Audio Engineering Society

Convention Paper 10453

Presented at the 150th Convention
2021 May 25-28, Online

Propagation Loss of Low Frequency Horn Loudspeakers: Is "throw" a real phenomenon?

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ABSTRACT

Horn loading is frequently used in sound reinforcement to increase efficiency and directivity of high and mid frequency transducers. Low frequency horn loudspeakers are less common due to their large size. Increases in available amplifier power and thermal dissipation in transducers have led to widespread use of high power, low efficiency dual 18" bass reflex loudspeakers. However, some manufacturers and enthusiasts continue to develop and use low frequency horn loudspeakers for their high efficiency and subjective audio quality. In the fields of live event production and noise control, there is sometimes a perception, or "urban myth" that horn low frequency loudspeakers project or "throw" sound a further distance than direct radiating low frequency loudspeakers. This is either considered to be beneficial, or problematic depending on the context. Considering the relevant acoustic theory, it is not immediately apparent why this should be the case, providing the loudspeakers are level matched and of similar physical dimensions. Unfortunately, there is very little investigation of low frequency horns in previous literature to aid in providing a definitive answer. Measurements in this paper demonstrate that horn and direct radiating low frequency loudspeakers and arrays closely follow the theory, and the difference in propagation loss is within measurement uncertainty. The implication for noise control of outdoor events, is that bass loudspeaker size and type are not especially relevant factors, and focus should instead be on system/array design and site layout.

1 Introduction

Modern sound reinforcement systems typically consist of two or more main loudspeaker arrays, augmented by a number of dedicated low frequency loudspeakers or subwoofers. The crossover point is typically in the range of 60-100Hz. Historically, all loudspeakers in a sound reinforcement system were horn loaded for maximum electroacoustic efficiency, including low frequency loudspeakers. This was due to the limitations of early power amplifiers, which could rarely deliver more than 300W into 8Ω. Modern developments in amplifier technology such as pulse width modulation (PWM), and improved materials and venting design in transducers has resulted in low frequency horn loudspeakers (or bass horns) largely being replaced by low sensitivity (95-99dB/2.8V/1m) high power (>2000W) dual 18" bass reflex loudspeakers. However, some manufacturers and enthusiasts continue to develop and use bass horns for their high efficiency and subjective audio quality. It is not uncommon for bass horns to have up to 10dB higher sensitivity than bass reflex subwoofers, which can result in significantly reduced power consumption.

1.1 "Throw"

In discussion between live sound engineers, consultants and enthusiasts in the real world and online, it is common to come across mention of the concept of "throw" and the idea that horn loudspeakers somehow project sound further than direct radiators. In many cases this is simply a misunderstanding of sensitivity and efficiency, as a horn with higher sensitivity will of course be louder at any distance than a lower sensitivity direct radiator, given the same input voltage. However, there is still a perception amongst some technically informed engineers and consultants that sound propagates differently from horns. Unfortunately, there is very little investigation of low frequency horns in literature to aid in providing a definitive answer.

1.2 Radiation from a point source

The simplest model of a radiating loudspeaker in space is an infinitely small monopole point source. Usefully, this is a reasonably accurate model of a subwoofer, which is typically much smaller (although not infinitely smaller) than the wavelengths it is producing. The intensity of a sound source is the sound power divided by the area over which it is spread. In the case of a point source in free air, this is the area of a sphere, $4\pi r^2$:

$$I=\frac{W}{4\pi r^2} \quad (1)$$

Simplifying, and approximating for pressure:

$$I\approx\frac{1}{r^2}\approx p^2 \quad (2)$$

Therefore:

$$p\approx\frac{1}{r} \quad (3)$$

And doubling in distance, in decibels:

$$20\log_{10}\left(\frac{1}{2r}\right)\approx-6\,dB \quad (4)$$

1.3 Radiation from infinite and finite line sources

The point source model is only valid when the source is much smaller than wavelength. If the size of the source is similar to, or larger than a wavelength, its behaviour changes. The next theoretical source is the line source, which is infinitely long in one dimension.

An infinite line source radiates cylindrical waves, so the area over which the energy is spread is now the surface of a cylinder $2\pi r$, rather than a sphere:

$$I=\frac{W}{2\pi r}\approx p^2 \quad (5)$$

Therefore:

$$p\approx\frac{1}{\sqrt{r}} \quad (6)$$

And in decibels:

$$20\log_{10}\left(\frac{1}{\sqrt{2r}}\right)\approx-3\,dB \quad (7)$$

It can be seen that pressure decreases as the inverse square root of distance, resulting in a *-3dB sound pressure loss per doubling of distance.*
A finite length line source behaves differently again. In the nearfield of a finite line source, there is a 3dB loss per doubling of distance, but this increases to a 6dB loss per doubling of distance beyond the "critical distance" or "transition distance" where to an acoustically distant observer, the finite line source appears to be a point source. (see figure 1)
The distance to the far field transition where the propagation loss reverts to -6dB per doubling of distance is frequency dependent. Equation 8 is an approximation for this relationship.
Where L is the length of the array and λ is the wavelength of the frequency of interest:

$$D\approx\frac{1.57\,L^2}{\lambda} \quad (8)$$

Practical examples with similar behaviour are large horizontal linear arrays of subwoofers along the front of a stage, or stacked or suspended subwoofers in vertical linear arrays.
Real world sources such as loudspeaker arrays will have slightly more loss vs. distance than theoretically predicted due to imperfect summation and additional sources of loss in the environment. Air absorption causes significant loss at high frequencies, but is negligible at low frequencies.

Figure 1 shows a comparative plot of the propagation loss for each simple source:

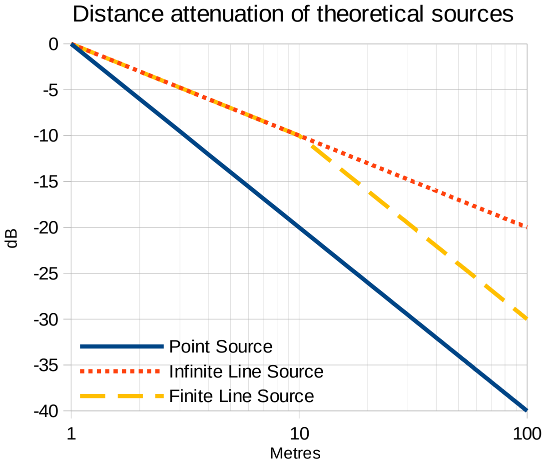


Figure 1. Propagation loss of simple sources

2 Measurement method

In a flat, grassy field, a ½" measurement microphone (B&K 4007) was used to take ground plane frequency response measurements at 20m intervals up to 100m from the loudspeaker(s) (as this was the extent of the longest microphone cable available). Dimensions of the field were nominally 250m x 180m to the nearest boundaries (trees). Additional measurements were taken at 1m to level match the two loudspeaker types. The microphone was equipped with a windscreen and placed on a square of plywood to reduce the effects of local surface variability. The measurement stimulus was a logarithmic sine sweep/chirp to maximise signal to noise ratio. Eight chirps were averaged into each measurement to further reduce noise.

Figure 2. Aerial view of measurement area and 100m measurement range (white line)

2.1 Loudspeakers under test

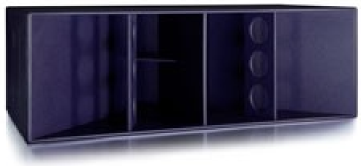


Figure 3. 2×21" low frequency horn loudspeaker

In the single and double cabinet tests, the horn loudspeaker was a dual 21" driver design with a frequency response of 40-250Hz and a half space sensitivity of 104dB/2V/1m.
Dimensions: 582×1686×867mm.

Figure 4. 2×21" bass reflex loudspeaker

In the single and double cabinet tests, the bass reflex loudspeaker was also a dual 21" driver design with a frequency response of 30-270Hz and a half space sensitivity of 102dB/2V/1m.
Dimensions: 718×1190×741mm.

Figure 5. 1×24" bass reflex loudspeaker

In the array tests, the horn loudspeaker was a single 24" driver design with a frequency response of 30-250Hz and a half space sensitivity of 104dB/2V/1m.
Dimensions: 702×992×1056mm

Figure 6. 2×18" bass reflex loudspeaker

In the array tests, the bass reflex loudspeaker was a dual 18" driver design with a frequency response of 40-270Hz and a half space sensitivity of 100dB/2V/1m
Dimensions: 580×1020×594mm

2.2 Frequency response and radiating area

Filters were applied to the loudspeakers under test to match their frequency responses and emulate a real application. The high pass filter was a 24dB Butterworth at 45Hz and low pass filter was a 24dB Linkwitz-Riley at 100Hz. The levels were matched at 1m and measured again at 20m to confirm. Figure 7 shows the responses at 1m. Note that the bass reflex response has softer "knees" than the horn. It was decided to leave this difference to investigate any effect that it might have on the far field frequency response and losses.

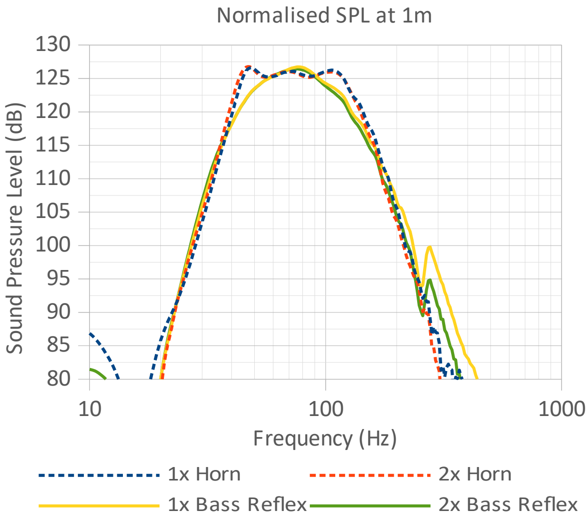


Figure 7. Frequency responses of tested loudspeakers, level matched to 125dB at 1m.

Other differences between the loudspeaker designs that could affect the propagation loss are the effective radiating area and largest dimension. Figure 8 shows that the dual 21" horn has more than double the radiating area of the dual 21" bass reflex. The maximum dimension of the radiating surface of the horn is also 580mm larger than in the bass reflex. Additional measurements of double stacks of both horn and bass reflex types were taken to investigate if these differences are significant. However, any effects are likely to be small, and may not be measurable.
In the array measurements two very different loudspeakers were chosen (a single 24" horn and dual 18" bass reflex), primarily because of availability and practicality, but also to investigate the behaviour of two radically different loudspeaker designs in a configuration very similar to a real application.

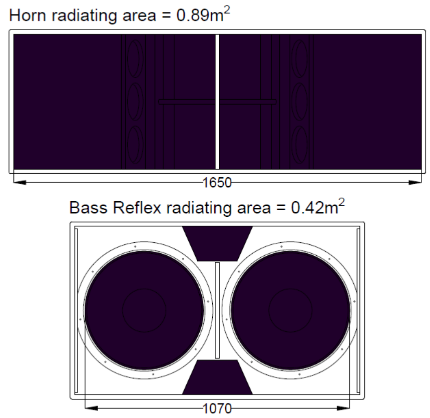


Figure 8. Dimensional comparison of horn and bass reflex loudspeakers

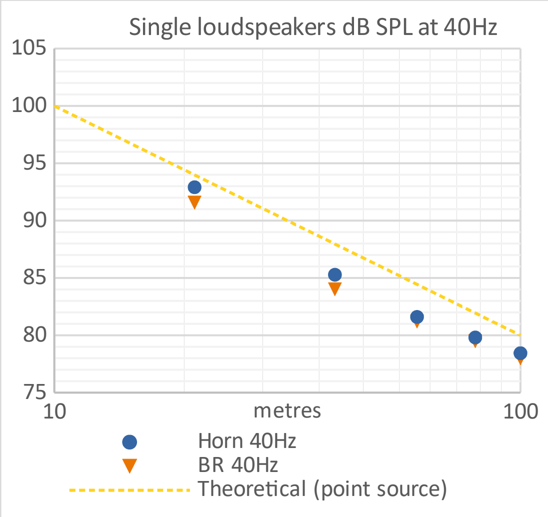
2.3 Measurements part 2: horn array

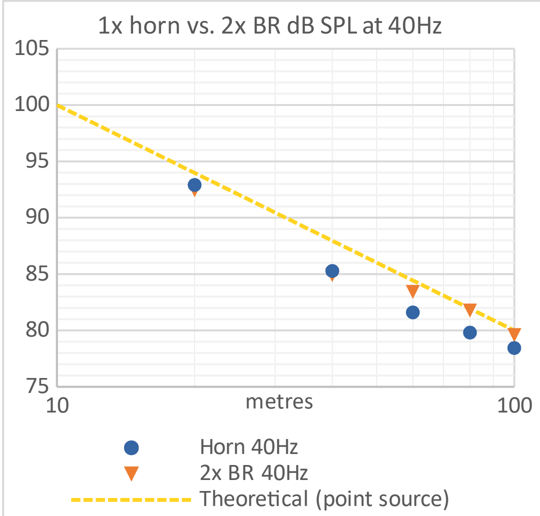
The second set of measurements investigate array behaviour and mutual coupling effects of low frequency horns. A typical ground stacked linear array of spaced loudspeakers was used, also referred to as a "broadside" array, a name inherited from the analogous concept in antenna design. Gain shading and delays were not applied to the array.
The horn array consisted of 7 single 24" bass horn loudspeakers. The bass reflex array consisted of 12 dual 18" bass reflex loudspeakers. Both arrays were arranged to be 7.8m in length, with some small gaps between cabinets. The gaps between the horn cabinets were 50mm. The gaps between the bass reflex cabinets were 20mm. The same method of spaced measurements along the 100m measurement range was repeated.

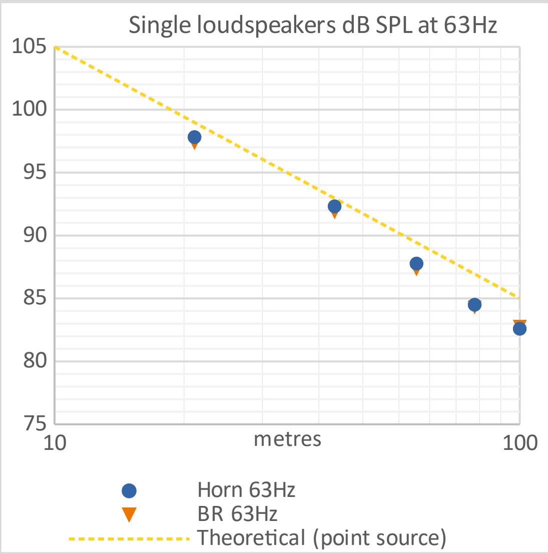
2.4 Measurements part 3: gradient cardioid arrays

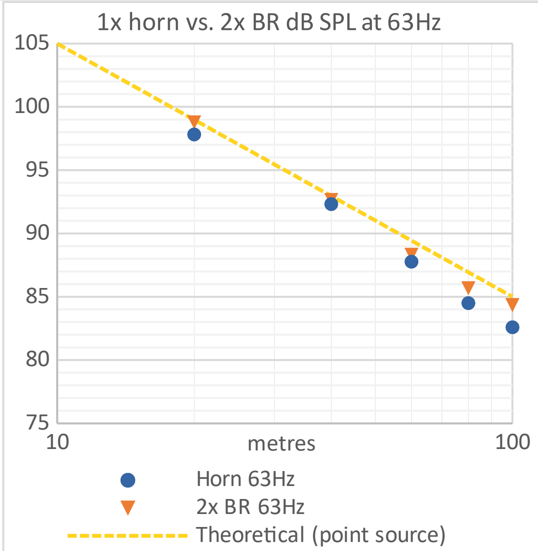
For particularly noise sensitive cases, it is necessary to use directional subwoofer arrays (often referred to as "cardioid" in reference to the polar pattern).
A popular method is the gradient cardioid array. This consists of at least one forward facing loudspeaker and at least one rear facing loudspeaker, typically in a 2:1 ratio, although this can be varied.
The forward facing loudspeaker is operated as normal, while the rear facing loudspeaker is polarity reversed and delayed by the path length from the front loudspeaker to the rear. Additional magnitude and/or phase equalisation may also be applied to the rear facing loudspeaker.
The final set of measurements compare the effectiveness of gradient cardioid arrays using horn and bass reflex loudspeakers.

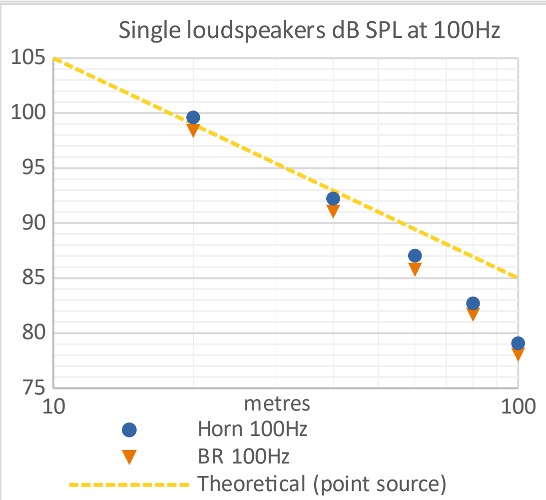
3 Results

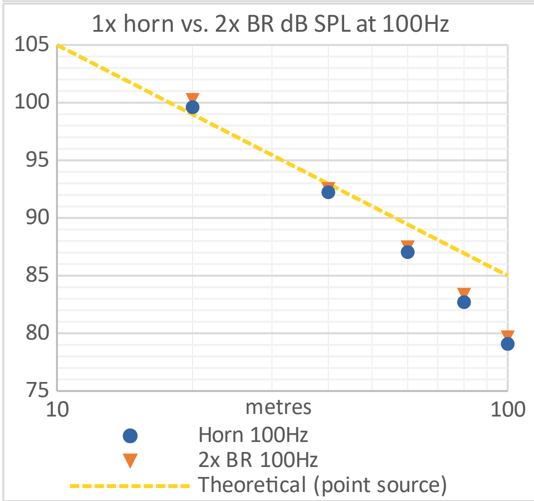

Single loudspeakers dB SPL at 40Hz
105
100
95
90
85
80
75
10
metres
100
Horn 40Hz
BR 40Hz
Theoretical (point source)

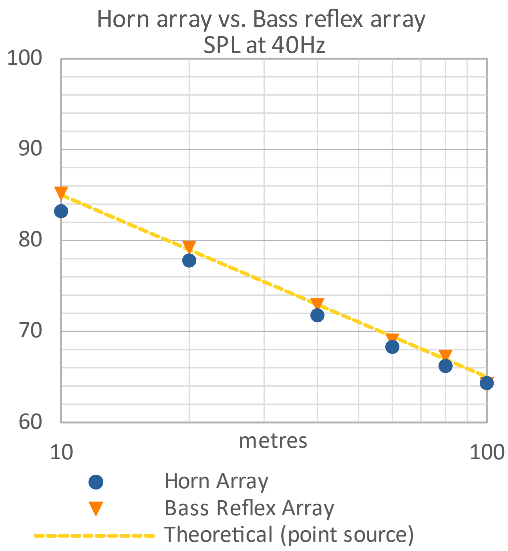

1x horn vs. 2x BR dB SPL at 40Hz
105
100
95
90
85
80
75
10
metres
100
Horn 40Hz
2x BR 40Hz
Theoretical (point source)

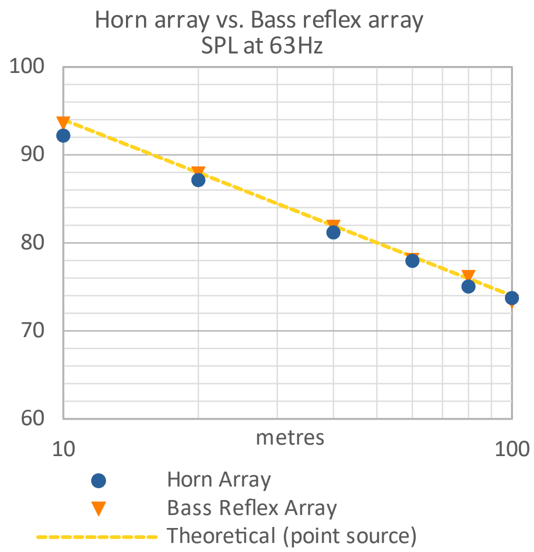

Single loudspeakers dB SPL at 63Hz
105
100
95
90
85
80
75
10
metres
100
Horn 63Hz
BR 63Hz
Theoretical (point source)

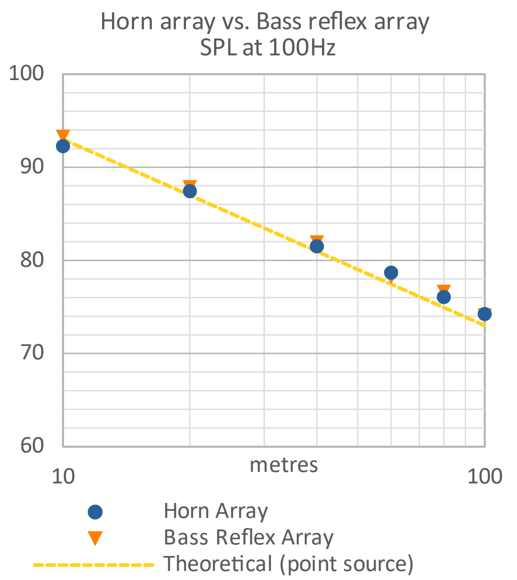

1x horn vs. 2x BR dB SPL at 63Hz
105
100
95
90
85
80
75
10
metres
100
Horn 63Hz
2x BR 63Hz
Theoretical (point source)

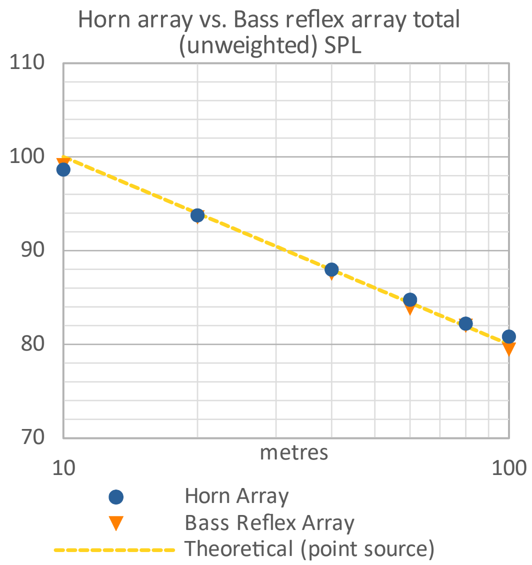

Single loudspeakers dB SPL at 100Hz
105
100
95
90
85
80
75
10
metres
100
Horn 100Hz
BR 100Hz
Theoretical (point source)


1x horn vs. 2x BR dB SPL at 100Hz
105
100
95
90
85
80
75
10
metres
100
Horn 100Hz
2x BR 100Hz
Theoretical (point source)

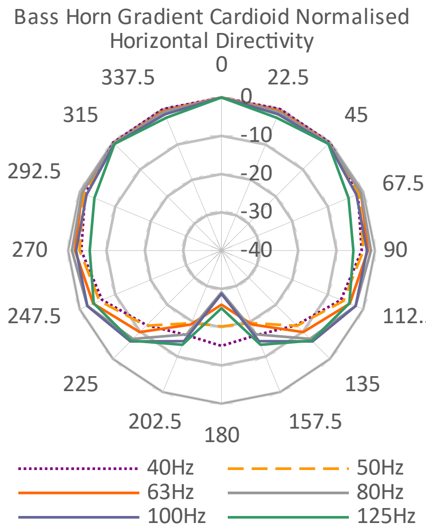


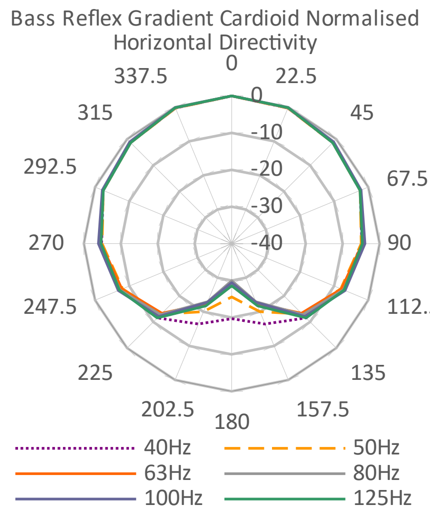






3.1 Comparison of bass reflex and bass horn cardioid arrays





4 Discussion

4.1 Single and double loudspeakers

The measurements of single and double horn and bass reflex loudspeakers demonstrate that both follow the modelled attenuation of a theoretical point source of -6dB per doubling of distance, with some deviations as would be expected. The size and type of the loudspeaker does not appear to significantly affect the propagation loss.
The main area of deviation is at higher frequencies beyond 50m, where there is more loss than predicted. This could be caused by a number of additional sources of loss in the real world, such as wind and absorption from the non-rigid and grassy surface. The grass was longer during the single loudspeaker measurements. The effect in the frequency range seen (above 63Hz) could be the result of the grass acting as an absorber. In 2015 Azkorra et al. Found that “green walls” have significant broadband sound absorption properties.

4.2 Linear/broadside bass arrays

The array measurements more closely follow the predicted loss of a point source of -6dB per doubling of distance. This could be the result of multiple sources averaging out the losses, or simply that the grass was shorter.
Again, there is very little difference between the two loudspeaker designs, despite the differences in driver size and cabinet design.
It is worth noting that as expected, there is no evidence of line source like behaviour, as this would entirely occur in the nearfield within 20m. The theoretical transition distance for a 7m long array ranges from 22m at 100Hz to 1.9m at 40Hz.
As with any real world (non-laboratory) acoustic measurement there are numerous sources of error.
Low frequency background noise is ubiquitous outdoors, so care was taken to ensure an adequate signal to noise ratio at 100m, without overloading the microphone at 10m. Multiple averaged log chirps also aided in reducing noise.

4.3 Gradient cardioid arrays

The gradient cardioid polar measurements display a number of interesting features. With these particular DSP settings, both loudspeaker types have a maximum rear rejection of around -30dB at 180°. The bass reflex array has a very consistent cardioid polar pattern vs. frequency. The inherent directivity of the bass horn is clearly visible at 125Hz 90° off axis, but this would be out of band in practical use. A typical crossover frequency is 85Hz. The consistency of the polar pattern could probably be improved with additional magnitude and/or phase equalisation. Overall, it is possible to achieve significant and useful rear attenuation using bass horns in cardioid arrays.

5 Conclusions

The most important conclusion is that horn and direct radiating low frequency loudspeakers and arrays closely follow the behaviour of a simple theoretical point source, and the difference in propagation loss is within measurement uncertainty.
The implication of this for noise control of outdoor events, is that bass loudspeaker size and type are not especially relevant factors, and focus should instead be on system/array design and site layout.

6 Further work

A related discussion that has persisted for many decades is the nature and extent of mutual coupling between bass horn loudspeakers, and how this compares or differs to direct radiating loudspeakers.
Some evidence of this was observed during the loudspeaker array measurements, such as changes in frequency response and extension.
A detailed investigation of the behaviour and underlying mechanism of horn coupling would be a useful and interesting avenue for further work.

Acknowledgments

Special thanks to Abe Scheele (Scheele Sound) and Colm Doyle (Hertz-U Sound) for their invaluable assistance in providing equipment and performing measurements of loudspeaker arrays in sections 3.2 and 3.3.

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