positioning speaker systems, given the size of the venue and the audience distribution, with the aim of optimizing the speaker coverage.

11.6.1 Speaker Coverage vs. Height

For illustration purposes, we will start with the simplest case – a small rectangular space that can be covered by just one speaker positioned at the front and centered left to right. We will ignore the influences of the room and audience for now and look at just the area of coverage of the speaker system.

One of the first things that we must determine about the speaker system being used is its directivity characteristics. Figure 11-4 shows a speaker system with the longitudinal axis and the vertical and horizontal planes highlighted. The longitudinal axis of the speaker system is an imaginary line running from the back of the cabinet and extending through the front of the cabinet at some point determined by the manufacturer. It is usually centered left to right on the front of the cabinet. The directivity characteristics, typically published as a set of dispersion plots, are referenced to this axis and these planes. There is usually one set of plots for the vertical spread or dispersion and one set for the horizontal dispersion. Figure 11-5 shows a typical set of plots for the vertical dispersion plane of a speaker system. Note that plots are given for a select set of frequencies, showing how the sound level decreases as we move above or below the longitudinal axis of the speaker. The plots for the horizontal plane will look rather similar, but show how the sound level varies as we move left or right of the longitudinal axis.

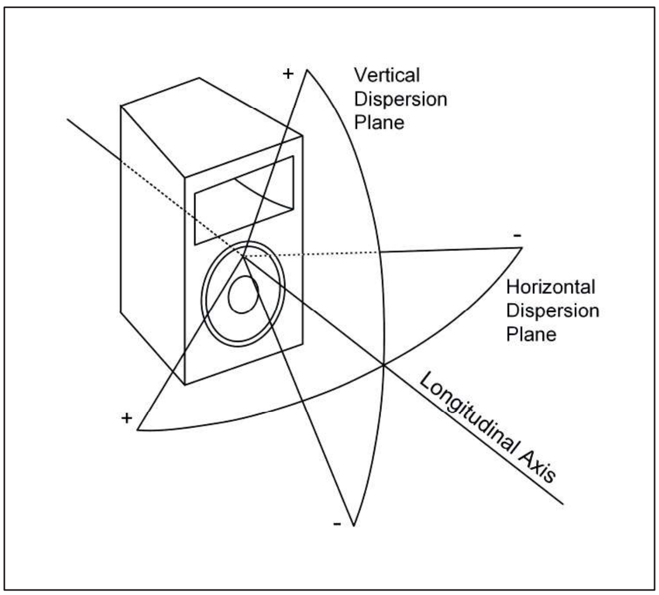

Figure 11-4 Reference Axis and Planes of Dispersion Plots

To examine some of the issues of coverage that depend on the height of the speaker, let us only consider a single frequency and a fixed coverage angle. This simplified approach will allow us to easily compare differences in coverage as we move the speaker around. To that end, we will use the information derived from the 2 kHz vertical dispersion plot and the angle where the sound level falls by 9 dB to determine the limit of coverage towards the front of the audience. This angle is shown by the round dot on the 2 kHz plot in Figure 11-5 and highlighted directly in Figure 11-6. It is about 40 degrees below the longitudinal axis in this particular plot. So now we can determine the forward limit of the audience to be the point where the -9 dB line intersects the plane of the average ear height. The rear of the audience space will be the point where the longitudinal axis intersects this same plane.

Figure 11-6 shows the difference in coverage with the speaker system at four different heights, while keeping the speaker the same distance from the rear of the audience. One thing that we may conclude from Figure 11-6 is that there is no advantage to raising the speaker system higher than

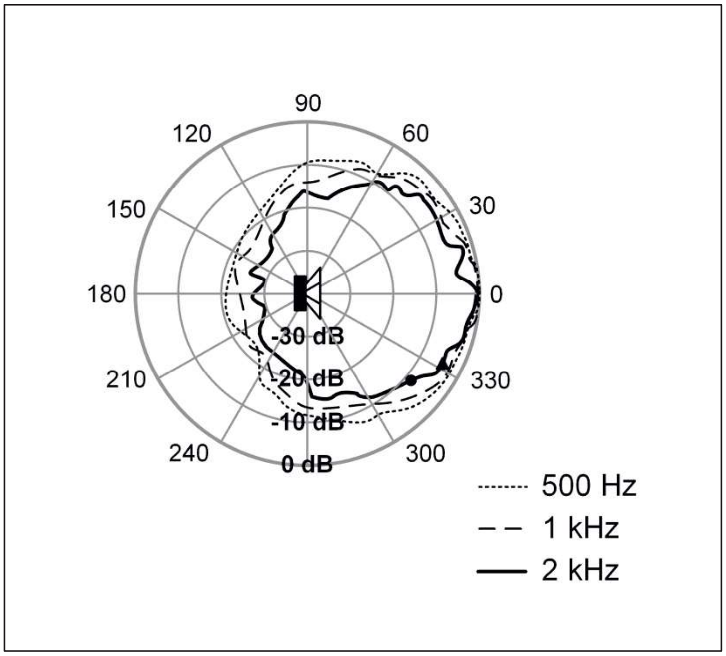

Figure 11-5 Vertical Dispersion Plots Showing Three Frequencies on One Graph

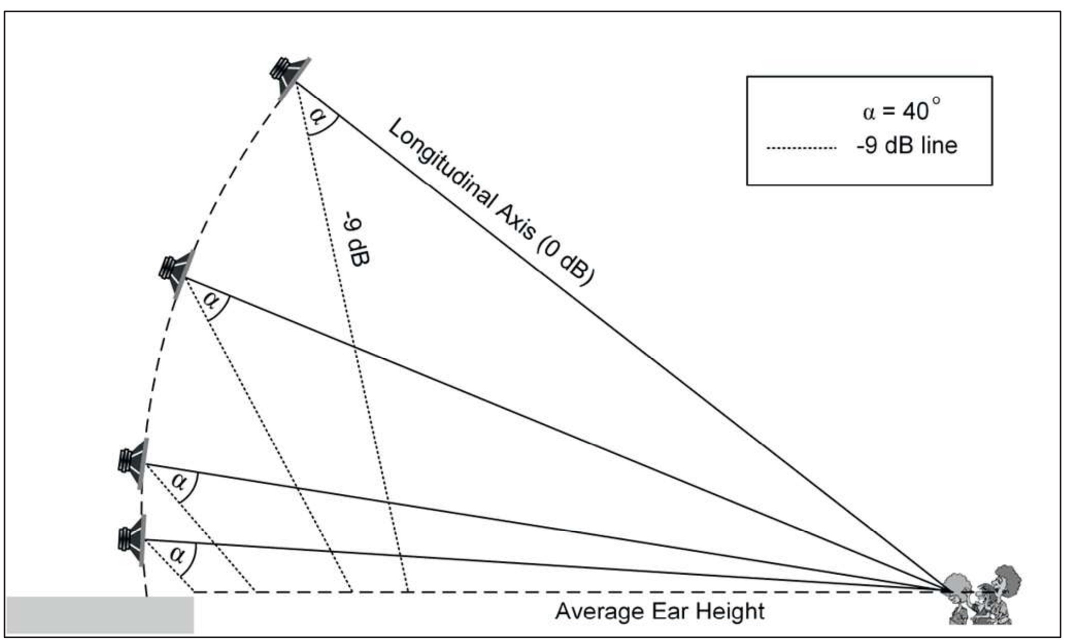

Figure 11-6 Coverage Area Varies with Loudspeaker Height

is necessary to have a clear line of sight to the rear of the audience. However, that would be a premature and incorrect conclusion. While there are some disadvantages to raising the loudspeaker system, there are also some advantages, and so we must examine the situation a bit more closely.

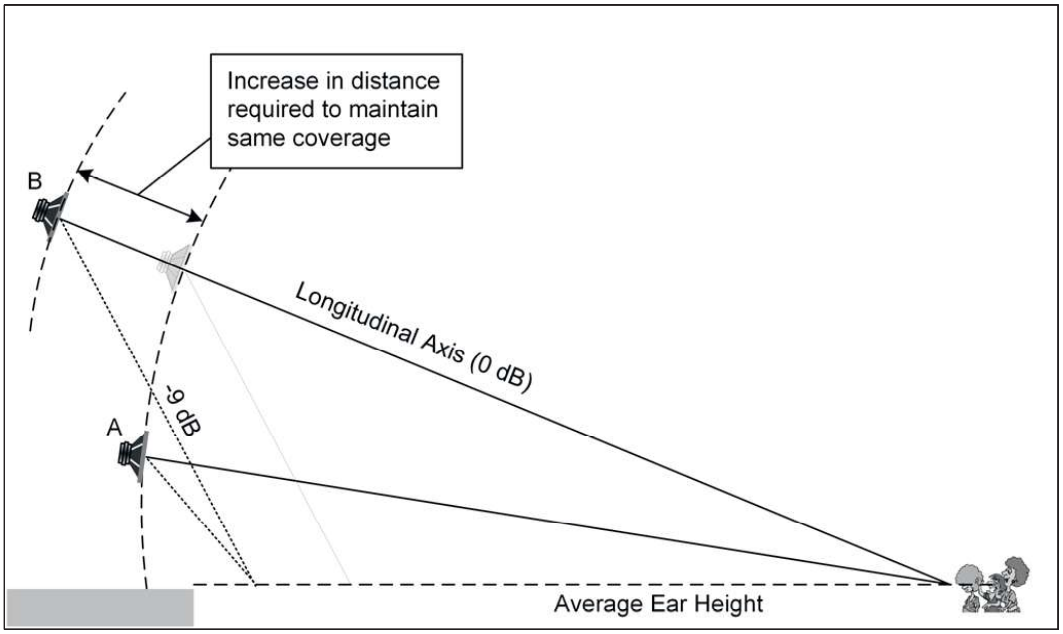

Figure 11-7 Raising Speaker While Maintaining Same Area of Coverage

We can see that as the speaker system is raised, the -9 dB line moves further and further back into the audience space, thus reducing the forward limit and effective area of coverage. In fact, Figure 11-7 allows us to conclude that there is a disadvantage to raising the speaker system more than necessary, because we can see that in order to maintain the same area of coverage when we raise the speaker system from position ***A*** to position ***B***, we have to move it farther back over the stage, thus increasing the distance to the audience. You may also recall from the discussion in Section 1.7 that the SPL decreases not in proportion to the distance, but with the square of the distance. Thus, the SPL in the audience area may drop quite a bit if we raise the speaker too high and try to maintain the same area of coverage. (Of course, if we needed to raise the speaker and maintain the same area of coverage without having to move the speaker deeper into the stage area, we could simple change to a speaker system with larger vertical dispersion.)

On the other hand, placing the loudspeaker system just high enough to have a clear the line of sight to the rear of the audience also has some disadvantages. Firstly, we are aiming more of the high energy output of the system at the back wall. This means that we will in turn get higher intensity reflections from the wall back into the audience area. Additionally, when the speakers are kept low, they are closer to the microphones on stage, and so the likelihood of feedback is increased. The biggest problem, though, with having the loudspeaker system down low is the large difference in SPL between the front and rear of the audience. This results from the large difference in distance between the speaker and the rear of the audience and between the speaker and the front of the audience. We can see this in Figure 11-8. For the upper speaker, the distance to the rear of the audience is ***AB***, while the distance to the front is ***AC***. The difference between these two is ***AB-AC***. Similarly, for the lower speaker, the difference in these distances is ***DB-DC***. From the diagram, it can be easily seen that ***AB-AC*** is much less than ***DB-DC***. Thus, when the speaker system is up high, this difference in distance is minimized, and consequently the difference in SPL between the rear and front is also minimized. Therefore, in selecting the height of the speaker system, we must balance coverage area with SPL variation and determine what is optimal for the situation.

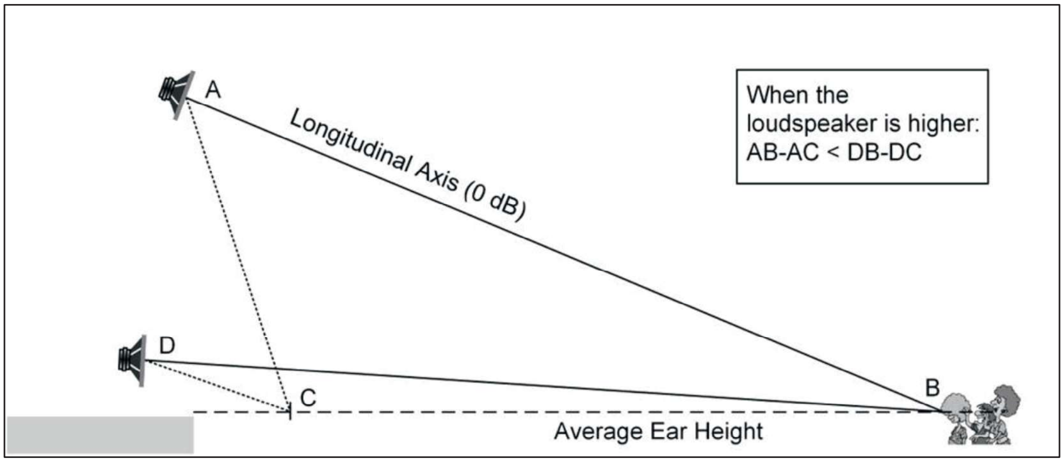

Figure 11-8 SPL Variation with Speaker Height

11.6.2 Determining Acceptable Speaker Coverage

One approach to positioning the speaker is to aim for farthest and strongest penetration from the system as our first goal. It is along the longitudinal axis that the sound level is highest, so we get the longest reach or penetration by aiming the longitudinal axis of the speaker system at the rear of the audience. Next we want to get the greatest coverage from the speaker. There are many variables that we can play with, so let us restrict ourselves in the following ways: Firstly, we will not fly the speaker system over the audience area – as a matter of safety, many municipalities disallow this. Furthermore, we will keep the system generally ahead of the performers on stage, which means that the speaker system will generally be above the forward section of the stage. Secondly, we will use the information derived from the vertical dispersion plots to determine the acceptable forward limit of coverage and help set the height of the speaker above the stage. In order to take into consideration the frequencies that are important for speech intelligibility, the calculation of the forward limit should be carried out by considering levels derived from the 2 kHz to 10 kHz dispersion data. However, in the example that follows, we will demonstrate the process by using the data for the 2 kHz plot. The process is the same for any frequency chosen.

Now suppose that the front and rear physical limits of the audience space are predetermined (as is the case with any already constructed enclosure), and that when we position the loudspeaker at some height ***h*** and aim its longitudinal axis at the rear limit, the forward limit of the audience space falls 40 degrees below the longitudinal axis, as shown in Figure 11-9. We now must determine, using the speaker's dispersion data, whether the SPL at the front of the space is within acceptable limits relative to some reference level established at the rear. Ideally, we would like the SPL to be the same at all points from the front to the rear of the audience space.

The arrangement in Figure 11-9 allows us to use the inverse square law to our advantage. Recall that the inverse square law tells us that every time we reduce the distance to the sound source by half, the SPL increases by 6 dB. As noted above, we would like that the SPL remain the same as we move from the rear to the front of the audience space. It is unlikely that this is exactly

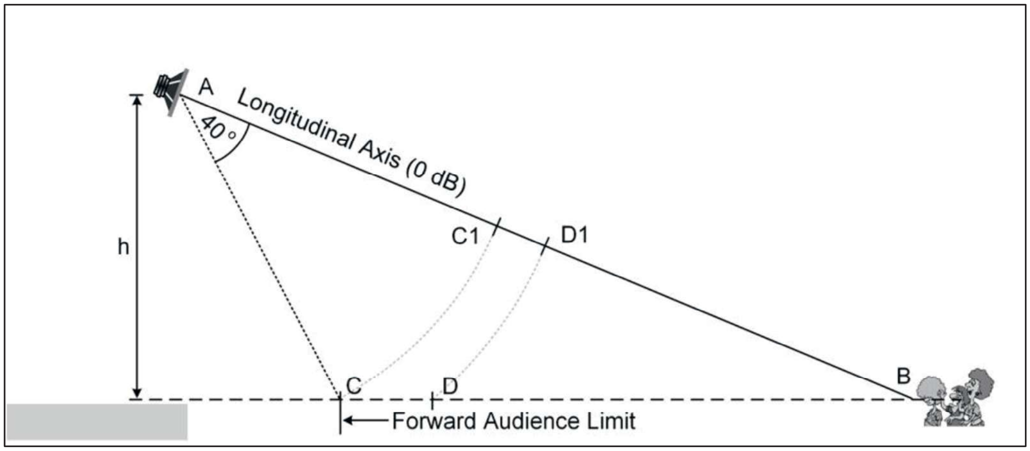

Figure 11-9 Determining Acceptable Speaker Coverage

achievable, but using the combination of inverse square law and speaker directivity, we should be able to come close to this goal. For example, let's say that the SPL at the rear of the audience is 100 dB. Points ***D*** and ***D1*** are on the arc that is half the distance from the rear of the audience to the speaker. Point ***D*** falls on a line that is about 28 degrees below the longitudinal axis of the speaker system. From Figure 11-5, we see that such a line gives us about a 5 dB reduction in SPL (shown by the triangle mark on the 2 kHz plot), but with the +6 dB SPL gain due to the inverse square law, the change in SPL at point ***D*** should actually be about +1 dB, giving an SPL of 101 dB.

Point ***C***, the forward limit of the audience space, is on an arc that intersects the longitudinal axis at ***C1***, which is roughly 0.4 of the distance from the speaker to the rear of the audience. Previously, we noted that point ***C*** is 40 degrees below the longitudinal axis. Again, from Figure 11-5, we can determine that we have a 9 dB reduction in level due to being 40 degrees off-center. At the same time, though, the inverse square law gives us an increase of ***20 log(1/0.4)*** dB, or about 8 dB. Hence, the actual SPL at point ***C*** is around 99 dB. Thus, we see that with the loudspeaker mounted at a reasonable height, we can keep the variation in SPL from the front to the rear of the audience acceptably small.

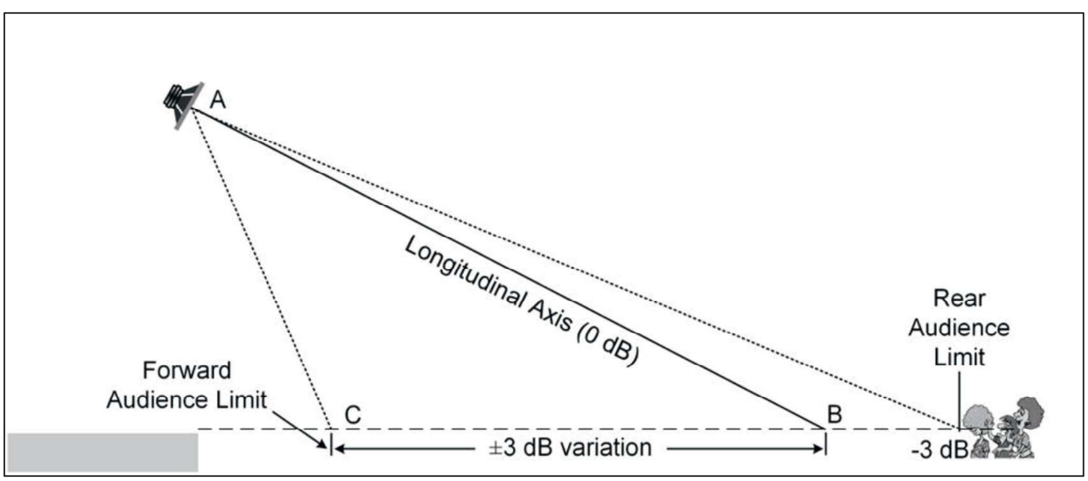

Figure 11-10 Speaker Coverage with ±3 dB Variation

If we relax the requirement of *no variation* in SPL from the rear to the front and allow the SPL to vary by ±3 dB (which is common industry practice), then we can increase our coverage area by tilting the longitudinal axis of the speaker down further, as shown in Figure 11-10. That is, the axis is no longer pointed at the rear of the audience, but at a point forward of that, so that the SPL at the rear of the audience is 3 dB less than at the point where the longitudinal axis intersects the plane of average ear height. By doing this, the forward limit of coverage moves closer to the stage. Viewed another way, we can leave the longitudinal axis of the speaker pointed as above, and the rear limit of the coverage area will extend farther from the stage.

One thing of note is that with this type of speaker setup, about half of the speaker's output is impinging on the rear wall. If the wall is highly reflective, a lot of sound will be reflected back into the audience and may lead to problems with intelligibility that we discussed earlier. If this type of arrangement were used in a permanent setup, one solution would be to place absorptive panels on the wall.

Doing this type of analysis by hand is clearly tedious, especially when we consider that this must be repeated for various frequencies and loudspeaker heights. Even a simple spreadsheet with the appropriate formulae would help a great deal, but the dispersion data for each speaker would still have to be entered by hand. There are, however, software packages available that make the above analysis easy to perform, and manufacturers often publish data sets for their installation series of loudspeakers that can be imported into some of these software packages, eliminating even the need to enter the dispersion data by hand.

11.6.3 Increasing Horizontal Coverage with a Single Cluster

Up to now we have been discussing the use of just one speaker system to achieve horizontal coverage of the audience space. Now suppose we want to increase the horizontal coverage of the system while still using just a single cluster of speakers centered left to right. We can do this by placing the speakers side by side and angling the cabinets so that the edges of their horizontal nominal coverage areas just overlap, as shown in Figure 11-11. This nominal coverage area is typically published by the manufacturer as the horizontal nominal dispersion specification, which is usually the -6 dB included angle averaged over a set of midrange frequencies (e.g. 1 kHz to 4 kHz). This arrangement should give us good results while almost doubling the coverage of the

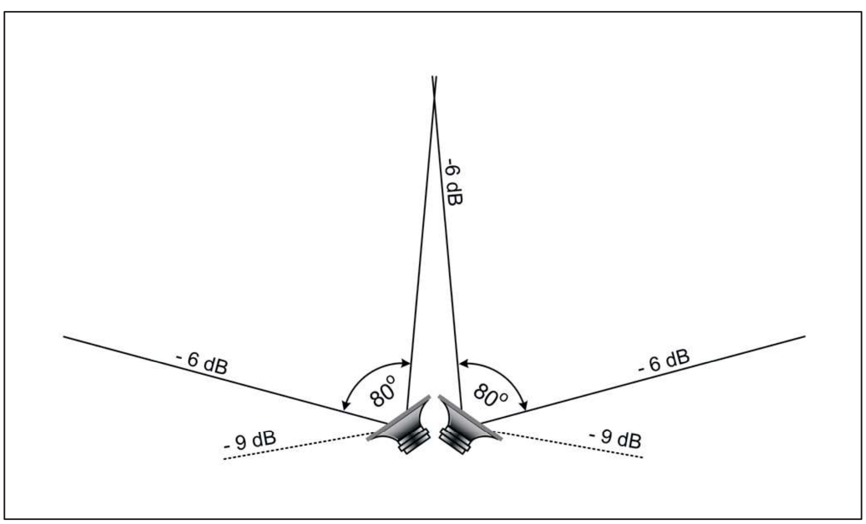

Figure 11-11 Splaying Speaker Systems to Increase Coverage

speaker system. In the example shown in Figure 11-11, the -9 dB combined coverage is around 200 degrees. Assuming the speakers are driven from the same source, then the sound waves along the centerline of the *cluster* will be correlated, and we should get a boost of around 6 dB (see Section 1.14) along the centerline due to the addition of waves from the two sources. Thus, the SPL drop along the original centerline should be limited, and the level should not be far off compared to the original level when only one loudspeaker system was used.

Note that the above discussion applies to mid to high frequency drivers only. For low frequency drivers, the coverage pattern is basically omnidirectional, and thus the horizontal extremes of the audience are already likely to be well covered. However, in placing the speaker cabinets next to each other to achieve the above coverage, we necessarily place the woofers close to each other. We know that if two low frequency drivers are placed next to each other, an increase of up to 6 dB SPL will be had from the usual doubling of sound power (depending on the position within the sound field and the relative phase of the waves arriving from the two drivers). However, mutual coupling occurs when large drivers are placed next to each other and the two drivers behave as one large driver. This mutual coupling gives us an additional 3 dB increase in SPL. Thus, with this arrangement, some EQing of the low end will likely be necessary to restore tonal balance of the overall sound.

11.6.4 Increasing Horizontal Coverage with Spaced Sources

Unless the speakers are being flown, we do not usually have a cluster of speakers in the middle of the stage. The usual arrangement is to have the cabinets at opposite sides of the stage, as in Figure 11-12. The horizontal dispersion of FOH loudspeakers tends to be quite generous, with the -9 dB angle being up around 70 degrees. By placing the speakers far apart, we will be able to cover most or all of the horizontal extent of the audience space. Again, similar to the discussion in Section 11.6.1, with the inverse square law coming to our support, positions off the longitudinal axis of a speaker but closer to the stage will not suffer drastic change in sound level (compared to other positions off the longitudinal axis). Furthermore, positions along the centerline between the

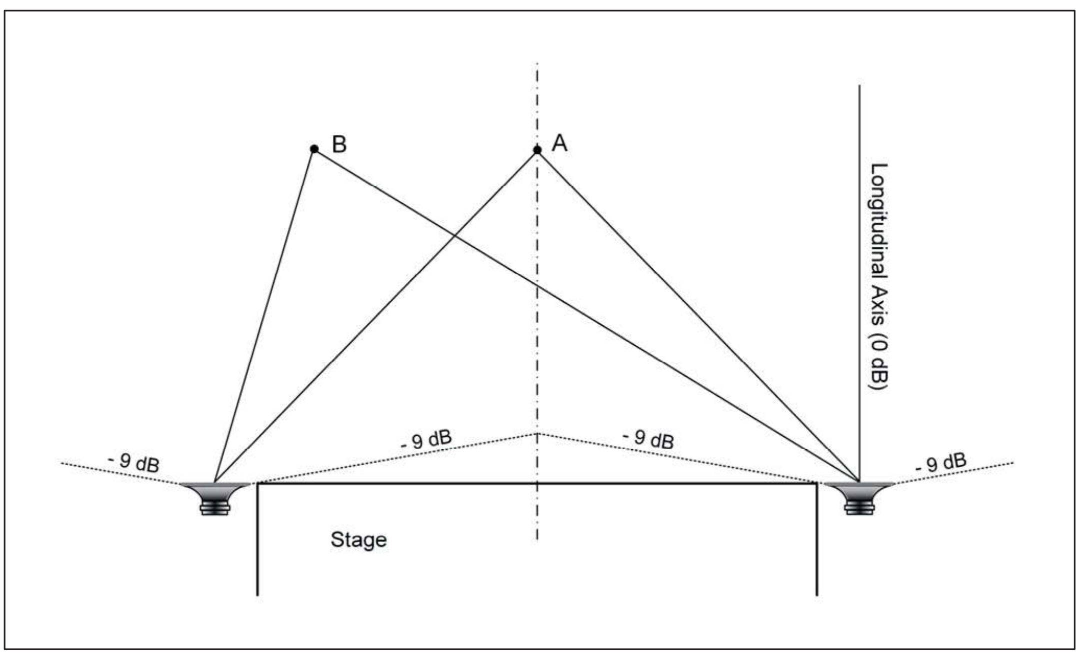

Figure 11-12 Coverage with Speakers at Edge of Stage

two speakers will have an increase of 6 dB SPL compared to using just one speaker. Off-center positions will also have an increase in SPL, but not 6 dB. This means that in the area between the speakers, we could extend the forward limit of the audience area to be bounded by the -12 dB angle, which in many cases is up around 80 degrees, and still have acceptable sound level. At such angles, though, the higher frequency (above 8 kHz) energy content of the sound is drastically reduced, and provisions would need to be made to restore that range of frequencies (such as using clusters or front fill speakers).

We should note that because the speakers are now widely separated, there will be some frequency response aberrations at most places in the audience area. Recall from the discussion in Section 8.9 that when two waves add, the end result depends on the relative phase of the waves. When the waves are completely in phase, the resultant wave has maximum amplitude. When the waves are completely out of phase, i.e. 180º or 1/2 wavelength, the result is complete cancellation. There are an infinite number of phase combinations between these two extremes.

At positions such as ***A*** along the centerline between the two speakers, all waves from the two speakers arrive at the same time and are in phase. Therefore, assuming no other external influences, an increase of 6 dB results for all frequencies and the frequency response should be relatively smooth. At positions off centerline, such as ***B***, the *difference* in distance from ***B*** to each speaker will exactly equal 1/2 wavelength of some wave. When this happens, waves of that particular frequency will be completely cancelled. If the difference is a whole wavelength, the waves will add just like position ***A***. Most frequencies, however, will have only partial cancellation. The resulting off-center frequency response looks similar to Figure 8-36 and is commonly called a comb filter response, because the nulls look like the teeth of a comb.

If the stage is very wide, or the audience distribution is very wide compared to the stage, we may use speaker clusters as discussed in the previous section at the sides of the stage to increase the horizontal coverage of the speakers.

11.6.5 Increasing Reach in Large Venues by Using Clusters

There is a practical limit to how far we can project sound from a single speaker system and still have adequate and relatively consistent coverage over a given area. If the venue is large, we will be unable to cover the entire depth of the audience with just one speaker system as described in Section 11.6.1. Take a look at the vertical dispersion plot for your speaker system and you will likely see that beyond the -9 dB range to the speaker, the sound level falls off very rapidly. Thus,

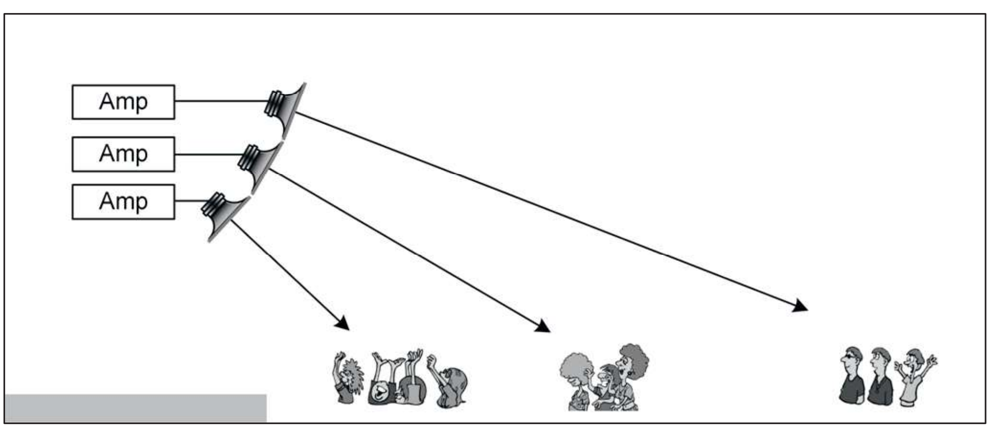

Figure 11-13 Increasing Coverage by Using a Speaker Cluster

the front of the audience will suffer if we are pointing the speaker as described.

To restore coverage at the front, one solution is to utilize a vertical array or cluster of speakers in a fashion similar to Figure 11-13. Here, speakers lower in the array are angled downward to provide coverage towards the front. The speakers may be driven and equalized separately to balance their output level and maintain a fairly consistent SPL along the depth of the audience. In such a case, the speakers covering the front will be driven at a lower level that those covering the rear, and the rear coverage speakers may need the high frequency end boosted since their output has to travel much farther through the air than that from the other speakers (recall that higher frequencies are absorbed more readily by air and audience than low frequencies).

11.6.6 Reverberation and the Limitations of Long Throw Speakers

Even if we use a cluster as described above, still there are practical limitations to how far we can project sound from a speaker system. You may have had the experience of being in a large gymnasium with hardwood floor, painted concrete walls, and a hard ceiling – all good reflectors of sound – and recall having the hardest time trying to understand what was being said over the loudspeaker system. The problem, of course, stems from the long reverberation time of the room and being situated beyond critical distance ($\boldsymbol{D_c}$) of the speakers being used.

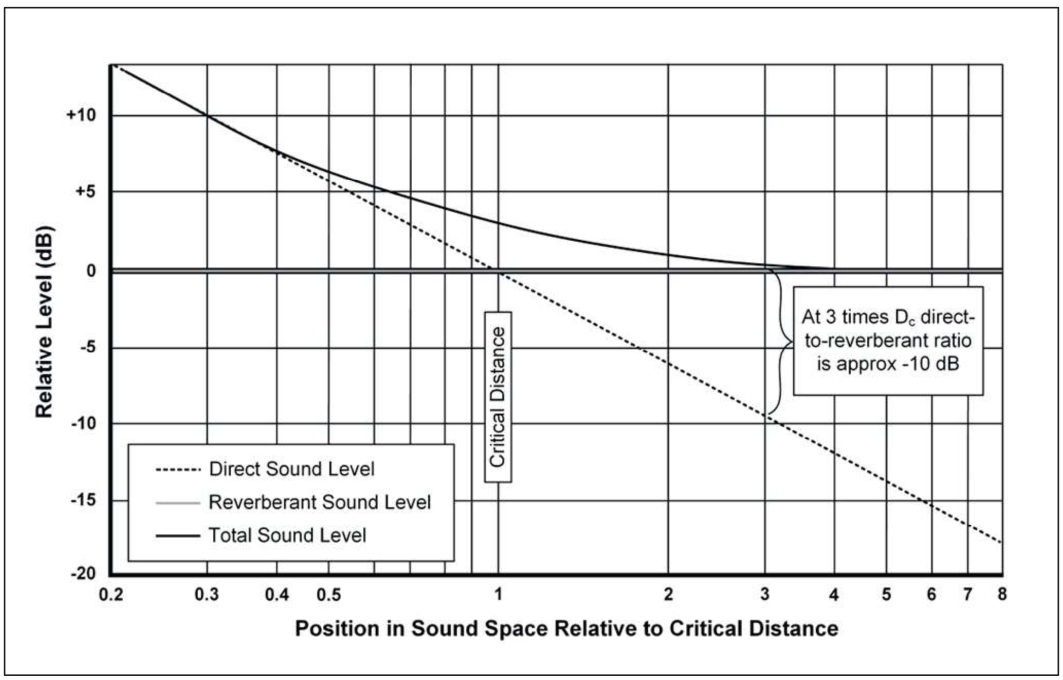

Figure 11-14 Relationship between Direct Sound and Reverberant Sound in a Room

In Section 11.3.1 we discussed the notion of critical distance and how it is affected by the reverberation time of the room. Recall that at critical distance the direct sound level produced by the source is the same as that of the reverberant sound field. Beyond critical distance the direct sound continues to decrease, but the level of the reverberant field remains more or less the same. This is shown in Figure 11-14. Furthermore, we said in Section 11.2.1 that long reverberation times facilitate the formation of distractor voices that work to degrade speech intelligibility. We may conclude from the work of researchers in the field of speech intelligibility[5, 6] that beyond approximately 3 times $\boldsymbol{D_c}$ (at which point the direct to reverberant ratio is around -10 dB) intelligibility falls to an unacceptable level. Therefore, if part of the audience is much beyond twice D_c, they will have an increasingly hard time understanding what is delivered over the sound system as speech intelligibility will be particularly degraded. Therefore, when designing the sound system, if any part of the audience space is much beyond twice D_c of the loudspeaker targeting the space, it is worthwhile considering a distributed system to bring that part of the audience back into a sound field with a more acceptable direct-to-reverberant level.

The equation given in Section 11.3.1 can be used to calculate D_c for a given speaker and room combination. For example, suppose we have a room whose volume is 2500 cubic meters and a reverberation time of 1 second. Suppose, too, that we are using a loudspeaker system with a directivity factor of 10 in this room. The D_c for this combination would be:

$$\begin{aligned} D_c &= 0.057 \times \sqrt{\frac{10 \times 2500}{1}} \\ &= 0.057 \times \sqrt{25\,000} \\ &= 0.057 \times 158.1 \\ &= 9.0 \text{ m} \end{aligned}$$

Thus, if the audience space extended much beyond about 18 m, we would consider either utilizing a higher Q loudspeaker or moving to a distributed system. The latter is discussed below.

11.6.7 The Distributed Approach to Increasing Reach

Figure 11-15 shows a distributed approach to extending coverage the audience space. The solution here is to aim the main FOH speakers towards the middle of the audience and use front fill speakers to direct sound to the front of the audience. These front fill speakers are typically driven at lower levels that the main house speakers. Since we have angled the FOH speakers so that the longitudinal axis does not point at the rear, audience locations beyond the major axis of the FOH speakers will need additional coverage, especially for the higher frequency sounds. In fact, even if the longitudinal axis is pointed at the rear of the audience, if the distance to the rear is greater than 30 m or so, additional coverage should be considered. Again, smaller equalized speakers can be used to extend the coverage in this area.

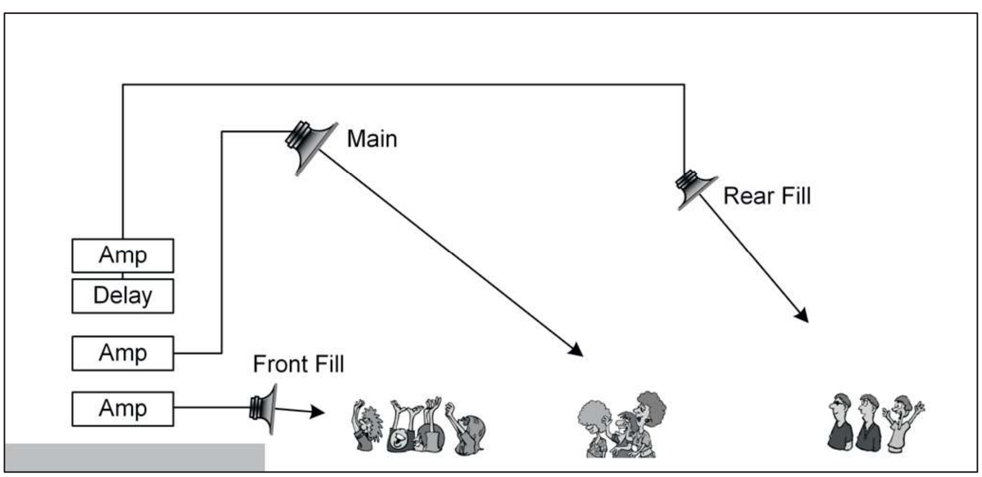

Figure 11-15 Increasing Coverage by Using Distributed Speakers