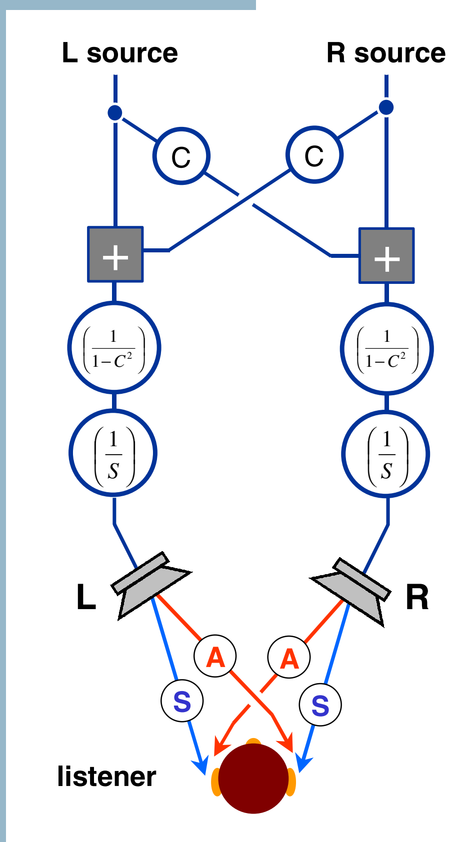
Transaural acoustic crosstalk cancellation

by Alastair Sibbald



The cancellation of transaural acoustic crosstalk is an essential and critical feature of all head-related transfer function (HRTF) based 3D-sound synthesis systems when loudspeakers are used for listening. Transaural acoustic crosstalk occurs when the left ear hears a little of the right channel and vice versa. The unwanted effect of crosstalk is to disable any 3D-sound cues that may be present and to restrict the virtual sound image to the confines of the loudspeaker placement (similar to conventional stereo). This phenomenon can be overcome by devising a suitable crosstalk cancellation scheme. The objective is the clean delivery of left- and right-channel binaural signals with unity gain into the respective ears of the listener and with zero gain into the opposite ears.

The foundations of transaural crosstalk cancellation were laid down by Atal and Schroeder[1] in 1962, when it was originally intended for hi-fi applications. By taking account of the angular placement of the loudspeakers, Schroeder[2] described clearly how appropriate signal processing filters could be devised for effective crosstalk cancellation (shown left).

This paper describes how transaural crosstalk effects disable natural 3D-sound cues, how a basic crosstalk cancellation scheme works and what the important features are. In addition, the proprietary Sensaura crosstalk cancellation system is introduced: it is user-configurable, such that it can be optimised for a range of loudspeaker placements at differing angles and distances.

1 Transaural crosstalk effects

The restricting acoustic effects of transaural crosstalk can best be illustrated by means of a practical example. Imagine that a recording is made using a pair of conventional microphones spaced apart by one 'head-width', just as they would be in an artificial head. This head-width separation distance of 20 cm includes the path around the side of the head; it is not just the actual width.

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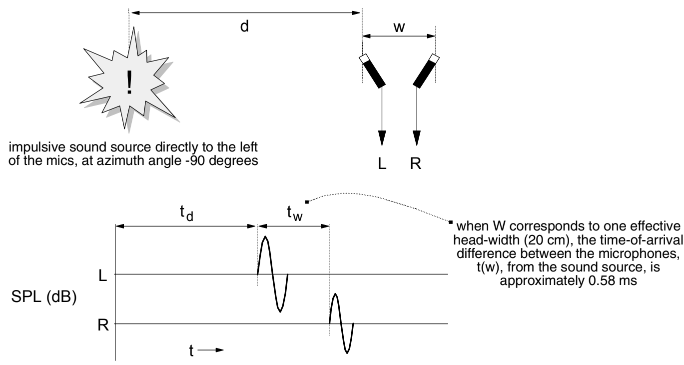

Figure 1: Recording an event with spaced microphones

This configuration would ensure that the inter-aural time delay cues are correctly incorporated into the recording. Imagine that a recording is made of a sound source placed immediately to the left of the microphone configuration, as is shown in Figure 1.

When the sound source emits an impulse, it is first recorded by the left-hand microphone before it is recorded by the one on the right. If the microphones were 20 cm apart, then the time-delay would be about 580 µs. Imagine now that this recording is being replayed on a two-speaker hi-fi system and that the listener is sitting in the 'correct' listening position, as is shown in Figure 2. Under these circumstances, with the speakers subtending angles of about ±30°, the inter-aural time-of-arrival delay (ITD) around the head from the loudspeakers is approximately 250 µs. When the impulse is replayed, it is emitted first from the left loudspeaker, followed, after the recorded 580 µs delay, by the right-hand loudspeaker. Figure 2 shows how the transmission of the impulses from the loudspeakers arrives at both ears, with the individual components labelled **W**, **X**, **Y** and **Z** for clarity.

The left ear first hears the primary sound **W** from the left-hand loudspeaker, followed by the crosstalk **Y** from the right speaker. However, the right ear first hears the crosstalk **X** from the left speaker before the primary recorded impulse **Z** from the right speaker, thus reducing the time-of-arrival delay from the expected 580 µs to 250 µs. Because the crosstalk sound derives from the same, real sound source, the brain receives a pair of highly correlated L and R sound signals, which it immediately uses to determine where the perceived sound source would be located. The brain, therefore, uses the effective inter-aural time-of-arrival delay of only 250 µs, which corresponds to the actual position of the left-hand loudspeaker at minus 30° azimuth. This position is where the brain (incorrectly) localises the sound source. The correctly timed, primary right-hand signal **Z** eventually arriving at the right ear is ignored because of the Haas/precedence effect, which is described in the following section.

The transaural crosstalk has, in effect, disabled the time-domain information that was built into the recording. Whereas the position of the recorded sound was actually -90° azimuth, the position of the reproduced sound is perceived to be only -30° azimuth.

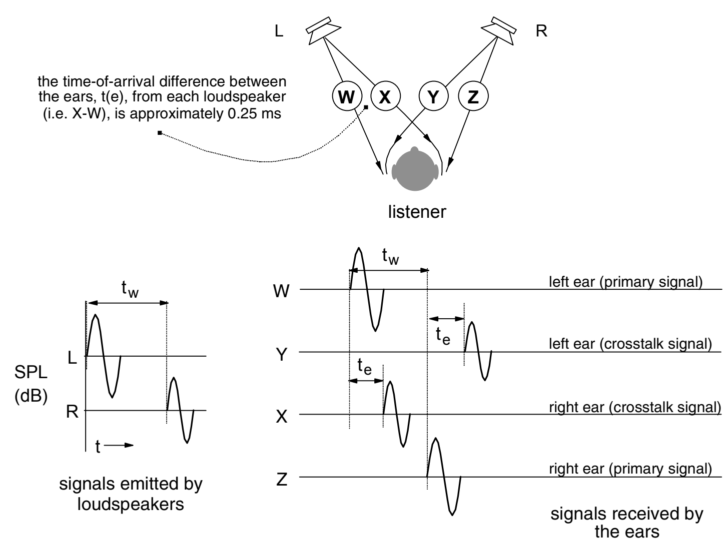

Figure 2: The cue-disabling effect of transaural crosstalk

In summary, the presence of transaural crosstalk restricts the conventional stereo sound image to the confines of the loudspeaker placement.

2 Haas/precedence effect

The Haas (or precedence) effect[3] is the phenomenon that, when presented with several similar pieces of audio information to process at slightly different times, the brain uses the *first* information to arrive to compute the direction of the sound source. It then attributes subsequent, similar sound packets with the same directional information.

For example, if several loudspeakers were playing music at exactly the same loudness in a room, *all* the sound would appear to come from the nearest loudspeaker and the others would appear to be silent. The first signals to arrive are used to determine the spatial position of the sound source and the subsequent signals simply make it sound louder. This effect is so strong that the intensity of the second signal could be up to 8 dB greater than the initial signal and the brain would still use the first (but quieter) signal to decide from where the sound originated.

This effect is known also under the names 'law of the first wave front', 'auditory suppression effect', 'first-arrival effect' and 'threshold of extinction', and is used for the basis of sound reinforcement used in public address systems.

The brain attributes great relative importance to *time* information as opposed to *intensity* information. For example, an early paper of Snow[4] describes experiments on compensating differences in left-right intensity balance using relative L-R time delays. It was reported that a 1 ms time delay would balance as much as 6 dB of intensity misbalance.

The precedence effect is relevant to the 3D-sound user when 3D soundscapes are created using many sources. Any signals deriving from a particular sound source (such as a reverb signal) will fuse with the primary signal if they are presented to the listener within about 15 ms of each other. Beyond this time, they begin to become discernible as separate entities.

Perhaps the precedence effect has evolved as a valuable survival mechanism, enabling the brain to cope with multiple reflections in an enclosed space. Thus, the true source of a sound may be identified without confusion from an array of first-order sound images.

3 Atal & Schroeder transaural crosstalk cancellation

One of the first practical transaural crosstalk cancellation (TCC) systems was described in the 1962 patent of Atal and Schroeder[1], later to be described more explicitly in the 1975 publication of Schroeder[2]. The latter disclosure describes the method for solving the multiple cancellation problem, where the crosstalk cancellation signals themselves need to be accounted for in such a way that they do not create errors which are compounded and propagated further.

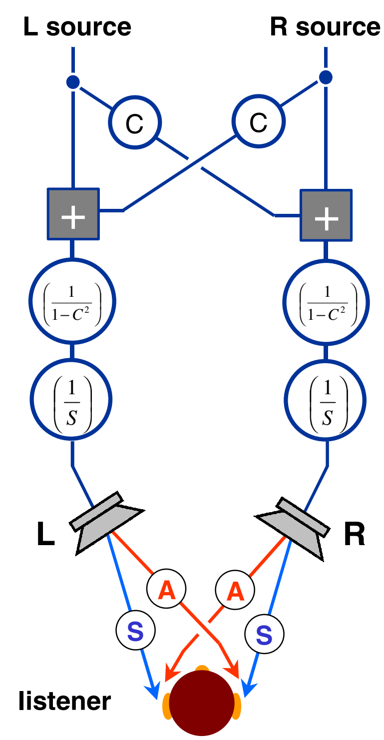

Figure 3: Conventional transaural crosstalk cancellation scheme (Schroeder[2])

The block diagram of the latter transaural crosstalk cancellation method, by Schroeder, is shown in Figure 3. The binaural signal sources are at the top of the diagram, passing down through the filtering system to generate loudspeaker-driving signals **L** and **R** respectively. The transmission function from a loudspeaker to the ear on the *same* side of the central axis is defined to be **S** and to the *alternate* side of the central axis to be **A**. It is commonly assumed that loudspeakers for stereo listening will be placed to subtend azimuth angles of ±30° with respect to the listener. **A** and **S,** therefore, can be established by direct measurement, ideally from an artificial head having physical features and dimensions representative of the mean human counterparts.

4 S and A functions

The amplitude components of typical transmission functions **A** and **S**, measured from an artificial head with canal simulator, are shown in Figure 4, using logarithmic frequency (x) and intensity (y) scales.

The important and notable features are as follows.

1. Both **A** and **S** functions converge at low frequencies.
2. There is a substantial boost in the mid-range response, typically about 30 dB at 2.9 kHz. This is caused by the combined resonances of both the auditory canal and the concha. It is possible to model these resonances separately. If the artificial head were without the auditory canal element, then the boost would be about 12 to 15 dB and at a higher frequency.
3. The dips and peaks at higher frequencies, above about 5 kHz, are caused by the physical convolutions on the pinna, combined also with harmonic resonances of the concha and canal. Some of the peaks and dips can be rather sharp (where the various effects combine or where a resonant cavity in the concha has a high acoustic Q factor). For example, in the data of Figure 4, at 11.5 kHz, the **A** and **S** functions overlap a little, which can cause problems if the data is to be used for filter design.

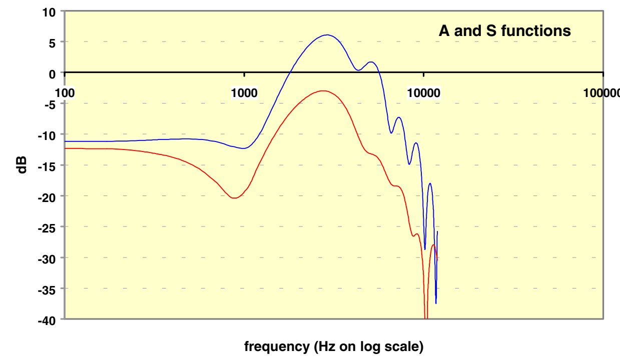

Figure 4: Typical A and S functions for a sound-source at 30° azimuth

5 Band-limited transaural crosstalk cancellation

Cooper and Bauck have patented a crosstalk cancellation system[5] which is essentially based on the Atal and Schroeder system, but featuring a pair of high-cut (~10 kHz) filters in the cross-feed system. The theory behind this approach is that, even if a perfect crosstalk cancellation system could be implemented, it would only function properly if the listener's head was totally immobile in the absolute centre of the sweet spot. The reason for this is that wave cancellation effects are dependent on the coincidence of primary wave peaks and cancellation troughs. When one wave of the cancelling pair is displaced, the cancellation is incomplete. For example, assume a listener's head was to move sideways such that the left ear was 5 cm closer to the left speaker and 5 cm further away from the right speaker. The *unwanted* crosstalk signal to the left ear from the right speaker would be shifted by 10 cm with respect to its intended cancellation wave from the left speaker. The cancellation would then be imperfect. In the extreme, when the displacement distance is equal to one-half of a wavelength, then *constructive* addition occurs, rather than *destructive* addition, and so the unwanted crosstalk signal can actually be magnified at particular frequencies, rather than destroyed. For the 10 cm example above, the frequency at which this occurs is around 1.7 kHz.

At first glance, this apparent sensitivity of cancellation effect with listener position is slightly disturbing. However, in practise, the creation of effective crosstalk-cancellation is not so critical as one might be led to believe by such calculations. This is because of the natural acoustic properties of the head and ears themselves, and the properties of the 30° HRTFs. In essence, as frequency increases, the head acts more and more effectively as an acoustic baffle, thus suppressing transaural crosstalk naturally. Consequently, there is little crosstalk to cancel at high frequencies and so the basic Atal and Schroeder method can be successfully used in hi-fi type configurations where the speakers are several metres distant from the listener.

There are other factors to be borne in mind. We are used to discussing the audio spectrum over the full 20 Hz to 20 kHz range, but most music fundamental frequencies lie below 1 kHz (the highest note a soprano sings is just over 1.1 kHz). Consequently, much of the audio energy we hear lies at the low-frequency end of the spectrum and this is not too demanding for crosstalk cancellation systems. Secondly, wave-cancellation and wave-addition effects occur equally with conventional stereo as they do with 3D systems and yet everyone accepts these effects without question. Indeed, many are not aware of their existence. However, if you play a (monophonic) 2.2 kHz sine wave through both L and R speakers of a stereo system, you will clearly hear some unpleasant effects as you move your head around. (This wavelength corresponds to twice the inter-aural time-delay, thereby creating significant natural destructive cancellation at both ears in the sweet spot.)

6 Fundamental gain options

Setting aside the intrinsic adjustments which can be made to crosstalk cancellation schemes, such as the use of appropriate **A** and **S** functions for particular loudspeaker angles, there is a more fundamental option related to the mode of signal delivery. The binaural signals bearing the 3D-sound cues can exist in one of two differing formats: (a) with a full external-ear function incorporated; and (b) with the external-ear function absent.

In the real world, we hear through the following audio chain:

sounds ⇒ external ear ⇒ auditory canal

...and this is what we consider sounds natural.

However, a sound recording made using an artificial head system featuring an outer-ear component (but not an auditory canal element) can be played on circumaural headphones quite satisfactorily. This is because the headphones acoustically dampen and inhibit the outer ear resonance. Hence, the listener is effectively listening through an audio chain as follows:

real sounds ⇒

artificial external ear ⇒

listener's own auditory canal

...and this is equivalent to the real-life situation. In this case, the audio signals must be delivered into the listener's ears with unity gain, such that the listener is 'hearing through a single set of ears'.

Option 1: unity-gain system

Now consider what occurs when the sounds are replayed via loudspeakers (and we ignore, for the moment, the transaural crosstalk effects). The listener hears the sound via his own external near-ear function (at 30°), **S**. This means that the audio chain now becomes:

real sounds ⇒

artificial external ear ⇒

listener's own external ear ⇒

listener's own auditory canal.

...there are effectively *two* outer-ear functions in the chain! This causes spatial degradation of the 3D effects, but also creates a gross tonal error (12 dB mid-range boost). Accordingly, in order to provide a transaural crosstalk cancellation scheme for binaural signals that specifically contain an outer-ear function, the gain factors into near and far ears must be set to unity and zero respectively.

Option 2: S-gain system

The above description relates to the first type of binaural format, in which a full external-ear function is incorporated. The second option, in which the external-ear function is absent, is also common and requires a different crosstalk cancellation algorithm. Why does this alternative binaural format exist? There are two main reasons.

First, it has long been recognised that when artificial head recordings are replayed via loudspeakers, they are tonally incorrect (for the reasons cited above in section 4, item 2). Thus, several manufacturers have incorporated equalisation circuitry into their artificial heads to compensate. The equalisation parameters are chosen to provide a flat response when the signals are played through loudspeakers by creating a mid-range band-cut, equivalent to an inverse outer-ear function. This is analogous to wearing headphones that dampen and inhibit the outer-ear response. The result is tonally satisfactory and comparable to stereo but, in the absence of transaural crosstalk cancellation, does not create a 3D-sound field for the user.

Secondly, it is often required to synthesise 3D-audio using head-response transfer function (HRTF) filters that emulate the acoustic properties of the head and ears. Many applications, such as computer games, feature playback via loudspeakers such that the user's own outer-ear function is invoked. It is convenient, therefore, to take advantage of this and create normalised HRTF filter sets in which all the individual HRTFs are divided by the 30° function. This reduces the dynamic range of the filters by 12 dB or so and enables greater accuracy in their design. Also, it is logistically easier to implement systems which mix 3D-synthesised audio with artificial-head material[6]. For example, in the SPU-800 Sensaura Digital Workstation[7], it is more effective and efficient to provide equalisation separately to a plurality of signals and then implement crosstalk cancellation as a final stage in the processing.

In circumstances where the external-ear function is absent in the binaural source material, but it is required that the listening mechanism includes one, then the transaural crosstalk cancellation scheme must deliver the sound into the listener's ears with a gain of **S**, rather than unity.

7 Unity-gain transaural crosstalk cancellation

Considering Figure 3 again, it will be appreciated that, if there was no crosstalk across the head, the transmission function from the right source to the right ear (and from the left source to the left ear) would be **S**. Hence, the goal of providing transmission functions of 1 (unity) from the right source to the right ear and 0 (zero) from the right source to the left ear can be achieved by simply adding a serial **(1/S)** function (the inverse of the same-side transmission function) between source and loudspeaker. The presence of crosstalk, however, requires a cancellation signal to be provided by the other loudspeaker.

For example, consider the process of transferring the R channel signal into the right ear only. The transfer from R loudspeaker to right ear is via the same-side function, **S**. The crosstalk from the R loudspeaker will arrive at the left ear with transfer function **A**. Therefore, we need to deliver a **(-A)** signal to the left ear from the L speaker in order to cancel it. However, we know that the transfer function from the L speaker to left ear is **S** and so the overall crosstalk cancellation feed from the R to L channel must be **(-A)** x **(1/S),** i.e. **(-A/S)**. This would deliver the crosstalk cancellation signal correctly to the left ear. (For convenience, this crosstalk cancellation feed function **(-A/S)** will be referred to as **C**.)

However, this cancellation signal also *cross-talks* to the other (right) ear and so this secondary crosstalk must also be cancelled (and so on, ad infinitum). Despite this apparently recursive problem, Schroeder showed that accurate crosstalk cancellation can be achieved by taking the basic configuration described above, adding extra correction filters and solving simultaneous equations to derive their values. These are calculated to be **($1/1\text{-}C^2$)** and (**1/S**), as shown in Figure 3.

In summary, transaural crosstalk cancellation can be achieved by feeding the R source via crosstalk filter **C** (which is equal to **(-A/S)**), and adding it to the L channel (and vice versa). The subsequent serial correction filters **1/(1-C²)** deal with the multiple cancellation problem and **(1/S)** corrects for the same side transmission (above). It would appear that the Atal and Schroeder scheme provides a theoretically ideal solution. By inspection of Figure 3, it can be seen that the overall transmission function from the right input (R) to the right ear (r), defined here to be $R_r(f)$, is:

$$R_r(f) = \left(\frac{1}{1-C^2}\right)\left(\frac{1}{S}\right)S + C\left(\frac{1}{1-C^2}\right)\left(\frac{1}{S}\right)A = 1 \qquad (1)$$

and the overall transmission function from the same (R) input to the left ear (l), defined to be $R_l(f)$, is:

$$R_l(f) = \left(\frac{1}{1-C^2}\right)\left(\frac{1}{S}\right)A + C\left(\frac{1}{1-C^2}\right)\left(\frac{1}{S}\right)S = 0 \qquad (2)$$

These results satisfy the cancellation requirements.

(It is useful to note that the compounded serial $\left(\frac{1}{1-C^2}\right)$ and $\left(\frac{1}{S}\right)$ terms simplify to $\left(\frac{S}{S^2-A^2}\right)$, and that, at low-frequencies, **A** and **S** are almost identical (both in amplitude and phase).)

The Atal and Schroeder configuration has been known to perform well[2]: "the practical experience... has been nothing less than amazing... virtual sound images can be created far off to the sides and even behind the listener". However, the early results were also reported to be very listener-position dependent: "...if the listener turns his head by more than 10° from the frontal direction ...the realistic illusion disappears, frequently changing into an 'inside the head' sensation". The author's experience is that the basic Atal and Schroeder configuration can work quite well for speakers at two metres distance or more. However, in critical listening tests using classical music, there are some minor audible artefacts when moving one's head sideways and back and forth. However, for PC applications the physical situation is different because the loudspeakers are relatively close to the listener. The importance of this has not been previously recognised. Accordingly, a special transaural crosstalk cancellation method has been devised to provide optimal cancellation at any given loudspeaker position and distance. We call this Sensaura XTC™ and it is described in a separate technical white paper.

8 S-gain transaural crosstalk cancellation

As shown above, in certain circumstances it is desirable to devise a transaural crosstalk cancellation scheme with built-in spectral equalisation to compensate for the *twice through the ears effect* (section 6, option 1).

The second option relates to circumstances where the external-ear function is absent in the binaural source material which requires that the overall listening chain be designed to incorporate an external-ear function. This is readily achieved by specifying the gain into the listener's ears to be **S**, rather than unity, and solving the near-ear and far-ear equations for **S** and 0, respectively, rather than 1 and 0.

9 Sweet spot

All stereo reproduction systems, including transaural crosstalk cancellation schemes, require that the listener is positioned in the so-called *sweet spot* area, such that the listener forms an equilateral triangle with respect to the loudspeaker pair. The loudspeakers, therefore, are present at azimuth angles of approximately ±30° from the listener. If the listener moves forwards or backwards from the sweet spot, both loudspeaker-to-ear path lengths change by similar amounts, so the crosstalk cancellation conditions still prevail and the sound image is little affected. If the listener moves sideways away from the sweet spot, however, then the crosstalk cancellation process is no longer so precise because the path lengths from the loudspeakers change in opposite ways (one increases as the other decreases) and so the sound image begins to deteriorate.

The size of the sweet spot depends upon the wavelengths of the sounds being heard. Low-frequency sounds, with wavelengths of several feet or more, create a large sweet spot that is very tolerant of head movement, whereas higher frequency sounds create a smaller sweet spot. However, it is fortunate that, at these higher frequencies (several kHz and above), the head itself acts as an efficient baffle, thus screening higher frequency sounds from the opposite ear such that much smaller amounts of crosstalk cancellation are needed. By inspection of the **S** and **A** function in Figure 4, for example, it can be seen that the level of crosstalk (i.e. the separation between the curves) with respect to the primary signal at 500 Hz is about -3.3 dB, whereas for most frequencies above 2.2 kHz, it is below -10 dB. As a consequence, the need for crosstalk cancellation diminishes naturally with increasing frequency.

10 Sensaura transaural crosstalk cancellation method

The purpose of the Sensaura transaural crosstalk cancellation algorithm is to provide the optimal cancellation configuration, which can also be adjusted to the angles and distances of individual loudspeaker pairs. **The method is based on the important observation that the relative level of transaural crosstalk is distance-dependent.**

The theory behind this is given in a separate white paper *Sensaura XTC™ crosstalk cancellation*. The method requires that the amount of crosstalk cancellation be controlled according to a transaural crosstalk factor, **x**. The benefits of this method are (a) improved effectiveness of sound imaging, especially in the rearward hemisphere and (b) the absence of position-dependent artefacts.

It is common practise to measure the **A** and **S** functions at a distance of one metre or greater, at which distance the LF levels are similar. However, as a non-central sound source approaches the head, the amount of transaural crosstalk (measured with respect to the primary signal) diminishes. The relative attenuation is largely independent of frequency, but is a function of azimuth and elevation angles.

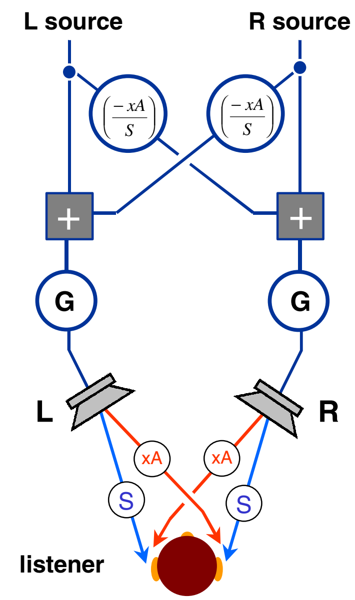

Figure 5: Generic Sensaura transaural crosstalk cancellation

This relative attenuation can be defined by a gain factor, **x**, applied to **A** with respect to **S**. For example, if we use **A** and **S** functions with mutually asymptotic LF values (as is usual), corresponding to an infinitely distant sound source, and we set $\mathbf{S}_{close} = \mathbf{S}_{distant}$ for comparison purposes, then $\mathbf{A}_{close}$ is given by: $\mathbf{A}_{close} = \mathbf{x} \,.\, \mathbf{A}_{distant}$, where **x** lies in the range $0 < \mathbf{x} \leq 1$. The **x** factor for a loudspeaker in the horizontal plane at azimuth 30° at two metres distance is about 0.94 and this value decreases for shorter distances.

For the present purpose, we shall assume that the **A** and **S** values used here, both in the diagrams and equations, are *distant* ones, with mutual LF convergence. A generic crosstalk cancellation structure can now be drawn to accommodate the **x**-factor of distance dependency, as shown in Figure 5. We set the cross-feed function now to be equal and opposite to the anticipated crosstalk signal, which makes it: **(-xA/S)**. The **G** blocks represent filter units that can be resolved for various required gain options to the near ear. Because we have defined the cross-feed function to be so, and the **G** blocks are common to both L and R paths, the crosstalk will always be cancelled fully.

It is now possible to solve for **G** explicitly in terms of **x**, **A** and **S** in order to achieve the

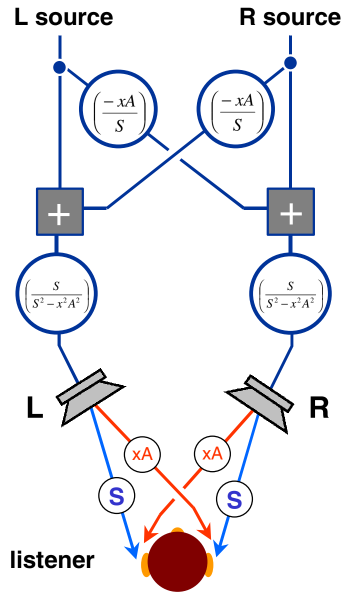

Figure 6: Sensaura XTC transaural crosstalk cancellation scheme (unity-gain option)

required goal of precise crosstalk cancellation, whilst dealing with the multiple cancellation problem correctly, as before, such that there is an appropriate gain factor between the right source and the right ear.

Unity-gain option

For use with binaural format option 1 (such as artificial head recordings) the unity-gain option is required (i.e. $R_r(f) = 1$).

The overall transmission function from the right input (R) to the right ear (r), $R_r(f)$, is:

$$R_r(f) = G.S + \left(\frac{-xA}{S}\right)G.xA \qquad (3)$$

and this must be equal to 1 for unity gain, as described above. Hence:

$$G.S + G.xA\left(\frac{-xA}{S}\right) = 1$$ and therefore:

$$G = \left(\frac{S}{S^2 - x^2A^2}\right) \qquad (4)$$

A consequence of this is that **G** becomes a function of **A**, **S** and **x** such that a relatively high degree of crosstalk cancellation occurs when **A**<**S**. The crosstalk cancellation reduces when **A** approaches **S** (e.g. at very low frequencies). **This creates an intrinsically stable system**, which is another advantage of this particular method.

Figure 6 shows the explicit configuration for the Sensaura unity-gain system.

The overall transmission function from the right input (R) to the left ear (l), $R_l(f)$, and *vice versa*, can be confirmed to be zero:

$$R_l(f) = G.xA + \left(\frac{-xA}{S}\right)G.S = 0 \qquad (5)$$

S-gain option

For use with binaural format option 2 (such as 3D-sound synthesis using normalised HRTF filters), the **S**-gain option is required (i.e. $R_r(f)$ = **S**). Again, this is achieved by solving the near-ear and far-ear transmission paths for **S** and 0, rather than 1 and 0.

The overall transmission function from the right input (R) to the right ear (r), Rr(f), given in equation (3), must be set equal to **S**, and hence:

$$G.S + G.xA\left(\frac{-xA}{S}\right) = S$$ and therefore:

$$G = \left(\frac{S^2}{S^2 - x^2A^2}\right) \qquad (6)$$

It will be noted that this is the product of the previous equation (4) and **S**, and that the implementation involves simply substituting the solution of (6) for **G** into Figure 5 to yield an **S**-gain version of the explicit unity-gain scheme of Figure 6.

The signal processing must be carried out in such a way that the phase relationships are preserved and that an appropriate time-delay is incorporated into each line immediately prior to the summation element. In this way, the cancellation signal arrives in synchronisation with the primary crosstalk signal, thus enabling cancellation to occur. Minimum-phase FIR filters are commonly used for this.

Sensaura XTC provides optimal transaural crosstalk cancellation for users of PC-based multimedia systems in which the loudspeakers are relatively close to the listener and might be at a variety of angles and distances, depending on the individual user's set-up configuration and preferences. This has been achieved by deriving a mathematical function for the distance and angle dependency of the transaural crosstalk factor, **x**, such that it can be calculated for any given loudspeaker distance and angle. This, in turn, can be used to control the amount of crosstalk cancellation that is implemented.

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