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Microphone Array Beamforming

by Jerad Lewis

INTRODUCTION

All MEMS microphones have an omnidirectional pickup response, which means that they respond equally to sounds coming from any direction. Multiple microphones can be configured in an array to form a directional response, or a beam pattern. A beamforming microphone array can be designed to be more sensitive to sound coming from one or more specific directions than sound coming from other directions.

Microphone beamforming is a rich, complex topic. This application note is only intended to cover the basic concepts and array configurations, including broadside summing arrays and differential endfire arrays. It covers design considerations, spatial and frequency responses, and advantages/disadvantages of different array configurations.

EXPLAINING DIRECTIONALITY AND POLAR PLOTS

Directionality describes the pattern in which the output level of the microphone or array changes when the sound source changes position in an anechoic space. All Analog Devices, Inc., MEMS microphones are omnidirectional (or omni), which means that they are equally sensitive to sound coming from all directions, regardless of the orientation of the microphone. Figure 2 shows a 2-axis polar plot of an omnidirectional microphone's response. This plot looks the same regardless of whether the microphone's port is oriented in the x-y, x-z, or y-z plane.

In this application note, any reference to the "front" of the array as the on-axis direction is the direction of the desired audio pickup and is labeled as 0° in polar plots. The "rear" of the array is at 180° and the "sides" refer to the space in-between, centered on 90° and 270°. All polar plots included in this application note are normalized to the 0° response level.

All equations involving the frequency and wavelength of sound use the relationship, $c = f \times \lambda$, where c is 343 m/sec, the speed of sound in air at 20°C. Figure 1 shows the relationship between frequency and wavelength for sound waves under these conditions. The Formula for Calculating Design Parameters section at the end of this application note lists equations for calculating the array design parameters used here.

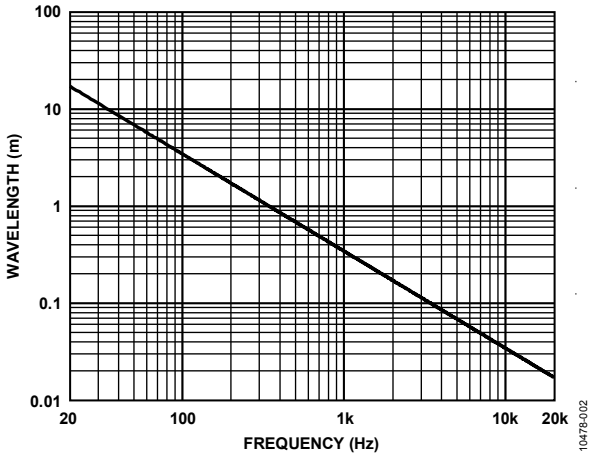

Figure 1. Frequency vs. Wavelength for Sound Waves in Air

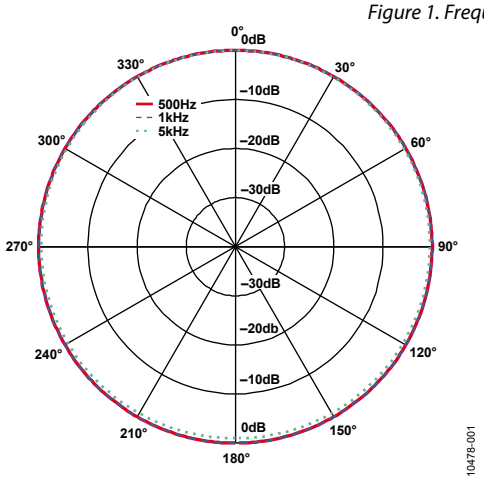

Figure 2. Omnidirectional Microphone Response Plot

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REVISION HISTORY

5/12—Rev. 0 to Rev. A

Changes to Figure 14 6

1/12—Revision 0: Initial Version

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BROADSIDE ARRAYS

A broadside microphone array is one in which a line of microphones is arranged perpendicular to the preferred direction of sound waves (see Figure 3). In this figure, d is the spacing between the two elements of the array. The sound from the broadside of the array is what is usually desired to be picked up.

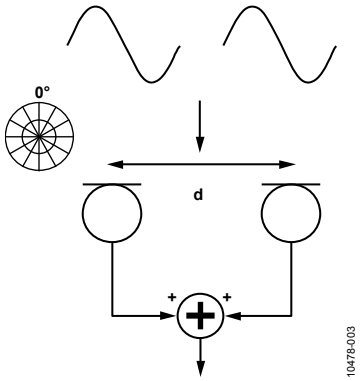

Figure 3. 2-Microphone Broadside Array

Broadside arrays can be implemented with basic processing; the microphones in the array are simply summed together. The downside to this type of array is that it can only attenuate sound coming from the side of the array. The rear-facing response always matches the front response since there is nothing differentiating pressure waves approaching the microphones from the front and the rear due to the axisymmetry of the array. A broadside array is useful in applications where there is not much sound incident from behind or above and below the array, such as for a television mounted on a wall.

In a 2-microphone broadside array, there are two minima in the response at 90° and 270°. The signal attenuation at these points is very frequency-dependent. The response approaches perfect cancellation as the half-wavelength of the incident frequency approaches the spacing between the microphones. For an array with two microphones spaced 75 mm apart, theoretically there is a perfect null at approximately 2.3 kHz (343 m/sec ÷ (0.075 m × 2) ≈ 2.3 kHz).

Above the frequency at which perfect attenuation occurs, the frequencies will alias and the polar response starts to show nulls at other angles. At this point, the side attenuation starts to decrease again. For example, in Figure 4 the 3 kHz signal (light blue line) is being aliased.

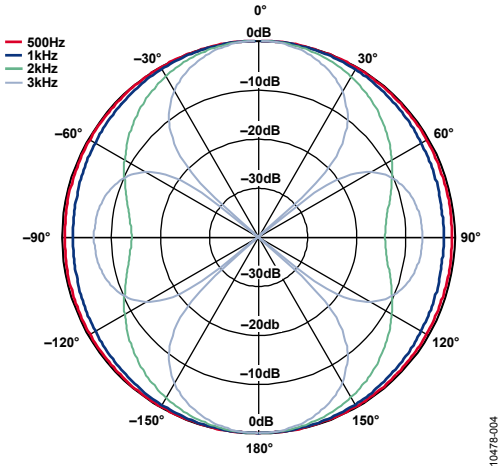

Figure 4. Response of a 2-Microphone Broadside Array with 75 mm Spacing

Frequency Response

A broadside beamformer has a flat frequency response on-axis since it is simply summing the signals from two microphones receiving the same signal. Figure 5 shows the normalized response of a 2-microphone broadside beamformer with 75 mm spacing. Off-axis, this figure clearly shows the nulls in the response.

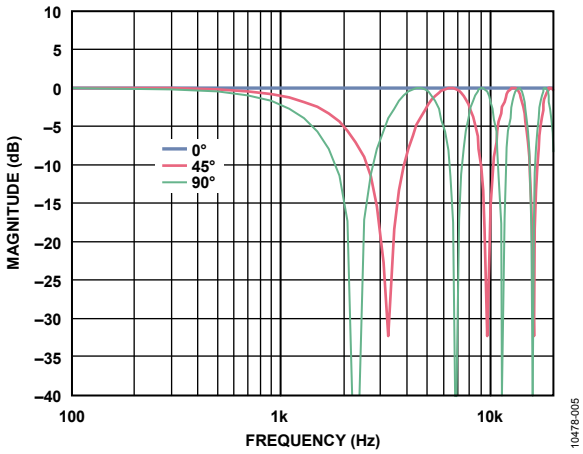

Figure 5. Normalized Frequency Response of a Broadside Beamformer at Different Incident Angles

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Broadside Arrays with More Elements

Broadside arrays with more than two elements can also be constructed by simply adding additional microphones in line with the original two, as is shown in Figure 6. Higher numbers of microphones in broadside arrays can achieve greater attenuation of sound from the sides of the array. Figure 7 shows the response of a 3-microphone broadside array with 75 mm spacing between elements. In this array, the sound from the sides is attenuated by 6 dB, whereas it was only attenuated by 3 dB in the 2-microphone broadside array. However, aliasing (cloverleaf pattern) occurs at even lower frequencies now because the total distance between all elements has been increased from 75 mm to 150 mm.

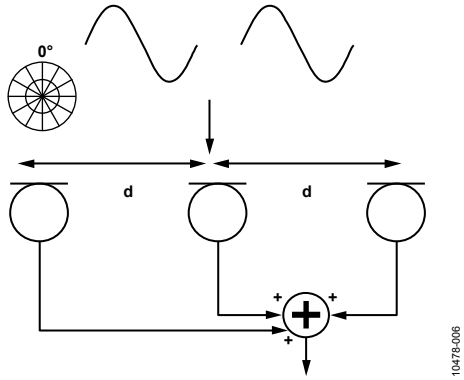

Figure 6. 3-Microphone Broadside Array

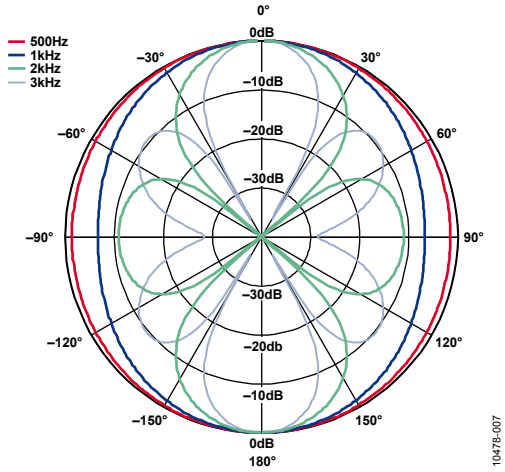

Figure 7. Response of a 3-Microphone Broadside Array with 75 mm Spacing Between each Microphone

Spacing microphones closer together in a broadside array raises the aliasing frequency, but reduces the attenuation at lower frequencies. This trade-off must be considered when designing a broadside array. Aliasing can be further reduced by applying different weighting coefficients to individual microphones in a multi-microphone broadside array. The main response angle of roadside arrays can also be steered to something other than the front of the array with delays on the outputs of individual microphones. Calculation of these coefficients and delays and the resulting polar patterns is beyond the scope of this application note.

ENDFIRE ARRAYS

An endfire array consists of multiple microphones arranged in line with the desired direction of sound propagation. When the front microphone in the array (the first that sound propagating on-axis reaches) is summed with an inverted and delayed signal from the rear microphone(s), this configuration is called a differential array. Figure 8 shows a 2-microphone endfire differential array with distance (d) between the microphones and the rear microphone delayed by n samples before the subtraction (or, invert-and-sum) block. This can be used to create cardioid, hypercardioid, or supercardioid pickup patterns, where the sound from the rear of the array is greatly attenuated.

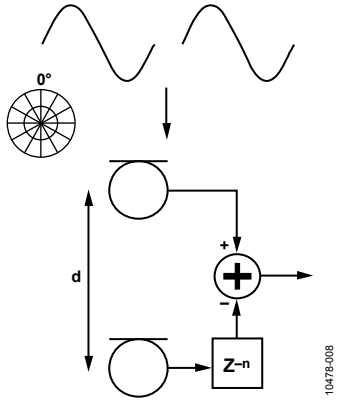

Figure 8. 2-Microphone Endfire Array

When both the distance between microphones and the time delay are properly selected, for frequencies less than the aliasing frequency the response of a delay-and-sum beamformer is a cardioid, or heart-shaped, pattern (see Figure 9). A cardioid pattern has no signal attenuation to the front of the array and theoretically completely cancels the sound incident to the array at 180°. The signals on the sides of a first-order (2-microphone) delay-and-sum beamformer are attenuated by 6 dB.

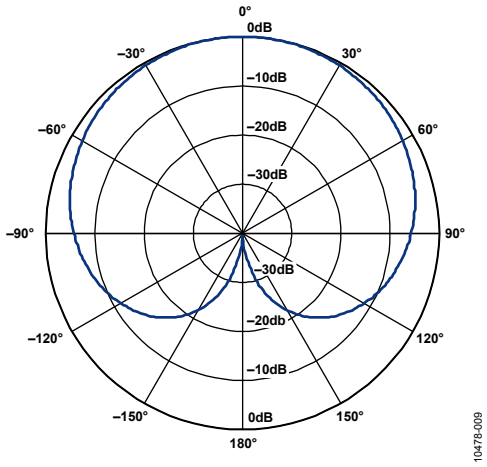

Figure 9. Response of a 2-Microphone Endfire Cardioid Beamformer

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The sound picked up by the different microphones in the endfire array differs only in the arrival time, assuming far-field propagation that can be approximated by a plane wave. To create a cardioid pickup pattern, the signal from the rear microphones should be delayed by the same time that it takes the sound waves to travel between the two microphone elements. This gives the system designer two degrees of freedom in designing an endfire beamformer: the distance between the microphones and the delay applied in the processor. In many audio applications, the choice of delay time is quantized by the sampling rate (f_S). If a DSP's delay is quantized by the period of a single sample, then when f_S = 48 kHz that minimum delay is 21 µs. At 20°C, the speed of sound in air is 343 m/sec, so a sound wave travels about 7 mm in 21 µs. Fractional sample delays can be implemented with different filters such as delayed sync filters, allpass filters, and FFT filterbanks, but this sort of processing is more in-depth than what is covered here.

As with the broadside array, the spacing between the microphones determines the first null in the desired direction response. The closer the microphones are spaced to each other, the higher in frequency this null is (and therefore wider bandwidth). The further apart they are spaced, the longer the physical length of the array is, possibly conflicting with the industrial design limitations. Again assuming f_S = 48 kHz, a 3-sample delay results in an acoustical time delay of about 63 µs. This is the time it takes sound to travel about 21 mm, which is the spacing between microphone elements for a cardioid pattern. The half-wavelength of an 8.2 kHz sound wave is 21 mm, so this is the null frequency. Figure 10 shows the response of the same endfire configuration shown in Figure 9, but here the response at 10 kHz is also shown. Along with the null in the rear, two additional nulls at about ±52° are also present.

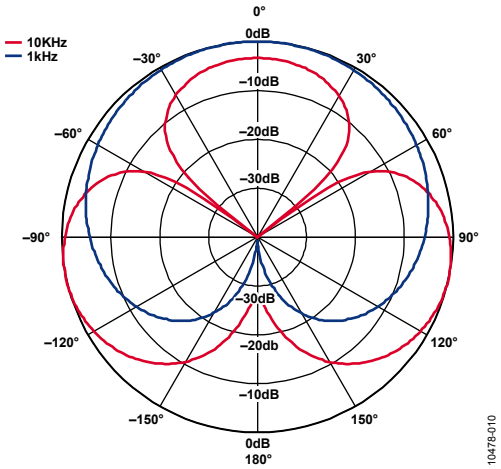

Figure 10. Frequency Aliasing in a 2-Microphone Endfire Beamformer

Matching the distance between microphones with the electrical delay is critical to good performance of the beamforming array. Figure 11 shows the effect of varying the physical distance between microphones while keeping the delay constant. For this example, a 3-sample delay is again used, which corresponds to a distance of about 21 mm to achieve a cardioid response pattern (f_S = 48 kHz). When the distance between microphones is less than 21 mm, the rear null is much less pronounced and the response is in a subcardioid pattern. When the physical distance is greater than 21 mm, the resulting pattern is a hypercardioid, with two rear nulls spaced equally from the 180° point. This may be desirable in applications where the desired rejection is not exactly to the rear, but may be more spread out, as the attenuation to the sides is also greater than that of a cardioid response.

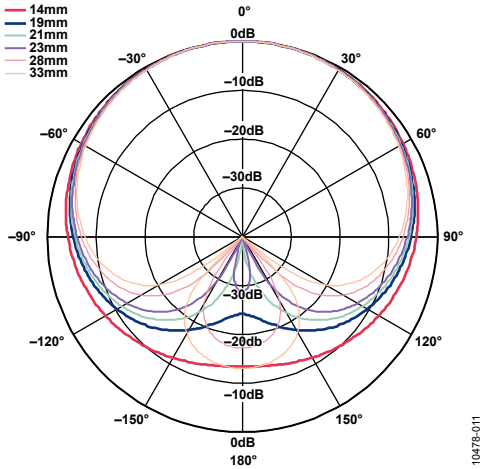

Figure 11. Effect of Varying Microphone Distance in an Endfire Beamformer

Frequency Response

The differential array beamformer does not have a flat frequency response, but rather has a high-pass filter response characteristic up to the null frequency. The response of a first-order beamformer (two microphone elements) rises with frequency at 6 dB/octave and flattens above the aliasing frequency. At the null frequency, the array theoretically has no output because the delayed signal exactly matches the signal from the front microphone.

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Figure 12 shows the frequency magnitude response of a 2-microphone differential array beamformer at different incident angles. In this plot, the 0 dB point is the output level of a single omnidirectional microphone. This beamformer is set up with 21 mm spacing and a 3-sample delay, so the on-axis null appears at about 8.2 kHz. On axis, the response is rising at 6 dB/octave up to the point where the quarter-wavelength of the incident signal matches the length between the two microphones. After this point, the response decreases to the null point and increases back to a maximum again at the ¾-wavelength point. Along with the on-axis null at the point where the spacing between array elements matches the half-wavelength of the incident signal, there are additional nulls at successive multiples of that half-wavelength.

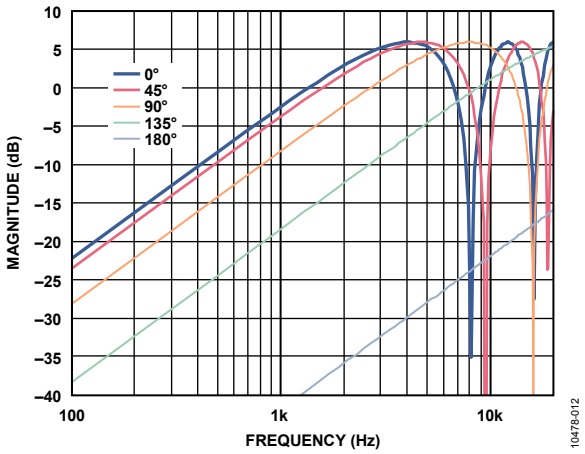

Figure 12. Frequency Response of an Endfire Beamformer at Different Incident Angles

Notice that the response for a signal incident at 90° is 6 dB below that of the signal at 0°, and it has its maximum output level at the on-axis null frequency.

An equalization (EQ) filter is typically applied to the output of a differential beamforming algorithm to flatten the response.

The null frequency should be selected so that it does not interfere with frequencies of interest, but not so high that low frequencies are attenuated more than is desired. In an endfire differential array with a single sample delay (f_S = 48 kHz) and 7 mm microphone spacing, the null frequency is at about 24.5 kHz and if the microphone spacing is 84 mm with a 6-sample delay, the aliasing frequency will be 4.2 kHz. A design typically requires the null frequency to be somewhere between these two examples, so that it is not so low that the null interferes with the bandwidth of human speech, or so high that the low-frequency response is highly attenuated. With these requirements in mind, the distance between the two microphones is typically chosen to match a delay of between two to four samples. Again, this is all assuming f_S = 48 kHz. All of these calculations scale linearly with the sampling rate.

Higher-Order Endfire Arrays

Higher-order differential array beamformers can be formed by adding additional microphones in line with the first two. This results in more rejection of sounds from the rear and side, but does, of course, require a longer physical distance in which the beamformer needs to be built. Figure 13 shows an example of such second-order (3-microphone) endfire beamformer.
A second-order endfire beamformer can achieve 12 dB of attenuation to the sides with the same null to the rear of the array, as shown in Figure 14. Here, the blue line is the response of the first-order (2-microphone) beamformer and the red line shows the response of the second-order beamformer.

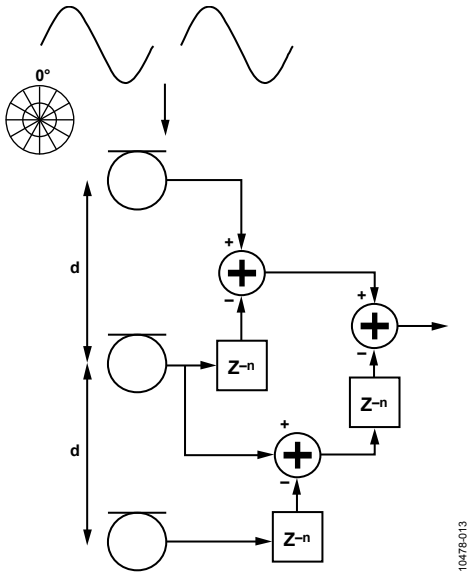

Figure 13. Second-Order Differential Beamforming Array

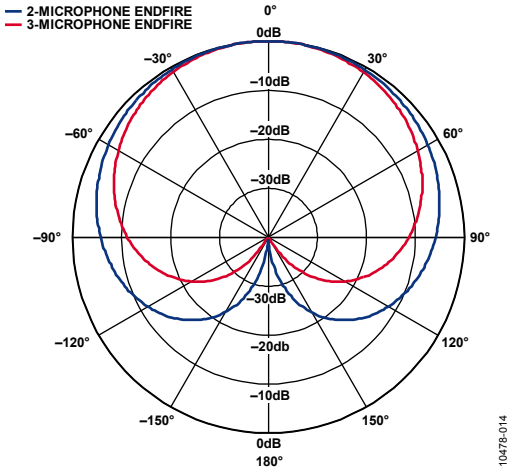

Figure 14. Comparison of First-Order and Second-Order Endfire Beamformers

This same line of thinking can be extended to even higher-order endfire beamformers, at the obvious expense of array size.

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MICROPHONE MATCHING

Good performance from a microphone beamformer requires that the sensitivity and frequency response of the different elements of the array be closely matched. Differences in these two parameters between different array elements result in a breakdown of the array's desired response. Nulls may not be as sharp and the array's directionality may not be properly oriented. The sensitivity and frequency response of Analog Devices' MEMS microphones are closely matched, so they make an excellent choice for use in beamforming arrays.

EFFECTS OF ARRAY PROCESSING ON SYSTEM NOISE

The effects on the SNR depend on the array configuration and processing, and may result in an increase or a decrease of the system SNR for different array topologies. It is important to select microphones with the highest SNR specification to maximize the overall system performance.

On axis, the broadside beamformer's output is analogous to simply summing two identical signals to improve SNR. In a broadside summing array, the self noise from multiple microphones is added together in power terms, resulting in a 3 dB increase in noise per doubling of the number of microphones. In this case, the signal level doubles for a 6 dB increase, while the noise sums incoherently for a 3 dB increase in overall level. This results in a 3 dB improvement of SNR. Off axis, this beamformer's signal output is not flat, as seen in Figure 5. At the off-axis incident angles, the SNR is reduced from the on-axis peak because of the reduced signal levels.

The effect on SNR of a differential array is more complex and is not quantitatively evaluated here. The on-axis frequency response of a 2-microphone differential array beamformer is 6 dB for frequencies with a wavelength twice the microphone spacing (about 4.1 kHz in the example shown in Figure 12). Around this frequency, the difference between the array's signal output and its noise is higher than each individual microphone's, but the signal/noise relationship across all frequencies is more difficult to calculate.

PLACEMENT OF MULTIPLE MICROPHONES

The linear distance between the sound ports of microphones in an array is only one path that should be considered when building a microphone array. Even though the Analog Devices MEMS microphones are very thin devices, there is still some nonzero height that should be considered in the array design. The acoustic center at the diaphragm of an Analog Devices MEMS microphone is 0.57 mm above the sound port. Along with the thickness of the PCB on which the microphone is mounted, this distance should also be considered when choosing the spacing between microphones. If all microphones are mounted in the same way (same PCB, same sound port length), then this is not a problem.

ADVANCED BEAMFORMING

This application note is intended to cover the basics of microphone beamforming and is in no way an exhaustive overview of this field of processing. Arrays with different numbers of microphones and different configurations are obviously possible, and the level of sophistication in the signal processing algorithms can be extended far beyond the simple algorithms described in this application note. More advanced algorithms can be used for voice tracking and beam steering, even with small numbers of microphones.

The arrays covered here are all linearly-spaced, but more advanced higher-order beamformers can be built with varying spacing between each pair of microphones in the array. This sort of configuration changes the null and aliasing frequencies and signal-to-noise ratio between the different microphones and can potentially result in an array with less noise and a wider usable frequency response.

COMPARISON

Table 1 shows the relative advantages and disadvantages of broadside and endfire beamformers.

Table 1. Comparison of Broadside and Endfire Beamforming Arrays

Array Configuration	Advantage	Disadvantage
Broadside Summing	Shallow array depth Processing is easy to implement (simple sum)	Lower off-axis attenuation Small spacing between microphones is needed to prevent aliasing
Endfire Differential	Better off-axis attenuation Smaller overall size	Deeper array depth More processing complexity (signal delay required) Attenuated low frequency response

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FORMULA FOR CALCULATING DESIGN PARAMETERS

Variables

d: distance in meters

c: speed of sound in air, in m/sec (343 m/sec at 20°C)

t: time in seconds

n: number of samples of delay in DSP.

t_D: time delay in seconds

f_S: sampling frequency in hertz

f_{NULL}: frequency of the null in hertz

Distance Sound Travels in a Specified Time

$$d = c \times t$$

Microphone Spacing to Match an n-Sample Delay

$$d = n \times c/f_S$$

Time Delay for an n-Sample Delay

$$t_D = n/f_S$$

On-Axis Null Frequency in a Differential Array

$$f_{NULL} = ½ \times c/d$$

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