Audio Engineering Society
Convention Paper 6628

Presented at the 119th Convention
2005 October 7–10 New York, New York USA

Physiological and content considerations for a second low frequency channel for bass management, subwoofers, and LFE

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ABSTRACT

By convention, frequencies below 90Hz produce no interaural cues useful for spatial sound or localization. Yet some claim they are able to hear a difference between a single subwoofer channel (whether or not to more than one subwoofer) and two ("stereo bass"). Reported research supports Jeffress' model of interaural time difference (ITD) determination in brain structures, and extending the accepted lower frequency limit of interaural phase difference (IPD). Meanwhile, uncorrelated very low frequencies (VLF <100Hz) exist in nearly all existing multi-channel music and movie content. The audibility, recording, and reproduction of uncorrelated VLF are explored in theory and experiments.

1. NATURE – THE BEST ENGINEER

Most fields of engineering that are concerned with a human interface – the range includes automobile design and airplane avionics as well as audio reproduction – can benefit from a study of human biology. For example, binaural neurons in the lower and mid-brain are chemo-electrical "operational amplifiers" complete with inverting as well as non-inverting inputs for differentiating Interaural Level Difference (ILD) and Interaural Time Difference (ITD) [1,2] and discussed in this paper as they apply to low frequency sounds. Other mammals and birds with hearing systems similar to ours provide measurements and understanding of the way human hearing works. The question of binaural perception of frequencies below 100Hz is answered in part by scaling to human HRTFs research using anesthetized mammals and birds. The results, confirmed by informal listening tests in the range 25~100Hz, are both exciting to the scientist and important for high quality audio reproduction.

In the vernacular termed "stereo bass," this paper explores the importance of binaural reproduction of audio at very low frequencies (VLF), namely:

1. Is it possible physiologically to perceive binaurally in the VLF range 16~100Hz?
2. Is reproducing bass frequencies binaurally discernible? Better sounding?
3. Does music CD and multi-channel movie DVD content support stereo bass?

The answer "yes," to all three questions above would have implications for high quality audio manufacturers, content producers, and home theater users.

2. BINAURAL PERCEPTION OF VERY LOW FREQUENCY (VLF)

Birds have remarkable abilities in detecting and interpreting low and infrasonic (in human terms) sounds – or, perhaps more precisely, comparing changes in air pressure side-to-side [3]. Birds in flight use pressure sensors in the feathers of both wings (analogous to piton tubes on aircraft) to control stability of flight. These same sensor pairs in migratory birds detect low and infrasonic ocean surf in order to navigate along coastlines when unable to see at night. Pressure changes at the rate of barometric weather patterns help them to avoid storms and to engage in feeding frenzies in preparation for waiting storms out. While these frequencies on the order of fractional Hz are *on the other side of the decimal point* from those sound engineers normally consider, they are an overture to binaural very low frequency hearing in mammals, including humans, as explored below.

For human audition, the range 16~100Hz is important because it encompasses 2⅔ of 10⅓ octaves 16Hz~20kHz normally accepted as audible. Considering musical frequencies, this range includes fundamentals of celli and timpani (>65Hz); bass violins and guitars (>33Hz); piano and bass drums (>27Hz); organ pedal tones (>16Hz); etc.

Frequencies below 16Hz are regarded as inaudible, but nevertheless relate to human binaural hearing. For example, states of consciousness ranging from *asleep* to *awake* as recorded by electroencephalogram (EEG) show characteristic "brain-wave" frequencies ranging from 1Hz~30Hz. These states are thought by some to be inducible as a Frequency Following Response (FFR) when listening binaurally to audible "carrier" sounds differing by 1~30Hz, their beat (difference) frequency being the FFR stimulus [4,5].

Musically, consider what happens when a bass violinist creates vibrato (Fig.1a). Direct sound at 41Hz (plus harmonics) arrives from the concert listener's right. At some later time, a reflection from the left wall arrives from the listener's left, while new vibrato tone, say 42Hz, arrives from the bass viol on the right. These arrivals, differing by a beat frequency of 1Hz, plus harmonics beats and other directional reflections combining in a "chorus" of sounds from a single source, contribute "envelopment" prized by live concert goers that would be appreciated just as much by home theater listeners if reproduced.

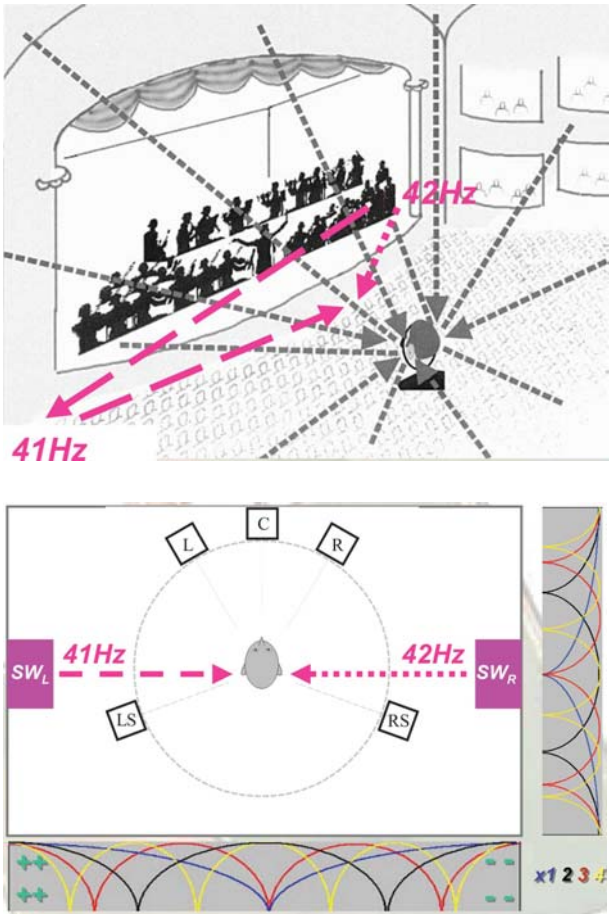

Fig.1 a) In acoustic spaces as the room "catches up," sounds of different frequencies arrive at a listener from different directions although generated by a single bass viol's vibrato. b) "Home theater" experiment discussed in section 6 to subjectively test audibility of this phenomenon using two subwoofer channels.

3. RECORDING V. LISTENING ROOM SPATIALITY

If in a large reverberant listening room a non-reverberant monaural recording of a bass violin is played through a loudspeaker placed where the instrument might be localized, spatial qualities of the listening room will also be heard. In this way, the listening space can superimpose its spatiality onto the recorded spatiality, or can substitute for it if weak or absent. This is practiced in the popular music recording style *musicians are here*, resulting in close-miked sources appearing to come from the speaker boxes [6,7].

For constant listening acoustics, the recording engineer controls whether the *musicians are here* or the *listener is there* by varying the spatiality of the recording. If the spaciousness of the recording is significantly less than that of the listening room, *musicians are here*; if the spaciousness of the recording is the greater, then *listener is there*. This *you are there* case is what the author means by "lifelike" reproduction. Rather than every recording sounding like the listening room ("intimate" but same-sounding), each recording sounds more like its real venue (you get to travel).

If the listening room is reverberant and large enough, one SW could produce binaural VLF spatiality due entirely to the listening room acoustics. Preferably however for *listener is there* results, the listening space is acoustically controlled, especially regarding its low frequency modal resonances (Fig.1b). Rather than adding much of its own VLF spatiality, this allows the recording spatiality to dominate. In this case, binaural bass management (BBM) and two (or even numbers of) subwoofers would be required, assuming that recorded VLF information imparts perceptible spatiality (Fig.2). The premise explored in this paper is: *If humans can perceive any difference hearing binaural v. monaural spatial cues in the VLF range, then it may be important for highest quality audio reproduction that bass management and subwoofers be two-channel.*

4. CONVENTIONAL WISDOM – STEREO BASS FOR 5.1

Traditionally, main channel speakers are full range and subwoofers are not used. However, with five or more main channels, this practice is expensive. Also, full range speakers are often not positioned in the listening room where modes (eigentones) are advantageous.

Conventional practice in most home theaters today is to redirect bass ("bass management") from all main channels to a single (monaural) subwoofer channel, even if to more than one subwoofer [8]. The turnover frequency is chosen as a compromise between the low-end capability of the satellite speakers, 5 or more for multi-channel surround sound, and the high-end onset of localizing the subwoofer (SW). Mid-range audio receivers typically fix this frequency at 100Hz, although higher-end equipment offers a selection, ranging from 40~160Hz. "Surround-in-a-box" makers may be secretive about their crossover frequency, but for one it has been measured to be 90Hz with little output 90~200Hz to avoid overdriving tiny satellite speakers. Adding confusion, one SW maker advertises "stereo bass management" as redirecting L and R (i.e. stereo) channels even though to only one SW (monaural). Actual 2-channel bass redirection is illustrated in Fig.2.

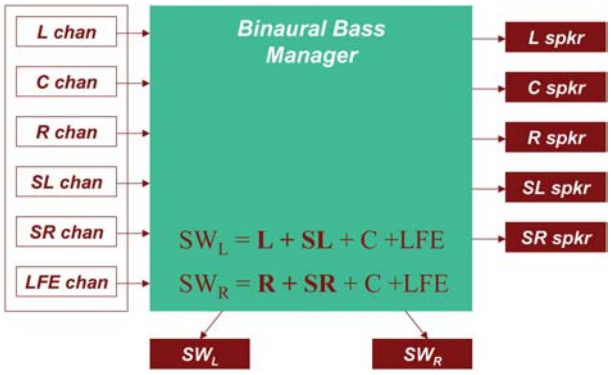

Fig.2 Block diagram of a binaural bass manager illustrates redirecting VLF from main channels to a subwoofer in the same hemisphere. Daisy-chaining four subwoofers offers additional possibilities for "positional-equalizing" listening room modes.

As said, an important distinction is whether spatial VLF information originates in the recording or in the listening room. Assuming transparent listening acoustics that are less reverberant ("drier") than the recording venue, intending a *listener is there* rather than a *musicians are here* impression, preserving low-frequency binauralism will be explored below in pursuit of lifelike audio reproduction. However, pursuing lifelike sound implies advancing other aspects of audio reproduction, perhaps in the future beyond 5.1/6.1/7.1, for example using Wavefield Synthesis (WFS) [9,10], Ambiophonics [11~17, www.ambiophonics.org], or High Sonic Definition (HSD) full sphere 3D (with height) [14,15,16, Appendix, www.filmaker.com].

5. THE CASE FOR PERCEIVING SPATIALITY 40~100HZ

While prior consensus is that VLF signals <100Hz have limited usefulness for humans for localization, it may be an error to assume that they therefore have no spatial qualities at all [18,19]. Any perceived difference means the difference between "live" impression and "just a recording." It is also an error to assume that content in music and movies does not already contain binaural cues at low frequencies, as will be shown below.

How might humans be physiologically equipped to hear binaural cues below 100Hz? Human brain structures contain "delay lines" and "coincidence detectors" precisely for the purpose of determining Interaural Time Difference (ITD) at frequencies below approx. 700Hz, where the ear-to-ear dimension is on the order of ¼ wavelength. Note that, considered on the logarithmic scale of 10 octaves of audible frequencies 16Hz~20kHz, 700Hz is midway, dividing the lower 5 octaves of ITD-dominated sounds from the upper 5 octaves that are dominated by Interaural Level Difference (ILD). So the ITD domain is half the audible range.

To continuously "measure" ITD, termed "running cross-correlation" by Blauert [20], the Medial Superior Olive and Inferior Colliculus of the brain process ipsilateral (near ear) and contralateral (opposite ear) signals, as illustrated in Fig.3, after the well-established model proposed by Jeffress in 1948. As shown, a direct sound just left of center initially strikes the left ear, is transduced, and starts down a neuron "delay line" L. At some later time, the sound rounds the head to the right ear, is transduced and starts up delay line R. Where these two signals meet, a binaural neuron representing "left-of-center" fires upon coincidence of their phase, and reports this to higher levels of the brain cortex for adaptive processing and conscious perception of *localization*. Many such binaural neurons, each able to fire accurately within 20° of interaural phase coincidence, are further sharpened in accuracy – by statistically adding their responses, along with complex inter-neural inhibitory and excitatory interactions that apply dynamic gain that favors a so-called "Best Phase" (BP) response approaching the predicted 0° to within approx. 5°, as illustrated in Fig.4. Then, higher brain structures apply adaptive responses to reach accuracy on the order of ±1° of azimuth (10μs ITD) that is commonly accepted as the limit of horizontal localization resolution.

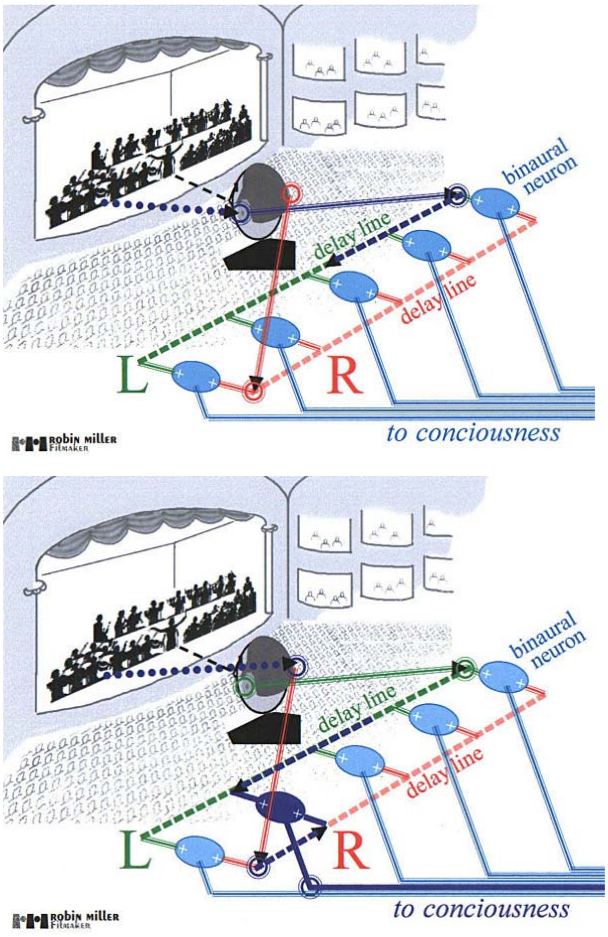

Fig.3 – „Coincidence detection" by binaural neurons in the brain exhibiting ~20° phase accuracy determines ITD <700Hz. a) A sound left of center is transduced by the left ear and signals down neuron delay line L. b) Soon after, the signal transduced at the contralateral ear travels up neuron delay line R, where a binaural neuron fires, indicating to consciousness that the sound is left of center. But how well does it work <100Hz?

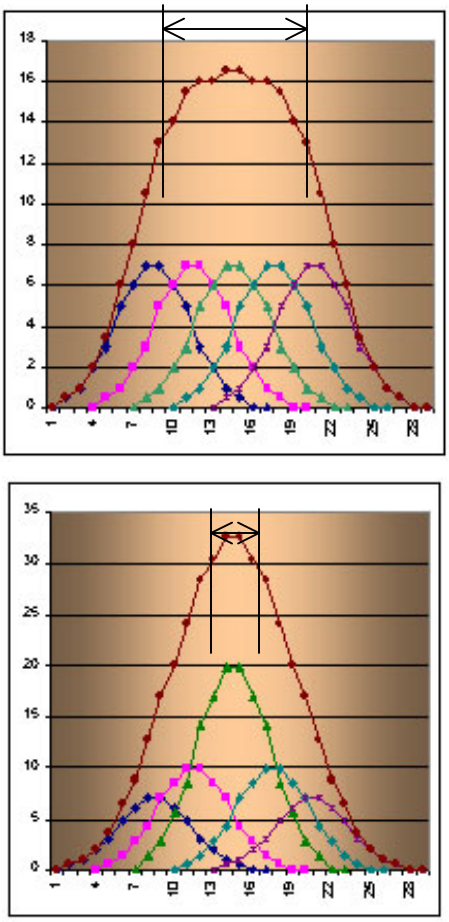

Fig.4 – a) Beyond summing the Gaussian response of many binaural neurons (five shown), b) mammals sharpen localization to a "Best Phase" response by applying contralateral inhibition and excitatory and adaptive "gain" illustrated in this model to reach accuracy on the order of ±1° horizontally. (Barn owls have vertically offset ears in their eye sockets to sharpen vertical localization as well, enabling them to prey in the dark.)

This ITD mechanism in humans and other mammals is truly marvelous, deserving the attention of audio engineers. But the question is: How low in frequency does this ability to localize extend? And even if accuracy diminishes at lower and lower frequencies, at what point does it cease to be a determiner of lifelike hearing? After all, the accepted limit of ITD resolution of 10µs represents only 6° of phase of a 40Hz tone. The correlation is the cosine, or 99.4% "monaural." Can we hear any spatiality in phase differences this small?

In recent research by Palmer et al, the Jeffress model has been confirmed by observing binaural signals introduced into guinea pigs and cats [21,22]. Cats and guinea pigs have neural auditory transduction and processing systems in their brains that are very similar to humans. Binaural neuron responses to low frequency sounds were observed using EEG under anesthesia. The results are that a cat's Best Phase extends to 190Hz, which when scaled to approx. four times larger human interaural dimension is equivalent to 48Hz. A guinea pig's BP extends to 250Hz, or 42Hz in human terms.

If human response can be inferred from cats and guinea pigs, binaural response in the octave 40~80Hz may be possible where heretofore it was considered impossible or negligible. Perhaps it is not accurate localization *per se*, but any noticeable difference heard – even subtly perceived as "just a recording" – is important for high quality audio reproduction.

6. INFORMAL LISTENING TESTS – BINAURAL 25~100HZ

The author's research into binaural VLF hearing began with the discovery of fuller low bass sounds during mixing of recordings using stereo bass management monitoring with two subwoofers on either side of the control room. Subsequently, the author championed a multi-format comparison demonstration at the AES 24th International Conference on Surround Sound in Banff, Canada in June 2003 [23] using stereo bass management and two subwoofer channels and speakers, and again observed less pleasing results when the subwoofers were switched (paralleled) to monaural.

More exhaustive, independent analysis (e.g. ANOVA) is needed to confirm the hypotheses in this paper. Preliminarily, an experiment was conducted using 1) a recorded sweep from 160Hz to 16Hz, first in monaural, then in stereo, for training; and 2) a recording with 1/6 octave steps descending from 100Hz to 25Hz center frequencies, alternating 7s monaural with 7s stereo. In the stereo bursts, channels differed in frequency by 1Hz. The monaural bursts summed the stereo channels so that the monaural result exhibited undulating level due to cancellations and reinforcements at the beat frequency of 1Hz. In this way, the only variable in the experiment was whether the higher-than-center and lower-than-center frequency signals were mixed electrically (monaural) or psychoacoustically (stereo). Any audible difference within each pair of bursts at each frequency step – whether obvious or subtle – could be attributable to binaural audition – and would, more or less, indicate that stereo bass was valid in the range of that step.

Six experienced audio and music professionals participated. Subwoofers capable of 18Hz –3dB and calibrated for 85SPL (minimizing any localizable distortion products) were placed at mid side walls, in order either to cancel or not excite all odd order lateral and medial modes, respectively [24], of a laboratory at FilmakerTechnology built as an „typical“ (USA) home theater – wood paneled and carpeted, 18x14x9.4ft (5.5x4.3x2.9m), with R_T = 0.46s at 31.5Hz, 0.33s at 63Hz, and 0.28 at 125Hz. Positioned as in Fig.1b, only even order modes at 63 and 79Hz were within the test range 25~100Hz so that spatiality due to listening room modes was minimized. As discussed above, it is usually preferable that listening acoustics are transparent in order to preserve spatiality captured in the recording [7].

The sweep recording 160~16Hz, first in monaural then in stereo, was used to train the listeners to hear the difference in spatial effects (along with any residual room mode artifacts) come and go as the sweep descended in frequency. The higher range of frequencies exhibited markedly more "externalized motion"-effect in stereo, which sensitized auditioners to detect that effect even if diminished at lower frequencies. Then the listeners evaluated the 13 step pairs descending in frequency from 100Hz to 25Hz, rating them *"0~4"* ("no effect" to "maximum effect") for spatiality, described as a definite out-of-head sensation of "motion."

Switching was not exactly "blind," as the auditioners quickly determined what was happening, – but it was unanimous that they heard a noticeable change – an improvement in spaciousness and envelopment when each pair of steps changed from monaural to stereo and down to 45Hz. The results were most effective at 56Hz and higher, receiving ratings of *"3"* or *"4,"* then diminished in effect at 50Hz (*"2"*) and 45Hz (*"1"*). No spatial impression was reported at less than 45Hz. Subjects described the monaural impression as merely "varying level" at the 1Hz beat frequency, and sometimes "strongly" and "uncomfortably" localizing in-head. In contrast, they described the binaural impression as "subtly" (=1), "moderately" (=2,3), or "strongly" (=4) enveloping, adding comments such as "swirling" around the room, or like a slowly revolving audio "hula-hoop"® around the head. Additionally, peaking of SPL at room modal frequencies, pronounced as expected while playing monaural bursts, were far less pronounced during stereo bass – a desirable bonus of smoothness in the VLF range.

Full range music recorded using spatial microphone techniques [25,26] with a head-spaced main microphone (PanAmbiophonic 4.0 [7]) was described as "lifelike," "more natural," "transparent," "less fatiguing," and "integrated with high frequency components" of the sound – important because subwoofer sounds were ipsilateral with harmonic sounds from the main channels. It was also observed that, with ipsolateral SW sounds, any localizable distortion products from the SWs, to which higher frequencies human hearing is more sensitive, would not, for example, alias as a reflection somehow arriving earlier from the farther (wrong) side. Widely-spaced microphones such as those advocated by Griesinger [27] would produce a more pronounced effect; coincident microphones, none. All participants expressed that they now desired stereo bass management and two subwoofers for themselves!

In demonstrations with presentations of this paper at the 23rd VDT Tonmeisters in Leipzig, November 2004, and to the combined Acoustical Society of America and Canadian Acoustical Association in Vancouver, May 2005, the descending 13 step test 100~25Hz was played using two 18in (45cm) drivers at the mid side wall positions. As above, each step was played first by mixing tones differing by 0.5Hz electrically so as to drive the subwoofers in monaural, then unmixed to reproduce VLF binaurally. At VDT by a simple show of hands, nearly all of approx. 40 attendees reported at 100Hz perceiving no "swirling motion" in monaural, but a definite "impression of motion" in stereo. Half the attendees heard "motion" down to 50Hz, 1/3 heard to 45Hz, and 1/5 heard to 40Hz. At ASA/CAA, again half of approx. 70 attendees reported perceiving "motion" to 50Hz, 1/3 heard to 45Hz, and ¼ heard down to 40Hz.

7. STEREO BASS IN EXISTING CONTENT – CD AUDIO & DVD MOVIES?

The case above for binaural bass would not matter if there were nothing available to the listener by way of content to hear. As it turns out, much if not most existing recorded material, both music and movies, already contains significant stereo bass signals, whether intended by the recording engineer or not, as illustrated below by a survey of oscillographs of stereo bass management of music CDs and the main channels of multi-channel movie DVDs. Therefore, *change* may not be implied in this paper for content producers, other than for monitoring the potential improvement in sound quality. As shown, uncorrelated VLF exists in stereo

music CDs and multi-channel movie DVDs – in the main channels, not the LFE, of course. As a side note, the survey of oscillographs below found LFE was sparingly used, and then only for very occasional explosive impulses, intended apparently to thump the chest (which because it is central is OK if monaural!). On the other hand, the existence of binaural VLF content in full range main release channels that are now typically processed in home theater systems and control rooms using bass management, whether in the receiver or separate bass manager, suggests that VLF reproduction should be two channel, feeding two (or even numbers of) subwoofers, positioned generally to the left and right of listeners.

Typical of most movie sound effects observed, from *Planet of the Apes II,* Fig.5 a) & b) dual- trace oscillographs of binaural bass manager outputs compare a 19Hz "eject" sound effect with and without mixing in the LFE. Since there is no difference, the LFE was not used in this instance. Fig.6a is a 43Hz "blast" effect with left-right difference modulated at 7Hz, a beat which, although probably synthesized unintentionally by the sound designer, is sub-audible (in the "theta" range of brain waves!). From the movie *Master and Commander,* Fig.7a~d show various binaural "groans," "cannon fire," "sea," and "doom" sound effects – all exhibiting strong binaural difference at frequencies ranging from 29 to 76Hz. (Note: The lighter trace is the FFT of the digital sampling oscilloscope.)

Finally, Fig.6b shows a 35Hz bass drum hit in the opera *Barber of Seville* recorded in Ambiophonics by the author – encoding an 500µs phase difference left of center for a source positioned there during recording and localized precisely during replay. This recording was among those that noticeably drew the author to the more lifelike possibilities of stereo bass.

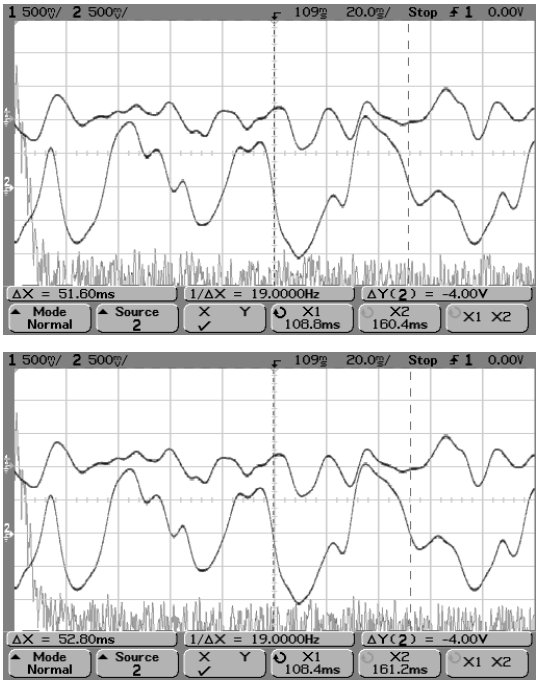

Fig.5 - DSO of stereo bass manager (L trace top, R bottom): a) 19Hz "blast" effect from *Planet of the Apes II* shows strong binaural content; b) mixing in LFE shows it was not used.

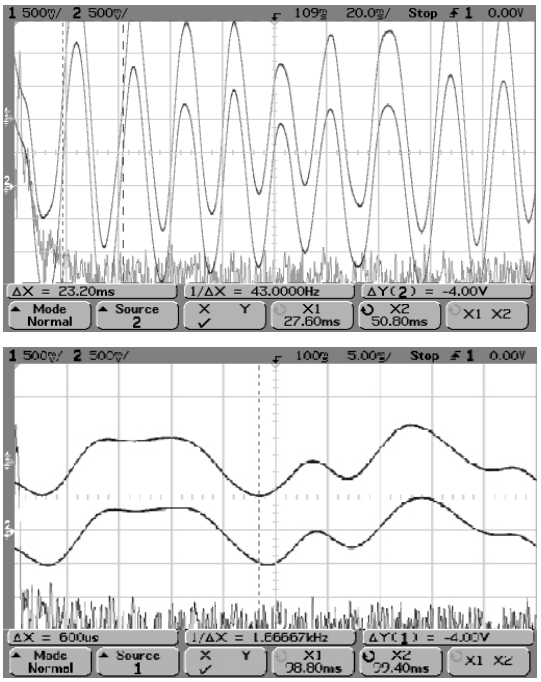

Fig.6 - DSO of stereo bass manager: a) 43Hz "blast" shows left & right channels difference-modulated 7Hz; b) 35Hz bass drum exhibits left leading 500µs for precise left-of-center localization.

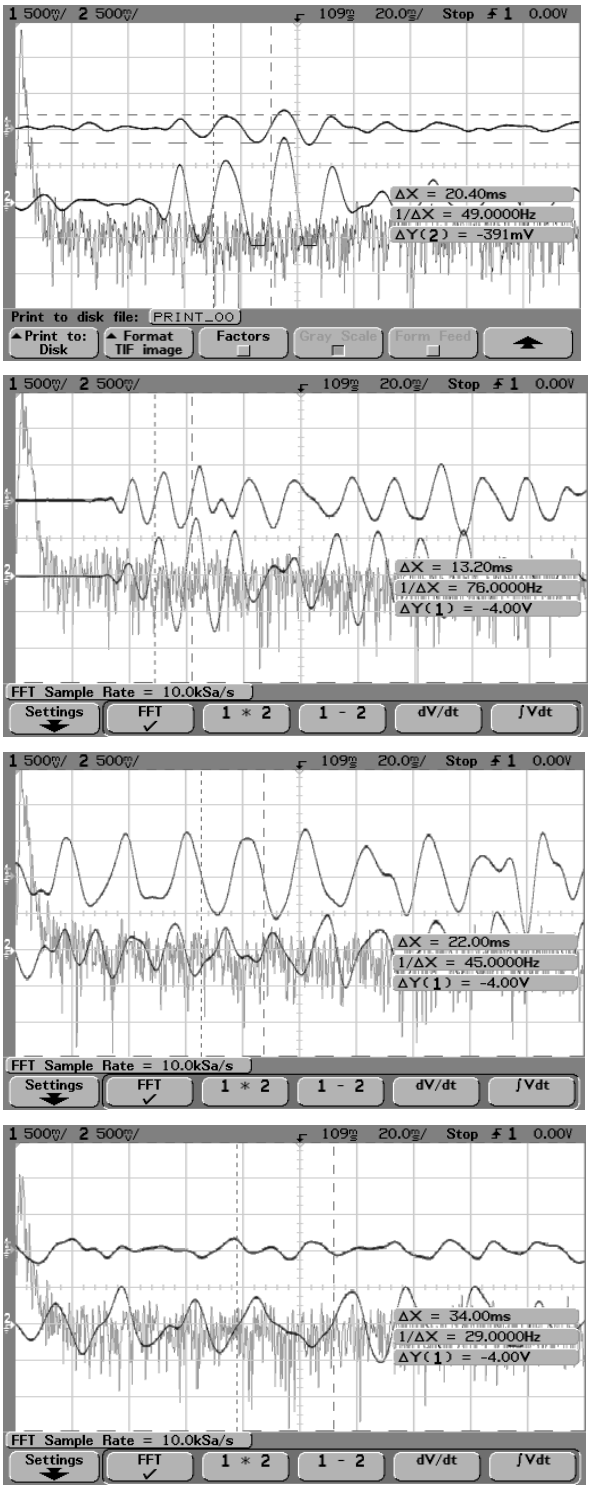

Fig.7 - DSO of stereo bass manager shows main channels of movie *Master and Commander* exhibiting binaural VLF: a) 49Hz "groan;" b) 76Hz "cannon;" c) 45Hz "sea:" d) 29Hz "doom."

8. IMPLICATIONS FOR BASS MANAGEMENT, SUBWOOFERS, & LFE FOR HIGH QUALITY AUDIO

A case in favor of two subwoofer channels implies paradigm changes for high-end users and audio receiver, bass manager, and subwoofer manufacturers and resellers – but possibly little change if any for content producers, as described below, because most existing content and practice already includes significant stereo bass information <100Hz, ready for users to enjoy by implementing appropriate hardware. However, standards [28] and common practice [29,6,8] have precluded stereo bass implementation and therefore reproduction. As of this writing, no mainstream audio receiver could be found incorporating stereo bass management. Only one stand-alone stereo bass manager (Outlaw ICBM) was found. While larger home theaters may have more than one subwoofer, they are fed from a monaural SW channel. Adding confusion, one SW maker advertises "stereo bass management" as redirecting both L and R (i.e. stereo) channels even though to only one SW (monaural). Actual 2-channel bass redirection is illustrated in Fig.2.

Using binaural bass reproduction as described in this paper, it is possible to raise the crossover frequency because the onset of localizing the subwoofers in either left or right hemisphere might be acceptable. In effect this onset is the first approximation of localization at the lowest frequencies, naturally accurate ±90º horizontal. This in turn allows smaller satellite speakers to be used for the main channels. If, as in home theater in a box, small satellite speakers are used already, output in the range from 90~200Hz might not need to go missing.

LFE (the "0.1" media channel) is a separate issue. Although it might seem that "stereo bass" implies a "5.2" mix, the survey of existing content, above, reveals two facts: 1) LFE is used sparsely in commercial movie content (and is usually not needed in music content); 2) LFE is intended and used sparsely only for a chest-thumping, frontally assaulting, impulsive effect. In the survey, LFE signals were not observed as tonic, nor at frequencies below 70Hz (otherwise fatigue or damage to equipment and ears might result). Since these observations describe transient central/frontal effects, continued use of a single LFE channel for its 10dB of headroom for monaural impulses seems appropriate.

At the low extreme of frequency, the author has discovered no argument in favor of stereo LFE below 40Hz, nor for main channel stereo bass <40Hz for that

matter. This is consistent with standards [28] and common practice [29,6,8] that have precluded stereo bass reproduction generally. Therefore, the impact of findings in this paper might be limited to stereo bass monitoring whereby content producers and audio manufacturers realize the potential of naturally binaural bass reproduction >40Hz for pleasing their customers.

9. LOCATING TWO (OR MORE) SUBWOOFERS – OTHER VIEWS

Two SW channels implies two or four (or more in even numbers) of subwoofers, driven by two channel bass management. In addition to at least doubling costs, conveniently locating these SWs becomes even more complex than positioning one, which is neither intuitive nor fully understood or prescribed authoritatively. For binaural VLF replay, two SWs should be located generally left and right of the listening area. Lateral difference may be maximized by placement at the extremes, i.e. along sidewalls, but front-back symmetry may not be critical binaurally, e.g. front left corner and back right corner, if more convenient or modally advantageous. Corner placement would excite all listening room modes, adding (undesirable?) spatial VLF information due to the room, especially if large.

Details of positioning warrant more discussion than is possible in this paper. Only by way of introduction to related thinking on this complex topic, Griesinger and Welti, presenting with the author at AES 116th Convention in Berlin May 2004 [18,19], AES 117th Convention in San Francisco October 2004, and ASA/CAA in Vancouver in May 2005, have offered approaches to SW positioning that take into account room modes, both laterally and medially (front-back and up-down, if significant). Welti offers a method of "positional EQ" favoring two SWs at mid sidewalls, where all odd order modes are suppressed – laterally by cancellation and medially by non-excitement [24]. In contrast, Griesinger would maximize room effects by overlapping medial pressure modes with lateral velocity modes [30], as shown in Fig.8 for the experimental listening room described above. Also, electronic room equalization may be used. The author has experience with these approaches in many venues and found that EQ and results are highly room-dependent as well as SW position-dependent. In laying out a medium to large listening space, the engineer has a choice whether the sometimes subtle recorded VLF spatiality is augmented (trounced) or not by the listening room.

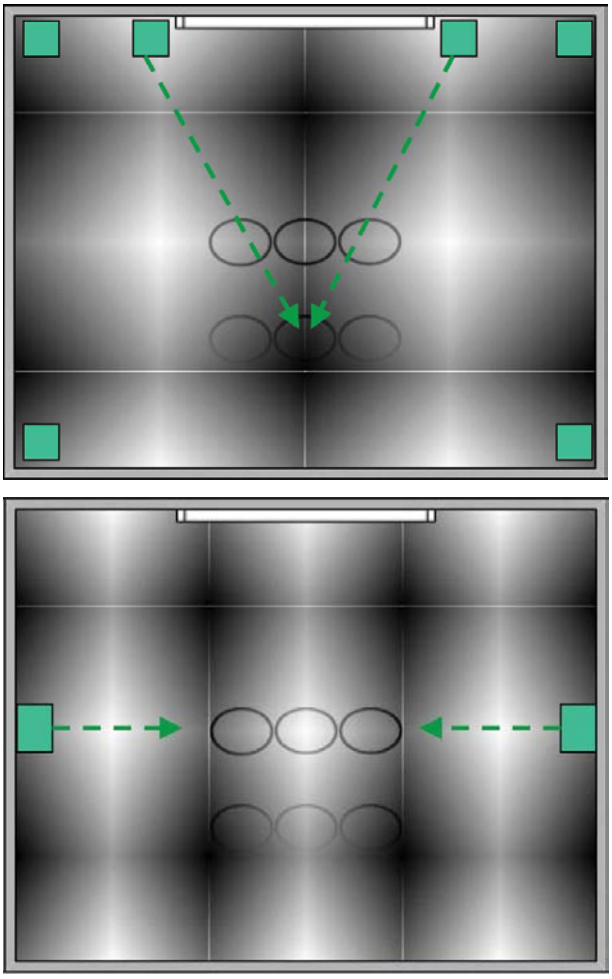

Fig.8 - Overlapping lateral velocity and medial pressure modes [30] shows which of six seating positions are "imprinted" (lighter shade) by the spatial effects of the experimental listening room. a) illustrates Mode 2,2,0 with lateral 63Hz overlapping medial 79Hz, but all seats are largely unaffected. b) illustrates Mode 3,2,0 with lateral 94Hz overlapping medial 79Hz, but the effect at all seats is suppressed because SWs are positioned at mid side walls, where odd order lateral modes cancel (and all odd order medial modes are not excited). Thus, the room is largely "positionally equalized" for transparent spatiality. Additionally, a) shows little modal excitation by stereo speakers positioned normally, but all modes are excited with SWs in 4 corners.

In contrast to "stereo bass", Nousaine [31] has argued that a second SW driven monaurally is perceived as more "enveloping" by virtue only of the approx. +4dB effective increase in SPL from coupling due to double the air displacement of two speaker cones. (His large listening room has eight 15in (380mm) drivers in four corners.) However, this view is consistent in the

author's experience with VLF spatiality contributed by a live listening room, discussed above, vying for or perhaps dominating spatial information in the recording.

The author finds that less than optimal placement of SWs for a given listening space and acoustic treatment can trump binaural bass captured in the recording. However, with optimized listening conditions, the more lifelike effects of stereo bass, even if subtle, are evident and pleasing.

10. CONCLUSIONS

The theory, informal listening experiments, and a survey of content show that:

- Binaural detection by humans in the octave 45~90Hz is physiologically possible;
- Music/movie VLF content exists (no new recording/mixing procedures are demanded);
- High quality reproduction implies two-channel bass management and two subwoofers as in Fig.2 (compatible with stereo, ITU 5.1/6.1/7.1, WFS, Ambiophonics, or HSD 3D as in Fig.9).

In addition, several more subjective inferences follow from use of binaural bass management:

- SW distortion products are more tolerable if ipsilateral (same side) as HF in main channels;
- Music/movie ambience was adjudged by professionals as: "more lifelike, natural, integrated with high frequency components of the same sound in main speakers;"
- Listeners were surprised; they now desire "binaural bass management" (BBM);
- 2-channel LFE (i.e. "5.2") is not warranted for sparse impulsive sounds, nor at all <40Hz;
- Use of two [even numbers of] subwoofers resulted in less pronounced resonance effects from room modes and supports "positional EQ" of the listening space.

The standard practice of precluding redirected stereo bass reproduction is consistent with this research only in having discovered little argument favoring stereo LFE, certainly not below 40Hz, nor for main channel stereo bass <40Hz. However, for greater enjoyment of much existing and new content, there is compelling argument in recognizing significant spatial perception in the previously ignored octave 45~90Hz, and therefore for binaural bass management and subwoofers.

11. ACKNOWLEDGEMENTS

This paper was previously presented at the 116th AES International Convention in Berlin, May 2004, at the 23rd German Tonmeisters (VDT) in Leipzig, Germany, November 2004 [32], and at the 149th International Convention of the Acoustical Society of America and Canadian Acoustical Association, Vancouver, Canada, May 2005. The author is grateful to Ralph Glasgal for his inspiration and wisdom and to the Ambiophonics Institute for support of the author's work. Special thanks to Howard Moscovitz for partnering in the experiments. All trademarks are those of their owners.

APPENDIX - HIGH SONIC DEFINITION (HSD) 3D

Use of binaural bass management in pursuit of more "real" audio reproduction implies advancement beyond 2-dimensional 5.1~7.1 surround toward a 3D future.

We live in a sphere of sound, not the circle of 5.1~7.1. Great rewards for listeners, content providers, and manufacturers look for a time when the speakers and listening room disappear and we are transported to the concert or to the movie or game scene. But listening in the center of a circle of 5.1~7.1 speakers is not as "real" as immersion at the center of the sphere of live hearing.

High Sonic Definition (HSD) is a Pat. pending system including a single point microphone, encoder, decoder and 10-speaker layout [14,15,16] illustrated in Fig.9. HSD simplifies the recording process and downmixes automatically to excellent 5.1~7.1 and stereo, including mp3, without decoder or extra speakers. When ready, the consumer adds the HSD decoder and speakers for lossless 3D reproduction from the same disc. Users may flexibly position speakers, sending them the correct signals by telling the decoder where they are, and have a choice of listening area size. Both producer and user libraries are not made obsolete; either may upgrade to 3D release or replay at will. Also, legacy stereo and 5.1 recordings play compatibly on the HSD 10-speaker layout. More information is at www.filmaker.com.

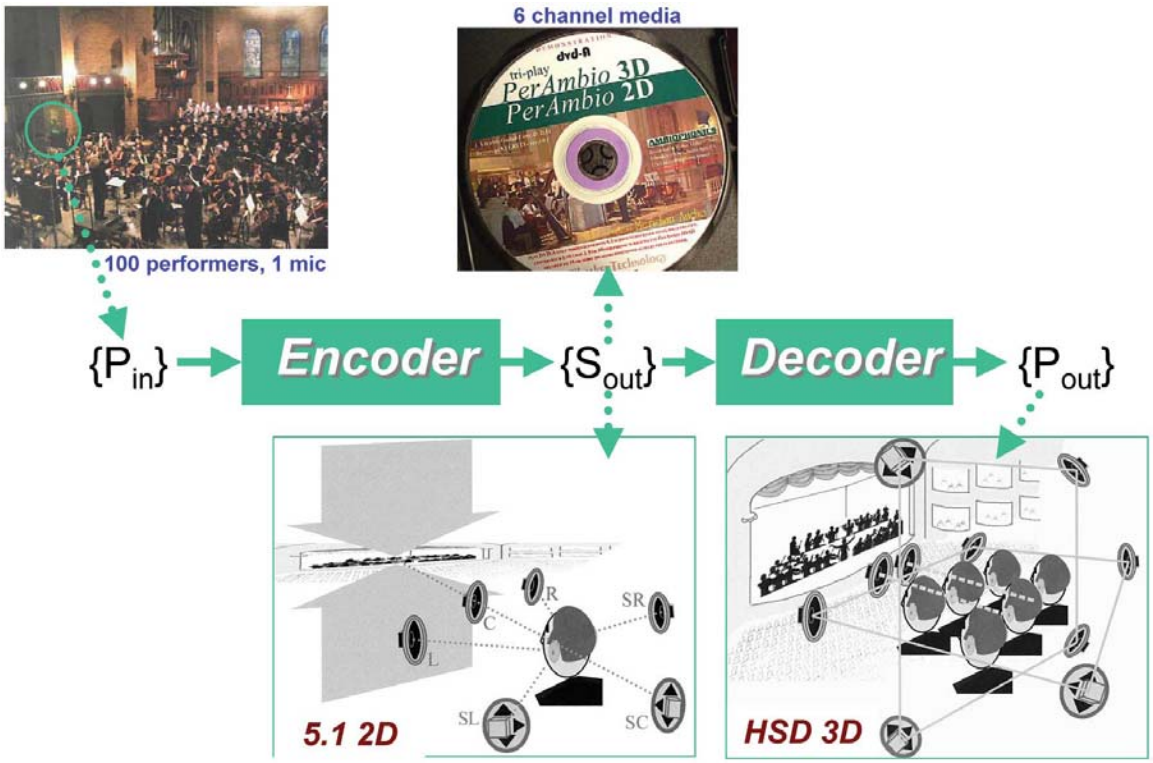

Fig.9 - High Sonic Definition 3D, aka PerAmbio 3D [14,15,16]. Signals from the HSD microphone are encoded to 6-channel media, playable in 5.1~7.1 without decoder. When ready for full sphere (with height) 3D, the user adds a decoder and speakers (10 total).

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