Quantitative Assessment of Surround Compatibility

A completely new method of assessing downmix compatibility has been developed by Qualis Audio. It yields quantitative measures and eliminates the need for users to interpret graphical displays to assess program material. Its quantitative nature allows pass/fail limits tests to be applied significantly reducing the subjectivity previously involved in downmix compatibility assessment. This document summarizes the hazards in downmixing, prior methods of assessment and describes the new approach invented by Qualis Audio. Its practical implementation and the advantages are explained.

Introduction

The premier format for content production is surround. When movies or prime-time television shows are produced today they are usually mixed in surround. This provides the mix engineer with the largest palette for creating artistic content. Most of the effort is spent on making the surround presentation as good as possible. However, when the production reaches the consumer more than half of the viewers will reproduce it in stereo or mono. Even in film there are theaters that do not have proper surround playback facilities.

Unfortunately, what the stereo viewers hear will not necessarily be what the surround equipped viewers hear. Surround mixes are complex beasts, consisting of many audio feeds combined into a coherent whole. These feeds may contain components common to one another. If the feeds are independent (contain no common information) they will retain their relative levels after downmixing to stereo or mono. If the feeds contain any common material, the relative levels after downmixing may change. Level changes result when the common signals are not in phase. Antiphase signals cancel when downmixed, reducing level or disappearing completely. Mic-ing issues can make a sound appear in two (or more) channels out of phase. If this happens to an actor, dialog can become unintelligible, viewers get upset.

Downmixing

Converting stereo programs to mono is generally done by simply summing the two channels together.

$$M = L + R$$

To prevent the peak amplitude from exceeding that of the original inputs the output is generally attenuated by 2 (-6 dB). This is well accepted practice from the earliest days of stereo.

However, the conversion of surround programs to stereo follows less uniform processes. Typically the LFE (low frequency effects) channel is omitted from the downmix. The remaining channels are mapped to the stereo pair based on their location in the surround mix. The left channels are combined, the right channels are combined and the center front (CF) is added to both the left and right channels.

For several reasons, the relative channel amplitudes are changed when they are summed. The human auditory system can separate sounds reproduced from different directions, even if they are at comparable levels. If these sounds are reproduced from the same location masking effects will be much larger. To enable the listener to understand the primary content in the front channels the surrounds are attenuated before summation. To maintain constant relative power when the center front is reproduced from two speakers instead of one it is necessary to reduce its amplitude in each speaker.

Consequently downmixing 5.1 into 2.0 is typically done using the following equations:

$$Lo = LF + 0.707\ CF + 0.707\ LS$$
$$Ro = RF + 0.707\ CF + 0.707\ RS$$

The factor of 0.707 represents a -3.0 dB attenuation of the surrounds and center front. The overall gain of the stereo channels is reduced by a factor of 1/(1+ 0.707 + 0.707) to keep peaks from exceeding the system peak capacity. Though the coefficients used above are the most common, others are occasionally used.

In an effort to make downmixed programs compatible with their Pro-Logic decoders, Dolby championed an alternate downmixing technique. It sums the surround channels into a single mono surround which is then phase shifted by +/- 90 degrees and added to the stereo pair. Since the surround content is oppositely phased in the stereo channels it is possible to partially separate it from the remaining content and send it to surround speakers on playback. The 90° phase shifts reduce the likelihood of surround content cancelling with that of the front channels. However, combining the surrounds into a single channel makes any antiphase content disappear in both stereo and mono reproduction. The antiphase encoding (+90° - -90° = 180°) makes all surround content disappear in mono reproduction.

The pro-logic compatible downmix equations are:

$$S = LS + RS$$
$$Lt = LF + 0.707\ CF + 0.707\ S(+90°)$$
$$Rt = RF + 0.707\ CF + 0.707\ S(-90°)$$

Dolby Digital and Dolby E metadata encodes downmix coefficients to be used by the decoder when reproducing surround content in stereo. Dolby E and the original Dolby Digital format allowed three attenuation choices for surround channels (0.707, 0.5 and 0), and three for the center front channel (0.707, 0.596, 0,5) when the decoder was operating in LoRo downmix mode. The metadata coefficients are ignored in the LtRt mode, the decoder uses fixed 0.707 values instead.

The Dolby Digital Plus system (called Enhanced AC-3 in ATSC A/52B) adds several more choices for downmix coefficients in metadata and allows specification of LtRt downmix coefficients. The coefficients may be specified independently for LoRo and LtRt methods. The center downmix coefficient is allowed to increase beyond -3 dB, up to as much as 3 dB of gain. This allows dialog level to be increased above the content in the left and right channels in an effort to improve intelligibility. The surround downmix gain is given more resolution, allowing a better balance between surround content being audible vs interfering with intelligibility of content in the left and right channels. The allowable downmix coefficients are shown in the table below.

	Allowable values for Center Mix Level							
				Values for Surround Mix Level				
Gain	1.414	1.189	1.000	0.841	0.707	0.595	0.500	0.000
dB	+3.0	+1.5	0.0	–1.5	–3.0	–4.5	–6.0	–inf

Phase Shift and Signal Cancellation

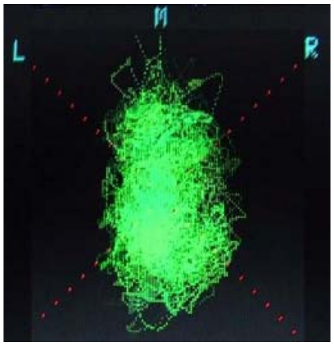
It is easy to calculate the level reduction which occurs when two sinewaves of differing phase are summed. The table at right gives the loss vs the interchannel phase. For example, a 160° phase difference causes a 15 dB level reduction compared to the in-phase case. Note that although it takes a substantial phase shift (90°) to get 3 dB of cancellation, larger loss comes with progressively smaller additional shifts.

Loss (dB)	Phase (deg)
0	0
1	54
2	75
3	90
4	102
5	112
6	120
7	127
8	133
9	138
10	143
11	147
12	151
13	154
14	157
15	160
20	169

There is a serious problem in implementing an assessment system based on phase. How is it to be measured? Measuring phase is easy with sinewaves; they are simple and consistent. Program material is far more complex and transient in nature. Sinewave measurements are generally performed with an oscilloscope or meter. Both have serious limitations when measuring complex dynamic signals like those arising in program material.

Brief Review of Compatibility Assessment

The conversion of surround to stereo or of stereo to mono involves combining channels together, algebraically summing their waveforms. Antiphase signals will cancel when combined, diminishing in level or disappearing completely. This can happen when individual channels are accidently inverted. However, the more insidious situation occurs when just one component in a surround mix appears in multiple channels but shifted in phase. This can easily happen when a single source is picked up by multiple non-coincident microphones. When the outputs of these microphones are combined there will be cancellations and the signal level will be reduced. If this happens to an actor's voice, dialog can become unintelligible and viewers, sponsors and producers get very upset.



Lissajous Display

Stereo to mono compatibility was traditionally monitored with a Lissajous display. Implementation was simple, the left and right channels drive the vertical and horizontal deflection of an oscilloscope. The display was preferably rotated counter-clockwise by 45°. The resulting display gives an indication of average phase relationships between the channels. A representative image is shown in the figure.

Interpretation of such a display is moderately simple, a line or ellipse tilted to the right is ok, a round fuzzy ball is generally good and a line or ellipse tilted to the left is bad. Experience, and knowledge of audio mixing concepts, is required to understand the characteristic shapes and spot the signs of trouble. This also presumes the user is actually watching the display when problems occur.

The size of a basic Lissajous display will change directly with the signal amplitudes. A 2-channel automatic gain control with a ganged control signal is often added ahead of the display to make the image clearly visible independent of signal amplitude.

Due to display space limitations or user demands for a simpler display, correlation and phase meters have become a common alternative to Lissajous displays. Correlation meters multiply the left and right signals together and perform a short-term running average of the result. Phase meters convert each channel to a logic waveform using a simple zero-crossing detector and drive the inputs of a set-reset flip-flop or an XOR gate. Again, a short-term running average is performed. Their advantage is simplicity of interpretation, a positive value is good, a negative value is bad. Unfortunately, the distillation of information into a single number further hides important detail and prevents problems being discovered.

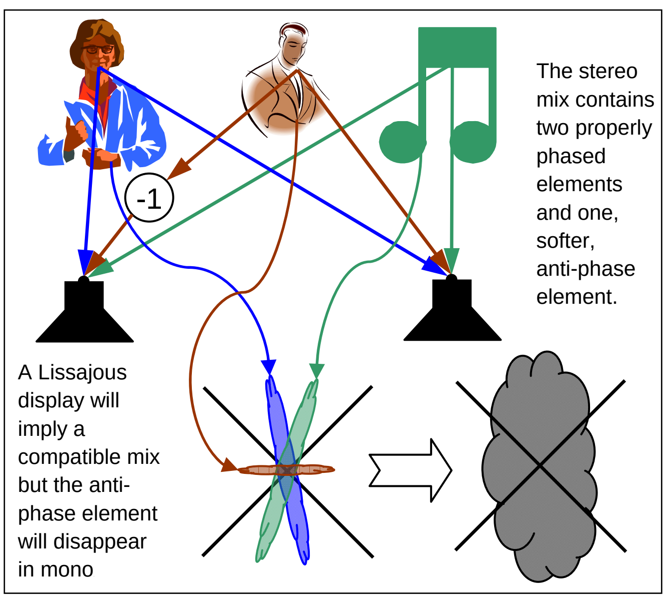
Now consider the case of surround program monitoring using Lissajous or correlation displays. The first problem in monitoring surround audio compatibility with correlation or Lissajous displays is the sheer number of channel pairs involved. Ignoring the LFE channel, a 5.1 program contains 10 channel pairs. Many commercial products only analyze neighboring pairs, others add the LF/RF channel pair. Even with this simplification there are 5 or 6 channel pairs to display.

The challenge facing the user is watching so many correlation meters or Lissajous patterns at the same time. With one exception, vendors of such tools have used various schemes to pack these displays onto a single XY display. All of these schemes take advantage of the redundancy evident in the four quadrants of the Lissajous display. Since the lower halves offer no additional information compared to the upper halves, the display may be truncated or folded at the horizontal axis. Packing 5 or more of these now truncated displays into a single picture is where the inventive differences between competing displays occur. Some manufacturers use color to get the additional dimensionality required, others use geometric transformations, and some use both.

Problems with Lissajous displays and phase meters

Lissajous displays show all signal components together. A stereo tone at 45° interchannel phase makes an ellipse. A stereo tone at 0° mixed with a different stereo tone at 180° makes a shifting ellipse. With real content everything is always moving. This makes discriminating between these two cases difficult and requires considerable experience.

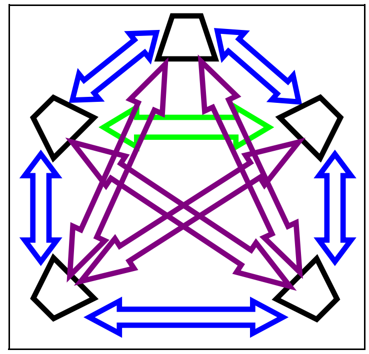
Consider the case illustrated in the figure below. The stereo mix contains two properly phased elements: dialog from an actress (shown in blue) and music (shown in green). The mix also contains dialog from an actor, mixed in anti-phase (shown in brown). A Lissajous display shows the vector sum of these individual waveforms which, due to the preponderance of properly phased material, will imply a compatible mix. However, when this material is reproduced in mono the actors dialog will disappear.



Limitations of Lissajous Displays

Phase and correlation meter approaches hide this even further. The single number descriptor hides the subtle clues that give an experience user an idea something may be wrong.

Extension to Surround



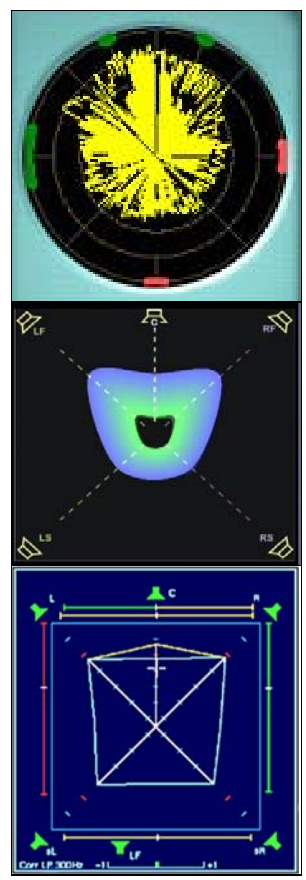
Pairwise Analysis of Surround Compatibility

Pairwise analysis of 5 surround channels requires analyzing 10 pairs as illustrated in the figure. Many commercial products only analyze neighboring pairs (shown in blue). One commercial product adds the LF/RF pair (shown in green). Extending pair-wise analysis to higher channel count surround systems becomes progressively more impractical. A 6 channel system requires analyzing 15 pairs, a 7 channel system requires 21 pairs.

Existing products pack five Lissajous patterns into one display for a 5.1 format signal. Each uses a different method of displaying the multiple two dimensional displays into a single display. The principal differences between approaches taken by various vendors are:

- How many pairs they show
- The geometric mapping used to combine displays
- The use of color
- The presence of additional displays on the screen
- Dynamic range control to maintain size as levels change

Representative Displays



Representative Displays

The first implementation folds each Lissajous pattern to obtain a display which occupies one quadrant. The instantaneous dot location is converted to a radius/angle representation and the angle value is scaled by (360/5)/180. Each of the 5 displays is then packed into a single circular display.

The center and bottom versions map level to the radius and phase to curvature. This produces a figure whose shape changes in proportion to the interchannel phase and whose size is proportional to level.

The top and bottom implementations add correlation (average phase) indicators outside the basic multidimensional Lissajous display. For the top display this replaces the information lost when the original two-channel Lissajous was folded twice. For the bottom display the additional meters improve the ability to detect small positive or negative correlations which otherwise must be detected as small deviations from straight lines comprising the basic pentagon shape.

The Compatibility Problem

Lissajous displays are the appropriation of an existing tool to solve a measurement need rather than a tool developed specifically to address the underlying user's requirements. Rather than respond to the more complex needs of surround audio manufacturers took the existing stereo tool and developed ways to extend its use to surround. These approaches ignore the fundamental problem of compatibility.

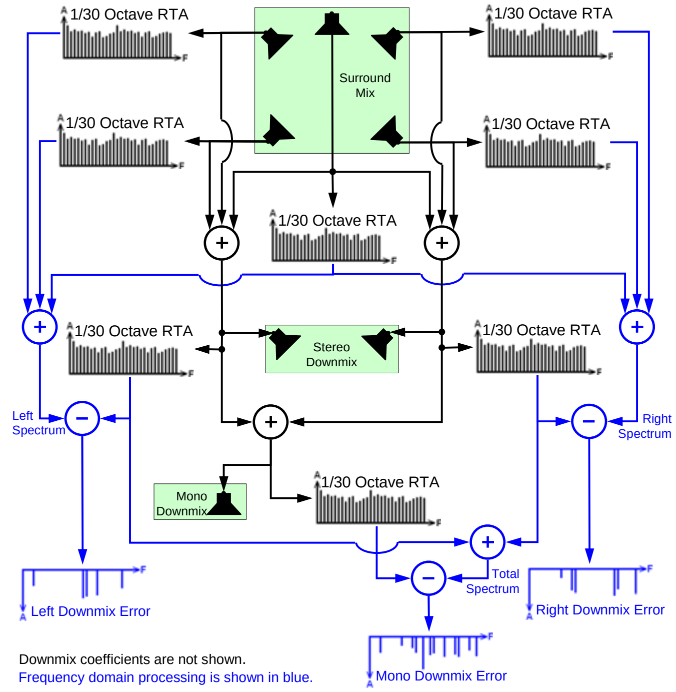
Mix engineers don't really want to know the phase between channels in their mix. They want to know if their mix will sound the same in stereo and mono as it does in surround. The surround displays don't directly answer that question, they measure phase and leave it to the user to determine the likely audible outcome. As a result, skill and experience become an important part of their use.

There is an additional, less recognized problem. Any meter or display, no matter how good at answering the underlying question, is only useful if it is watched. If the user is not looking at the display its results are of no value.

A New Approach to Compatibility Analysis

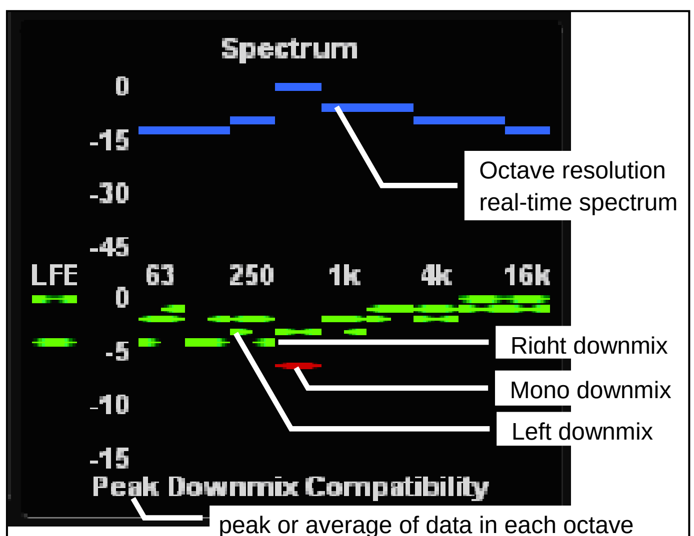
If the goal is that the stereo and mono downmixes sound the same as the original surround mix, why not assess this directly? First, consider what it means that two mixes sound the same, especially when the downmix process intentionally changes the relative channel levels. The definition that makes the most sense is that whatever sounds appear in the original mix should also appear in the downmixed version. The levels should be unchanged, except for intentional changes introduced by the downmix process. Unintentional changes caused by phase differences are what need to be detected.

The solution is shown in the figure below. The surround signal is downmixed to create the same signals that a stereo or mono listener will hear. The surround channels and the downmixed channels are measured with 1/30th octave real time analysis. For a 5.1 format input this requires 9 separate real time analyzers, one for each of the original inputs, two for the stereo downmix and one for the mono downmix. The spectra of the original channels are then downmixed using the same coefficients used to create the time domain downmixes. The downmixed spectra, $\Sigma X(f)^2$, are compared to the spectra of the downmixes $(\Sigma X(f))^2$. If no cancellations occur in the downmix process the results are identical. In practice there will be differences. By subtracting these two spectra the differences



Downmix Compatibility Assessment

Since the two stereo downmix channels are independently assessed the result is three difference spectra, one each for the left and right downmixes and one for the mono downmix. These correspond to what the listener will perceive as content missing from the downmix. Since the measurement is performed on 256 frequency bands the resulting 768 data values would result in a very dense display. To simplify the presentation the results are grouped by finding the peak or average reduction in each octave from 63 Hz to 16 kHz. These 27 results are displayed as a function of frequency as shown in the figure below.



Downmix Compatibility Display

To the original question: "Will it sound the same in stereo and mono as it does in surround?" we can answer: "These frequencies will drop X dB in stereo. these will drop Y dB in mono." The user must simply decide how much reduction in level is acceptable and over what frequency range. The display shows what will be missing from the downmix in terms the mix engineer can readily understand.

LFE Channel Issues

The system as implemented also assesses a largely unrecognized problem in surround reproduction involving the LFE channel. With the notable exception of cinemas, spaces used to reproduce surround sound are small enough that the surround and LFE channels sum linearly at the listening location. The assumption of power summation is not valid at the distances and frequencies involved.

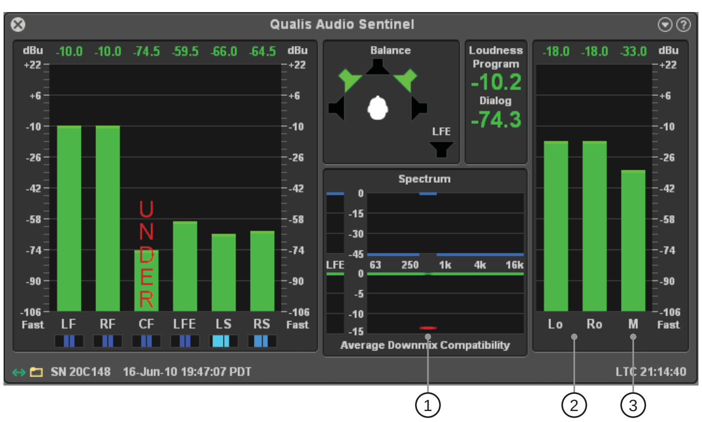
Consequently, phasing issues between the LFE and the surround channels will have a serious impact on low frequency reproduction. If the LFE includes content which is present in the surround channels its loudness when reproduced will depend on the relative phases. It is possible for cancellations to occur, resulting in reduced bass content when monitored in surround. The tendency will be for the mix engineer to increase the low frequency content to obtain the desired balance.

Since stereo and mono downmixing excludes the LFE the cancellation will not occur and the listener will perceive excessive bass.

To warn of the potential for this to occur the system described above also compares the spectrum of the mono downmix plus the LFE with the sum of the spectra of these channels. If cancellations occur when the LFE is included they are displayed on a separate bar at the extreme left of the downmix compatibility display.

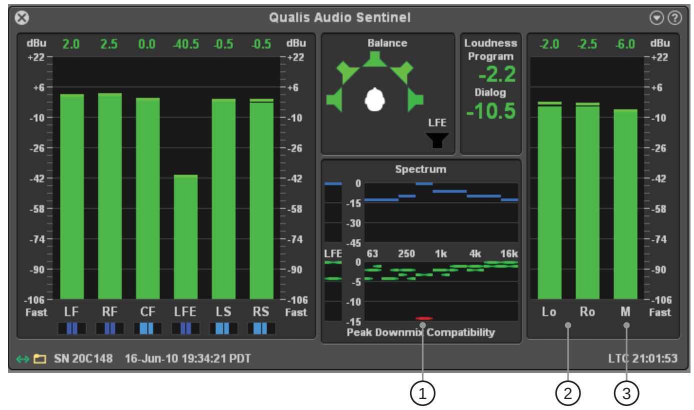
A Practical Example

To illustrate the relationship between phase measurements and downmix loss measurements produced by the Qualis Audio Sentinel a simple experiment was performed. A 500 Hz sinewave was used to provide LF and RF signals with a 160 degree interchannel phase difference. The resulting display is shown in the following figure.



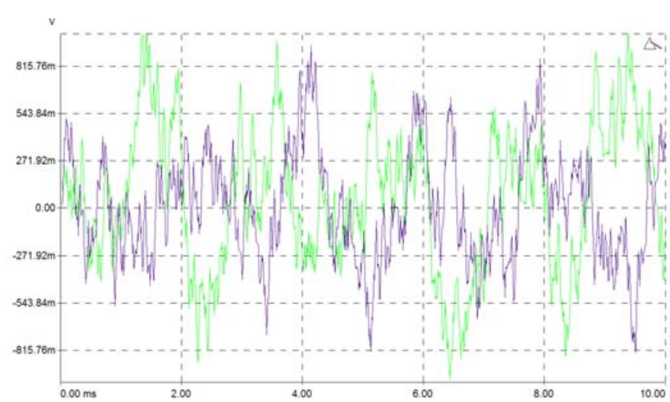
The mono downmix signals level is shown on the far right bargraph[3] and is approximately the expected 15 dB down. (The mono downmix bargraph is scaled to compensate for the level increase resulting from summing two channels together. Similarly the left and right downmix bargraphs[2], include a scale adjustment for the gain produced by downmixing 5 surround channels). The Average Downmix Compatibility (a spectral representation of the loss of signal represented in octave bands) display similarly shows an approximately 15 dB level reduction at 500 Hz. This is indicated by the red bar[1] in the display.

Next a complex signal is constructed by mixing the same phase shifted sinewaves with independent random noise. Additional noise sources drive the remaining surround channels. Feeding these signals to the Sentinel results in the display shown below. The Downmix Compatibility display reports the peak (worst case) downmix loss in each octave.



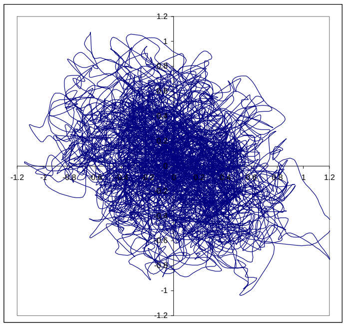
The level of the mono sum[3] is only reduced about 3 dB relative to the left and right downmix levels[2], even though (as before) the sinewave[1] has decreased in level by 15 dB. Assume the sinewave represents important content inadvertently recorded with a phase error and the noise represents the remaining program content. The program balance would be seriously compromised and viewer dissatisfaction would be likely.

Let's examine how this condition compares to the Sentinel measurement when using Lissajous or correlation displays. Though it is easy to define a phase difference between the sinewaves, it is very difficult to do so for the complete signals. Looking at these signals in the time domain does not give a clear indication that such a substantial cancellation will occur. The sinewave in noise signal measured above is shown below as seen on a two channel audio analyzer in the time domain.



Displaying this same data in Lissajous form is (surprisingly) less suggestive of the cancellation as shown in the figure below. This looks very much like an "ideal" stereo signal with only a hint of an antiphase component.

Comparing either of these displays against a template representing a 160 degree limit is practically impossible. Subjective judgment would overwhelm the process and cause endless problems in application. Applying these same displays on typical program material would be even more problematic.



A Quantifiable Alternative

To insure uniform application of an interchannel phase limit Qualis Audio suggests that existing specifications be restated as the equivalent compatibility loss value. For example, a 160° limit would become -15 dB. The result will be objective and consistent acceptance testing at ingest and a more informative and helpful tool in production and operations. The attenuation of particular frequencies in the program content during downmix is a concept that is easily grasped by personnel throughout the organization. It can be clearly disseminated outside the organization as well, leading to less confusion and fewer problems producing programs of a consistently high technical quality.

Furthermore, should compatibility acceptance criteria be changed in the future, the Sentinel allows selection of a value with a direct relationship to listener perception. Stakeholders are more likely to reach consensus when discussion is framed with a term they use daily (dB) rather than one which they may only occasionally use (degrees) and rarely in the context of program material.

In addition, the Qualis Audio technology also allows limiting the frequency range over which these comparisons are performed, allowing tighter performance criteria within the critical voice band. Low and high frequencies, which may be important artistically but of lesser importance to viewer satisfaction, may be exempted. Similarly, duration may be considered in setting a threshold. Brief passages which contain excessive phase shift, and consequently excessive cancellation when downmixed, may be ignored but cancellation which is sustained for a selectable time period will be identified. The Sentinel allows specification of the degree of cancellation, the frequency range tested and the duration required to constitute a problem.

Furthermore all testing is inherently automated, requiring no human intervention until noncompliant program is identified, alarmed and measurements logged for later recall and examination.

Extensions

Unlike conventional approaches to assessing downmix compatibility, the technique described here scales to as many channels as desired. Furthermore, there are no limitations on the locations represented by the channels since no attempt is made to create displays with a physical representation of interchannel relationships. Consequently it may be used to assess behavior in cinema systems with 5 front channels such as the Sony SDDS format.

Conclusion

The Qualis Audio Sentinel Surround Sound monitor produces simple and objective answers to questions of program downmix compatibility. The quantitative nature of its results allows more consistent decisions and enables unattended, automated assessment. In addition, the Sentinel provides comprehensive, continuous monitoring and assessment of many other important parameters of surround sound program material.

The Sentinel performs all measurements unattended and instantly detects common errors and quality problems, while sounding alarms and delivering remote error notification by email. All measurements and alarms are logged for later recall and examination. Both real-time and logged data may be accessed through a unified interface using a standard web browser.

Notes

For more details please see "Automated Assessment of Surround Sound" by Richard Cabot, presented at the 127th AES Convention in New York, October 2009 or visit www.qualisaudio.com .

The technique described here is the subject of a pending US patent application.

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