AN-210

Designing Linear Arrays with Directional Microphones

Introduction

Traditional MEMS microphones are omnidirectional, meaning they pick up sounds from all directions. However, in many applications it is desirable to pick up a single sound source (i.e., a person’s voice) while rejecting all background noise and reverberation. To accomplish this, arrays with multiple microphone arrays are often used to form a directional beam that isolates a specific person's voice. The more directional the beam, the more background noise is rejected, resulting in better isolation of the person’s voice.

When designing microphone arrays using traditional omnidirectional microphones, there are several fundamental tradeoffs. It is difficult to create a “beam” with sufficient directionality that is consistent across the audio spectrum (20Hz - 20kHz) while also maintaining high audio quality (quantified using a metric called signal-to-noise ratio, or SNR). A microphone array designer must choose whether to sacrifice the quality of the captured speech to eliminate distracting background noise, or to allow the unwanted noise to come through the captured audio to maintain integrity of the speech signal.

Soundskrit’s directional MEMS microphones eliminate the challenging design decisions imposed by traditional omnidirectional microphone arrays. Designers must no longer trade-off between background noise rejection and speech signal quality. Soundskrit’s technology eases the constraints imposed by microphone arrays and brings unparalleled performance to the end user. However, before looking at the advantages of microphone arrays using directional microphones, we will build a deeper understanding of the challenges associated with omnidirectional microphone arrays.

Signal-to-Noise Ratio

A microphone’s **signal-to-noise ratio**, or **SNR**, is defined as the ratio of the microphone’s sensitivity relative to its noise. The sensitivity is the magnitude of a microphone’s electrical response to a given acoustic stimulus (i.e., sound). The microphone’s noise relates to its electrical output when it is not subject to any acoustic stimulus. When listening to an audio signal, the noise of the microphone is perceived as a white noise in the background. The lower the noise of the microphone relative to its sensitivity, the less the irritating white noise is heard by the listener. A high SNR directly translates to a high-quality audio signal.

As a person moves further away from the microphone, the sound level of their voice diminishes, reducing the speech signal captured. It is important that the noise level of the microphone is much lower than the captured speech signal to avoid audible hissing in the audio. Having high SNR increases the distance at which a microphone can capture sound effectively.

Directivity Index

The **directivity** of a microphone describes its sensitivity to sound coming from a particular direction (commonly referred to as the **direction of arrival**). An omnidirectional microphone has the same sensitivity regardless of the direction of arrival of the incoming sound. In contrast, the sensitivity of a microphone array changes as the direction of arrival changes. The **directivity index (DI)** of a microphone or microphone array measures the ratio of the output for a sound positioned directly in front of the directional beam versus the output in a diffuse sound field with the same amount of total acoustic power. A **diffuse sound field** is one in which the energy of the sound is uniform across all directions. Therefore, the directivity index of an omnidirectional microphone is 0dB since it captures sound equally from all directions. The more directional a beamformer is, the higher its directivity index. For example, a microphone with a dipole beam pattern has a directivity index of 4.8dB. In many practical environments, the undesired background noise may be diffuse in nature, such as reverberation in a closed office or babble noise in a crowded restaurant. In these scenarios, the background noise does not come from one or more specific directions, but rather all directions relative to the microphone. A microphone array with a directivity index of 4.8dB can reject 4.8dB of this diffuse background noise.

Unfortunately, traditional arrays built from omnidirectional microphones have a directivity index that is frequency dependent. At low frequencies, the microphone arrays may have a more omnidirectional response, while at high frequencies, unwanted sidelobes may appear in the directivity patterns. Thus, when looking at the directivity index, it is important to consider the directivity index at all frequencies in the audible range as this better describes a system’s ability to reject ambient noise and isolate the voice of a user. Therefore, we look at the **average directivity index (**$\overline{DI}$**)** from 20Hz to 20kHz. When computing the average directivity index, a logarithmically weighted average across the frequency spectrum is used as described in Soundskrit’s AN-110, “Attributes of Soundskrit Directional Microphones”.

Traditional Broadside Beamformer

One type of microphone array is the **broadside array**. In a typical broadside microphone array, two or more microphones are positioned along a line that is perpendicular to the direction that a desired sound is propagating from. For example, if a person is speaking and their voice propagates along a direction *y*, then the two or more microphones are placed along a direction *x*, with a spacing *d* as illustrated in Figure 1.

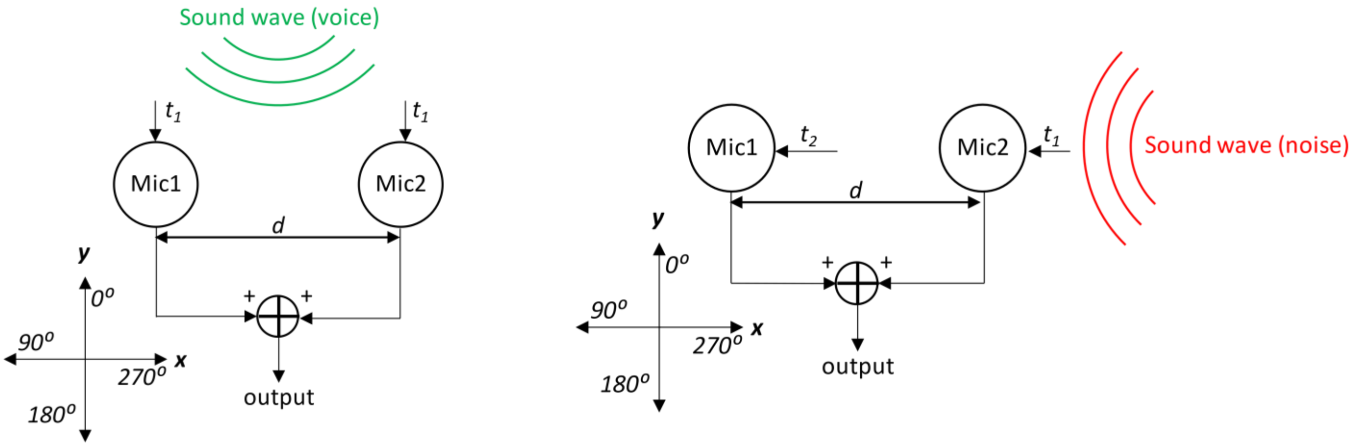


Figure 1: Broadside array using omnidirectional microphones sound arriving from 0° (left) and 90° (right).

In a **delay-and-sum** broadside array, the outputs of the two microphone signals are summed. Any sound propagating along direction *y* arrives at the two microphones at the same time, whereas any sound propagating in a different direction arrives at the two microphones at different times. The closer the sound is to direction *x*, the larger the difference in time it takes for the sound wave to reach both microphones. For example, in Figure 1, when a sound wave arrives at the array from an angle of 0° it reaches *Mic1* and *Mic2* at the same time *t1*. In contrast, when the sound wave arrives from an angle of 90°, it reaches *Mic2* at time *t1* and *Mic1* at a later time *t2*. The difference in arrival time of the sound wave at the two microphones corresponds to a phase difference between the signal at the two microphones. When summing the microphone signals, sounds propagating along the direction *y* are completely in-phase and generate a sound signal with an amplitude twice that of a single microphone. When summing the out-of-phase microphone signals from sound propagating along direction *x*, the output is reduced relative to the former scenario. Thus, the broadside microphone array captures sounds travelling along direction *y* with the highest sensitivity, but will capture sounds traveling along direction *x* with reduced sensitivity.

Figure 2 shows the directionality pattern and frequency response of a broadside microphone array with a spacing of *d = 40mm* using omnidirectional microphones. The frequency response is normalized such that 0dB corresponds to the sensitivity of a single microphone.

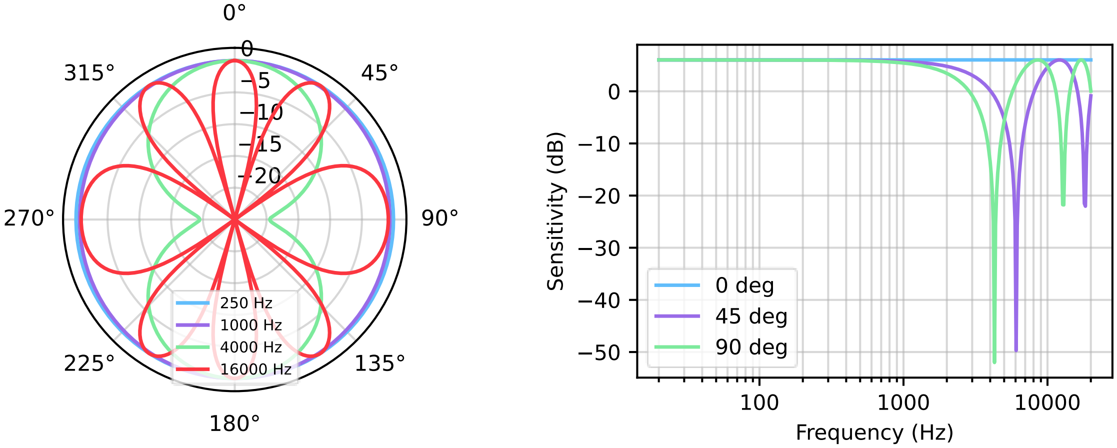


Figure 2: Polar pattern (left) and normalized frequency response (right) of a broadside array with 40mm spacing.

As shown by Figure 2, the microphone array has its greatest sensitivity for sounds along the direction *y* (0° and 180°) while rejecting sounds along the direction *x* (90° and 270°). By summing the signal of the microphone array, the on-axis sensitivity increases by 6 dB as shown by the frequency response. However, summing the microphone signals also increases the noise. Since the microphone noise of each microphone is uncorrelated, the output signal's noise only increases by 3 dB. Therefore, this results in a total increase of SNR by 3 dB relative to a single microphone.

Unfortunately for broadside beamformers, the directionality of the array is not consistent with frequency. As the frequency changes, so does the directionality pattern. The broadside beamformer achieves perfect rejection along the direction *x* when the half-wavelength of the incident sound is equal to the spacing between the two microphones. At this frequency, the sound signal of the two microphones is perfectly out-of-phase for sounds arriving from the direction *x*.

For a spacing of 40 mm between the microphones, this corresponds to a frequency of 4.25 kHz. Below this frequency, the response of the array becomes more omnidirectional as the phase difference between the two microphones shrinks regardless of the direction of arrival. Therefore, the array struggles to reject low frequency ambient sound. Above the frequency where the array spacing is equal to a half-wavelength, aliasing occurs. The system is unable to differentiate between the actual frequency and a lower frequency signal with the same phase difference. This creates unwanted sidelobes in the polar pattern, degrading the microphone's directivity and shifting the nulls of the microphone array to different angles.

An inconsistent beam pattern across the audio spectrum has several adverse effects. First, the ability of the microphone array to reject ambient diffuse noise across all frequencies is reduced. While the broadside beamformer exhibits good directionality at 4.25 kHz, it quickly deviates outside of this frequency. Unfortunately, broadside arrays are effectively omnidirectional at low frequencies—they look no different than just a single microphone. And at high frequencies, a significant amount of noise can find its way into the audio signal due to the sidelobes produced from aliasing.

Second, an inconsistent beam pattern can be detrimental to a microphone array's ability to reject direct sources of noise. **Direct sound sources** are sounds that propagate from a specific direction, such as the noise from a TV or a child in the background of a conference call. Direct noise sources are typically much louder than diffuse noise. Thus, it is desirable to orient the **null** of the microphone array pattern, or the angle at which the microphone has the least sensitivity, at the direct noise source to provide a significant amount of rejection. The null of a microphone array can often provide ~20 dB of noise rejection. However, as shown in Figure 2 above, the null angle changes at high frequencies where the microphone array suffers from aliasing. This makes it difficult to reject all the frequencies of a direct noise source by pointing a null at it.

Third, the changing beampattern as a function of frequency results in “**off-axis coloring**”. The sensitivity of the microphone array at angles that are **off-axis** (i.e., not 0°) changes as a function of frequency, particularly in the high frequency range. Thus, sounds arriving off-axis to the microphone get distorted by the changing microphone frequency response, and the tonality of the true sound in the environment is not preserved. In many real-world scenarios, the environment around a microphone produces a significant number of reflections of a desired voice signal. These reflections arrive off-axis to a microphone array at any angle. When this reflected sound (which is colored by the microphone array) is mixed with the desired on-axis sound, it corrupts the audio quality of the captured speech.

In the above example, the microphone array had a spacing of 40 mm. At low frequencies, the microphone array appeared omnidirectional since the phase difference seen at the two microphones was relatively small regardless of the direction of an incoming sound—it was as if both microphones were effectively seeing the same signal. To improve directivity at the low frequencies, the spacing between the microphones can be increased. For example, if the microphones are spaced 75 mm apart, a sound wave arriving off-axis takes longer to hit the second microphone relative to the first, creating a larger phase difference. As shown by Figure 3, the microphone array achieves a greater directivity at low frequencies compared to when the spacing was 40 mm.

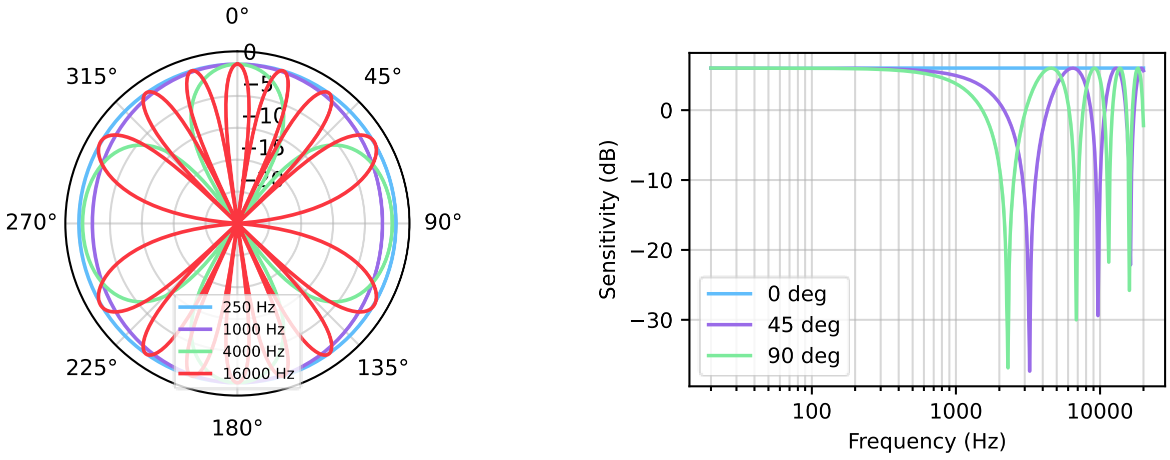


Figure 3: Polar pattern (left) and normalized frequency response (right) of a broadside array with 75 mm spacing.

Unfortunately, because of the larger spacing between the microphones, the array begins to experience aliasing at a lower frequency, 2.27 kHz, when spaced 75 mm apart. In terms of SNR, the broadside array with a larger spacing also sees a 3 dB increase in SNR compared to the single omnidirectional microphone. A broadside beamformer with two microphones will always see a 3 dB increase in SNR regardless of the spacing.

Alternatively, the aliasing frequency of the microphone array can be pushed to higher frequencies by spacing the two microphones closer together. For example, when the microphones are spaced 10 mm apart, the directionality and frequency response of the microphone array look as shown in Figure 4.

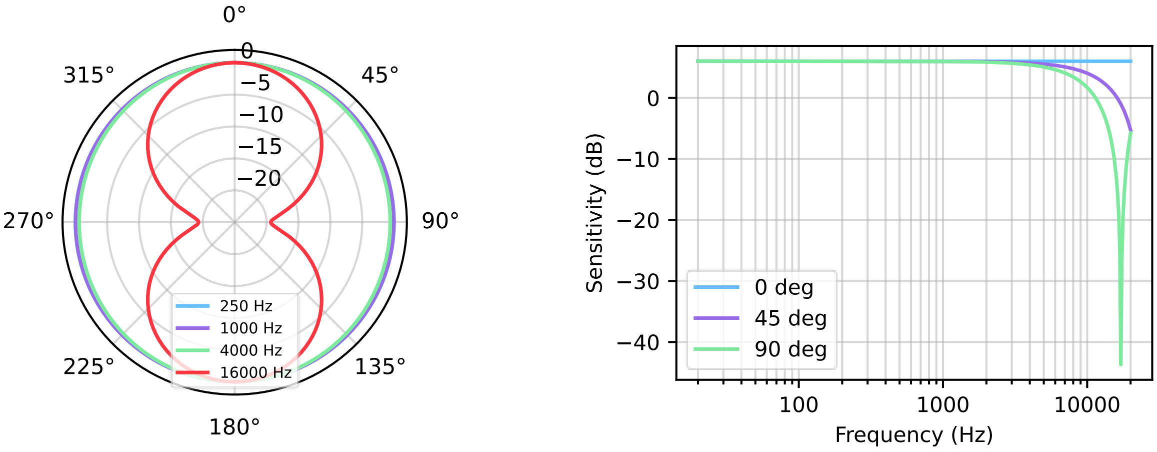


Figure 4: Polar pattern (left) and normalized frequency response (right) of a broadside array with 10mm spacing.

Though the aliasing frequency is pushed up to 17 kHz, the array now appears omnidirectional for a greater range of frequencies at the low end of the audio spectrum. This configuration barely achieves any directionality across the audio spectrum.

In general, a broadside microphone array is only able to achieve decent directivity without aliasing for a very limited bandwidth. While a designer of microphone arrays can set the spacing between the microphones to give directivity in a small frequency range of interest, they cannot achieve good directionality across the entire audio spectrum. For environments with a wide spectrum of ambient noise and reverb, a broadside beamformer struggles to provide clear isolation of a user's voice. Figure 5 plots the directivity index against frequency for a broadside beamformer with the three discussed spacings. The average directivity index looks at these values across the entire audible range. Due to the unstable nature of the directionality patterns from broadside beamformers, the average directivity index for the three different spacings range from 0.7dB to 1.8dB, a small improvement from a typical omnidirectional microphone. Furthermore, to get above 1dB of average directivity, the array needs to be placed in a configuration that aliases around 4kHz, well within the range of important frequencies for speech and audio pickup.

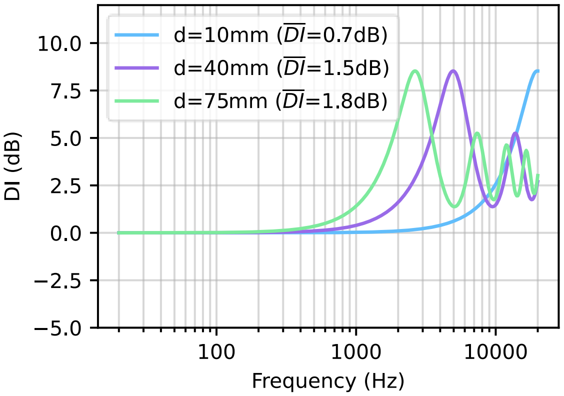


Figure 5 Directivity index versus frequency of a broadside beamformer

Traditional Endfire Beamformer

In a typical **endfire array** (also known as a **differential microphone array**), two or more microphones are positioned along a line that is parallel to the propagation direction of a desired sound. For example, if a person is speaking and their voice propagates along the direction *y*, then two microphones are placed along the direction *y*, with a spacing *d* as illustrated in Figure 6.

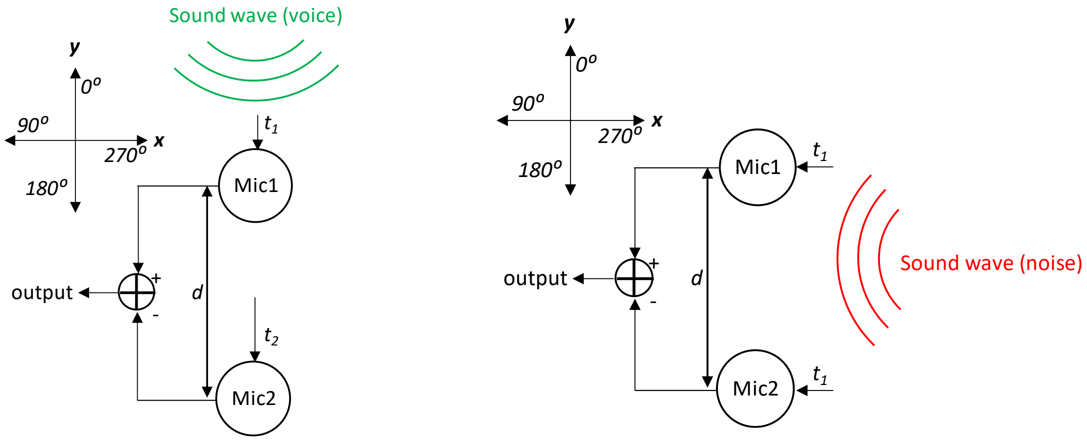


Figure 6: Endfire array using omnidirectional microphones with a sound arriving from 0° (left) and 90° (right).

In an endfire array, the outputs of the two microphone signals are subtracted. Any sound propagating along direction *x*, arrives at the two microphones at the same time, whereas any sound propagating in a different direction arrives at the two microphones at different times. The closer the sound is to direction *y*, the longer the time delay between the sound reaching each microphone. For example, in Figure 6, a sound wave propagating at an angle of 0° reaches *Mic1* at time *t1* and then arrives at *Mic2* at a later time *t2*. The difference in arrival time of the sound wave corresponds to a phase difference between the signal at the two microphones. When subtracting the two microphone outputs, a larger phase difference corresponds to a larger output signal. When sound propagates along the direction *x*, the signals from each microphone will be completely in-phase and the output of the differential signal cancels out. Thus, the array captures sounds travelling along direction *y*, while attenuating sounds traveling along direction *x*.

Figure 7 shows the directionality pattern (normalized to 0 dB) and frequency response of an endfire microphone array with a spacing of *d = 40 mm*.

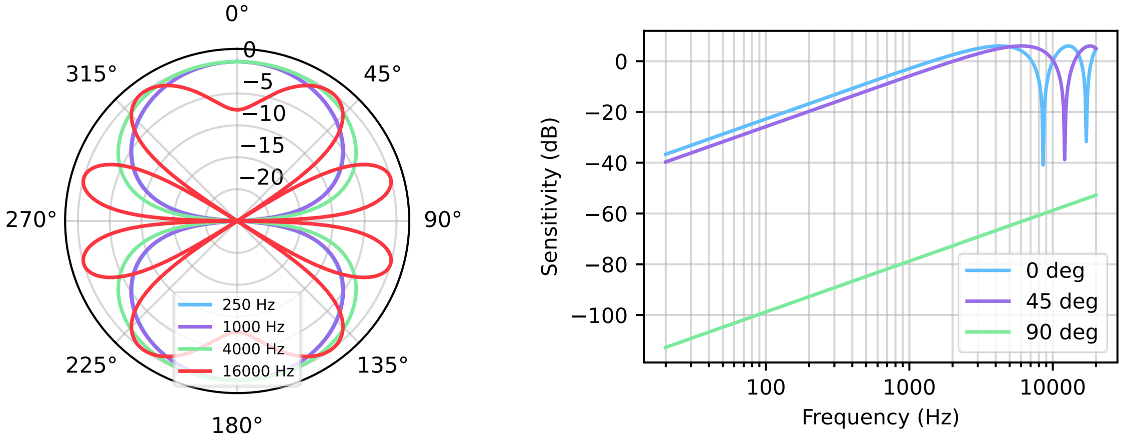


Figure 7: Polar pattern (left) and normalized frequency response (right) of an endfire array with 40mm spacing.

The microphone array has its greatest sensitivity for sounds along the direction *y* while rejecting sounds along the direction *x*. Because the array subtracts the two microphone outputs, the on-axis sensitivity of the array is severely attenuated. In other words, the differences seen by the two microphones are typically very small. The lower the frequency of the incoming sound, the lower the sensitivity of the array. This results in a SNR reduction of about 11.5 dB relative to an individual microphone. In order to get directionality, the differential microphone array suffers a significant loss in SNR, degrading audio quality. And still, it experiences aliasing at frequencies above 4.25 kHz.

To improve sensitivity at the low frequencies, the spacing between the microphones can be increased. For example, the microphone spacing may be increased to 75 mm. Because the microphones are spaced further apart, a sound wave arriving on-axis will take longer to arrive at the second microphone relative to the first, creating a larger pressure difference between the two. As shown in Figure 8, the microphone array achieves greater sensitivity at low frequencies.

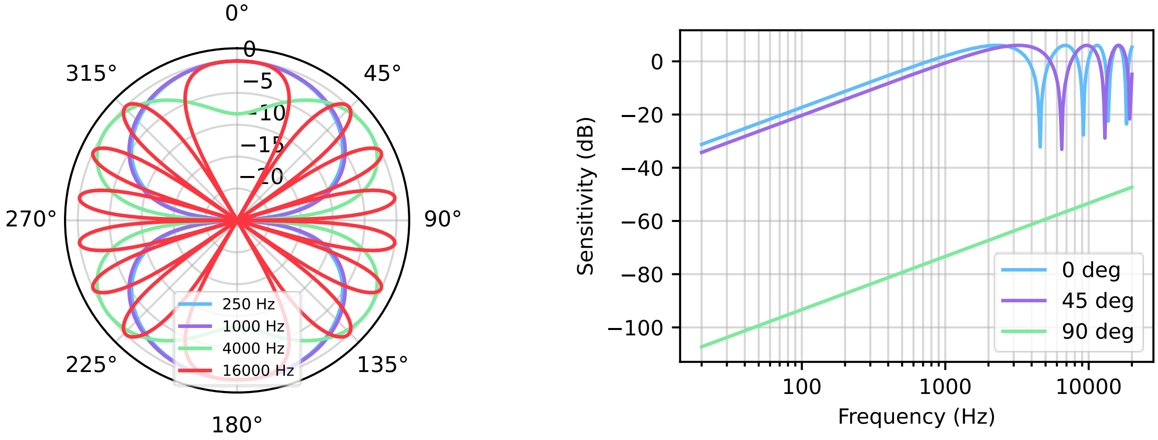


Figure 8: Polar pattern (left) and normalized frequency response (right) of an endfire array with 75 mm spacing.

By spacing the microphones further apart, the sensitivity of the output at low frequencies is increased, but the array now experiences aliasing at 2.27 kHz. The improved low frequency performance is achieved at the detriment of high frequency performance. This results in about 12 dB reduction in SNR relative to a single omnidirectional microphone. Thus, the SNR reduction experienced by the endfire array, relative to a single omnidirectional microphone, is similar for 40 mm and 75 mm spacings.

Alternatively, the aliasing frequency of the microphone array can be pushed to higher frequencies, and the directionality preserved, by spacing the two microphones closer together. For example, when the microphones are spaced 10 mm apart, the performance of the array appears as shown in Figure 9.

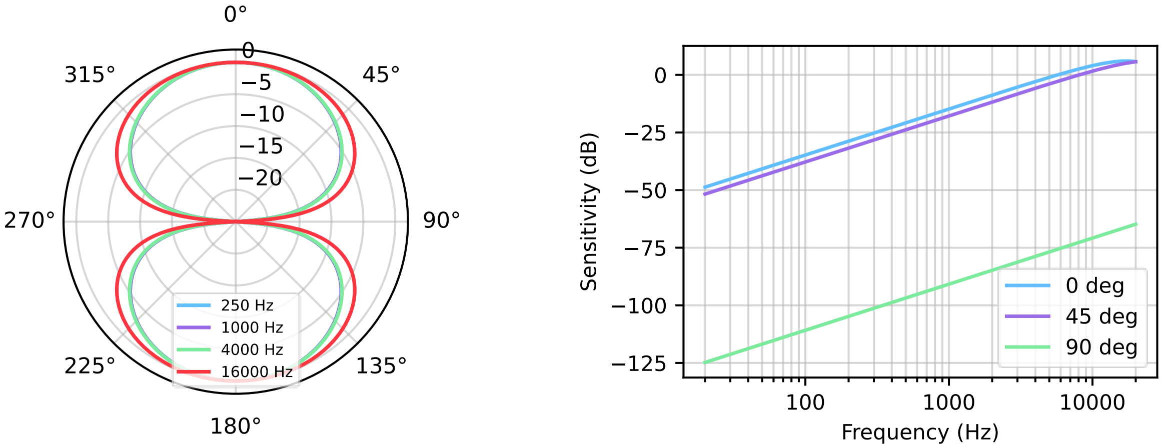


Figure 9: Polar pattern (left) and normalized frequency response (right) of an endfire array with 10mm spacing.

The aliasing frequency is increased, and the array finally exhibits good directionality across the audio spectrum. However, this comes at the cost of reduced acoustic sensitivity. When two microphones are spaced so close together, the pressure difference between them is incredibly small, resulting in an effective SNR that is 17 dB less than that of a single microphone! This massive reduction in SNR leads to poor audio quality and a speech signal that is overpowered by microphone noise.

Like the broadside microphone array, the endfire microphone array is only able to achieve acceptable performance for sounds whose half-wavelength is close to the spacing between the two microphones. The endfire microphone array is fundamentally limited in usable bandwidth. A designer of microphone arrays cannot create a 2-microphone endfire array that achieves both high sensitivity and consistent directivity across the audible spectrum. Figure 10 shows a graph of the directivity index as a function of frequency for an endfire beamformer with the three spacings previously discussed.

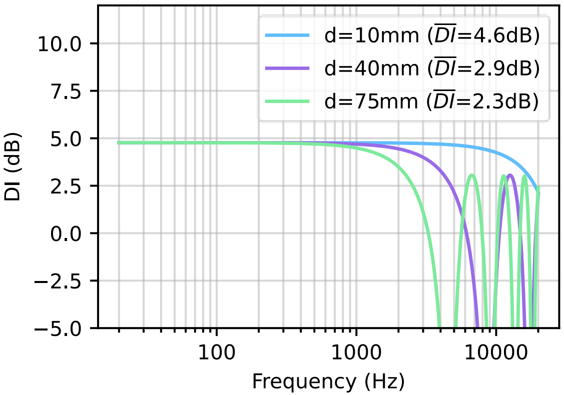


Figure 10: Directivity index versus frequency of an endfire beamformer with different spacings

The average directivity index of a differential endfire beamformer with 10 mm spacing provides improved directionality with an average directivity index of 4.6 dB. However, this comes at the cost of an effectively unusable SNR. The only way to salvage the SNR of the microphone array is to increase the spacing, which reduces the average directivity and introduces aliasing at essential frequencies in the audio band.

The differential array can achieve better directionality than a broadside array but suffers from another challenge: sensor mismatch. Typical omnidirectional MEMS microphones have +/- 1dB matching in sensitivity. As we've seen, due to the small differences in pressure between the two microphones, the differential array already has greatly reduced sensitivity. This is especially true at low frequencies where the difference between the two sensor outputs is particularly small. At these frequencies, small mismatches between the microphones can have a greater impact on the array performance since they are larger in proportion to the pressure difference seen by the microphones. This has an adverse effect on the array's directionality. Figure 11 shows the directivity index versus frequency for a differential array with 10 mm spacing for different amounts of sensitivity mismatch.

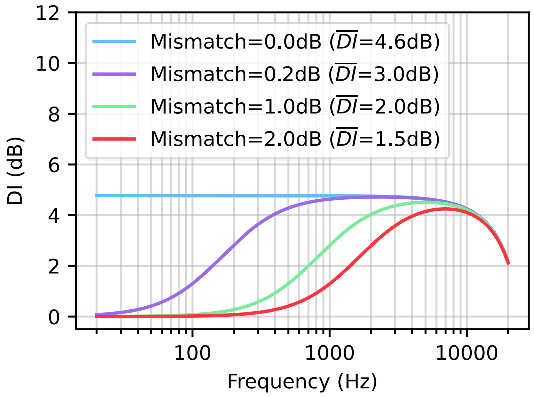


Figure 11: Directivity index versus frequency of a 10mm endfire beamformer with and without sensor mismatch

With only 0.5 dB mismatch in sensitivity, the average directivity index of a differential array with 10 mm spacing can drop by 2 dB. Specifically, the differential array loses a significant amount of directionality at the low frequency end of the audio spectrum. Thus, differential microphone arrays are very sensitive to manufacturing-related mismatches between sensors which can arise from the fabrication of the transducer itself or integration into the end-product.

When choosing between broadside or differential endfire beamformers, system designers must make a choice between preserving the SNR or obtaining directionality in order to reject unwanted ambient noise and reverb. In both scenarios, the audio quality of the signal is reduced.

The Soundskrit Directional Microphone

Soundskrit is introducing the first MEMS directional microphone with consistent directionality across the audible spectrum and high SNR for great sound quality. By leveraging an innovative MEMS transducer that is inherently directional, Soundskrit's technology does not rely on two separate transducers to achieve directionality. Thus, it does not suffer from the frequency-dependent behavior seen by spaced omnidirectional microphone arrays. Figure 12 below shows the consistent dipole beam pattern of Soundskrit's SKR0400.

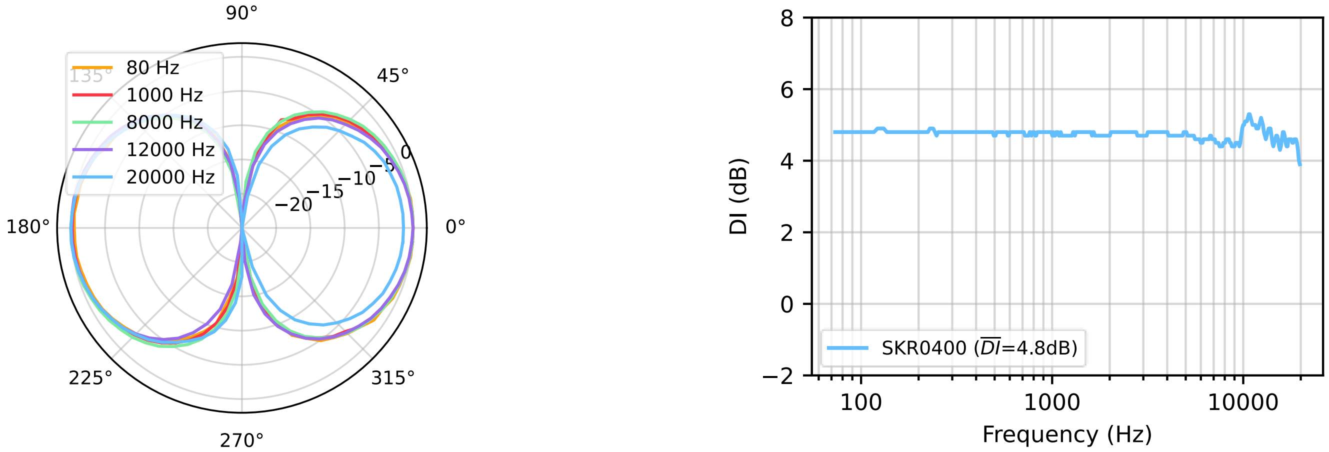


Figure 12: Polar pattern (left) and directivity index vs. frequency (right) of the SKR0400.

Soundskrit's microphones maintain an average directivity index of 4.8 dB, do not experience aliasing, and maintain a consistent null across the audible spectrum. This is incredibly advantageous when designing audio capture systems that need to isolate a user's voice while eliminating background noise. Soundskrit microphones inherently provide 4.8 dB of diffuse noise rejection in the hardware alone, without any signal processing. This reduces computational constraints on the signal processing and allows for overall better voice clarity.

Unlike the omnidirectional microphone-based endfire array which suffers from a massive loss in sensitivity when used to provide a dipole output, Soundskrit's technology maintains a high SNR. Figure 13 shows the SNR of the SKR0600 compared to a traditional 2-microphone differential array with 10mm spacing using 70dB omnidirectional microphones.

As can be seen from figure 13, the traditional microphone array loses 17 dB SNR when used to create a dipole beam pattern, for an effective SNR of only 53 dB. Meanwhile, the SKR0600 achieves an SNR of 67 dB, more than 10 dB higher than its omnidirectional microphone counterpart.

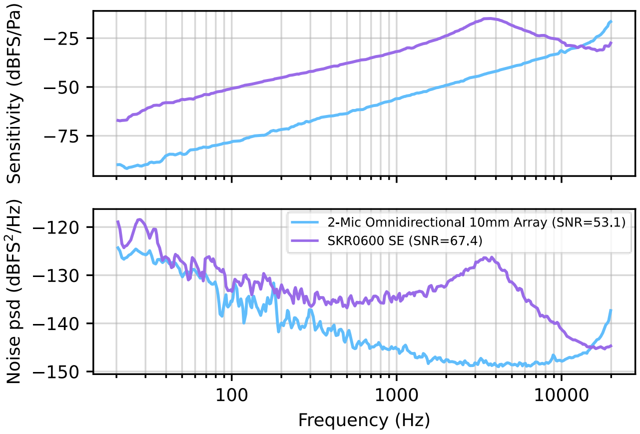


Figure 13: SNR of the SKR0600 versus a differential microphone array using two 70dB omnidirectional microphones with 10mm spacing

Soundskrit's directional microphones are the ideal solution for voice capture, providing a high-quality audio signal with natural rejection of unwanted background noise. Soundskrit brings the power of traditional microphone arrays into a single, small form factor microphone. The single-microphone solution reduces power consumption and computational burden typically imposed by traditional microphone arrays. Furthermore, because Soundskrit achieves directionality from a single transducer, it is not prone to typical manufacturing-related problems that lead to microphone mismatch among arrays.

Broadside Beamformers with Directional Microphones

In applications where performance is of utmost importance, it is possible to replace the multiple omnidirectional microphones in a traditional array with multiple Soundskrit microphones. For example, the 2-microphone omnidirectional broadside array can be replaced by a broadside array of 2 Soundskrit microphones. Figure 14 shows the directivity index versus frequency of a 2-microphone broadside array using Soundskrit microphones with different spacings.

The broadside array of Soundskrit microphones achieves an average directivity index between 5.2 dB and 6.3 dB depending on the spacing. This is a big improvement from its omnidirectional counterpart which provided less than 1.8 dB of directivity. Like the broadside array of omnidirectional microphones, the Soundskrit microphone array also sees an increase of SNR by 3 dB when used in this configuration. However, while traditional broadside arrays of omnidirectional microphones provide extremely limited directivity, the inherent directionality of the Soundskrit microphones enable the broadside beamformer to become an effective tool for voice isolation, especially in products such as laptops or TVs whose form factors are limited to broadside configurations.

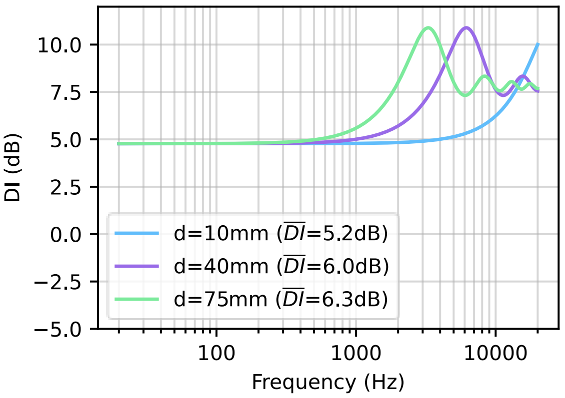


Figure 14: Directivity broadside array with Soundskrit microphones

Endfire Beamformers with Directional Microphones

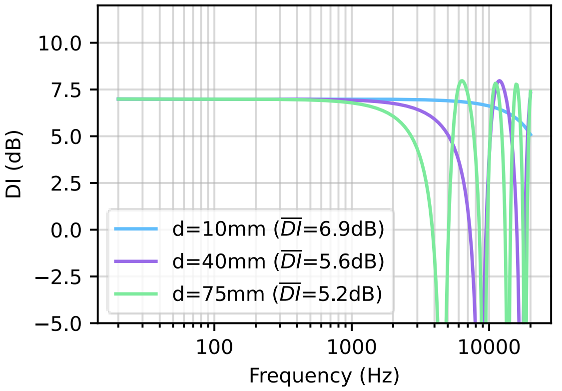


Figure 15: Directivity index of endfire array with Soundskrit microphones

Like the broadside beamformer, the 2-microphone omnidirectional endfire array can be replaced by an endfire array of 2 Soundskrit microphones. Figure 15 shows the directivity index versus frequency of a 2-microphone endfire array using Soundskrit microphones with different spacings.

The Soundskrit microphone array achieves an average directivity index of up to 6.9 dB depending on the microphone spacing, much greater than what can be achieved with 2 omnidirectional microphones. However, like the endfire array of omnidirectional microphones, an array of directional microphones will also see a reduction in SNR when used in this configuration. Thus, it is best for applications in which the highest SNR is not necessarily needed, for example, in applications where the microphone array is close to the user's mouth.

Summary

When using omnidirectional microphones in arrays, there is a fundamental tradeoff between SNR and directivity. If high SNR is needed, a broadside beamformer can be used with limited directionality. Otherwise, for applications with substantial noise or reverb, a differential endfire beamformer can be used to provide more directionality, at the expense of reduced SNR and thus audio quality. Further, due to aliasing effects, only a limited bandwidth of directionality can be achieved. A microphone array designer must choose which frequencies are most important to them and set the spacing of the microphone array accordingly. For the increasing number of applications in which wideband audio is now desirable, the best option is to use many microphones with different spacings to cover the full audio spectrum.

Fortunately, Soundskrit is providing a tool for audio systems unconstrained by the same fundamental tradeoffs of omnidirectional microphone arrays. As shown, Soundskrit's microphone provides high directivity across the audio spectrum without sacrificing SNR. Multiple Soundskrit microphones can be arrayed like traditional omnidirectional microphones or leveraged in new array architectures to provide even better performance. When audio was first introduced to consumer devices, very limited bandwidth was the acceptable. This was "good enough" for the time. Now, as audio performance comes to the forefront of many new consumer devices, a solution with a higher standard is needed.

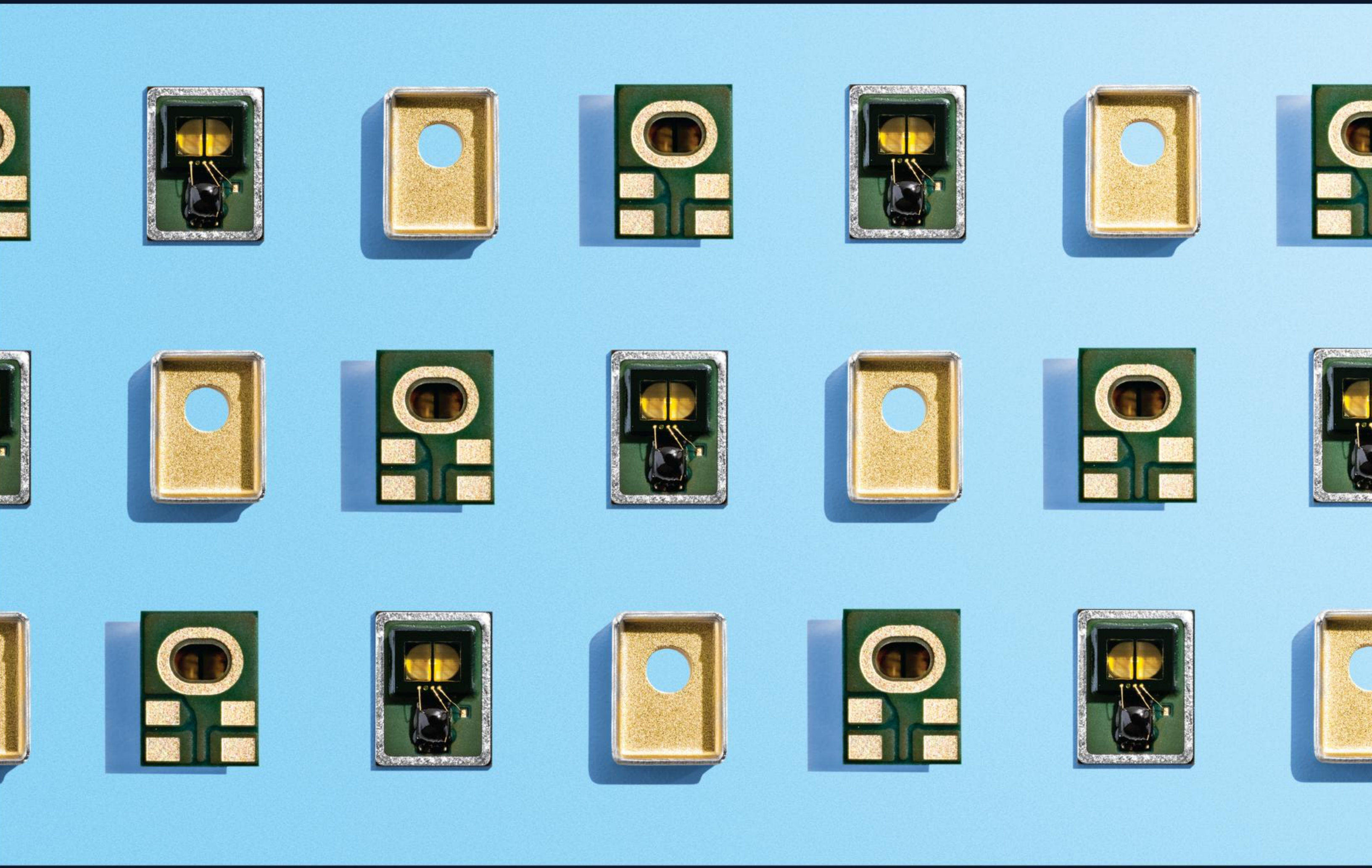
Additional Support

For further information on Soundskrit's products, visit our website at http://www.soundskrit.ca where you can find more application notes, datasheets, and purchasing information. If you have any questions or need technical support, please reach out to applications@soundskrit.ca.

Revision Label	Revision Date	Sections Revised
-	November 2022	Initial release
A	April 2023	Updated formatting
B	February 2025	SKR0600 plot, Minor improvements, clarity

Soundskrit developed the first high-performance directional MEMS microphone on the market, leveraging years of research in bio-inspired MEMS based on how spiders and other insects in nature hear. In combination with Soundskrit's in-house audio processing algorithms, directional microphones can be used to capture and isolate any sound in an environment with a fraction of the size, power, and computation of traditional omnidirectional-based microphone arrays.

Soundskrit was founded in 2019 and is headquartered in Montreal, Quebec with an R&D facility in Ann Arbor, Michigan.



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