Loudspeaker Requirements in Object-Based Cinema

By Paul Peace

Abstract

Object-based cinema formats present acoustical design challenges in the loudspeakers used in theaters, which require analytical study. This paper presents an in-depth analysis of the acoustic delivery requirements in a typical theater utilizing these formats. Further, the paper proposes a metric for loudspeaker placement and selection to be used in theater design. This becomes particularly useful for surround loudspeaker specifications knowing that object-based theaters utilize venue-specific rendering engines. The metric provides a means to both improve performance and reduce system cost compared to current methods.

Keywords

Immersive audio, immersive cinema, loudspeakers, object-based cinema.

Introduction

Object-based cinema formats are a growing trend with numerous commercial implementations emerging over the past few years. The immersive formats—as they are called—offer film creators abilities within the audio content that were never before possible. These formats utilize mixes based on audio object metadata not tied to any particular loudspeaker layout. In theory, this eliminates the requirement for a set number or dedicated locations for the loudspeakers in a theater.

The new formats allow audio information to originate from anywhere in the virtual space of an audience, i.e., front, side, above, behind, and this can be done as a singular direction, general direction, or entirely environmental. This demands new loudspeaker locations be introduced into the theater beyond the standard 5.1 arrangement and that each loudspeaker have the ability to serve as a stand-alone presentation device. As such, each loudspeaker must present audio information to the entire theater at proper levels and with proper signal integrity. This is a new B-chain requirement in cinema.

The rendering engines used to translate metadata into actual loudspeaker signals use the theater geometry and loudspeaker location information to derive each content signal. This calculation, however, has to assume the loudspeaker can deliver its signal to all audience areas uniformly.

> **The topic of this paper focuses on the complexities of object-based cinema geometries that make them unique to standard cinema and other performance venues.**

The practical execution in immersive theaters has been a trial-and-error effort up to this point. Most theaters to date have been existing 5.1 theaters converted into the new formats, which has put pressure to use existing equipment. Loudspeakers and locations optimized for 5.1 use are very different from loudspeakers and placements optimized for object-based use. The industry is still trying to catch up to this new challenge.

The presented metric and analysis is primarily based on two closely related performance criteria pairs: 1) frequency response and level uniformity and 2) timing and directional uniformity. The first criteria pair is directly related to loudspeaker performance and the second pair relates to loudspeaker positioning in the theater. Both are equally important. It will be shown that the current practice does not represent optimization in any category. Object-based cinema will greatly improve once these elements are optimized.

This paper is not meant to be a primer on basic loudspeaker performance. There is much information on this topic found elsewhere. This paper provides specific information on the criteria specific to object-based cinema. Cinema loudspeakers should have frequency response, power response, transient response, distortion behavior, etc., within high-performance professional qualifications. The topic of this paper focuses on the complexities of object-based cinema geometries that make them unique to standard cinema and other performance venues.

Digital Object Identifier 10.5594/JMI.2017.2703198
Date of publication: 28 June 2017

1545-0279/17©2017SMPTE

History and Perspective

It should be noted that object-based cinema, in general, does not present new requirements to the primary left-center-right (LCR) screen and low-frequency audio range (LFE) loudspeakers. The proposed metric, as one would expect, has relevance in specification and placement of all other loudspeakers, with names such as surrounds, heights, fills, gaps, and tops. While the Immersive formats have different suggested placements, emphasis, and names for these, the general requirements are all very similar and all fall into the metric requirements outlined later. For simplicity in this paper, the term *surround* represents all of these different loudspeakers—regardless of their placement in the room.

Surrounds started as a monaural distributed array of simple loudspeakers. Object-based cinema requirements are dramatically different. It is quite interesting to read Ioan Allen's 1991 paper "Matching the Sound to the Picture"[1] and the masterful job of detailing the definition of surrounds at that time: "And what is most important about a surround channel is that it should surround. A signal should not have a specific directional source, and coverage of the theatre area should be uniform." The new object-based formats are a major shift in philosophy and this has brought on new acoustical requirements that are nontrivial. Each surround loudspeaker is no longer a single element of a larger array. Surrounds are now stand-alone devices that must present in solo and in perfect harmony with its many neighbors. All-surround loudspeaker development up to the advent of the immersive formats was based on the older criteria. The new formats present fundamental performance requirements for surround loudspeakers that can only be described as a very difficult acoustic challenge.

It is important to recognize that modern theaters use stadium risers with a general trend toward high back or recliner/lounger seating. Both of these put additional obstacles to loudspeaker placement and directivity that standard seating does not:

- Lounger seating utilizes fewer seats per theater and is proving to be very popular. Therefore, these theaters have a significantly higher attendance rate with patrons in what was once the cinematic nose-bleed seats (this means the first three rows) on a regular basis. The ability of loungers to recline and their more spacious footprint greatly improves comfort and the visual experience in those rows compared to the traditional layouts. Loudspeaker coverage, however, is traditionally poor in these seats in most theaters.
- Object-based formats that layer the side surrounds very often require the lower layer to be within the acoustic shadow line of the seating headrest. The metric must address this phenomenon.

The analyses of this paper are not based on a single format, but evaluate all the acoustical requirements of surrounds for any object-based format. For analysis reference, traditional channel-based formats will be presented as well when useful.

The Studio Environment

The goal of a cinema audio system is to precisely recreate what was first created in the studio.

The acoustic models shown in **Fig. 1** represent actual rooms and were chosen carefully to represent the average of these room types. The comparison of the two environments is important because the geometries and the associated loudspeaker requirements of the two spaces are quite different. The diagrams in **Fig. 1** show the basis of the metric performance pairs. The sound pressure level (SPL) mapping in **Fig. 2** maps the two rooms from center screen location. The left side directional lines for both are shown in **Fig. 3**. The timing gap between two side surrounds is shown in **Fig. 4**.

The theater is by far the more complex and difficult venue in which to achieve uniform acoustical performance as should be evident from the graphs shown.

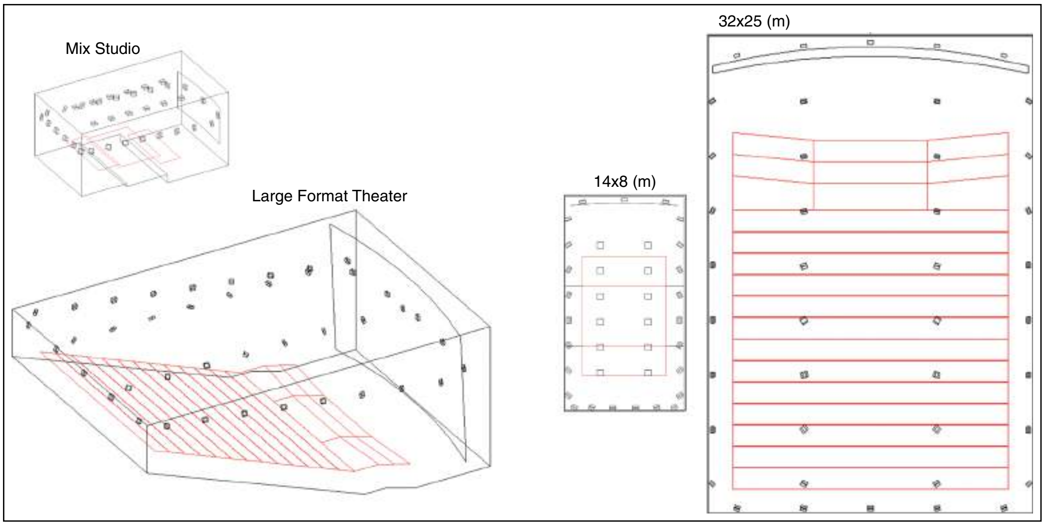

FIGURE 1. Scale models of actual mix studio and large format theater.

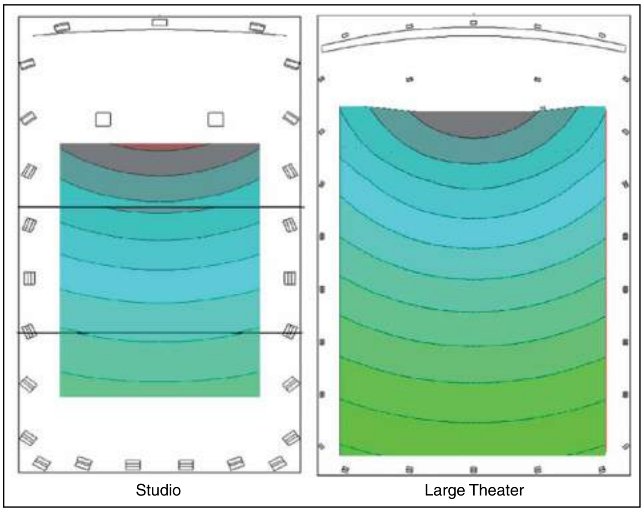

FIGURE 2. SPL maps showing inverse square attenuation.

Inverse square mapping frequency response is specific to a given point in space in relation to a loudspeaker (typically on-axis). If we put a frequency response and level requirement to many points in space (an audience area), then directivity must be considered. To understand what points in space are of interest and how they relate to each other in terms of level, we use SPL maps of the room as a guide.

The first important SPL map evaluation relates to an inverse square loss (ISL) map. To fully grasp the significance of ISL mappings, some explanation is offered here. One can look at these from two perspectives: (1) the SPL level in each seat if the loudspeaker were an omnidirectional source, or, more importantly, (2) the maps show the natural loss of sound pressure as the energy radiates away from its source, i.e., loss due to distance. Both the statements are true and can be helpful in understanding the mappings' significance.

Note: All SPL mappings in this paper are shown in 1 dB increments. The actual dB values labeled on the graphs are not referenced to any calibration level. They are useful as relative to each other at any level, including calibration level.

An ideal loudspeaker will produce a uniform sound field across an entire audience. This is only achieved if each seat receives the same acoustic energy level relative to the next. The ISL maps, therefore, indicate a directivity function for the loudspeaker's acoustic radiation. Put simply, the loudspeaker must present more intense energy to the areas furthest from it and less intense energy to those seats closest to it. This phenomenon is true for any loudspeaker in any space or application. The following will put focus on the unique challenges in this regard in object-based cinema.

Cinema is a multiple source audio experience that relies on each loudspeaker presenting its signal uniformly to all seats and in Balance with all other loudspeakers. The requirement for all loudspeakers to Balance with each other—in all seats—presents a more difficult challenge for the loudspeaker's directivity function than commonly seen in performance venues. Object-based cinema is the most extreme example of this. Cinema room acoustics present a further challenge as it is intended to be nonparticipatory in the strictest sense, i.e., there is no supportive reverberant field to aid in overall level uniformity.

As can be deduced from **Fig. 5**, the ISL mappings show that object-based cinema requires the directivity function to have specific "shapes" that are different for the various locations in the room and with specific control out to 21 dB with very wide angles!

Note: It is common in the audio industry to refer to a loudspeaker's directivity function in terms of its 6 dB down points. This is a reference to a horn or transducer's 1/2-power solid angle.

From an audio system standpoint, it is also a holdover from the days of building horn clusters in the performance venue, where one would adjust each horn to intersect at the 6 dB contour lines. This nomenclature stuck as a spec sheet phrase and created the misconception that there is something special about the 6 dB contour in a loudspeakers' behavior.

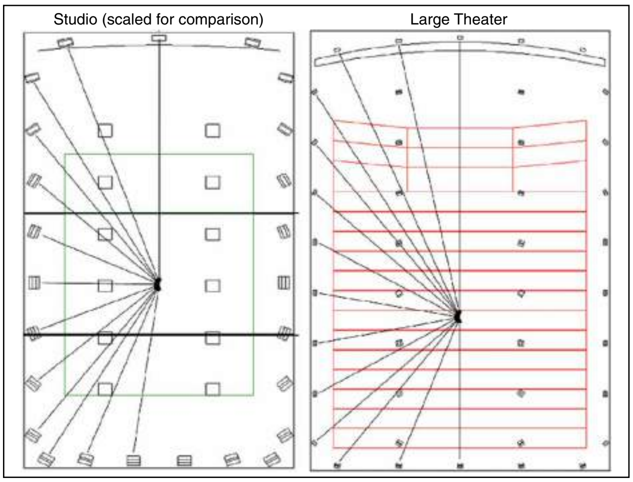

FIGURE 3. Directional maps of each loudspeaker to reference.

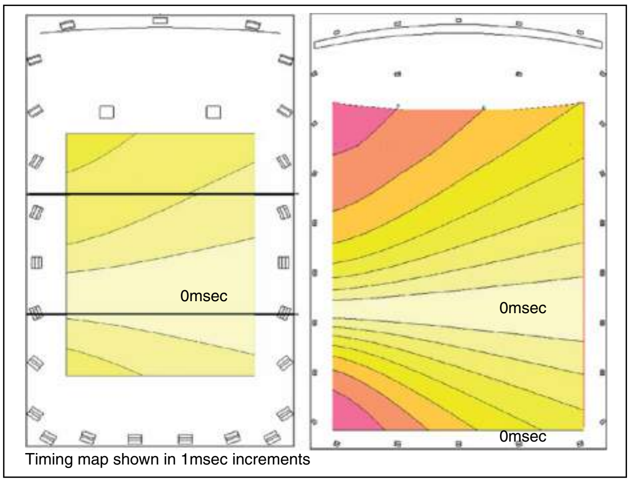

FIGURE 4. Timing maps for each venue for two side surrounds.

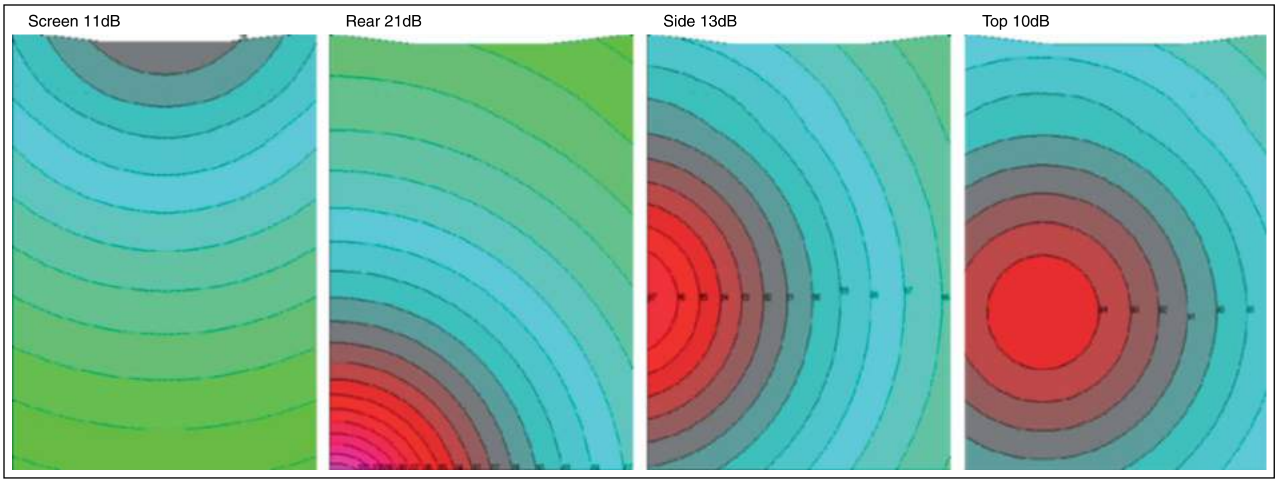

FIGURE 5. ISL maps for general locations in a theater.

To further the point, **Fig. 6** shows the coverage from these same locations using loudspeakers with typical directivities as used in most theaters at present. This shows the very difficult challenge for loudspeakers in object-based cinema. It is easy to see that the screen locations have the easiest directivity requirement. Traditional techniques do not work well in the surround positions as should be apparent above. It should be understood at this point that coverage in most venues would require a maximum SPL variance within +/−3 dB. For all surround positions, this would be less than 10% of the audience. 5.1 and earlier surround formats did not experience these issues. **Figure 7** is the same mapping of a traditional 5.1 layout and it is easily within general coverage tolerances. There are new products and techniques that improve this even further. It should be clear that Immersive formats present a dramatic new challenge.

Excellent Balance is required for Immersive effects to be executed. Balance is defined as those seats with signals from all loudspeakers within a certain +/−dB window. The calibration point in the theater is the only point guaranteed to reach Balance. Coverage uniformity of each loudspeaker determines Balance for all other seats.

The SPL maps translate directly to Frequency Response. As an example, **Fig. 8** shows a typical off-axis response normalized to an on-axis response. The green and red curves are two possible variations measured on a –8 dB contour line on the SPL map. The red line is the response of a typical surround off-axis vertically while the green curve is off-axis horizontally.

The normalized response technique can also extend to the maps. **Figure 9** shows difference maps of a surround coverage normalized to center loudspeaker coverage. While typical SPL maps show the absolute coverage, the difference maps show the coverage Balance between two loudspeakers. If there is perfect Balance, the entire map would be one color—in this scale: blue/green. A useful tool in cinema is to map each surround normalized to a screen loudspeaker. Another important Balance map is to view the difference between left/right pairs.

These maps show typical object-based cinemas to have +/−12 dB variances in coverage Balance overall with no centralized common good area. There will be wildly varying hot and cold coverage areas. The calibration point is virtually

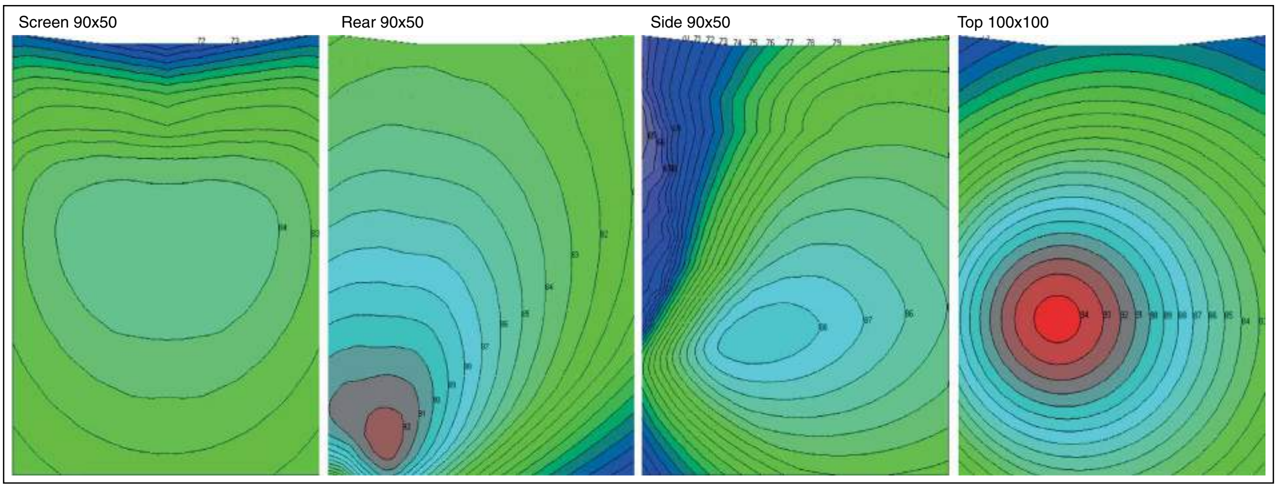

FIGURE 6. SPL maps for general locations in a theater using typical directivities.

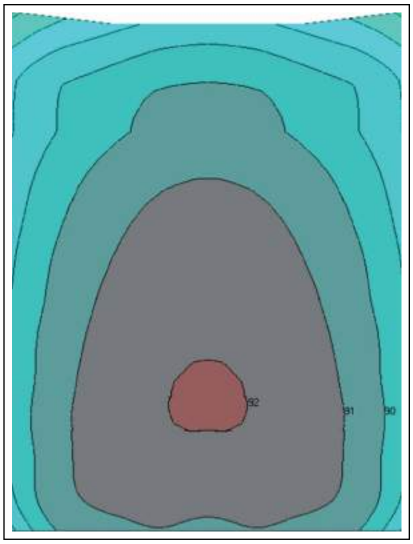

FIGURE 7. Typical 5.1 surround coverage map.

the only place there will be good Balance. These maps represent typical rooms and typical loudspeakers. This is the state of Immersive theaters in practice today.

A Solution?

The solution for improved coverage Balance is directly related to loudspeaker directivities better matching the room requirements. So what does a properly designed directivity pattern look like? A mathematical modeling tool was developed to explore this question. **Figure 10** shows a typical center screen loudspeaker with two "ideal" directivities: an ideal 90° × 50° and a mathematical ideal that matches the audience area. The 90° × 50° ideal directivity is purely based on the 6 dB contour values. The mathematical ideal directivity is purely based on the room geometry. Each color change in the plots represents a 3 dB change in level.

Figure 11 shows a comparison between the directivity balloons of: (1) a mathematical model 90 × 50 directivity balloon (left), (2) a real 90 × 50 directivity loudspeaker (middle), and (3) a mathematically derived

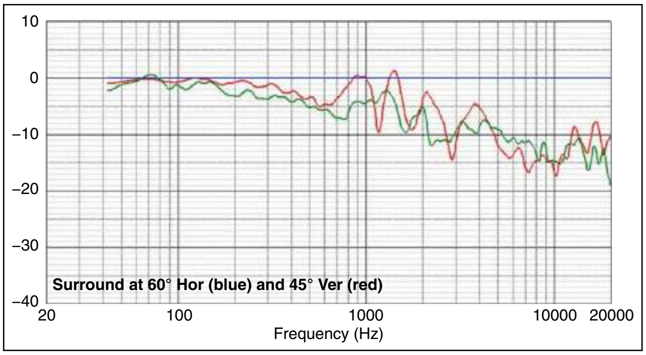

FIGURE 8. Typical frequency response curves for 8 dB contour areas.

ideal center loudspeaker balloon corresponding to the SPL map shown **Fig. 10**. The patterns look very different because two are derived from a loudspeaker point of view and the third is derived from a room point of view. The room derived pattern is an exact complement of the ISL differential across the audience.

For reference, each color shown on the balloons represents a 3 dB transition. Therefore, this ideal balloon shape is critical over a 10 dB range.

We will now evaluate the room derived balloons—**Fig. 12**—for the three generic surround locations previously explored. We know from their ISL maps that the directivity requirements are very different.

Likewise, their balloons are dramatically different, not to mention quite a challenge to create acoustically. This confirms the earlier deduction that at least four distinct directivity patterns are necessary in object-based cinema and they are anything but simple.

The ideal rear directivity is unique by its very focused energy, which has to be aimed downward to match the seating rake of the room.

The energy grazes the seating plane and must exhibit control beyond its 18 dB contour. The ideal side directivity is 180° wide and must take on the tilt of the stadium seating rake. It is also asymmetric as is needed

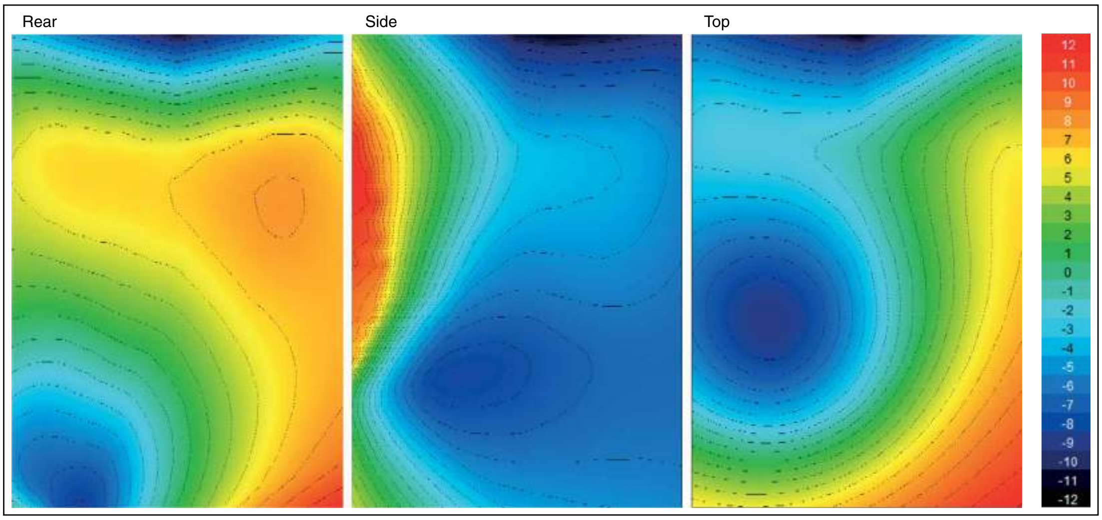

FIGURE 9. Surround coverage patterns normalized to center screen loudspeaker coverage.

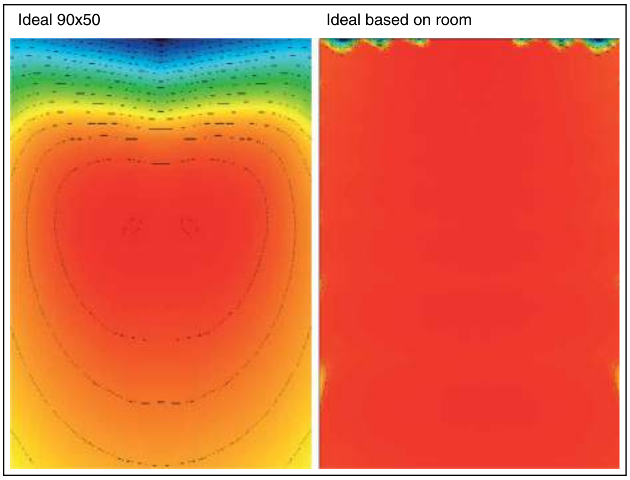

FIGURE 10. Typical center coverage versus ideal center coverage.

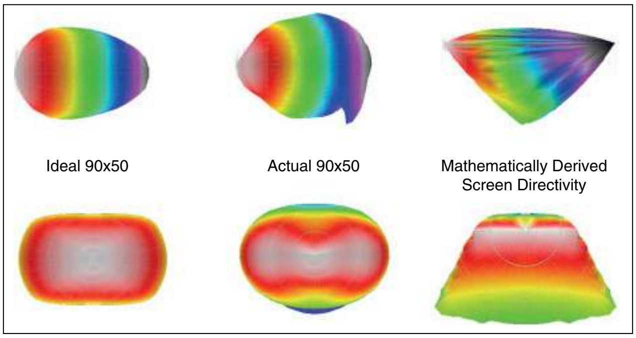

FIGURE 11. Directivity balloons for actual and virtual loudspeakers.

for proper energy distribution in the vertical plane. The ideal ceiling top position has a unique doughnut feature to eliminate the hot spot directly underneath it and is a very sculpted 360° pattern.

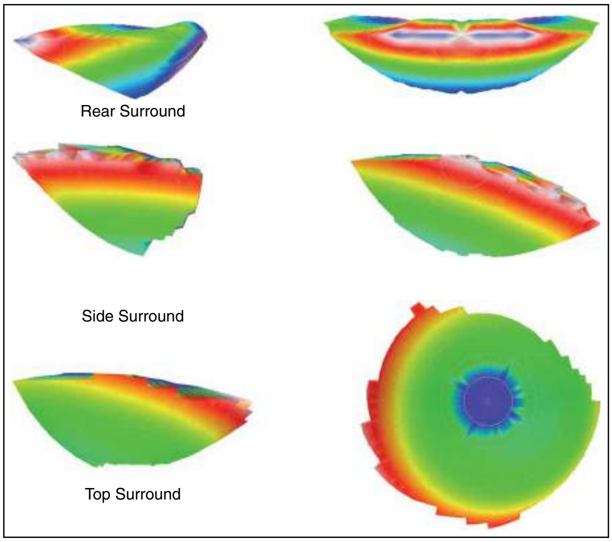

FIGURE 12. Mathematically derived surround directivity balloons.

All Locations

Figure 13 shows the object-based theater surround locations typical for all Immersive formats. The main LCR screen locations are common for all. Theater geometry mandates the rear locations and ceiling locations be virtually the same for all formats. The addition of fill and height screen loudspeakers is format dependent and all are included. The side surrounds provide the most variation in placement. These ultimately translate to three "layers" of surrounds and are labeled as upper, middle, and lower in our model as shown below and are format dependent.

Figure 14 shows the ISL mappings for all positions. We will explore the details of these in the following pages.

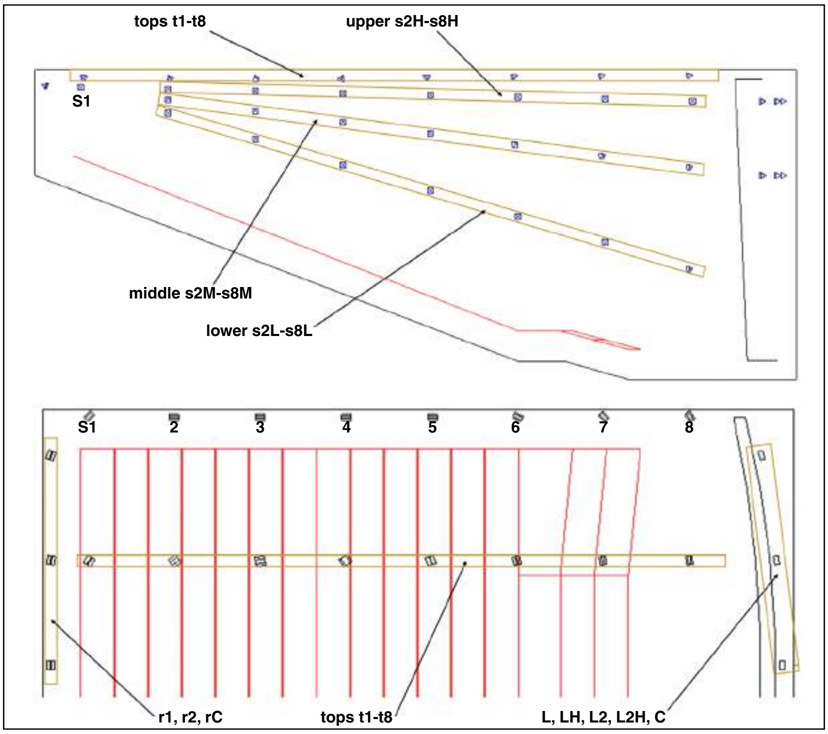

FIGURE 13. Immersive surround locations in a theater.

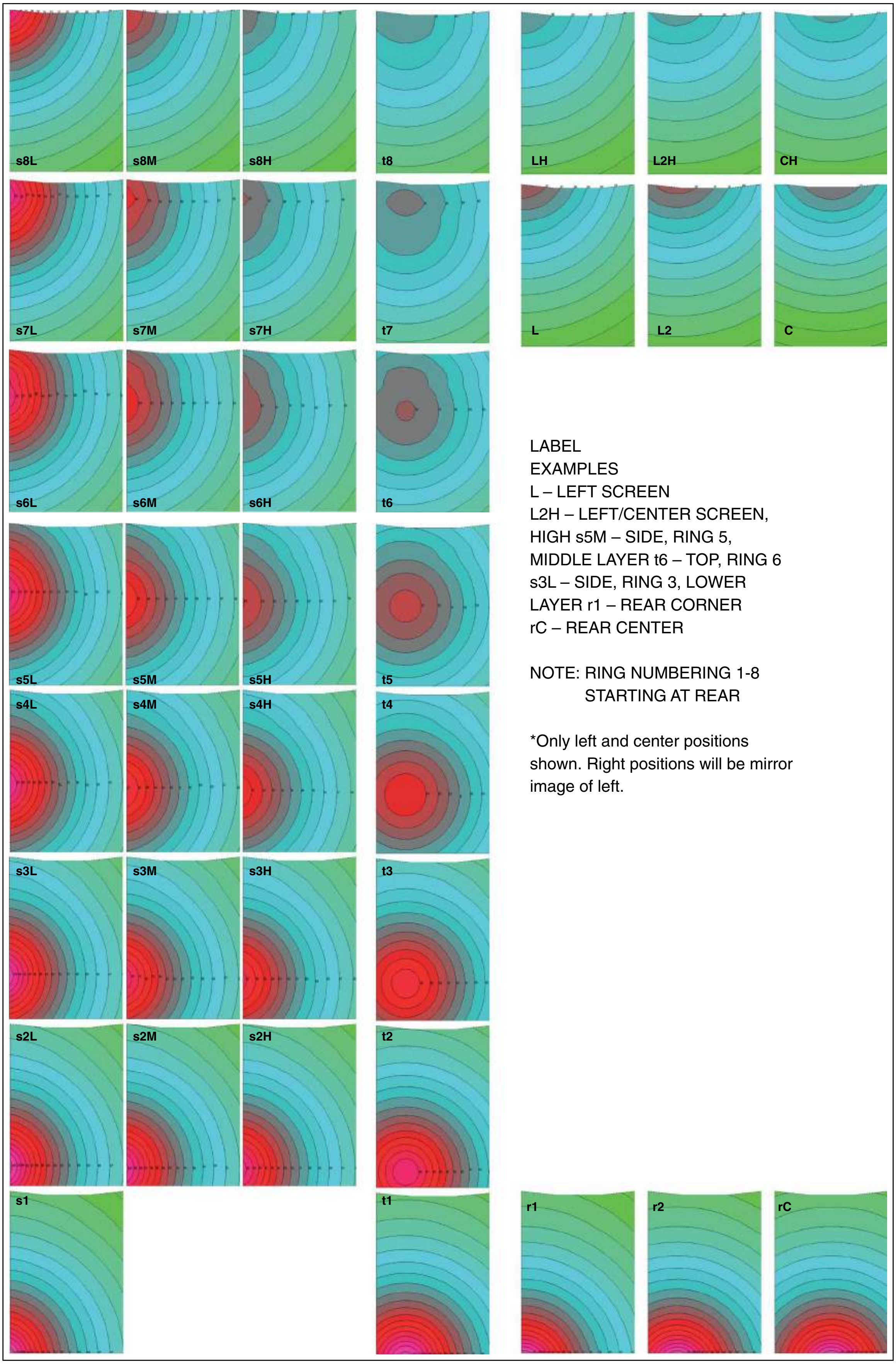

FIGURE 14. ISL maps for all locations in object-based cinema.*

The theater model includes eight surround rings and this number is typical for this room size. For analysis purposes, these are labeled as shown in the right of **Fig. 14**. It should be noted that none of the object-based layers use the same positioning as is typical for 5.1/7.1 cinema, which would be slightly higher than the lower layer. This becomes an issue when Immersive theaters play 5.1/7.1 content. As should be evident, all layers share the S1 (rear side) position.

The S1 position becomes a least common denominator design limitation for all formats due to low ceiling elevation in a typical stadium seating architecture.

Those formats that utilize side surround layers present a difficult challenge in stadium seating architecture that will be explored later in this paper.

The mappings reveal that there are four directivity trends that relate to the front, rear, side middle, and top middle of the room.

The front group is shown in **Fig. 15** and includes the tops and sides in this area. All see similar angular requirements and ISL differentials. It will be immediately evident that the directivity groups relate to placement in the room, but do not track with conventional practice. The data show that all loudspeakers within 4 m of the screen have the same basic directivity and output capability regardless of location.

Figure 16 shows the positions in the rear of the room that have similar angular requirements and ISL differentials. The interesting thing is that they are on the rear wall, on the side walls, and on the ceiling. Regardless of wall orientation, these loudspeakers must graze the seating plane and have shape control out to their 18 dB contour. The front group **Fig. 15** sees a much less dramatic ISL rate and only has to control out to their 10 dB contour.

The front and rear positions all share similar "throw" distances and therefore have similar output requirements. The two remaining groups are very different in this regard. Their requirement is much wider coverage angles but less energy in any single direction.

Figure 17 shows the middle group mappings and includes the 3–6 rings of side and tops (4 and 5 are shown, 3 and 6 are not but virtually identical). These differ from the other groups by the requirement of 180° width angular requirement and "seeing" the seating rake from an orthogonal direction.

The tops are shown in **Fig. 17**, but have a greater vertical angular requirement underneath them and slightly different ISL rate. Therefore, tops 3–6 make up the fourth group. Note that tops 1 and 2 are in the rear group, tops 7 and 8 are in the front group.

With this important information, four loudspeaker directivities should be implemented in object-based cinema rooms. This can be four distinct loudspeakers, loudspeakers with configurable coverage patterns, or loudspeaker arrays configured to accomplish the appropriate directivities. It should be noted that all surrounds should exhibit very similar sonic characteristics.

Note: One exception to the general groupings are the lower layer sides s7L and s8L. Their close orientation to the seating plane match the rear positions closer than the front positions.

The Metric

Much emphasis has been given to the directivity requirements as they relate directly to the Frequency Response and Level metric. If directivity is poor, so is Frequency Response, Balance, and level for a large portion of seating area. Therefore, to establish a design metric one must first establish what portion of the seating will receive adequate Frequency Response and Balance from all the loudspeaker locations. It has been seen in practice that there are approximately four regions of operation

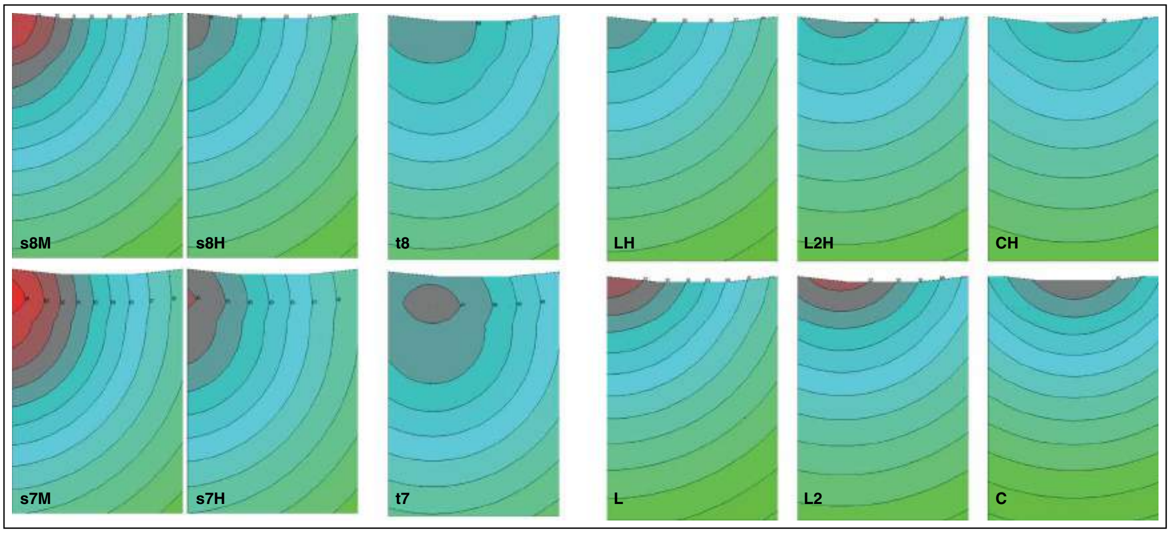

FIGURE 15. ISL maps for the front group.

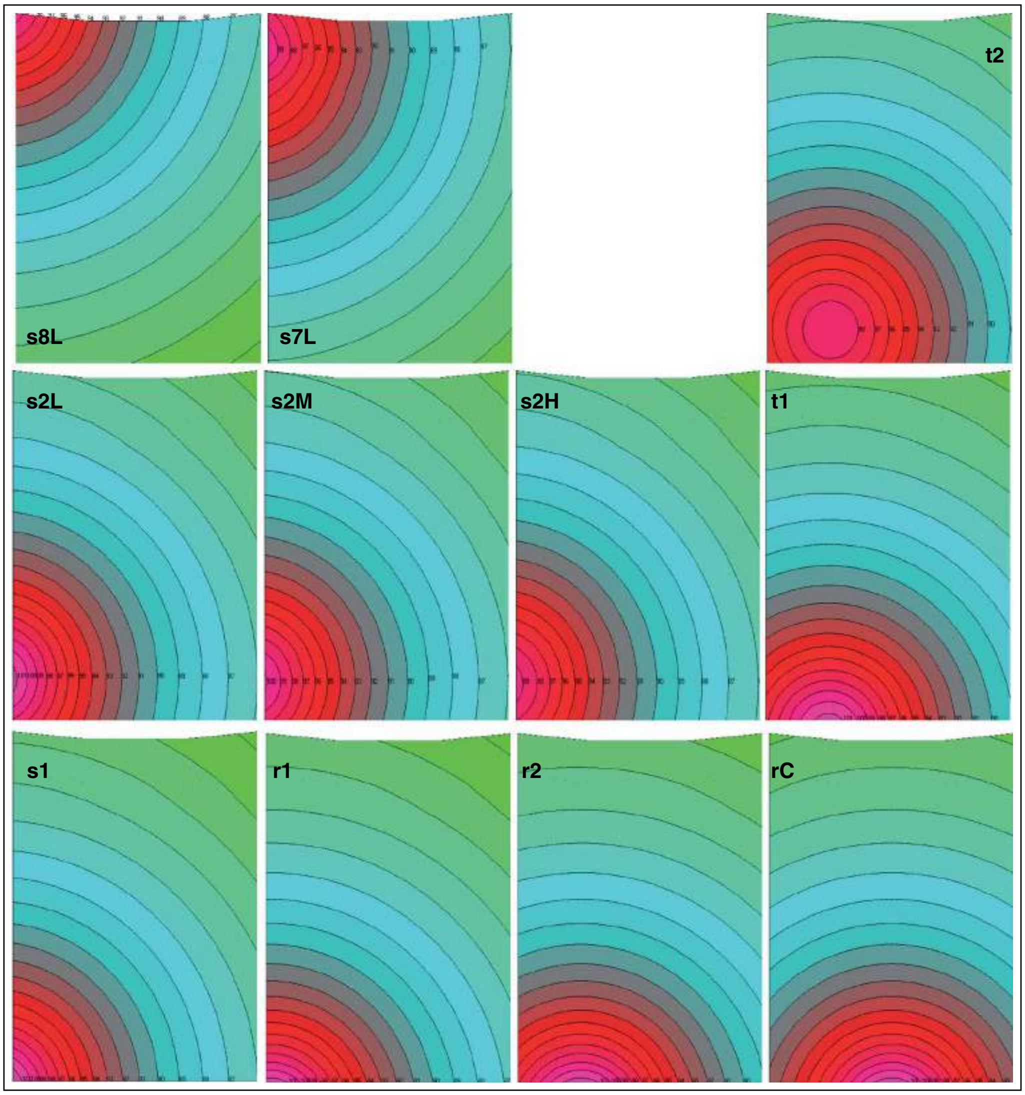

FIGURE 16. ISL maps for the rear group.

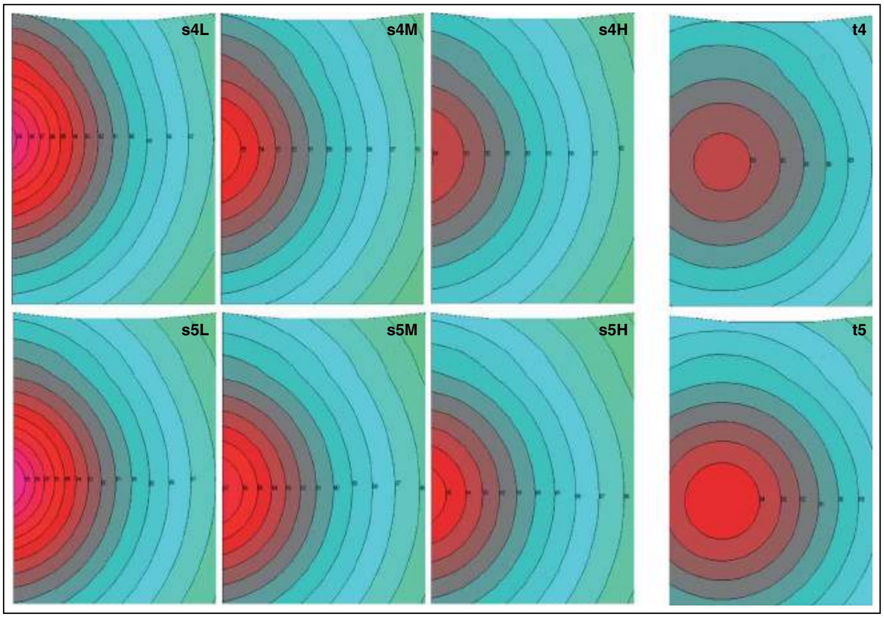

FIGURE 17. ISL maps for the two middle groups.

when considering Balance: Very Good [+/−1 dB], Good [+/−2 dB], Acceptable [+/−3 dB], and Poor [all others]. Before Balance can be established, however, the reference coverage loudspeaker (usually center) must be examined to have acceptable coverage in all seats. In this regard, no seat outside the 6 dB SPL contour of the reference loudspeaker can be considered anything but in the poor category. This is due to the calibration with the LFE channel—even if all other loudspeakers Balance with it. **Figure 18** shows this area for our center loudspeaker shown previously.

It has been shown that the generic locations introduced earlier are good representations of the four directivity groups required. If we evaluate the current practice in this way and develop Immersive performance zones, one can deduce a layout for all loudspeakers. **Figure 19** shows the normalized SPL maps shown earlier but only with the good Balance areas revealed. Likewise, **Fig. 20** shows the same loudspeakers with the left/right Balance area revealed. All six areas must now overlap to reveal the actual complete system Balance area.

Figure 21 shows the overlap region once normalized to the calibration point in the room. This represents the good zone and is the area within +/−2 dB for all channels, i.e., the system Balance area—less than 10% of the audience.

It should be apparent that the current practice produces a small area of Balanced coverage. As loudspeakers are improved and these areas get larger, surround placement will become more critical.

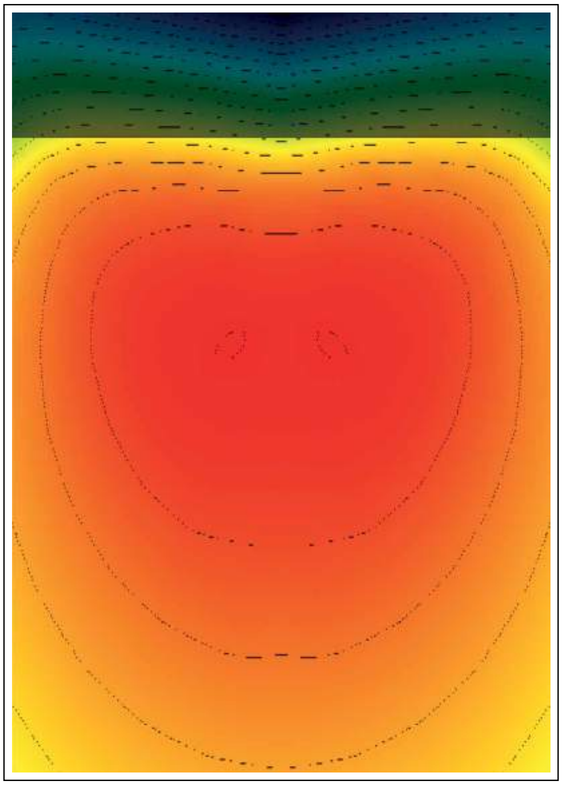

FIGURE 18. Typical center SPL map showing poor region in gray.

Directionality and Timing

Only once the coverage zones are established can directionality be evaluated. Directionality can have effect even in areas with poor Balance, but if level and frequency response are well outside acceptable ranges, then the Immersive effect is lost or grossly exaggerated. Therefore, loudspeaker placement in terms of directionality should only be done for those regions within the acceptable Balance zone. (In current theaters, this is not much larger than the area shown in **Fig. 21**).

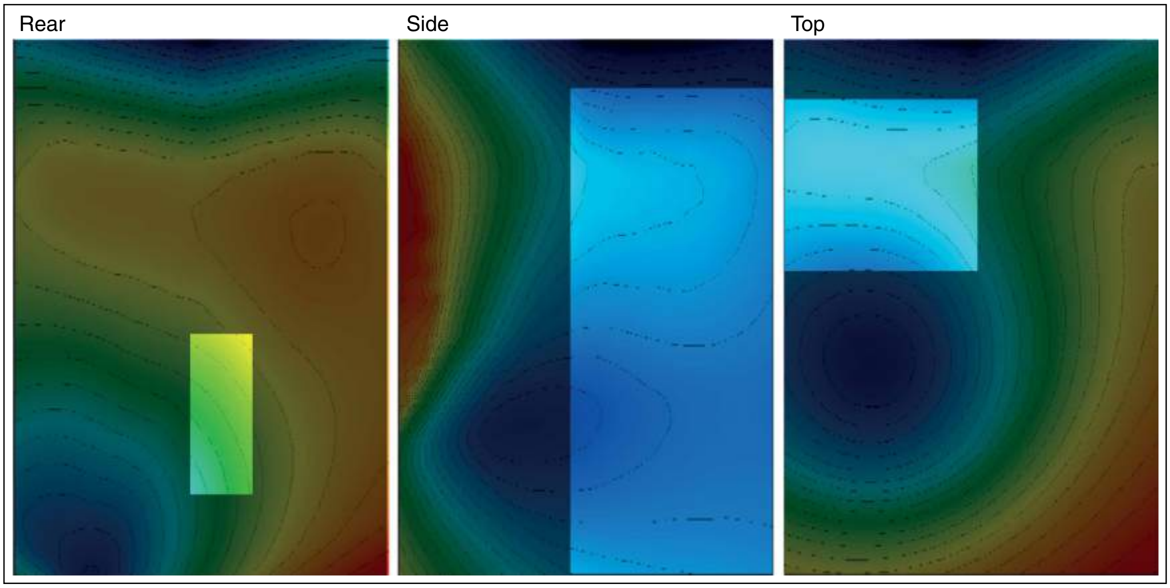

FIGURE 19. Surround coverage where in Balance with screen loudspeakers poor region in gray.

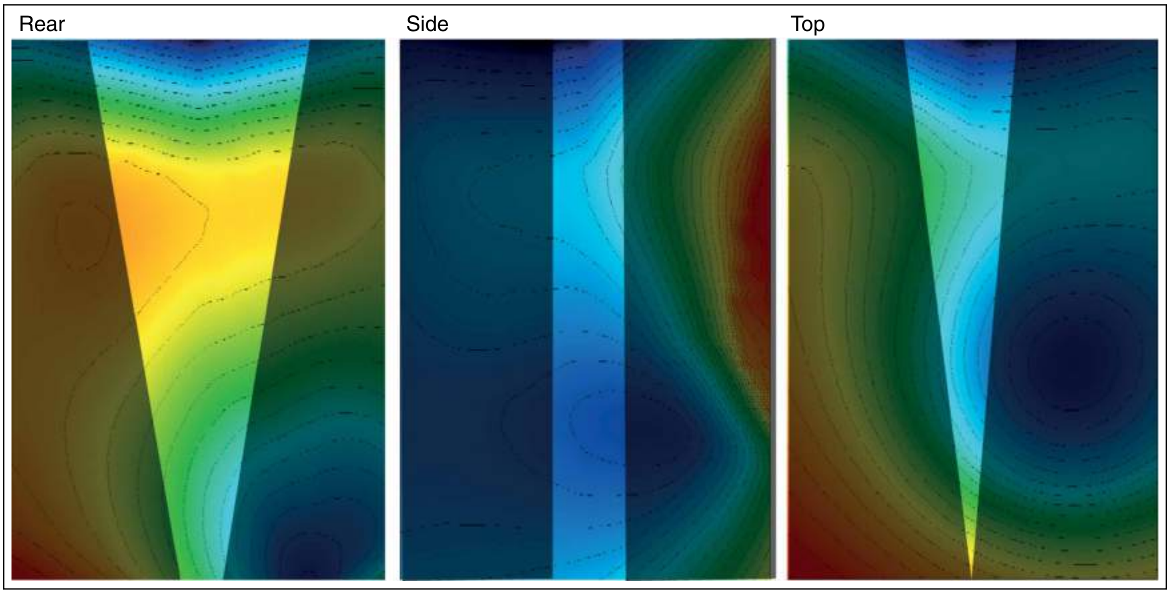

FIGURE 20. Surround coverage where in Balance between left and right pairs poor region in gray.

Surround placement in Immersive theaters began by using the 5.1 placements that preexisted. This was out of necessity and was not theoretical. As the Immersive formats have evolved, a growing trend is to now allow surround pairs to be used to try and improve coverage. This, of course, reduces the directional granularity, which is one of the features of object-based cinema.

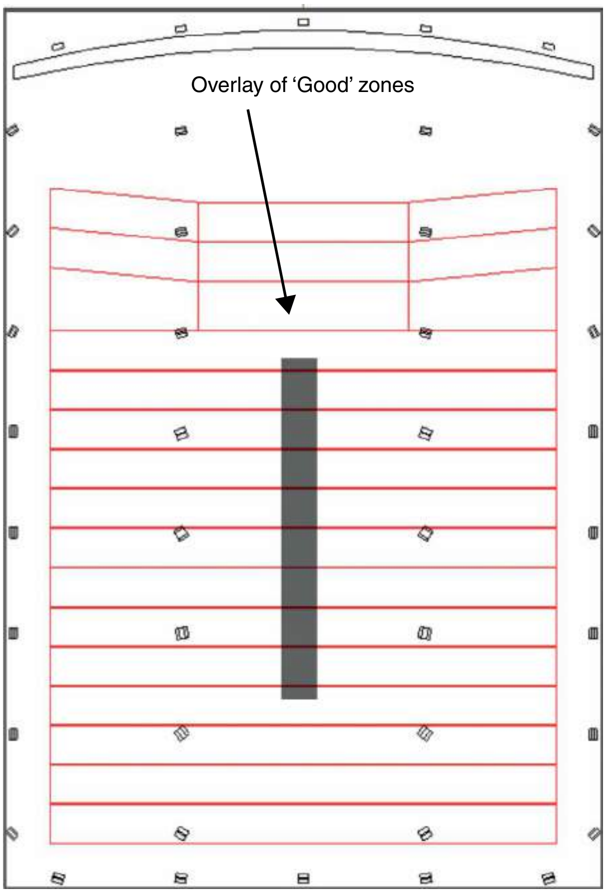

FIGURE 21. Immersive system Balance area.

In addition, paired loudspeakers suffer from severe comb filtering. **Figure 22** shows the result of surround pairs that are aimed in the same basic direction—which is the common practice for side surrounds. The interference patterns are frequency dependent and very different from each other. In addition, a pairing loses a distinct acoustic origination point, greatly diminishing directionality. Pairing surrounds is not the solution.

The directionality matrix should be founded on the layout established in the studio using basic stereo imaging rules. Then, apply this only considering the actual area in the theater that receives adequate frequency response and level. In a theater with an acceptable Balance zone of 50% of the theater that is 16 m wide, directionality would place side wall surrounds at approximately every 3 m and for 40%, every 4 m. For 20%, which is common in current practice, 5 m is sufficient.

Timing considerations are compromised in almost every way in a large room compared to the studio environment. This is one metric that cannot be scaled or be fixed. Timing, of course, can be set perfect if one is in the calibration point, but disintegrates quickly beyond. The point is, however, that timing should be the last metric considered and should never take precedence over the others. If the layout has only 25% good Balance metric, timing is virtually irrelevant if the directionality metric is proper. Only when the Balance percentage gets quite large will timing need to be considered beyond the placements required by the directionality metric.

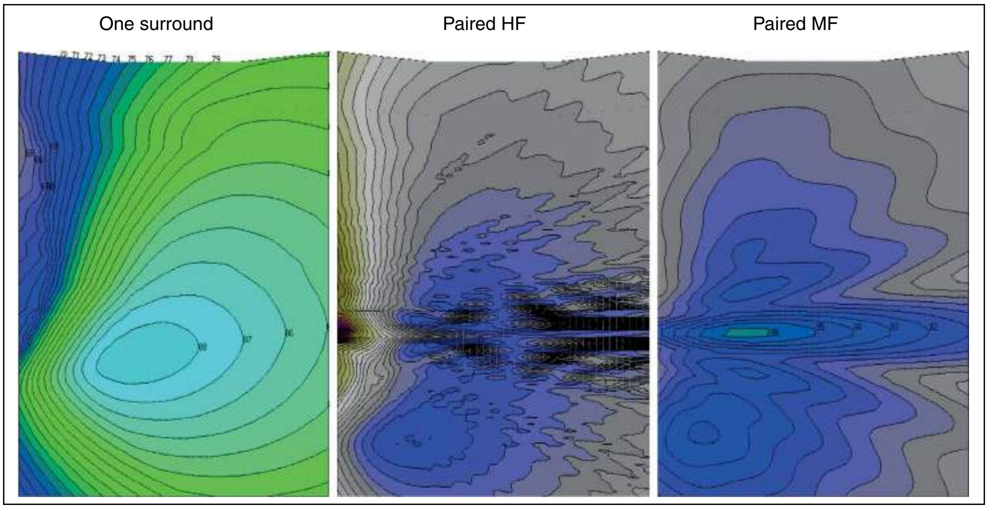

FIGURE 22. SPL maps of paired surrounds.

Conclusion

Object-based cinema is a medium with great potential. This potential will only be manifested in theaters when cinema loudspeakers can "catch up" with the acoustical requirements presented here. Immersive cinema audio is about precision, power, and subtlety. There can be no precision or subtlety without every seat receiving the correct signal. The general practice is to put more traditional surrounds in place to make up for the core deficiency demonstrated when the exact opposite is needed: fewer, but very specific loudspeakers placed strategically. This technique will deliver a much more enveloping and immersive audio experience.

This paper suggests new directivity models to be utilized in loudspeaker design for cinema and a metric for placing loudspeakers in Immersive theaters. As directivities are improved and Balance zones become larger, field studies will be required to further develop the directionality and timing metrics. Those undertaken to date all suffer from the physical limitations outlined here, and therefore are flawed in that manner. The placement metrics to date have been largely anecdotal. Practical aspects simply dominate those particular decisions at present.

Acknowledgments

I wish to thank Alexander Terekhov, Harman Professional, for his valuable help in writing the difference mapping tool used in this paper. Thanks also to the entire acoustics engineering and cinema teams at Harman Professional for their support, and to Alvis Wales and his mentorship through all of my years at IMAX Corporation and since. Much of my understanding in this paper is due to his support and encouragement and many hours spent commissioning theaters together.

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Presented at the SMPTE 2016 Technical Conference & Exhibition, Hollywood, CA, 26–29 October 2016.