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Scalable Tri-play Recording for Stereo, ITU 5.1/6.1 2D, and Periphonic 3D (with Height) Compatible Surround Sound Reproduction

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ABSTRACT

Objectives: Take the next step toward reproducing human hearing AND make better recordings in 5.1. In life, we hear sources we see – but also reflections and reverberation we don't see. Each sonic arrival is individually direction-stamped by our unique HRTF, including height, tonally colored by our pinna. Preserving 3D directionality is key to life-like hearing. A practical, scalable approach is presented (pat.pend.) – a way to "transform" 3D (full sphere) recordings for uncompromised 2D reproduction in stereo or 5.1/6.1 without any decoding. By adding a decoder and speakers, full 3D is losslessly "reconstituted" from 6-channel media. Experimental "tri-play" 6-channel "PerAmbio 3D/2D" recordings have been made and demonstrations presented (AES 114th Amsterdam 3/2003 & AES 24th Banff 6/2003) with praised results.

1. EVOLVING REALISM FOR MUSIC & MOVIES

Just as monaural sound reproduction had finally to yield to stereo and stereo to 5.1, so two-dimensional (2D) surround in the horizontal plane will progress toward life-like 3D (with height). In essence, the more the directionality of sound is preserved in 3-space, the more natural the result, as determined by our unique HRTF.

However to date, recording practice in 5.1, like stereo, favors *spaciousness* and simulating *timbre* (tonality) at the price of accurate *localization* – as though mutually exclusive [1,2,3,4,5]. Progress is needed to realize *all three,* as in real life. A new system [6,7] from microphones to media to speakers, "PerAmbio 3D/2D," takes a step toward life-like 3D sound with correct spatial impression, timbre AND localization, and that plays compatibly in stereo, 5.1/6.1 2D, and full 3D using available 6-channel media and 10 or more speakers in a home theater or height-modified cinema.

2. GOALS: COMMERCIAL & ARCHIVAL

Musicians, record labels, and home theater owners have much to gain from lifelike 3D reproduction that is compatible with well-accepted stereo and 5.1/6.1 [8]:

- Priceless performances can be preserved;
- Producers' libraries are more future-proof;
- Consumers' collections will not become obsolete.

For music-only, these objectives translate into future value to musicians, producers, hardware manufacturers,

and consumers – deliverable today on DVD-A, SACD, and DTS-ES Discrete CD. DVD-V movies could also provide an alternate mix in PerAmbio 3D (DTS-ES 6.1 Discrete). Other applications for 3D reproduction are:

- Multi-media/Virtual Reality
- Amusement rides
- Simulation/training
- Auto sound
- Cinema/TV (ATV requires AAC implemented)

3. HISTORY, HEARING, & HEIGHT

Human hearing is unique to us as individuals due to our own HRTF (head-related transfer function), learned at an early age, re-learned after trauma or loss with age, and thus difficult to generalize with auralization. In acoustic spaces, hearing is bound by perceptions called psychoacoustics. Musicians, who "play acoustics" as extensions of their instruments, and recordists are likely to be most sensitive; consumers can learn to be.

When stereo caught on in the 1950s, the author recalls that musicians often favored monaural – Why? Described as the "stage door" effect, mono sounded correct tonally AND was localized at a point in 2D for coming through a narrow opening in the orchestra shell wall. The "sweet spot" included the entire stage wing. Mono sounded like live listening backstage!

On-stage, stereo fell short of localizing instruments, as Blumlein himself knew in the 1930s, bunching the panorama of sounds at the speakers (the "hole in the middle") and confusing the pinna about important central soloists, because their sound was coming from speakers far from center. Add that ambience was redirected to frontal speakers, far from around and behind. But consumers, therefore producers, cared more that it sounded *spacious*. Acoustic music recordists (classical, jazz, folk, etc.) adapted by choosing to get the timbre "correct" and the "sweet area" large by using spaced omnidirectional microphones in various layouts. More accurate but less spacious sounding coincident M-S 2D and Ambisonic 3D approaches were less successful.

ITU 5.1/6.1 surround sound (2D) extends stereo to envelop listeners, but only horizontally, lacking height (3D) and therefore not fully realizing the illusion of live human hearing, explored next. New research into surround sound such as 2D Wavefield Synthesis (WFS) and 3D High Order Ambisonics (HOA) are important work and the author finds demonstrations impressive and their potential great. However, their application to home theater may wait for resolution of impracticalities such as large numbers of high quality microphones, channels, speakers, higher noise, limited frequency range, etc.

4. PRACTICAL 3D – FILLING A NEED?

This paper presents a more imminent path to more life-like sound that: a) provides uncompromised 2D in 5.1 or stereo today, and b) embeds 3D information for future replay while minimizing obsoleting entertainment providers' libraries or consumers' collections and preserving priceless musical performances for ever-newer audiences. The "tri-play" format - deliverable in today's media - combined with high performance in 5.1, stereo, and 3D might increase consumer demand for surround equipment and software today and in the future.

But firstly, why will we want 3D? Because in life, we hear what we see - but also what we don't see. We usually see direct sources, often arranged in a horizontal circle around us. But in non-anechoic conditions, there is much we hear that we can't see - reflections and reverberation coming from all directions of a sphere (Fig.1). In an acoustic space, each arrival is direction-stamped, tonally colored by our unique HRTF, including height colored by comb filtering by our pinna, and is associated with a direction learned from childhood, leading to our unique perception of "live" hearing.

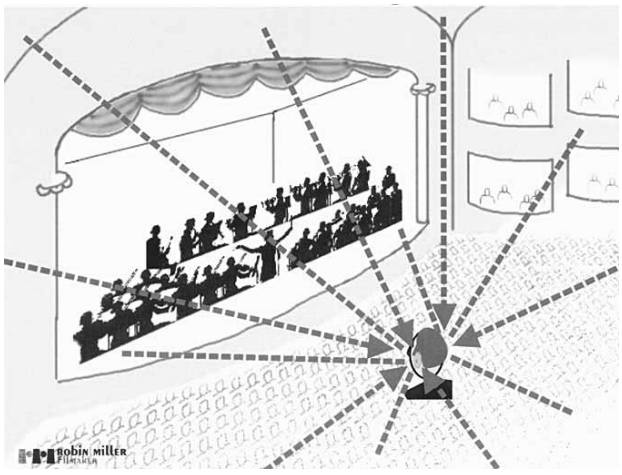

Fig.1. In life, we hear both sources we see and reflections we don't see – a major factor of tonality, as musicians "play" the acoustics as extensions of their instruments. Preserving 3D directionality is key to lifelike hearing.

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Each musical note triggers a dynamic buildup of differently colored sonic arrivals until all are integrated in the steady state of the note's final timbre. Then after the direct source stops, the multi-colored set of unseen sounds collapses, generally in the order it was built. Musicians "play" this acoustic response as extensions of their instruments, carefully forming each note while listening as the audience does to this complex seen/unseen interplay of sounds. Preserving the 3D directionality of the native acoustics is key to life-like hearing. Take away true 3D and it sounds "canned."

5.1 is surround sound only in 2D - a circle without height components for our pinna to color. For movies, for which 5.1 was intended, the picture compensates for falling short of fully life-like sound. However, a 3D sonic "image" would complete the cinema/ATV "picture" beyond four sides of the frame, not just two. For audio-only such as music, there is no picture, and the illusion more obviously falls short of life-like. To achieve a compelling illusion of "live," we must preserve the 3D directionality of reproduced sonic components - unseen as well as seen, direct as well as diffuse.

We need a systems approach to 3D full sphere surround sound reproduction, from musicians' instruments to home theater owners' ears, using practical arrays of microphones, channels, and speakers. An objective of the system was to produce 5.1 with quality potentially superior to re-panned multi-track masters originally made for stereo prior to surround. For capturing 3D live, the paper explores a hybrid solution to the deficiencies of any one of the current 3D approaches. However, 3D for renowned acoustic spaces can be convolved from impulse responses, requiring only 2-channel delivery if implemented in user equipment.

The system embraces a tri-play release method to "transform" the 3D information for uncompromised 2D reproduction in 5.1 - without decoder or relocating speakers - "folding" the captured 3D information by projecting height components onto the horizontal plane of 2D 5.1. This is accomplished by selecting one of a number of defined modes appropriate to the music and venue, but reversible and changeable in the mastering stage. By adding a decoder and speakers, full 3D can be losslessly "reconstituted." 6 full-range channels are required, available today in DVD-A, SACD, and DTS-ES Discrete CD or DVD-V. A 10-speaker isotropic array is described that provides 3D with a broad "listening area" and also complies with legacy 5.1 releases. However, pseudo-random speaker layouts are explored that users might accommodate more readily.

For audio-only such as music, the tri-play "PerAmbio" (periphonic-ambiophonic) system described increases entertainment providers' ROI by reducing costs for 3D re-release and adds value to their libraries and users' collections. In addition, priceless musical performances could be preserved for new audiences that might increase demand for 3D reproduction.

Experimental recordings have been made and informal listening tests and demonstrations conducted in 2003 in conjunction with AES in Amsterdam and Banff. A patent is pending on the processes described.

5. HYBRID APPROACH TO 3D – "PerAmbio"

5.1 (ITU R-775) has renewed interest in localization, now with 5, 6, or 7 speakers – still only in the horizontal plane – e.g. experiments using directional microphones, such as OCT by Theile [9] and MMA by Williams [10]. But some tonmeisters at the Banff, Canada, AES 24th International Conference on Surround Sound preferred the timbral result of five spaced omnis, even though instruments jumped around the stage note by note.

However, we hear in many more directions than 5 or 6 – and only some of these lie in the 2D horizontal plane (Fig.1). As our pinna color differently sound from each direction, the resulting brain-integrated tonality will not be correct unless directionality in 3D is preserved. Reproduced in 3D, musicians participating in the author's experiments exclaim "Finally, it's my sound." – the sound that, together, they, their instruments, and the room synthesized in performance.

At AES114 in Amsterdam and AES24 in Banff, the author demonstrated the theory that if no one surround recording system is perfect [2], perhaps a hybrid of two is better. "PerAmbio 3D" combines a wide, accurate front stage using Ambiophonics [11,12,13,14,15,16] with ambience using Ambisonics [17]. As in the Appendices and references, Ambio uses a crosstalk-cancelled pair (Ambiopole) of high quality speakers placed in front 16° apart, while Ambisonics uses eight or more satellite-quality speakers placed almost anywhere else (Fig.2).

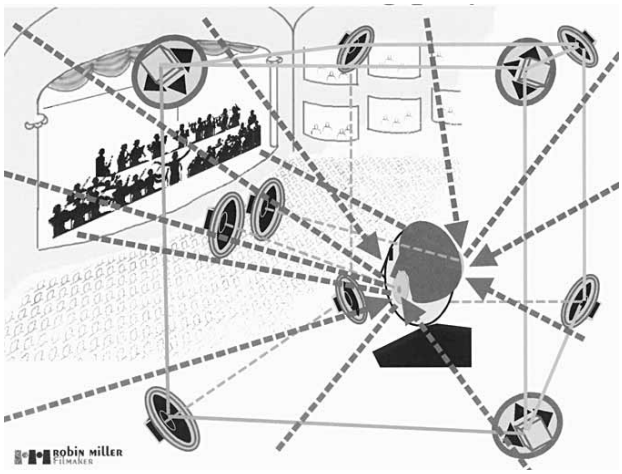

Fig.2 - PerAmbio 3D combines an accurate, spacious front stage with tonally correct envelopment using 8 or more satellite-quality speakers positioned flexibly (cube layout shown) as programmed in the decoder. In effect, all speakers "disappear," along with the walls of the listening room.

The two components of the PerAmbio 3D hybrid complement each other: Ambiophonics' focused front stage fills in Ambisonics' weak one, while Ambisonics' envelopment preserves timbre in a listening area that exceeds 5.1/6.1 because more surround speakers playing at lower levels can be approached more closely before they can be localized. Serious listeners on the median plane are believably transported to the recording venue, as all speakers and listening room walls "disappear."

Most importantly PerAmbio 2D/3D is "transformed" for media release, playable uncompromised in stereo or 5.1/6.1 surround (2D) without any decoder or additional speakers. Then at any time, the home theater owner can add a decoder and additional speakers for lossless 3D reproduction, described in detail below.

5.1. 3D for large audiences & cinema

Since PerAmbio 3D/2D is compatible with stereo and 5.1/6.1, a 3D hybrid playback is possible for large audiences such as the cinema by adding flexibly placed height speakers to the standard 5.1/6.1 theater speaker layout. This only compromises frontal sounds for those six theater-goers seated in the theater's "sweet area" (approx. 1.5m^2 [9]) compared to the wide, accuracy of pure ambiophonics that is obtainable when one or at most two serious listener(s) play the same PerAmbio

3D/2D transformed mix at home. PerAmbio 3D could greatly enhance music and sound effects, while dialogue would still mostly be anchored by the center speaker.

Cinema screen speakers are the same for PerAmbio 3D as current standards. Surround and height speakers may be pseudo-randomly positioned and the decoder programmed where they are in azimuth & elevation (same as in home). Height speakers for the theater need not be large, as pure height cues are >1kHz [18].

6. SYSTEM FOR COMPATIBLE 3D/2D

Three elements define the system (pat. pend.) for delivering 3D surround audio in compatible 2D form:

1. Microphone array for 3D/2D recording;
2. "Shiny Disc" 3D/2D "Transformation;"
3. Home Theater replay - owner's choice of:
   a. ITU 5.1/6.1 standard layout for 2D replay;
   b. Speaker array & decoder to "Reconstitute" 3D

This systems approach gives both the producer and the consumer practical choices and added value:

- For the ***producer:*** whether to capture and when to deliver a "transformed 3D/2D" release of higher value because it plays today in 5.1/6.1 and in the future in 3D (or may be re-released as 3D).
- For the ***consumer:*** whether to purchase a 3D/2D release and, separately, when to augment his/her 5.1/6.1 home theater to "reconstitute" 3D (by adding four or five small speakers and a decoder).

6.1. 3D/2D Microphone Recording Array

PerAmbio 3D/2D uses six microphones feeding six recording channels. A second approach is to record just two microphones and convolve 3D ambience in post or replay [16]. Additional spot microphones are possible. However, when lifelike 3D is replayed, it is evident that spot mics are needed less, if at all. (This is also the case with main-microphone techniques for 5.1/6.1 – revealing to many veteran recordists that the need for spot mics in the first place was to "fix" stereo's shortcomings.)

Fig.3 - PerAmbio microphone array combines a baffled and pinna-less ellipsoidal head, or Ambiophone, with 1st-order Ambisonics microphone using discrete capsules (B-format). (A back-facing sphere is also shown.)

Fig.4 - PerAmbio 3D/2D microphone array combines a baffled pinna-less ellipsoid "Ambiophone" developed by the author and a 1st-order (B-format) Ambisonics microphone atop realized using high quality discrete capsules. Note that the transducers of the Ambiophone are at human ear positions.

Fig.3 & 4 show a PerAmbio 3D microphone array. The front stage, to be reproduced using a crosstalk-cancelled ambiopole pair, uses a baffled and pinna-less sphere [19], ellipsoid [20] or Ambiophone. Envelopment is recorded as 1st order B-format (W,X,Y,Z channels) using a Soundfield or discrete microphones (shown).

As with any recording, it is important to position the array to taste by monitoring in both 3D and 2D. Spot microphones may be mixed and panned within front channels FL, FR as they do not affect 3D reconstitution, although panning through center produces phantom images. A hard C channel results from the B-format transform and contributes a stable center image when moving around the listening space, as with 5.1/6.1.

Alternatively, B-format ambience can be sourced by 3D auralization, convolved during post-production or by the user from a library of 3D hall impulse responses. Ambisonics is summarized in Appendix B. In Appendix A, Ambiophonics after Glasgal et al [11,12,13,14,15,16] contributes a 120°-wide stage with ±5° imaging accuracy using a closely spaced "ambiopole" speaker-pair and crosstalk cancellation.

6.2. "Transformed" 3D Tri-play "Shiny Disc"

Although it would be trivial to simply deliver the six native PerAmbio channels instead of standard ITU 6.0 channels, it would repurpose these channels entirely. Instead, a lossless algebraic matrix "transforms" the six 3D channels to play compatibly without decoding, flattened to standard ITU 5.1 or 6.1 horizontal 2D surround speaker layouts (Fig.5 & 6). Or the disc can be decoded to PerAmbio 3D full sphere surround by recovering the Ambisonic B-format plus a binaural-based Ambiophonic front stage (Fig.7). The PerAmbio 5.1/6.1 transformation is linear and bi-directionally lossless. Users can implement full sphere 3D surround by adding a matrix decoder and 4 or 5 speakers.

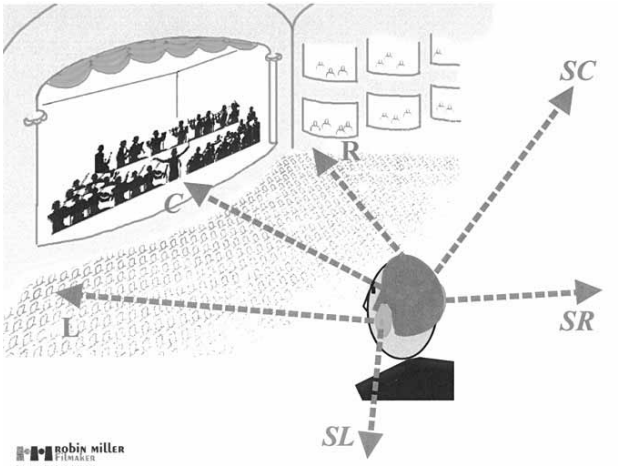

Fig.5 – Recording perspective using Transform mode ***i'*** that encodes 3D for direct replay in ITU 5.1/6.1 (see Fig.8a,b) and future 3D reconstitution.

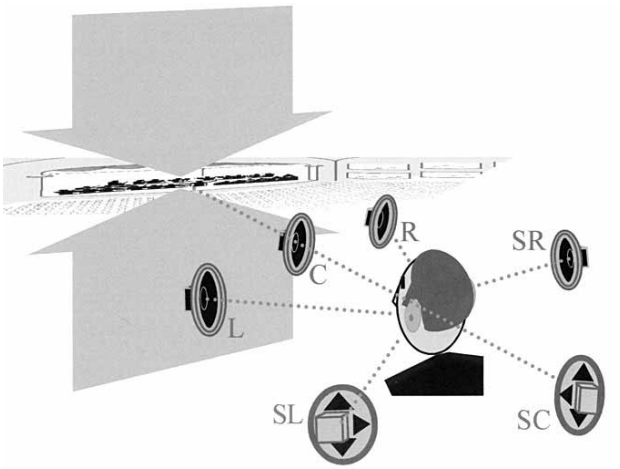

Fig.6 - PerAmbio replay in 2D flattens to ITU 5.1/6.1 as speakers lie in the horizontal plane. Only listening room reflections contribute height, but these are invalid, so tonality is as in ITU 5.1/6.1. Tri-play PerAmbio 3D/2D recordings deliver 5.1/6.1 surround or stereo until the user implements 3D.

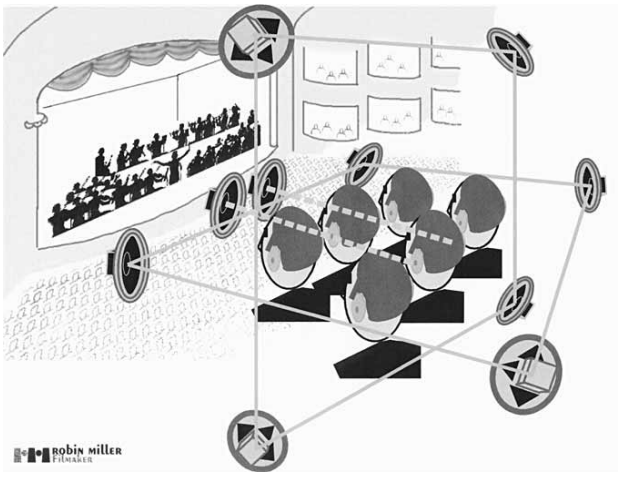

Fig.7 – PerAmbio replay implemented in 3D (bi-square shown) preserves correct timbre using 10 speakers + subwoofer(s). For serious music listening, two sit in the median plane. For 5.1, viewers move back 26% of the speaker diameter, where angles match ITU standards (see Fig.14).

6.3. 3D/2D Recording Transform Modes

If metadata permitted, the recording engineer could have available all 80 combinations ($=3^4-1$) considered for encoding 3D directionality into 6 full-range ITU-compatible media channels for direct replay in 5.1/6.1. For 3D replay, decoding corresponding to the recording mode is implemented in DSP. It is also possible for users to download new matrices via the Internet.

The author has identified [7] six useful "modes" for music recording, cinema ambience, and multichannel broadcast (Fig.8a, b). Work is ongoing to refine these selections. A mode chosen during recording may be changed in post-production, or by a user with a "smart decoder," reconstituting original channels and making a new transformation. Changing the tilt of a raised (suspended) microphone is also easily done. In DVD-A mastering, a flag is set in metadata of the tri-play 3D/2D disc for automatic selection by replay equipment.

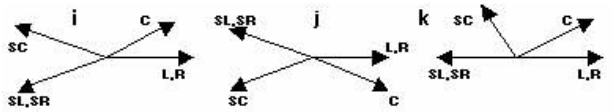

Fig.8a - Elevations of PerAmbio Transformations i, j, & k to ITU 5.1/6.1 of amphitheater, concert with soloist & audience, and arena. Source is right.

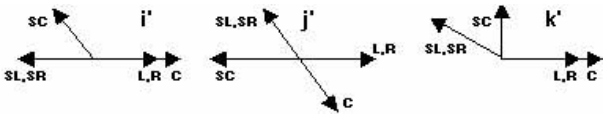

Fig.8b – Elevations of "tilted" modes i', j', & k' that transform PerAmbio 3D to ITU 5.1/6.1 for opera, drama, and organ behind choir (source is right).

For ease of use, mnemonics describe the three basic modes, i, j, & k, in terms of channels C, SC, SL, & SR: **"i"** represents C and SC "inclined" upward while SL & SR incline downward. **"j"** "juxtaposes" these pairs. **"k"** lying on its back has C and SC angling upward from the corner channels, which lie flat.

Three tilted variants **i'**, **j'**, & **k'** rotate C, SC, SL, and SR with respect to L,R by any practical angle, e.g. –30°, in order to raise the microphone (suspended or on a high stand). The output of the baffled "ambiophone" varies only slightly with height incidence, so physical tilting is inconsequential for FL,FR channels. The same applies were a sphere or ORTF microphone used for FL,FR.

From experience, recording engineers might identify applications described below for each of the six modes (keeping in mind they can be changed in post or replay):

i The microphone array is placed at source level (L, R), below acoustic shell reflections (C), e.g. an outdoor amphitheater event, with audience low and behind (SL, SR) and raked upward (SC).

i' The array is on a high stand or hanging in an opera house or symphony hall, the orchestra widely spaced in a pit or strings downstage (L, R), singers or winds upstage (C), hall ambience back (SL, SR) & up (SC).

j The array is more closely placed before a small ensemble at source level for direct sound and early floor and sidewall reflections (L, R), higher direct solo and ceiling reflections (C), and hall ambience from back-up (SL, SR) and back-down (SC).

j' The array hangs closer to a proscenium to pickup downstage sounds (L, R), upstage drama (C), high-back ambience (SL, SR), and audience (SC).

k The microphone array is in an arena with sports play-action or musical instruments at microphone level (L, R), and with good high-front (C) and back (SC) crowd sounds or ceiling ambience.

k' The array is suspended in a cathedral with upstage choir (C) and front-of-church organ divisions and floor reflections (L, R), antiphonal and congregation in back (SL, SR), and organ trumpet overhead (SC).

6.4. Tri-play 3D/2D Transformation

After recording six PerAmbio 3D channels, given as **{Pin}** in 6x1 matrix form, a "transformation" matrix **{S}** for standard 5.1/6.1 surround is applied to obtain the 6 ITU-compatible media channels **{Sout}** as follows:

$$\{Sout\} = \{S\} \bullet \{Pin\}$$

$$\begin{pmatrix} L \\ R \\ C \\ SC \\ SL \\ SR \end{pmatrix} = \begin{pmatrix} s(L,FL) & s(L,FR) & s(L,W) & s(L,X) & s(L,Y) & s(L,Z) \\ s(R,FL) & s(R,FR) & s(R,W) & s(R,X) & s(R,Y) & s(R,Z) \\ s(C,FL) & s(C,FR) & s(C,W) & s(C,X) & s(C,Y) & s(C,Z) \\ s(SC,FL) & s(SC,FR) & s(SC,W) & s(SC,X) & s(SC,Y) & s(SC,Z) \\ s(SL,FL) & s(SL,FR) & s(SL,W) & s(SL,X) & s(SL,Y) & s(SL,Z) \\ s(SR,FL) & s(SR,FR) & s(SR,W) & s(SR,X) & s(SR,Y) & s(SR,Z) \end{pmatrix} \times \begin{pmatrix} FL \\ FR \\ W \\ X \\ Y \\ Z \end{pmatrix}$$

For a standard ITU home theater surround system, a multichannel disc (6 discrete channel DVD-A, SACD, or DTS-CD/DVD-V) plays **{Sout}** directly in 5.1/6.1. If the speaker layout is 5.1, current implementations sum SC information into SL and SR speaker feeds at –3dB.

When the user augments his/her system for fully periphonic 3D, a "reconstitution" matrix **{P}** is applied, implemented in DSP in response to flags in metadata that select one of six recording modes to recover losslessly PerAmbio 3D – in matrix form **{Pout}** – as follows:

$$\{Pout\} = \{P\} \bullet \{Sout\}$$

Since matrix {P} is the inverse of matrix {S},

$$\{Pout\} = \{S\}^{-1} \bullet \{Sout\}$$

$$\begin{pmatrix} FL \\ FR \\ W \\ X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} s(L,FL) & s(L,FR) & s(L,W) & s(L,X) & s(L,Y) & s(L,Z) \\ s(R,FL) & s(R,FR) & s(R,W) & s(R,X) & s(R,Y) & s(R,Z) \\ s(C,FL) & s(C,FR) & s(C,W) & s(C,X) & s(C,Y) & s(C,Z) \\ s(SC,FL) & s(SC,FR) & s(SC,W) & s(SC,X) & s(SC,Y) & s(SC,Z) \\ s(SL,FL) & s(SL,FR) & s(SL,W) & s(SL,X) & s(SL,Y) & s(SL,Z) \\ s(SR,FL) & s(SR,FR) & s(SR,W) & s(SR,X) & s(SR,Y) & s(SR,Z) \end{pmatrix}^{-1} \times \begin{pmatrix} L \\ R \\ C \\ SC \\ SL \\ SR \end{pmatrix}$$

PerAmbio 3D reconstitution is lossless if

$$\{Pout\} = \{Pin\}$$

Experiments [7] have led to simplifying matrices to 4x4, shown in Fig.9 & 10 for six transformation modes. For reconstitution, Fig.11 & 12 also show signal-to-noise ratio loss of 1.4 to 3dB – a cost of less than ½ bit in 24.

Mode "i" (inclined) — 4x4 coefs x 0.8500

°Up*	{Si} \	{Pin}: FL	FR	W	X	Y	Z
0	{Sout}: L	0.850	0.000				
0	R	0.000	0.850				
30	C			0.601	0.736	0	0.425
30	SC			0.601	-0.736	0	0.425
-30	SL			0.601	-0.368	0.638	-0.425
-30	SR			0.601	-0.368	-0.638	-0.425
min/max rec	Transformation {S} 4x4 or 6x6			W=0.707W	cosAcosE	sinAcosE	sinE

Mode "j" (juxtaposed I; descending C)

°Up*	{Sj} \	{Pin}: FL	FR	W	X	Y	Z
0	{Sout}: L	0.850	0.000				
0	R	0.000	0.850				
-30	C			0.601	0.736	0	-0.425
-30	SC			0.601	-0.736	0	-0.425
30	SL			0.601	-0.368	0.638	0.425
30	SR			0.601	-0.368	-0.638	0.425
min/max rec	Transformation {S} 4x4 or 6x6			W=0.707W	cosAcosE	sinAcosE	sinE

Mode "k" (on it's back)

°Up*	{Sk} \	{Pin}: FL	FR	W	X	Y	Z
0	{Sout}: L	0.850	0.000				
0	R	0.000	0.850				
30	C			0.601	0.736	0	0.425
60	SC			0.601	-0.425	0	0.736
0	SL			0.601	-0.425	0.736	0.000
0	SR			0.601	-0.425	-0.736	0.000
min/max rec	Transformation {S} 4x4 or 6x6			W=0.707W	cosAcosE	sinAcosE	sinE

Fig.9 - 4x4 matrix {S} transforms six-channel PerAmbio 3D into one of three modes i, j, or k for ITU 5.1/6.1 replay without a decoder, or with a converter back to PerAmbio 3D. Selection is reversible in post or replay.

Mode *i' high tilted*

°Up*	{Si'} \	{Pin}: FL	FR	W	X	Y	Z
-30	{Sout}: L	0.850	0.000				
-30	R	0.000	0.850				
0	C			0.601	0.850	0	0.000
60	SC			0.601	-0.425	0	0.736
0	SL			0.601	-0.531	0.638	-0.184
0	SR			0.601	-0.531	-0.638	-0.184
min/max rec	Transformation {S'} 4x4 or 6x6			W=0.707W	cosAcosE	sinAcosE	sinE

Mode *j' high tilted*

°Up*	{Sj'} \	{Pin}: FL	FR	W	X	Y	Z
-30	{Sout}: L	0.850	0.000				
-30	R	0.000	0.850				
-60	C			0.601	0.425	0	-0.736
0	SC			0.601	-0.850	0	0.000
60	SL			0.601	-0.106	0.638	0.552
60	SR			0.601	-0.106	-0.638	0.552
min/max rec	Transformation {S'} 4x4 or 6x6			W=0.707W	cosAcosE	sinAcosE	sinE

Mode *k' high tilted*

°Up*	{Sk'} \	{Pin}: FL	FR	W	X	Y	Z
-30	{Sout}: L	0.850	0.000				
-30	R	0.000	0.850				
0	C			0.601	0.850	0	0.000
90	SC			0.601	0.000	0	0.850
30	SL			0.601	-0.368	0.736	0.213
30	SR			0.601	-0.368	-0.736	0.213
min/max rec	Transformation {S'} 4x4 or 6x6			W=0.707W	cosAcosE	sinAcosE	sinE

Fig.10 - 4x4 matrix {S'} transforms six PerAmbio 3D channels into one of three tilted modes i', j', or k' for standard ITU 5.1/6.1 replay without a decoder (–30° tilt shown). Selection is reversible in post or replay.

6.5. 3D/2D Mastering & Release

Are the efforts of true 3D reproduction justified by subjective results? So far in its development, the answer regarding PerAmbio 3D/2D is yes; its life-like, natural sound has been described by attendees at demonstrations (recording engineers and musicians; see comments below) as "blowing away the walls [of the listening space]" and "transporting" them to the recording venue. No longer mutually exclusive is the life-like tonality for all listeners along with accurate localization for those one or two described as "serious" on the median plane.

As with any new technique, recording engineers will find that some relearning is necessary. Microphone positioning, choice of Transformation mode (changeable in post), and use of (need for) spot microphones have been mentioned above. Work is ongoing to refine the microphone array is used. Generally, channel level calibration is similarly critical to 5.1/6.1.

Different from 5.1/6.1, timbral robustness of PerAmbio 3D/2D varies less with recording venue. For example in reverberant recordings, coloration of stage (direct) sound is less prominent because the diffuse sound captured in 3D has more influence [21].

While correct stage localization is contributed partly by Ambisonics, it is the Ambiophonic contribution that dominates, but only for one or two "serious" listeners on the median plane. Ambiophonics degrades away from it, but there, overall timbre is largely unaffected due to Ambisonics' predominance, so listeners off median do not feel deprived. For them, the listening area is actually a larger proportion of the listening space than for 5.1/6.1 since any one surround speaker is operating at lower level and therefore may be more closely approached before it is localizable. Timbre and spatial effects are quite listenable even outside the speaker sphere.

Transformation may in the future be implemented in a hardware encoder or audio workstation software, as currently implemented by the author. Similar to common practice, monitoring in stereo, 5.1/6.1, and 3D will reveal the need for changing the transformation mode, adjusting relative levels of stage v. ambience components, and other compensations.

After mastering, the tri-play recording can be released on DVD-A, SACD, or DTS-ES Discrete CD or DVD-V. DVD-A standards are met because the six channels are the speaker feeds. 6 channel broadcast e.g. for HDTV is possible when AAC is implemented.

7. REPLAY IN A HOME THEATER

Produced as above, the transformed 3D/2D release plays directly and uncompromisingly in 2D stereo or 5.1/6.1 (5.0/6.0 in absence of a 0.1 LFE media channel). No decoder or other alterations are needed for an ITU-standard home theater until 3D capability is desired. The release is "3D-ready" until that time.

7.1. 3D Reconstitution

When the home theater owner chooses to install 3D, speakers and power amplifiers must be added, as below. "Reconstitution" of 3D is performed by a decoder (e.g. DSP chip in a receiver now in prototype form) that applies the inverse of the transformation matrix chosen for the recording. One of six or more reconstitution matrices may be automatically selected if implemented in metadata in mastering the DVD-A. Six reconstitution matrices are in Fig.11 & 12.

--ITU 6.1-to-PerAmbio reconstitution--> {B} noise degradation dB 1.41

{Pi} \ {Sout}:	L	R	C	SC	SL	SR	{Pout}
{Pout}: FL	1.176	0.000					1.00
FR	0.000	1.176					1.00
W			0.624	0.208	0.416	0.416	0.71
X			0.679	-0.679	0.000	0.000	0.50
Y			0	0	0.784	-0.784	0.50
Z			0.294	0.882	-0.588	-0.588	0.50
Reconstitute {P}	min/max		-0.784	1.176	{Pout}-{Pin}= 0		{P}x{Sout}

--ITU 6.1-to-PerAmbio reconstitution--> {B} noise degradation dB 1.41

{Pj} \ {Sout}:	L	R	C	SC	SL	SR	{Pout}
{Pout}: FL	1.176	0.000					1.00
FR	0.000	1.176					1.00
W			0.624	0.208	0.416	0.416	0.71
X			0.679	-0.679	0.000	0.000	0.50
Y			0	0	0.784	-0.784	0.50
Z			-0.294	-0.882	0.588	0.588	0.50
Reconstitute {P}	min/max		-0.882	1.176	{Pout}-{Pin}= 0		{P}x{Sout}

--ITU 6.1-to-PerAmbio reconstitution--> {B} noise degradation dB 2.66

{Pk} \ {Sout}:	L	R	C	SC	SL	SR	{Pout}
{Pout}: FL	1.176	0.000					
FR	0.000	1.176					
W			0.609	-0.352	0.703	0.703	0.71
X			0.861	-0.497	-0.182	-0.182	0.50
Y			0	0	0.679	-0.679	0.50
Z			0.000	1.358	-0.679	-0.679	0.50
Reconstitute {P}	min/max		-0.679	1.358	{Pout}-{Pin}= 0		{P}x{Sout}

Fig.11 - 4x4 matrix {P} (lightly shaded) reconstitutes six PerAmbio 3D modes i, j, & k without loss for fully periphonic 3D surround.

--ITU 6.1-to-PerAmbio reconstitution--> {B} noise degradation dB 1.41

{Pi'} \ {Sout}:	L	R	C	SC	SL	SR	{Pout}
{Pout}: FL	1.176	0.000					1.00
FR	0.000	1.176					1.00
W			0.624	0.208	0.416	0.416	0.71
X			0.735	-0.147	-0.294	-0.294	0.50
Y			0	0	0.784	-0.784	0.50
Z			-0.085	1.104	-0.509	-0.509	0.50
Reconstitute {P}	min/max		-0.784	1.176	{Pout}-{Pin}= 0		{P}x{Sout}

--ITU 6.1-to-PerAmbio reconstitution--> {B} noise degradation dB 1.41

{Pj'} \ {Sout}:	L	R	C	SC	SL	SR	{Pout}
{Pout}: FL	1.176	0.000					1.00
FR	0.000	1.176					1.00
W			0.624	0.208	0.416	0.416	0.71
X			0.441	-1.029	0.294	0.294	0.50
Y			0	0	0.784	-0.784	0.50
Z			-0.594	-0.425	0.509	0.509	0.50
Reconstitute {P}	min/max		-1.029	1.176	{Pout}-{Pin}= 0		{P}x{Sout}

--ITU 6.1-to-PerAmbio reconstitution--> {B} noise degradation dB 3.08

{Pk'} \ {Sout}:	L	R	C	SC	SL	SR	{Pout}
{Pout}: FL	1.176	0.000					1.00
FR	0.000	1.176					1.00
W			0.609	-0.352	0.703	0.703	0.71
X			0.746	0.249	-0.497	-0.497	0.50
Y			0	0	0.679	-0.679	0.50
Z			-0.431	1.425	-0.497	-0.497	0.50
Reconstitute {P}	min/max		-0.679	1.425	{Pout}-{Pin}= 0		{P}x{Sout}

Fig.12 - 4x4 matrix {P'} reconstitutes six PerAmbio 3D tilted modes i', j', & k' without loss and restores any tilt for periphonic 3D replay (+30° shown).

7.2. 3D Speaker Layouts

PerAmbio played in 3D is scalable from 10 to 14 to 26 speakers. At this point, 6 channels of reconstituted 3D become 10 or more speaker feeds (plus redirected bass to a subwoofer). Amplifier power for the two front channels may be 100~200W; 8 or more ambience channel power amplifiers may be 50~100W.

Two front speakers must be of high quality and precisely placed for optimal imaging of staged sources. All other ambience speakers may be satellite-quality, as power requirements are less and pure height cues are >1kHz [18]. 8 ambience speakers is the minimum, for which isotropic positioning is ideal (pair-wise opposite is a good second choice); 12 or 24 speakers may be placed randomly and the decoder told where they are in degrees of azimuth and elevation.

Isotropic choices for 8 speakers that perform well in the author's tests are a cube, bi-square (Fig.2, 7,13), and a modified bi-square after Barbour [18] with UL,UR raised to 60° and DL,DR raised to 30° to be pair-wise opposite and easier to position in domestic settings. 3D replay preserves timbre for all audience members who are not near any speaker. However, this distance may be less – hence the listening area larger – than for ITU 5.1/6.1 as 3D ambience is at lower levels. For serious music listening, two sit in the median plane for added stage localization from the Ambiophonic front pair.

AMBISONIC SPEAKER FEEDS		cosAcosE	sinAcosE	sinE	Speaker placements	
Gen Ambis8 Dec	W	X	Y	Z	Azim°CCW	Elev°Up
LF	0.707	0.707	0.707	0.000	45	0
RF	0.707	0.707	-0.707	0.000	315	0
UL	0.707	0.000	0.707	0.707	90	45
UR	0.707	0.000	-0.707	0.707	270	45
LB	0.707	-0.707	0.707	0.000	135	0
RB	0.707	-0.707	-0.707	0.000	225	0
DL	0.707	0.000	0.707	-0.707	90	-45
DR	0.707	0.000	-0.707	-0.707	270	-45

Fig.13 8x4 Ambisonic matrix (shaded) for bi-square array (after Gerzon).

7.3. Playing legacy ITU 5.1 using 3D Layout

Once a 3D layout has been installed, listening to the user's collection of stereo and ITU 5.1 recordings is a matter of moving back 26% of the speaker diameter (Fig.14), with adjustments by the receiver's DSP for different levels and delays. Center feeds both FL, FR with minimal comb filtering as they are closely spaced.

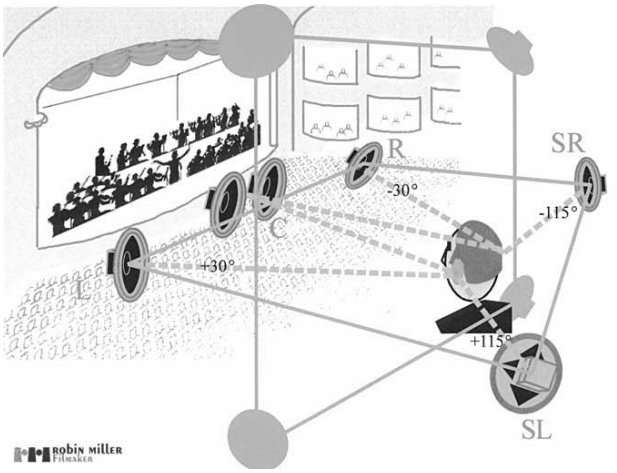

Fig.14 – PerAmbio 3D bi-square layout accommodates audience of six using 10 speakers, plus subwoofer(s). For best 3D music, two listeners sit in the median plane. For 5.1, viewers sit back 26% of the speaker diameter, where angles meet ITU standards (DSP changes levels/delays).

8. PerAmbio 2D/3D DEMONSTRATIONS

At AES114th Convention March 2003 Amsterdam, The Netherlands, attendees heard PerAmbio 3D/2D reproduced on 5.1 (courtesy Meridian Audio) and 6.1 (courtesy Genelec) systems of high quality. The demonstration of a Vivaldi guitar concerto began in 2-channel stereo and switched midway to 5.1/6.1 transformed from 3D. During the stereo portion, attendees could easily hear that moving slightly off the median plane caused the guitar to "toggle" from a phantom center to the nearer speaker. Upon switching to transformed PerAmbio 2D, two major improvements were observed. First, the center guitar image stabilized and attendees were able to walk freely in the listening space (except near a speaker). Second, the tonality of guitar and orchestra became "natural."

In 3D, the author led the Ambiophonics Team in a multi-format comparison demonstration at the AES 24th International Conference June 2003 in Banff, Canada [22]. Switching simultaneously made recordings among 19 speakers, approx. 100 attendees compared stereo, ITU 5.1, Ambiophonics 2.0 with hall convolution [23], PanAmbio 4.0, and PerAmbio 3D. OCT [9] was used for ITU 5.1/6.1 and the system described here and in prior papers [6,7] for PerAmbio 3D.

In Banff, George Massenburg told the author "PerAmbio wins hands down – you really make your point [about the importance of height/3D]." Jean Marie Geisjen: "I like PerAmbio best, but 5.1 was close." Tomlinson Holman: "I liked 5.1 best for timbre [but] PerAmbio second because of height effect." David Griesinger: "Nice sounding 5.1, but in the "sweet spot" Ambiophonics does what nothing else can - you are there." David Josephson: "PerAmbio is most impressive; 5.1 second." Jim Barbour: "The addition of [PerAmbio] is a great idea...and sounded great...imaging with crosstalk cancellation is sensational."

While these listening "tests" are informal, in both Banff and the author's studio in Bethlehem PA USA the response upon hearing PerAmbio 3D is typically wide-eyed and smiling, if not a jaw-dropping. Pianist Fr. Seán Duggan: "It puts you in the middle of the performance." Oboist Lisa Kozenko: "Finally it's my sound after all these years." Audiophile James Robertson: "I can't tell which speakers are playing." and "It doesn't sound like THIS [control] room, it sounds like THAT [studio] room!" Composer Howard Moscovitz: "This is the way [surround] is going to be." Conductor Donald Spieth: "I want it; when can I have it?"

ANOVA testing is planned to confirm results.

9. CONCLUSIONS

A new system has been developed called PerAmbio 3D/2D that is capable of life-like 3D sound with correct spatial impression, timbre AND localization – and that plays compatibly in stereo, 5.1/6.1 2D, and full 3D using available 6-channel media and 10 or more speakers in a home theater or height-modified cinema. The results have been praised by recording engineers, musicians, and audiophiles in informal tests and demonstrations.

Market-driven as well as technical questions remain: As ITU 5.1/6.1 surround sound continues to achieve market acceptance, will that audience demand 2D surround music recordings of higher quality? Will they want 3D in the future? The author concludes that they will if led by engineers, producers, and artists who provide them access to 3D via extensible recordings, delivery standards, replay systems, and compelling

content. The choices available with PerAmbio 3D/2D would add value for users, entertainment providers, and equipment manufacturers of tri-format recordings on 6-channel DVD-A, SACD, or DTS-ES Discrete CD/DVD-V and replay equipment for music-only, movies, virtual reality, amusement rides – and in the future for 3D ATV broadcasts, movies, and Internet Webcasts.

Issues include relearning by practitioners, providing 3D broadcast delivery standards (e.g. AAC 6.1 channel for ATV), hardware implemention, and avoiding onerous complexity for users – although some might feel that "10 speakers must be twice as good as 5!"

PerAmbio 3D/2D is practical today, offering compatible "tri-play" stereo, ITU 5.1/6.1, & 3D using any of the current 6 channel media formats (DVD-A, SACD, or DTS-ES Discrete CD/DVD-V) and a tri-play user speaker layout. In sum, PerAmbio 3D/2D offers a unified system of recording, release, and user implementation that plays with no decoding on standard 5.1/6.1 horizontal 2D surround systems today, or with a decoder on fully periphonic 3D systems tomorrow.

10. ACKNOWLEDGEMENTS

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Appendix A – family of Ambiophonics

PerAmbio 3D/2D belongs to the Ambiophonics family, championed by Ralph Glasgal, including:

- Ambiophonic 2D [16] – 2.0 channels to 2 or more speakers (+SW) with hall convolution (Fig.15);
- PanAmbio (panor-ambiophonic) 2D [12] – 4.0/4.1 channels to 4 or more speakers (+SW) (Fig.16);
- PerAmbio (periphonic ambiophonic) 3D [7] – 6.0/6.1 channels to 10 or more speakers (+SW).

Ambiophonics works with pinnaless binaural records but enhances many stereo releases, adding 3D ambience by hall convolution, and presenting a wide, accurate stage with no pinna confusion for central voices. Also compatible with 5.1/6.1, specially recorded PanAmbio (2D) and PerAmbio 3D/2D releases allow music lovers and audiophiles a greater level of listening precision.

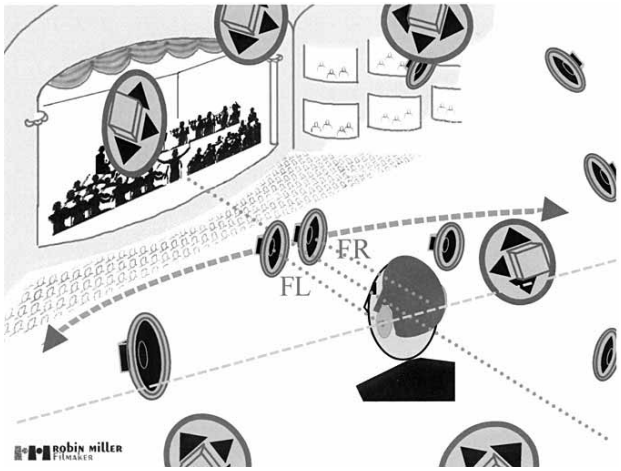

Fig.15 - Ambiophonic 2.0 turns stereo "inside-out," reproducing a 120° wide, accurate front stage. 3D ambience is added by convolution using hall impulse response. Many stereo recordings play compatibly in Ambio.

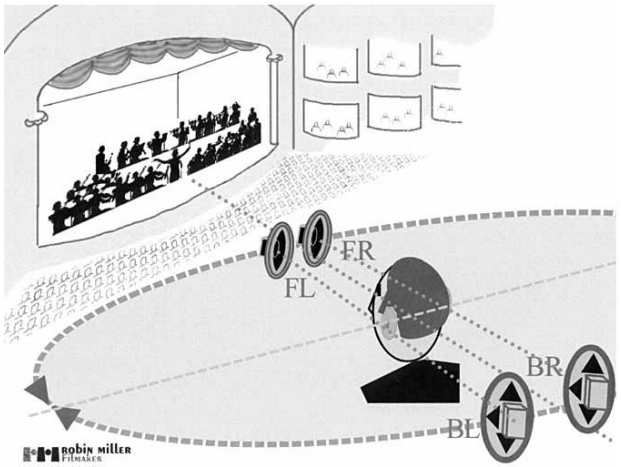

Fig.16 - PanAmbio 4.1 duplicates the wide front stage in back, "pulling" sides to the edges of the "cone of confusion" of hearing. 2D recordings made with two ambiophones play compatibly on 5.1/6.1 systems.

Because they are more precise, all ambiophonic playback requires good listening acoustics [24]. For PerAmbio 3D:

- Acoustically treated room with RT less than recording venue and symmetrical layout of the speaker sphere with listeners seated near the center;
- Two high quality speakers plus 8+ satellite-grade (total of 10 speakers or more) plus subwoofer(s);
- DVD-A/SACD/DVD-V/CD DTS-ES Discrete player with 6 full range channels;
- Decoder* that selects the transformation mode;
- Crosstalk-canceller* for front speaker pair;
- Bass manager accommodating 10+ speaker feeds;
- 2 higher and 8 or more lower power amplifiers;
- Calibration of channels at listening position within ½dB using an SPL meter and filtered pink noise.

* possible on a DSP chip, now in prototype form. A number of listeners not near any one speaker can enjoy

the enveloping 3D, but only one or two on the median plane will hear accurate 120° wide front localization. Mixes intended for ITU 5.1/6.1 can be enjoyed by simply moving back 26% of the speaker diameter – see Fig.14.

Appendix B – WFS & Ambisonics

A development of Delft University [25] and IRT [26] is Wavefield Synthesis (WFS) – a 2D surround recreation of either plane wave (distant) or point sources even within the speaker array. WFS has been installed in a special purpose theater and may be practical soon elsewhere, but it requires many speakers and channels. Since it is 2D (horizontal only), it cannot reproduce height, but a hybrid system is also possible.

Used in PerAmbio 3D, Gerzon [17] approached wavefield synthesis in 1985 using an omni (W) and three bi-directional microphones aimed forward, leftward, and upward (X, Y, & Z). Four recording channels (B-format, 1st order) supply a unique hypercardioid signal to any number of speakers given their position in degrees Azimuth A and Elevation E as follows:

$$s_{A,E} = 0.5W + \cos A_n \cos E_n \bullet X + \sin A_n \cos E_n \bullet Y + \sin E_n \bullet Z$$

Ambisonics can be created by assignment, e.g. monaural dialogue or effects using a 3 dimensional pan pot, much as 5.1 can by a 2-dimensional one. 1st order B-format (4 channel) stems of music or ambient sound effects can be combined to a 4 channel Ambisonic mix.

While higher order Ambisonics is dawning [27] (9 or more channels), 1st order Ambisonics fails where wavefronts are spherical e.g. close sources or reverberation in small spaces, but farther, reproduction is overly ambient. For more distant plane waves and pan-pot simulation where the pressure channel W is not uncorrelated with velocity components X, Y, & Z, Ambisonics suffers lack of spaciousness, similar to coincident M-S. Good spatial impression requires spaced microphones, such as the Ambiophone.

Hierarchical MLP [28] offers more discrete channels on DVD-A and AAC [29] offers more than five for broadcast. For current 6 channel media, Ambiophonics combined with Ambiophonics – PerAmbio 3D – has envelopment + frontal imaging + spatial impression.

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