to locate, but provide data for Figure 7. In contrast, the ITU 3/2 replay exhibits maximum error of 45° (75° each side is solidly reproduced by a speaker at 30°) as is illustrated in Figure 7.

6 (&12) Marching Bands on Parade – 3:40
Subject Angle 180°; recreated surround

Unlike others above, this excerpt illustrates "up-producing" surround from a 2-channel stereo field recording using editing and mixing of original and additional processed tracks such as for film mixing. For ITU 3/2, L/C/R is derived after Gerzon [15]. To evaluate creative potential in post-production, surround is six effects tracks derived from the original stereo, edited and processed to simulate crowd and building echoes. The illusion has been successful with all listeners to date.

In benchmark PanAmbio 2/2, the result is plausible envelopment of a listener standing on the

sidewalk while bands march by in the street, beginning extreme right and continuing to extreme left, with cheering and building echoes around and behind. Groups of instruments are heard to move smoothly (no perceptible angular distortion) across right-of-center through center to left-of-center to a degree of realism that the listener can readily imagine it. In contrast, ITU 3/2 replay of course is confined to the 60° triangle, but creates a satisfactory illusion nonetheless. In further contrast to traditional two-speaker stereo replay, the ITU 3/2 result exhibits less angular distortion, with no perceptible "hole in the middle."

Ambiophonic principles applied to ATV production

Listening in ITU 5.1 is a more enjoyable experience than 2-speaker stereo and is driving home theater purchasing by mainstream consumers. This acceptance could avoid the "chicken & egg" dilemma of introducing new entertainment technology – consumer systems for advanced television and advanced music-only are already being installed! Now with an audience having the means for surround sound, will they demand music recordings of high quality in surround? Will PanAmbio make a difference in the enjoyment of advanced multichannel television and DVD? Will producers and engineers apply advanced approaches to add quality and therefore user-ownership value to their recordings, films, and broadcasts? Implicit in these issues is relearning by practitioners and onerous complexity for users.

Use of "main microphone" for natural sound

Many if not most recording engineers and television A-1s use a number of microphones "p" (mnemonic 'phones) mixed live or recorded to q" tracks (mnemonic "traqs") and then mixed down to stereo, 5.1, etc. using large console mixers. Practitioners feel safer having control over each sound, even though the introduced clutter of phase cancellations, panning mismatches, and acoustic feedback (if live) increases with the number of microphones (NOM). Therefore, *tonmeisters* recording classical and other acoustic music often prefer one of several forms of "main microphones" for their cleaner results under controlled or selected acoustic conditions, but often still use "spot" mikes for safety and for controlling in post the contribution of weaker or solo instruments – again risking artifacts increasing with the NOM.

Ambiophonic playback widens and reveals more plausible front stage localization even if widely-spaced main microphones are used, but the results are superior using a main microphone that builds-into the recording HRTFs – an approximation of the Interaural Level Difference ILD and Interaural Time Difference ITD of the human head and its shadow from the opposite side. Another HRTF – comb-filtering by the pinna for direction-finding – is best left to the listener's own pinna, which are unique. So recording using a pinna-less sphere microphone, baffled from reverberation if hall convolution using DSP is to be used, produces best results in the author's experience, delivering both wide, accurate front-stage localization and balance AND natural spaciousness due to the largely uncorrelated signals from the near-spaced diaphragms. With care, a Center may be derived using matrix methods described by Gerzon [15] or perceptual steering such as Dolby ProLogic II or Lexicon Logic Seven.

Results with the pinna-less sphere [16] often obviate the need for spot microphones – or at least reduce the level and resulting clutter and artifacts. If used, spot microphones integrate well with the main microphone when they are mixed using Room-Related Balancing [9] to contribute energy in the form of artificial but natural-sounding early reflections using multiple delays. Center dialog ADR and Foley effects with separate ambience microphones use a combination of RRB and delay that just compensates for the distance from the source to the ambience microphones. A second sphere, separated from the first by a baffle, can be used for the surrounds, as shown in Figures 5 & 6 above. Surrounds can be fed by a variety of pickup methods, ranging from the back sphere above to hall-facing cardioids to a Hamasaki Square of four figure-of-eight microphones [17]. The author has used several approaches in the demonstration recordings above.

Ambio monitoring of stereo and 5.1

Ultimately, post-production decisions and approval of a final product must be made while monitoring in the delivery format. However during a 5.1 production, monitoring using Ambiophonic (front only) or PanAmbio surround techniques has demonstrable operational advantages. As a location recording engineer and television "A-1," the author uses a portable Ambiophonic monitoring system. Its compactness suits off-base production trucks. Its "you are there" capability transforms the audio booth into the performance space, just as it will the home theater. Subtle application of spot microphones, panning errors with respect to the main, and phase coloration (from comb filtering) are revealed and can be dealt with quickly in the heat of the session or live telecast. Musical directors more quickly approve because they now can discern individual voices and a "natural" blend, balance, and impression of hall ambience. Audiences are happier and stay tuned when less distracted by even an unconscious feeling that "something's not right." Especially for musical events, there is often less to "fix" in post, lowering costs.

For any surround approach to achieve maximum results – particularly if precise localization and balance is expected, such as with acoustic music – the listening environment is critical, especially for PanAmbio because its subtle capabilities can be more easily destroyed. Informal evaluations below were made in a control room, a home theater, a large demonstration room, and an automobile – with better results obtained in better acoustics. Generally, the listening room should be symmetrical or acoustically treated and "drier" than the recording venue. Requirements for PanAmbio replay are in Appendix A.

Compatibility between 4.1 and 5.1

Progress need not come at the all-or-nothing price of compatibility: mixes intended for ITU 5.1 can be played with good results on the above PanAmbio setup by selecting "no/phantom center" on the decoder/receiver. Conversely, PanAmbio recordings can be played with good results using the standard ITU 5.1 speaker layout (center images will be phantoms and the Center speaker silent; possibly available for repurposing?). Especially in cramped remote location vehicles, ITU 5.1 production mixing can benefit as described above using PanAmbio monitoring.

PanAmbio 4.0 recordings play well even without crosstalk cancellation on standard ITU 5.1 home theater speaker layouts. Note that the pinnaless sphere microphone upon which PanAmbio is based was intended for stereo over speakers, and works the same for the L/R and LS/RS stereo pairs of 5.1. As above, a 2-channel-to-3-speaker matrix can also be used in post or replay. Further, the front/back spacing of twin spheres in PanAmbio creates additional stereo pairs L/LS, and R/RS, which come into play should the listener rotate his/her head – a natural human action used to confirm source direction (more likely when listening to music; less likely concentrating on a picture). Conversely, 5.1 mixes of ATV broadcasts and DVD-Vs reproduce very well – some say better – for one or at most two viewers using the two stereo dipoles and crosstalk cancellation of PanAmbio by setting the decoder to "no/phantom center." (Recall that central voices are uncolored as they are favored by Ambio/PanAmbio's frontal speakers.)

Audiophiles may want to facilitate both ITU and "true" PanAmbio in a single listening room. This requires moving four speakers or switching nine – the home theater's subwoofer, receiver/decoder, and universal DVD player are the same (C unused for PanAmbio). Distribution formats for PanAmbio can be the same DTS-CD, DVD-V, DVD-A, SACD, or multi-channel broadcast using AC-3 (Dolby Digital) in Document A52/A of the ATSC Advanced Television standard [18]. PanAmbio is intended for one or at most two critical listeners, and is unsuitable for large audiences such as the cinema. See Appendix A for the requirements for PanorAmbiophonic reproduction. Home theater audiences of six or more could in the future enjoy full sphere Periphonics, explored next.

A compatible path to Periphonic surround (with height) for future re-release of priceless recorded performances is to simultaneously record in Ambisonic B-Format, which adds a natural sounding, 3D enveloping ambience to Ambiophonics. This hybrid approach has been demonstrated by the author and his colleagues [19] and combines compatibility with users' 5.1 installations today PLUS uncompromised Periphonic front localization AND natural spherical spaciousness that is ready for users of tomorrow.

Next: *Periphonics* – full sphere 3D surround?

"Multichannel surround sound" as it applies to advanced television today only includes surround in the horizontal plane. Only left and right boundaries of the frame are extended by the sound "image" to full circle; vertical sound is contributed only by reverberation of the theater (significant if large) or home theater (ranging from not much to awful if untreated). This definition of "surround" was predicated on the oversimplification that humans have but two ears on a horizontal axis.

However, human ears also have pinna. These remarkable appendages are direction finders for fine horizontal localization to about 1°, but also cueing height and depth above and below the plane of the ears – so future ATV, cinema, and music sound might well expand the definition of "surround" to include height. Indeed, IMAX's five story screen hides a single height speaker near its top. One need only experience full sphere surround reproduction, as the author demonstrates daily, to recognize that its contribution is as important to the ear as a jump in picture resolution of HDTV is to the eye.

Why height?

When we experience a live event, our eyes-brain system resolves an image with "pixels" measuring half a minute of arc, exceeding high definition television at normal viewing distances. And we are immersed in a bubble of vibrating air, where at a sporting event, for example, we expect to hear the crowd and PA elevated, and to hear the action below. Or the inverse – an air show or fireworks above and the crowd below; a lofty pipe organ with choir below. In a church, we would surely notice if organ and choir were squashed together at the horizon. Or if at the opera, suddenly the ceiling and floor were on the same plane, so that all the reflections we've come to expect to be strongly and spherically directional would flatten, erasing much of the acoustic signature of the hall, along with our envelopment within and enjoyment of it. We expect in real life our ears-brain system to resolve a sonic "image" with acuity of one degree horizontal and a several degrees vertical – due to changes in comb filtering by the pinna with varying elevation. In real life, we would be astonished, were 3D sound suddenly absent!

Conversely, since we can not yet expect this level of realism from current home theater, we are just as astonished when we hear our first reproduction of full periphony – 3D sound that blows away the walls of the listening room, coming at us from everywhere in the *sphere* – not just the circle – wherein *we* are the psychoacoustic center. While further technical description is beyond the scope of this paper, the aesthetic effect of full-sphere surround sound certainly defies this verbal description. Most who have heard the author's demonstration of it drops their jaw, goes wide-eyed, and expresses a desire to have it.

While for listeners who have heard them compared 5.1 is satisfying in spaciousness and envelopment, hybrid "PerAmbio 6.1.10" – at a "cost" of one more channel and five more speakers – adds full sphere directionality of Ambisonics and the accurate front stage localization of Ambiophonics. Most say that the reproduction is remarkably natural anywhere (except near a speaker) within the Ambisonic sphere – and is still enjoyably spacious and enveloping even outside the Ambisonic array. At the Ambiophonic focus, the front stage localization accuracy compels a sense of "you are there." For some, given the choice, these improvements will justify their added cost; for others, they might not. The ideal system would combine economy, good performance, extensibility for producers, broadcasters, and users, compatibility by users, and full 3D periphonics.

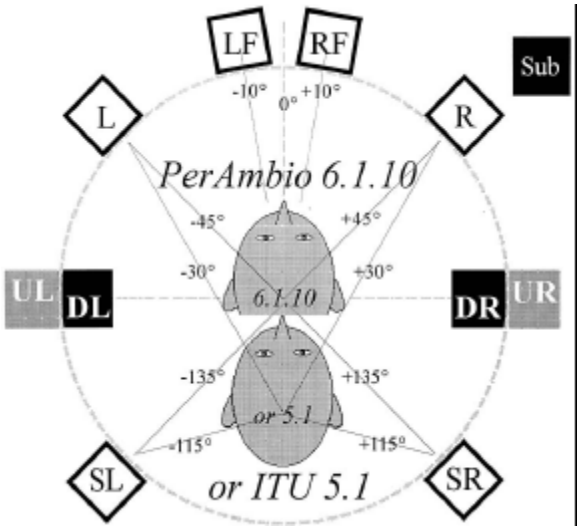

Fig.8 – Compatible PerAmbio 6.0.10 spherical surround hybrid of Ambisonics + Ambiophonics accommodates audiences up to six. For 5.1, viewers sit back 26% of the speaker diameter, where the angles meet ITU standards (DSP changes levels/delays). For 3D music appreciation, one or two listeners sit at the focus of 10 speakers.

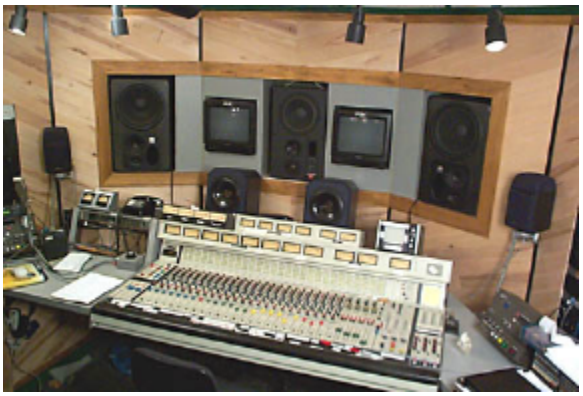

Fig.9 – Multi-format monitoring (showing 7 of 15 speakers plus 2 subwoofers) is switchable between PerAmbio 6.1.10 and ITU 5.1 in the control room of FilmakerStudios (see Fig. 8 but needs no change in level/delay). The common "Sweet spot" accommodates two within control room's reflection free zone. In addition to Periphonic 3D surround demonstrations, this facility produces compatible 4.1 and 5.1 mixes including those on the 2-channel and multichannel evaluation CDs available to professional audio engineers at www.filmaker.com.

What users need to hear 3D periphonic surround?

The author and his colleagues have demonstrated full sphere periphonic surround sound using two experimental methods that use 2, 4, or 6 full-range media channels. The author has produced recordings and soundtracks using these methods and plans with his colleagues to demonstrate results to the scientific and production communities at the AES 24th International Conference in Banff, Alberta, Canada, June 2003 comparing ITU 5.1 with simultaneously recorded reproduction as follows:

1) "2.0.10"[2] Ambio / 4.1.12 PanAmbio can be expanded with convolved surround, described above, using 3D hall impulse responses and, with 10 or more speakers (scalable by the user), is suitable for concert broadcasts of "acoustic" music. The media need only 2 (Ambio) or 4 (PanAmbio) channels of audio, as the surround speakers are fed by convolution. 8 or more surround speakers may be "satellite-size" and placed flexibly as long as an "intelligent convolver" is told where they are.

2) "6.1.10" PerAmbio/Ambisonic hybrid with 10 or more speakers (scalable at the user's option) offers compellingly realistic reproduction of direct sound sources impinging on the listener from any direction in spherical space using only 6 full range media channels. This approach could make ATV extensible to 3D surround. Again, the 8 or more surround speakers may be "satellite-size" and placed almost anywhere convenient as long as the decoder (DSP) is told where in the listening room they are.

For reference, the third method is classical Ambisonics "4.0.8+," which Michael Gerzon introduced to the audio community with slowly increasing acceptance since. Requiring 4 full-range media channels, Ambisonics "analog-encodes" directionality in 3-space and is replayed using regular arrays of speakers (from the 8 corners of a cube up to the 20 vertices of a dodecagon) with a unique feed derived for each placement by a matrix. An brief overview of Ambisonics is in Appendix B; information and links are at www.ambisonic.net. Demonstrated to the SMPTE Philadelphia Section by the author in 1990, Ambisonics can conjure up approximate localization of sources in 3D for a precisely centered

[2] In the form *r.lfe.s, r* = # media channels, *lfe* indicates presence of a boom channel, *s* = # unique speakers/feeds.

listener, but lack spaciousness since the SoundField microphone array Ambisonics uses is coincident. The hybrid technique in 2) above supplies spaciousness and sharpens the localization for the front stage.

All these "progressive approaches" share a common issue of inconvenience. Flexible locating of satellite-size speakers helps, but 6.1.10 requires more of them and more wires to run. Fig. 8 illustrates a compatible layout of 10 speakers, switchable between PerAmbio 6.1.10 spherical surround and ITU 5.1 for a home theater audience of up to six within $1.5m^2$ [9]. The central focus is for critical Periphonic 3D music listening. 5.1 listeners simply move back 26% of the speaker diameter for an ITU standard layout, necessitating DSP changes in levels and delays to four speakers: SL, SR, and LF & RF fed together as C.

Users may not be savvy enough or willing to deal with menus to select among even today's DVDs multiple formats, let alone changing speaker layouts, levels, and delays. If available in the future, smarter receiver/decoders could read metadata, broadcast or recorded on the DVD, and automatically select between two or more speaker layouts, crosstalk cancellation, and dozens of hall acoustic impulse responses much as MIDI instruments are a mere table-lookup for PC soundcards.

Compatible multi-format recordings captured today would allow users to upgrade their systems as they are able without obsolescing producers' masters or users' DVD libraries. Ambio 2.0 is extensible through PanAmbio 4.1 to PerAmbio 6.1.10. The author has successfully experimented with a single 3D PerAmbio 6.1 multichannel-encoded bitstream that could compatibly downmix at the receiver to PanAmbio 4.1, ITU 5.1, stereo, and monaural.

How might this paradigm shift – making available to users extensible formats beyond 5.1 – come about? Historically, if a major musical artist, filmmaker, or television producer believes the artistic benefits of full sphere surround will help him or her to new heights in reaching his or her audience, they will demand the technology and programs that deliver it.

What broadcasters need to deliver 3D periphonic surround?

ATV using AC3 is capable of delivering 5.1 channels, usually to exactly 5.1 speakers one-for-one. However, full sphere Periphony, although requiring at least 8 speakers to be perceived fully as 3D surround with height, does *not* require 8 media channels. Reproduction systems such as Ambisonics and hybrid approaches being explored by the author and his colleagues use fewer media channels by deriving from them as many unique speaker feeds as the user's current system needs. Requirements are 6 full range channels + LFE in one 6.1 multichannel-encoded bitstream.

As of this writing, the author knows of no implementation that exists for delivering 6 full range channels + LFE (one discrete encoded 6.1 bitstream) over terrestrial broadcast, nor discrete multichannel over the Internet. For DVD-V replay, DTS has introduced DTS-ES Discrete 6.1 and experimented with PC use and online using Apple QuickTime 6.0. PC soundcards are available that support 5.1 for playing DVD-V and DVD-A. Broadcasters might simulcast 6.1 using multichannel streaming online, e.g. using QT 6.0 or Ogg Vorbis open source codec that support multichannel, but implementations so far do not.

What producers need to deliver 3D periphonic surround?

The author's premise here is that, in the near term, more compelling ITU 5.1 surround content and production values will add to advanced television's success. In the longer run, knowledge of psychoacoustics will lead, perhaps sooner, to new standards. ATV is missing but a single link – a 6.1-channel (full-range, discrete) encoded bitstream – from being able to deliver compatible full-sphere surround that downmixes to 5.1 or stereo, as explored above. Physical media such as DVD-V, DVD-A, SACD, and DTS-ES 6.1 Discrete-encoded CDs can deliver full-sphere surround today!

Toward this end, the author and his colleagues are exploring and applying psychoacoustics principles and developing compatible and extensible tools, including those introduced in this paper, for the practicing television, cinema, and music sound engineer. Fig. 9 shows an audio control room at the author's studios with multi-format monitoring (15 speakers, plus subwoofers – see Fig. 8 but needing no changes in levels or delays), switchable between PerAmbio 6.1.10, ITU 5.1, stereo, and monaural. The common "sweet spot" accommodates two listeners within the studio's reflection free zone. This facility mixes original PerAmbio 6.1 channel recordings (full, spherical soundfield) with innovative post-production approaches, such as Ambiophonic auralization of surround from existing stereo recordings using DSP convolution by hall impulse response. PerAmbio 6.1.10's "naturalness" – where speakers seem to "disappear" and the listener is "transported" to the recording space – has implications as well in the smaller but high-end "purist" audiophile market.

Producers of ATV, cinema, and music surround need workable, repeatable, and cost-effective techniques that in some cases correct long-standing practice, steeped in stereo's "legacy." There are issues of education and (re)learning regarding proper ways to mic, mix, and monitor, explored above. But most importantly, the creative community must, as it has historically, introduce users to beneficial results, so that the market can demand that manufacturers and broadcasters do their part to supply.

MCN – multichannel numbering "r.lfe.s"

To more clearly identify surround formats – and because speaker feeds "s" no longer relate one-for-one to the number of media channels "r" (mnemonic "radioed") – the author uses, and encourages others to consider using MCN, multichannel numbering (I might prefer Miller Channel Numbering!). Simply append to the commonly used number of media channels, such as 5.1, a second decimal point and number to indicate the number of unique speaker feeds. The example in Figs. 8 & 9 would be designated "6.1.10" – indicating 6 full range media channels, with optional LFE channel, and 10 unique speakers delivering hybrid Ambiophonic/Ambisonic periphonic surround – or 6.0.10 for music-only. Subwoofer(s) are always implied at the user's option, depending upon the needs of his installation for a common woofer or desire for booming SFX from an LFE channel when present.

Other examples using MCN are 5.1.5 (ITU 5.1 standard), 5.1.6 (Dolby EX – surround center is matrixed from SL, SR), 2.0.2 (stereo or simple Ambiophonics), 2.0.10 (Ambio with convolved surround), 4.0.4 (simple PanAmbiophonic horizontal surround), and 4.0.8-to-20 (Ambisonics 3D).

Work in developing Periphonic reproduction

6.1.10 (hybrid PerAmbio/Ambisonic) and 2.0.10 (Ambio with 8-channel convolved surround) are relatively economical yet effective means of full 3D periphonic reproduction. Objectives of further work by the author and his colleagues relative to Advanced Television include:

- Optimizing the 6.1.10 layout and alternative(s) for both home and studio;
- Developing DSP algorithms for crosstalk cancellation and ambience using 3D hall impulse responses;
- Develop automobile PanAmbio reproduction (demonstrated by the author and his colleagues at 111th AES in New York, Dec 2001) and applicable to rear-seat ATV or DVD replay;
- Encouraging distribution of 6 full-range audio channels to enable periphony via broadcast or Internet;
- Develop a main microphone array that is more camera-friendly e.g. for live ATV events and concerts;
- Introducing artists, producers, and engineers to PanAmbio and Periphonic to stimulate demand.
- First PanAmbio 4.1 broadcast, Webcast, and DVD (-V, -A, SACD, or DTS-CD) release;

- First PerAmbio 6.1 broadcast, Webcast, and DVD (-V, -A, SACD, or DTS-encoded CD) release.

ANOVA analysis is planned to statistically rank simultaneously made experimental recordings of dozens of musical genres and natural sounds by trained auditioners [20, 21]. New recordings of various genres continue to be made with prototype microphones in a variety of acoustics to contrast leading approaches and explore compatibilities between formats. Multichannel recordings are described above and are available (www.filmmaker.com) for professional education and future analysis. Compatible production techniques, such as Ambiophonic monitoring for 5.1, are being developed for practitioners to implement based on traditional techniques as well as Digital Audio Workstation sweetening and mixing for distribution to growing 5.1 home theaters – and possible future 4.1 to 6.1 installations.

Conclusions

Listening in ITU 5.1 is a more enjoyable experience for the audience than 2-speaker stereo and is driving home theater purchasing by mainstream consumers. This acceptance could avoid the "chicken & egg" dilemma common to any introduction of new entertainment technology – i.e. consumer systems for reproducing advanced television and advanced music-only are already being installed! Now with an audience having the means for surround sound, will they demand music recordings of high quality in surround? They might if led by producers and engineers who apply advanced approaches to add quality and therefore user-ownership value to their recordings, films, and broadcasts. Issues include relearning by practitioners and onerous complexity for users – although some will feel that "10 speakers must be twice as good as 5!" But progress need not come at the all-or-nothing price of compatibility: mixes intended for ITU 5.1 can be played with good results on the PanAmbio 4.1 setup in Fig.2 by selecting "no center" on the decoder/receiver. Conversely, PanAmbio 4.0/4.1 recordings that combine superior front localization AND natural spaciousness and envelopment, can be played with good results using the standard ITU 5.1 speaker layout (center will be silent). ITU 5.1 production mixing can benefit using PanorAmbiophonic microphony and monitoring. For professional education and evaluation of these approaches, 2.0, 4.0, and 5.0 CDs are available at www.filmaker.com. Finally, a path to compatible Periphonic 3D surround (with height) for multi-format DVDs today or future ATV broadcast is the proposed hybrid approach PerAmbio 6.1.10 in Fig.8, demonstrated by the author and his colleagues, that is compatible with 5.1 horizontal surround today and is extensible to full periphonic 6.1.10 tomorrow.

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Appendix A: Requirements for playing PanAmbio 4.0 / 4.1

To fully realize PanAmbio playback requires stringent listening acoustics [22]. Having both ITU 5.1 and PanAmbio 4.1 requires moving four speakers (or switching nine) – the studio's bass-manager or home theater's subwoofer, receiver/decoder, and DVD player can be the same (C unused for PanAmbio). Distribution formats can

be DTS-CD, DVD-V, DVD-A, SACD, or multi-channel broadcast using AC-3 (Dolby Digital) in Document A52/A of the ATSC standard. Requirements for PanAmbio playback are:

- Symmetrical or acoustically treated room and layout with RT less than recording venue and with one or at most two listeners seated at the center of speaker pairs directly front and back at less than the acoustic room radius.
- Universal DVD/CD player or DTV receiver with 4-channel output (2 AES/EBU or one multi-channel encoded serial digital connection, coax or optical e.g. S/PDIF – C unused);
- Decoder (digital stream to multi-channel analog) – C unused – or integrated in 5.1 home receivers. Alternative is all-digital integration of crosstalk-canceller, bass manager, and power amplifiers below;
- Crosstalk-cancellers – two DSPs, ideally based on impulse response of speakers used, currently in prototype form (see Figure 21) – evaluation CD [8] has tracks pre-cancelled for "generic" speakers;
- Amplifiers/bass manager typical of 5.1 studio units and home receivers and accommodating multi-channel inputs (S/PDIF coax or optical) and four speaker feeds (C unused) plus subwoofer if any;
- 4 main speakers with vertically in-line components, full range or common-woofer/satellite systems. Dual PanAmbio and ITU 5.1 requires moving four speakers (or switching nine). Subwoofer optional if main speakers are full range and producers decide the ".1" LFE channel is not needed for music;
- Calibration of channels at the listening position within ½dB using an SPL meter and filtered pink noise.

Note that mixes intended for ITU 5.1 can be played with good results on the above PanAmbio setup by selecting "no/phantom center" on the decoder/receiver. Conversely, PanAmbio recordings can be played with good results using the standard ITU 5.1 speaker layout (center will be silent).

A periphonic alternative is Ambio 2.0 (front-only, 120~150° wide reproduced stage) that uses 8+ surround speakers fed ambience convolved from impulse responses of any hall for many existing stereo recordings. Ambio 2.0 and PanAmbio 4.1 avoid the anomalies of two-speaker stereo caused by the 60° triangular speaker placement – anomalies are not necessarily intrinsic to stereo recordings. For more information, see www.ambiophonics.org.

Appendix B: Very brief overview of Ambisonics

Several decades ago, Michael Gerzon approached soundfield synthesis by using an omni (W) and three coincident bi-directional microphones aimed forward, leftward, and upward (X, Y, & Z). The array can be realized using individual microphones, or packaged as in a SoundField microphone. Four recording channels (B-format) can decode to any number of speakers, derived by adding to the W channel X, Y, & Z in proportion to the cosine of the horizontal azimuth and sine of the vertical elevation of each speaker's position. Just as M-S "cosine-encodes" two channel intensity stereo as would a stereo pan pot, Ambisonics can, be created by assignment, say of monaural dialogue or sound effects, using a 3 dimensional pan pot, much as 5.1 can by a 2-dimensional one. B-format (4 channel) stems of music or ambient sound effects can be combined by linear addition to a single Ambisonic mix.

Although sound pressure W is somewhat uncorrelated with velocity components X, Y, & Z, pure Ambisonics suffers from lack of spaciousness, similar to coincident M-S. Spaciousness seems to demand spaced microphones, such as the Ambiophone (baffled, pinnaless sphere), which also capability of wide, accurate front stage localization when played Ambiophonically. Combined, hybrid Ambisonics + Ambiophonics results in the best of both worlds – 3D envelopment + front stage localization and spaciousness, as in PerAmbio 6.1.10 above.

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