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The implementation of MEMS microphones for urban sound sensing

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ABSTRACT

The urban sound environment of New York City (NYC) is notoriously loud and dynamic. The current project aims to deploy a large number of remote sensing devices (RSDs) throughout the city, to accurately monitor and ultimately understand this environment. To achieve this goal, a process of long-term and continual acoustic measurement is required, due to the complex and transient nature of the urban soundscape. Urban sound recording requires the use of robust and resilient microphone technologies, where unpredictable external conditions can have a negative impact on acoustic data quality. For the presented study, a large-scale deployment is necessary to accurately capture the geospatial and temporal characteristics of urban sound. As such, an implementation of this nature requires a high-quality, low-power and low-cost solution that can scale viably. This paper details the microphone selection process, involving the comparison between a range of consumer and custom made MEMS microphone solutions in terms of their environmental durability, frequency response, dynamic range and directivity. Ultimately a MEMS solution is proposed based on its superior resilience to varying environmental conditions and preferred acoustic characteristics.

1. INTRODUCTION

Noise pollution is an increasing threat to the well-being and public health of city inhabitants [24, 8, 7]. Large advances have been made in noise prediction over the last few decades, with applications utilizing GIS technologies and sophisticated noise transmission modeling [25, 11, 9]. However, the complexity of sound propagation in urban settings and the lack of an accurate representation of the distribution of the sources of this noise have led to an insufficient understanding of the urban sound environment. The presented project aims to continuously measure and ultimately understand these urban sound environments. It is a multidisciplinary collaborative effort between New York University's (NYU) Center for Urban Science and Progress (CUSP) and the NYU Steinhardt School's Citygram Project [16, 18, 19, 12, 17]. The impetus of the Citygram project is focused on the lack of sufficient mapping paradigms for non-ocular energies in urban settings. These energies, namely, sound can have a profound effect on a cities inhabitants and the key to understanding this effect firstly lies in the measurement of this energy. NYU CUSP's interests are focused on the noise of New York City, including how it impacts on the health of the city's population, correlates with urban problems ranging from crime to compromised educational conditions, and affects real estate values. While a number of past studies have focused on specific contexts and effects of urban noise [10, 15, 26, 23, 20, 4], no comprehensive city-wide study has been undertaken that can provide a validated model for studying urban noise in order to develop long-lasting interventions at the operational or policy level.

The project is currently using NYC as a "lab" with the aim of creating a model that can be utilized and implemented in other cities around the world. With its population, its agency infrastructure, and its ever-changing urban soundscape, NYC provides an ideal venue for a comprehensive study and understanding of the problem of urban noise. To achieve this goal an initial network of low cost acoustic sensing devices were designed and implemented to capture long-term objective acoustic measurements from strategic locations throughout the city using wireless communication strategies. These prototype remote sensing devices (RSD's) currently incorporate a quad core Android based mini PC with Wi-Fi capabilities, and a custom MEMS microphone, whose characteristics are detailed in this paper. Acoustic data captured from each sensor node is comprised of a standard set of low-level audio descriptors for use in analysis, online mapping and visualization. The initial goal is to develop a comprehensive cyber-physical system [1] that provides the capability of capturing, analyzing and wirelessly streaming environmental audio data, along with its associated acoustic features and metadata - including automatic source identification.

To capture this acoustic data with sufficient spatial resolution, a dense and large scale monitoring network is required that isn't constrained by high microphone costs. The relatively new technology of Microelectromechanical Systems (MEMS) microphones have been extensively utilized in consumer electronic devices and have the potential to provide the combination of audio quality and low cost that a viable network of this type requires.

The EU Directive (2002/49/EC) [5] resulted in the production of noise maps for major urban areas across Europe in 2007, to inform strategic planning for noise control. However, many authorities across Europe found it difficult to use these noise maps for any kind of mitigation or action planning, due in part to a lack of confidence in the output data reflecting reality and the lack of any temporal variation. The solution to this relied on more extensive measurement initiatives, which were prohibitively expensive. In response to this, the National Physical Laboratory (NPL) in London began the DREAMSys project in 2007 to investigate the use of MEMS microphones in noise surveying applications [1, 2]. The project proved that a custom made measurement grade MEMS microphone could be successfully utilized in large scale noise surveys to enhance noise mapping initiatives. Their wireless and relatively low cost, distributed measurement system revealed a high degree of consistency with traditional noise measurement equipment. As impressive as the DREAMSys project is, however, the cost of each custom made sensor unit would be comparatively high when compared to the current projects goals of an ultra low cost distributed sensor solution consisting of commercially available off the shelf components.

1.1. MEMS Microphones

MEMS microphones have been around for over thirty years [6], primarily utilized in telecommunica-

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[1] Network connected, distributed computing systems monitoring physical phenomena

tion systems such as cellphones and low-power consumer electronic devices. In recent years, however, interest in MEMS microphones has expanded due to their versatile design, greater immunity to radio frequency interface (RFI) and electromagnetic interference (EMI), low-cost and environmental resiliency [14, 22]. Electret microphones, for example, have a limited operating temperature range, whereas MEMS can operate from -40 to 100 °C. In fact, research dating back to 2003 was investigating the development of MEMS microphones with measurement grade characteristics such as enhanced sensitivities as high as -33dB re. 1 V/Pa and noise levels of 23dB(A) [22]. The continued pressures on audio hardware manufacturers to miniaturize components, to reduce printed circuit board (PCB) area and ultimately reduce end product weight and dimensions resulted in the widespread adoption and mass production of the extremely small MEMS microphones. Current MEMS models are generally 10x smaller than their electret counterparts. This miniaturization has also allowed for additional circuitry to be included within the MEMS housing, such as an amplification stage and an analog to digital converter (ADC) to output digitized audio in some models. MEMS microphones provide all this functionality in a self contained unit with an exceptionally small footprint, as opposed to an electret system that would require all of these extra stages to be implemented on separate circuitry, consuming more space and power. The production process used to manufacture these devices also provides an extremely high level of part-to-part consistency in terms of acoustic characteristics such as sensitivity and phase response, making it more amenable to multi-capsule and multi-sensor arrays, where consistency of individual microphones is paramount. MEMS microphones therefore have much smaller production tolerance ranges than other microphone types.

In this system we investigate the Knowles SPU0410LR5H-QB shown in Figure 1. The silicone diaphragm MEMS microphone has a manufacturer quoted “flat frequency response” between 100 and 10kHz. It requires a 3.6 V supply and draws only 120μA. In addition, it’s quoted as having a sensitivity of -38dB re. 1 V/Pa and a signal-to-noise ratio of 63dBA.

In order to test the Knowles MEMS microphone a

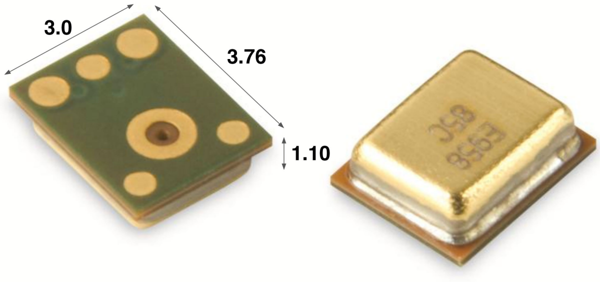

Fig. 1: Knowles SPU0410LR5H-QB MEMS microphone (dimensions in mm)

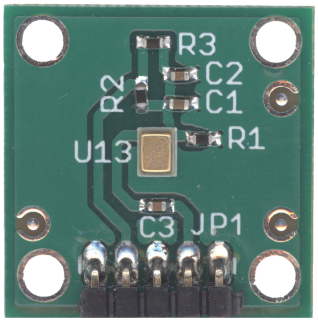

Fig. 2: MEMS microphone custom PCB (microphone in center)

PCB shown in Figure 2 was designed and fabricated to condition the power to the microphone, provide direct current (DC) as well as included radio frequency (RF) filtering. The PCB was designed so that it is powered from a regulated 5V DC power source through a voltage divider to obtain 3.4V to the microphone. A 0.1μF and a 1.0μF capacitor were connected across the power pads of the microphone to provide adequate filtering of the power. A 0.1μF capacitor was connected in series with the output of the microphone to block any residual DC component from the output of the microphone. Space has also been left on the board for any future components, such as preamplification. The test results below are measured using the configuration described.

The small size of the MEMS microphone makes it particularly well suited for the capture of acoustic wave-fronts in the temporal domain. A number of beam forming array configuration were designed, fabricated and tested, achieving impressive results with near field directional configurations [21]. Research is ongoing to explore designs for temporal capture and spatial location using MEMS microphones in novel array configurations. A future application for these type of arrays has also been considered for the current project in the later stage of sound source localization. A prototype MEMS array containing 10 of the Knowles SPU0410LR5H-QB microphones was fabricated for testing, shown in Figure 3. This unit also incorporated a built-in microphone preamplifier circuit and battery. All MEMS capsule outputs were summed to produce a single combined monaural output. Directivity measurements were carried out on this unit, which are described in Section 2.3.

2. MEASUREMENTS AND RESULTS

To adequately understand and compare the advantages of MEMS microphones for urban noise monitoring applications, three omni-directional consumer grade microphones were subjected to the same frequency and dynamic response tests. The sections below details the measurements for a Panasonic WM-64PC electret, a Polson OLM-10 consumer lapel electret and a Blue Snowflake condenser microphone alongside the aforementioned MEMS. The Panasonic and Polson electret capsules are enclosed in a plastic case, 7mm in diameter, surrounding the microphone with each incorporating a thin fabric covering over the capsule front. The Blue microphone is housed in a spherical plastic case of diameter 40mm with a woven metal grill acting as a windscreen. The bottom ported MEMS microphone is mounted flush to a 1mm thick printed circuit board (PCB), with dimensions 30x30mm. The MEMS port diameter on the underside of the PCB measures 1mm. Also of note is the inline preamplification of the two electret mics. The Polson includes a 1.5V button cell battery powered preamp and the Panasonic uses a phantom powered inline device. With the Blue being a USB audio device it incorporates a built-in preamp and analogue to digital converter (ADC). The MEMS microphone itself is quoted as incorporating an output amplifier, so was provided with no extra preamplification. The differing configurations of each of these microphones may ultimately affect the measured frequency response and dynamic range, however, the microphones would be installed in the projects RSD's as sold to reduce construction time and costs, so will be tested in this state.

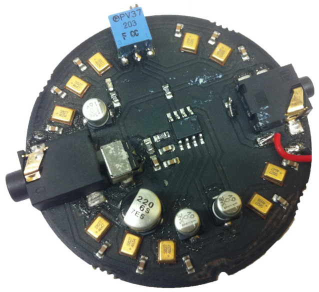

Fig. 3: MEMS array beam-forming prototype incorporating 10 Knowles SPU0410LR5H-QB MEMS microphones (gold in color) and preamplifier

Prior to each experiment, each microphone was calibrated to a -12dBFS peak by adjusting the input gain in response to a pink noise signal produced by the Genelec 8020B loudspeaker. This was performed using the Pro Tools digital audio workstation (DAW), with all audio input routed through a Mackie 1202-VLZ PRO mixer. As such, equality was ensured across all microphones and the response of each system could be consistently compared.

2.1. Frequency response

As with most sound and noise measurement systems, a flat frequency response is ultimately desired to ensure an accurate transduction and representation of a given soundscape. The urban sound environment is made up of a broad spectrum of acoustic content ranging from low frequency traffic rumble to high frequency brake screeches. Therefore, this application requires a microphone that can transduce a wide range of frequencies in a relatively uniform way.

Measurements were conducted in a semi-anechoic research laboratory at New York University, Steinhardt. The MATLAB toolbox: Scan IR [3] was used to generate two three-second 20Hz-20kHz logathrithmicly increasing sine-sweeps and capture the impulse response of each microphone. Sound was played back from a Genelec 8020B active speaker and a reference omni-directional Earthowrks M30 microphone assumed to be flat from 20Hz-20kHz was used to subtract the room and speaker coloration on the impulse response. All microphones were placed at one meter from the center of the speaker on-axis, 1.6m from the floor.

As shown in the frequency response plot Figure 4, the custom MEMS operates closest to a flat frequency response. On the other hand, the Panasonic and Polson electret microphones only exhibit similar flat responses at low frequencies. Whereas the custom MEMS microphone maintains a uniform flatness in frequency response, both electret microphones elicit distinct peaks in the 2-8 kHz ranges. Additionally both microphones display a significant trough near the 12kHz range. Lastly, unlike any of the other microphones, the Blue Snowflake condenser reveals a collection of large troughs at 2.4, 6.6, 11, 15 and 20kHz. Furthermore, the flat response qualities gathered from the Blue Snowflake appear only between 400-1250 Hz. As expected, the substantial frequency coloration resulting from the Blue Snowflake makes it an unfit microphone for the proposed applications. In sum, based solely on frequency response, the custom MEMS microphones significantly surpasses the other small-sized microphones tested.

2.2. Dynamic range measurements

In order to determine the suitability of the microphones under scrutiny for capturing the urban sound environment a process of dynamic range testing was carried out. This provided a measure of the microphones noise floor, dynamic range and maximum transducible SPL before distortion. Once again these measurements will incorporate the effects of any preamplifier circuitry present. Each microphone was once again set to equal input level by subjecting each to a fixed level pink noise signal and ensuring the input level within the DAW was -12dBFS. The ideal dynamic characteristics for a microphone in this application are: large dynamic range to ensure a wide range of sources can be captured in the far field, a low noise floor to accurately capture lower level signals and a high maximum SPL to transduce high level impulsive sources, prevalent in urban settings.

Noise floor and dynamic range measurements are determined by the amplification applied by the microphones preamplifier and any input gain applied on the mixing desk. As previously mentioned, each microphone was calibrated to produce the same input level when subjected to pink noise presented at a consistent level for each microphone with 0dB input gain applied at the preamplifier stage. Noise floor measurements were taken by placing an NTI Audio XL2 type 1 sound level meter (SLM) directly adjacent to the respective microphone and emitting an increasing pink noise signal from a Genelec 8020B loudspeaker. This signal was increased in level until the noise floor of the microphone was matched, where the dB reading from the SLM was then noted. For the dynamic range measurements the SLM was used for reference and comparison with the other microphones. The dynamic range test consisted of a ten-second pink noise signal linearly increasing from 0 to 110 dB SPL. Once each measurement was captured, the dynamic response of each system was compared to the reference levels captured by the XL2 resulting in the data shown in Table 1. The maximum SPL levels quoted refer to the point at which the microphones output signal is at the point of saturation or peak amplitude of the 16 bit DAW, where this bit rate is the proposed rate to use for the projects audio capture and processing stage.

As seen in Table 1, the noise floor levels of the MEMS and Panasonic electret are favorably low in comparison to the other microphones under test. With the Polson and Blue's intended near field uses of lapel and audio blogging microphone respectively, these high noise floors may not pose too much of a problem as signal to noise ratios will still be accept-

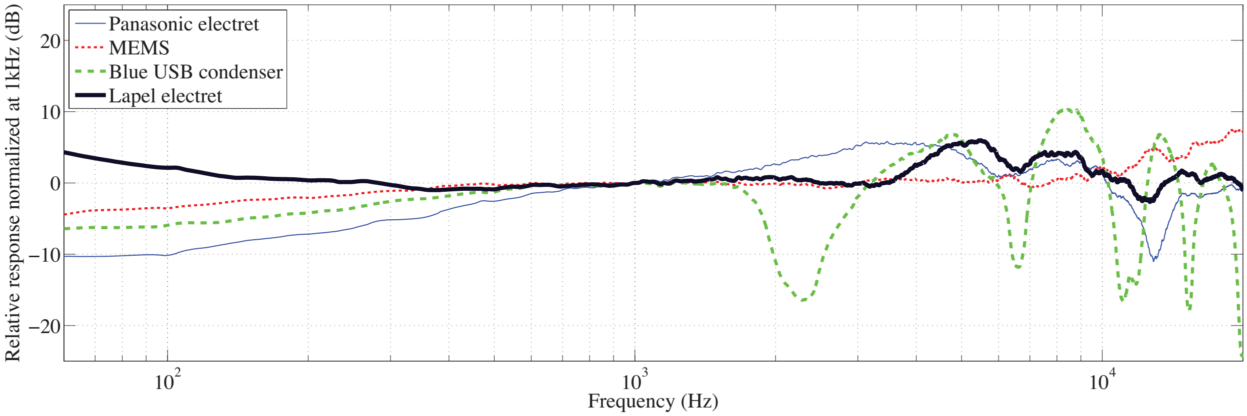

Fig. 4: Microphone frequency response comparisons

Microphone	Noise floor	Dynamic range	Max SPL
Custom MEMS	44dB	62dB	106dB
Panasonic electret	42dB	60dB	102dB
Polson electret	52dB	54dB	107dB
Blue Snowflake condenser	56dB	49dB	106dB

Table 1: Dynamic range and max SPL comparisons

able. The MEMS microphone revealed a dynamic range of 62.4dB, compared to Panasonic's 60.2dB, Polson's 54.2dB and Blue's 49.6dB. Similarly the maximum SPL reported by the MEMS microphone was 106.9dB, Panasonic 102.5dB, Polson 106.9dB and Blue 106.1dB SPL. Evidently, the MEMS microphone dynamic range is wider than the electrets, a result of the lower noise floor observed on these devices. Nonetheless, maximum SPLs are relatively equal between microphones with the exception of the Panasonic showing approximately 5dB SPL less. In other words, though all microphones exhibit a high threshold, our custom MEMS microphone provides the largest dynamic range.

2.3. MEMS array directivity

To determine the directivity of the custom MEMS microphone array, the unit was subjected to two 3 second sine sweeps from 20Hz-20kHz at 15 ° angle increments from 0-90 ° in azimuth, with symmetry about 0 ° assumed. Speaker and room response were factored out by subtracting the same condition response of an Earthworks M30 measurement microphone assumed to be flat in frequency response from 20Hz-20kHz. The MEMS array exhibits relatively omnidirectional response upto 2kHz when varying both azimuth and elevation. After this, attenuation of upto 17dB is seen off-axis in the 8kHz band. Azimuth and elevation directivity stays relatively similar so only the azimuth plots are shown in Figure 5. As signal distance increases from 0.5-4m, the array seems to exhibit more directional characteristics, especially in the 4kHz-8kHz region. This suggests that these MEMS array may be more adept at aiding source localization with a prevalence of high frequency components, such as sirens or birdsong.

The increase in directivity at increased distances from the array also means this unit may be more suitable for far field applications. Directivity testing will also need to be performed with the MEMS array mounted in its future housing to observe the inevitable effects this will have on its response.

3. FUTURE WORK

The initial steps in developing a prototype sensor

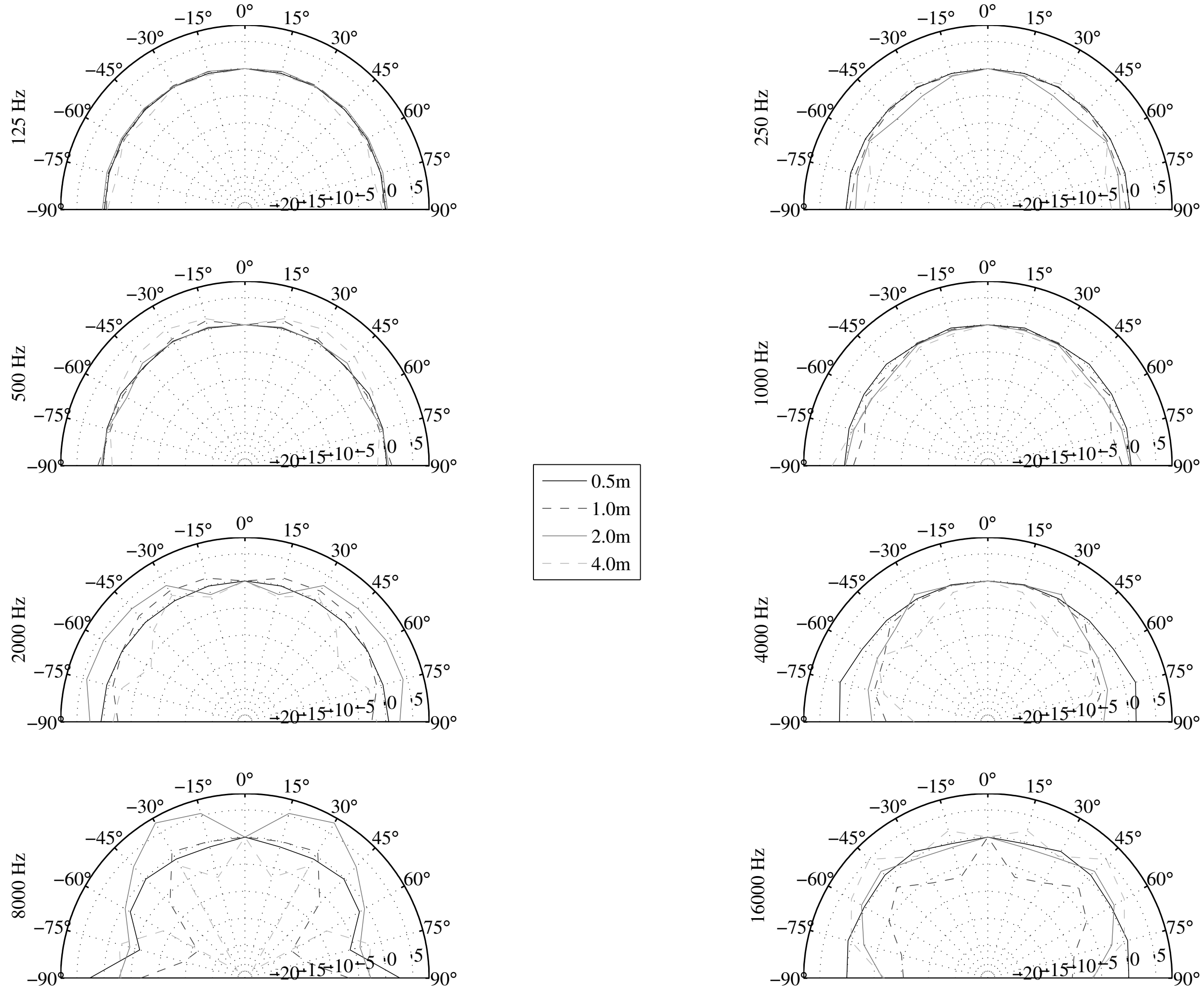

Fig. 5: MEMS array directivity polar plots varying azimuth and distance

system for our application combines numerous components including microphone selection, the design of casings, power supply, wireless technology, and software solutions for real-time urban soundscape monitoring. Further testing will be performed on the MEMS microphone to determine the extended low frequency response and to design a filter to compensate for this response. In the next stage of the project's hardware deployment, the design and testing of a ruggedized casing for all of the sensors components will be incorporated [13]. This casing is necessary to protect all the RSD components from environmental factors, as well as to supply the microphone with the necessary power, data streaming capabilities, and mounting systems. As a result, however, the implementation of such a casing will affect the frequency response and directivity of the microphone, for which we will test for. Additionally, the casing will provide vibration dampening, microphone porting, RFi noise reduction, and wind shielding to optimize the functionality of the sensor. A variant of the 10 capsule MEMS microphone array will be involved in further housed directivity testing to determine its suitability for urban sound source localization.

4. CONCLUSION

This paper sought to provide an initial study on the relatively underused MEMS microphones with consumer grade microphones for urban soundscape monitoring. A series of quantitative measurements were conducted on each microphone to compare the frequency response and dynamic range of each system. The data clearly showed that MEMS microphones surpassed its competitors both in frequency response and dynamic range. In terms of frequency response, only the custom MEMS microphone generated a relatively flat response. The Panasonic and Polson electrets resembled the MEMS' flat frequency response but only for lower frequencies, with distinct high frequency peaks and mid-frequency troughs. Similarly though most microphones had a rather equal maximum dB SPL level, only the MEMS portrayed a wider dynamic range. In both measurement tests, however, the Blue Snowflake USB microphone produced the least favorable results, from an irregular frequency response with various troughs and peaks, to a small dynamic range and low maximum dB SPL. The housing and audio circuitry of this particular microphone may have had a large part to play in this outcome. It is therefore concluded that the MEMS microphone will be used in future sensor development and will be further tested for its suitability as the acoustic sensor in the current project's remote sensing devices. The MEMS array tested in Section 2.3 does show a directional response at higher frequencies and will be investigated further in its proposed source localization application.

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