3D Sound Source Localization and Sound Mapping using a PU Sensor Array

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This article considers the application of an array of pressure and particle velocity sensors to acoustical source localization. This approach can remove a number of disadvantages of the traditional aeroacoustical testing methods because particle velocity sensors are sensitive to the angle of incidence of the incoming sound and whereas pressure sensors are not. Hence, pressure-particle velocity (p-u) arrays tend to have a sharper main lobe in the lower frequency range where the phase differences between pressure sensors are small. In the higher frequency range, phased pressure arrays tend to exhibit side-lobes due to aliasing if the sensor spacing is too large. This aliasing problem can be alleviated by using particle velocity sensors such that the sources do not need to be localized from phase differences alone. This article describes p-u based source localization techniques and the experimental validation of these techniques in an anechoic environment using 24 loudspeakers. Various configurations of sensors and source localization methods are studied. The spectra of the sources are determined for each of these cases and the results are compared to the actual spectra and to the determined spectrum using a phased pressure array, showing the advantages and limitations of this new approach.

I. Introduction

Particle velocity sensors have been used for acoustic source localization for many years in underwater acoustics[12], but the use of these sensors for source localization in air is a more recent development. With the invention of the Microflown sensor in 1994, acoustic particle velocity in air became a directly measurable quantity[2]. The Mircroflown sensor consists of two wires which are heated to 200°C above ambient temperature (see figure 1 – left and middle). As the air flows past, the upstream wire gives off some heat to the air such that the downstream wire is cooled less than the upstream wire. This difference in temperature causes a difference is measured by the electrical circuitry, making it possible to measure acoustical particle velocity.

Acoustic vector sensors were first applied to acoustic source localization in air by Raangs et al. in 2002[6], who used measured sound intensity vector to localize a single monopole source. The application of particle velocity sensors in near-field acoustic holography has been pioneered by Visser et al. in 2002[7]. They applied the inverse boundary element method (IBEM) to the particle velocity measurement data showed a noticeable increase in accuracy by means of simulations and experiments. Not much later, Jacobsen discovered the theoretical reason why the accuracy improves[8].

A more recent development is the application of acoustic vector sensors to the problem of localizing multiple sources in the far field. In 2009, Basten et al. applied the MUSIC method to localize up to two sources in using a single acoustic vector sensor[5]. In the same year Wind et al. applied the same method to localize up to four sources using two acoustic vector sensors[3,4]. This approach was further extended in[11], where simulation results of a method similar to DAMAS was compared to MUSIC.

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A different approach has been taken by Druyvesteyn et al, who used multiple frequencies to localize up to 3 sources based on only the particle velocity[9]. In unpublished research of these authors, it has been shown by means of simulation that up to 6 sources can be localized using only 4 channels, provided that the number of used frequencies is large enough.

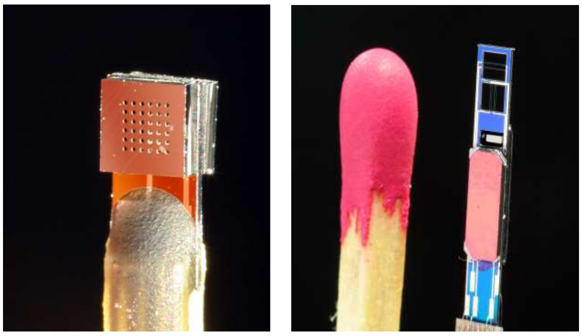

Figure 1. The Microflown sensor. *Left: Velocity sensor with a micro machined windshield. Right: A miniature version of an Acoustic Vector Sensor (AVS).*

This article considers methods to localize several stationary point sources. These methods have many applications and an example is acoustic airport monitoring. Pressure-based systems for this purpose are already on the market. Even for pressure based systems, null-steering methods such as MUSIC[3] make it possible to localize multiple sources using a much smaller number of sensors than the conventional beamforming method. However, even with these advanced processing techniques, pressure-based source localization methods tend to give inaccurate results in the low frequency regime, where the phase difference between the sensors is small and in the high frequency regime, where aliasing can cause ghost sources[3]. This problem can be avoided using particle velocity sensors[5]. For example, consider an acoustic vector sensor. It consists of three perpendicularly placed particle velocity sensors and a pressure sensor, all at the same location. The plane wave response of this sensor is frequency independent. Hence, the usable frequency range is not limited by the shape of the array, only by the frequency limitations of the sensors (20Hz-10kHz). The aim of this study is to gain a better understanding of acoustic source localization using p-u arrays. The opportunities and limitations of various arrays and various source localization techniques are discussed.

This article is built up as follows. Section II discusses the measurement setup and the arrays that are used and section III outlines the theoretical background of the source localization methods. Section IV compares the results of various arrays and methods for a single source and section V compares the ability of the arrays to distinguish a large number of sources. Source localization using a four channel pressure array is compared to source localization using a (four channel) AVS in section VI. Finally, conclusions are drawn in section VII.

II. Experimental Setup

Twenty-four loudspeakers are placed in the large anechoic room of TNO Science and Industry in Delft, the Netherlands. The sources are arranged in a cubic grid of 3x3x3 with a spacing of 1.2m (see figure 2). The center column of sources is left out to leave room for the sensors. Although the loudspeakers are positioned up to an accuracy of only 30mm, the locations are known more accurately because they are triangulated from distance measurements.

The loudspeakers produce white noise during the experiments. First, each of the loudspeakers is played separately. To be able to determine the number of sources that can be localized simultaneously, the number of sources is increased from one, to two, three, etcetera, until all twenty-four sources play uncorrelated white noise simultaneously. For each number of sources, a large number of source combinations are used to study the impact of the source locations on the ability to localize them.

Three p-u arrays are used. The first array consists of four acoustic vector sensors, of the type Microflown USP (see figures 3a and 3b (left)). The second array is the acoustic camera, which consists of twelve pressure sensors and twelve particle velocity transducers (see figures 3a and 3b (middle)). The third array consists of six pressure sensors and six particle velocity transducers. This setup is known as the velocity gradient setup (see figures 3a and 3b (right)).

Figure 2: Setup. *Twenty-four sources are arranged in a cubic grid of 3x3x3 loudspeakers, where the centre column of loudspeakers is left out.*

Figure 3a: Three P-U arrays. *Left: AVS quad. Middle: Acoustic Camera. Right: velocity gradient array.*

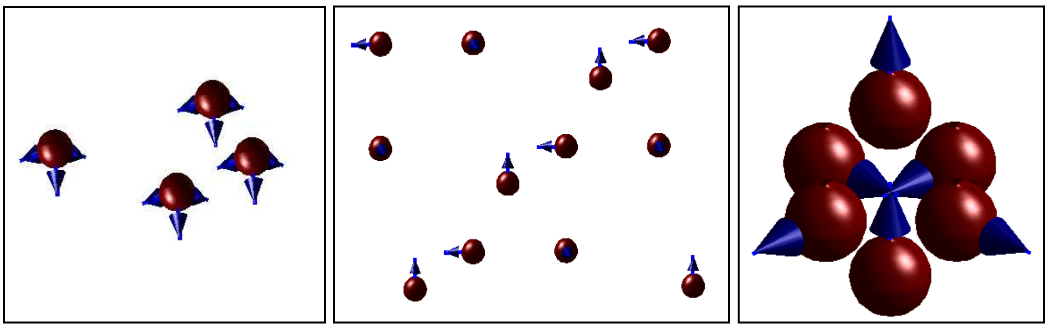

Figure 3b: Schematic drawing of the three P-U arrays. *Red sphere: pressure sensor, blue arrow: particle velocity sensor. Left: AVS quad. Middle: Acoustic Camera. Right: velocity gradient array.*

III. SOURCE LOCALIZATION METHODS

This article compares three source localization methods. Although each of them has a different theoretical and historical background, each of these methods has been used in aeroacoustics to determine source locations based on measurement data from a phased pressure array.

Conventional beamforming is the oldest source localization technique. This method is most widely used as a sound mapping technique: a method to determine the sound level at every source point. Nevertheless, the largest peak in the beamforming map is the *maximum likelihood estimator* of a single point source in the presence of white sensor noise. Although other source localization methods tend to yield a better separation between multiple sources, conventional beamforming is the most widely used because it is robust to noise and it is straight-forward to implement.

The second and third methods are both known as *adaptive* beamforming methods. The second method is the Minimum Variance Method, also known as the Capon method. It yields a much clearer beamforming map if the sources are uncorrelated point sources at a decreased robustness against white noise[1]. The third method is the MUSIC method, which was developed by Schmidt[10]. Its mathematical formulation is similar to the Minimum Variance Method but its ‘beamforming map’, termed the MUSIC spectrum, contains peaks with infinite height if noise is absent. A disadvantage of the MUSIC method is that the number of sources must be known before source localization can take place.

Each of these methods follows from theoretical considerations. An excellent summary of the theory underlying these methods is given in by Johnson and Dudgeon[1] but a brief explanation of the equations used for this article is given in the appendix of this article.

IV. LOCALIZATION OF A SINGLE SOURCE

This section compares the accuracy of various source localization methods for three sensor configurations. The measurement data is base on white noise from a single loudspeaker. An important new aspect of this article is the fact that the methods are applied to the sensor grid positions which have been measured using laser distance meters, but also to sensor positions which have been determined using sound from known loudspeaker locations[13]. To be able to make a fair comparison, the loudspeaker used in this section has not been used to determine the location of the sensors.

Figure 4 depicts the response of all four methods to a single point source. It can be seen that the Capon method, MUSIC and the Eigenvalue method lead to almost indistinguishable results and an angle error between 0.6 and 2.8 degrees. Conventional beamforming behaves differently. It exhibits side lobes and the error is 3.7 degrees. Further study has shown that the Capon method, MUSIC and the Eigenvalue method give similar results for any number of sources and for all setups, because their underlying formulations are very similar. The Capon method is the most attractive because it does not require prior knowledge of the number of sources. Hence the Capon method will be compared to the widely used conventional beamforming method in the rest of this section.

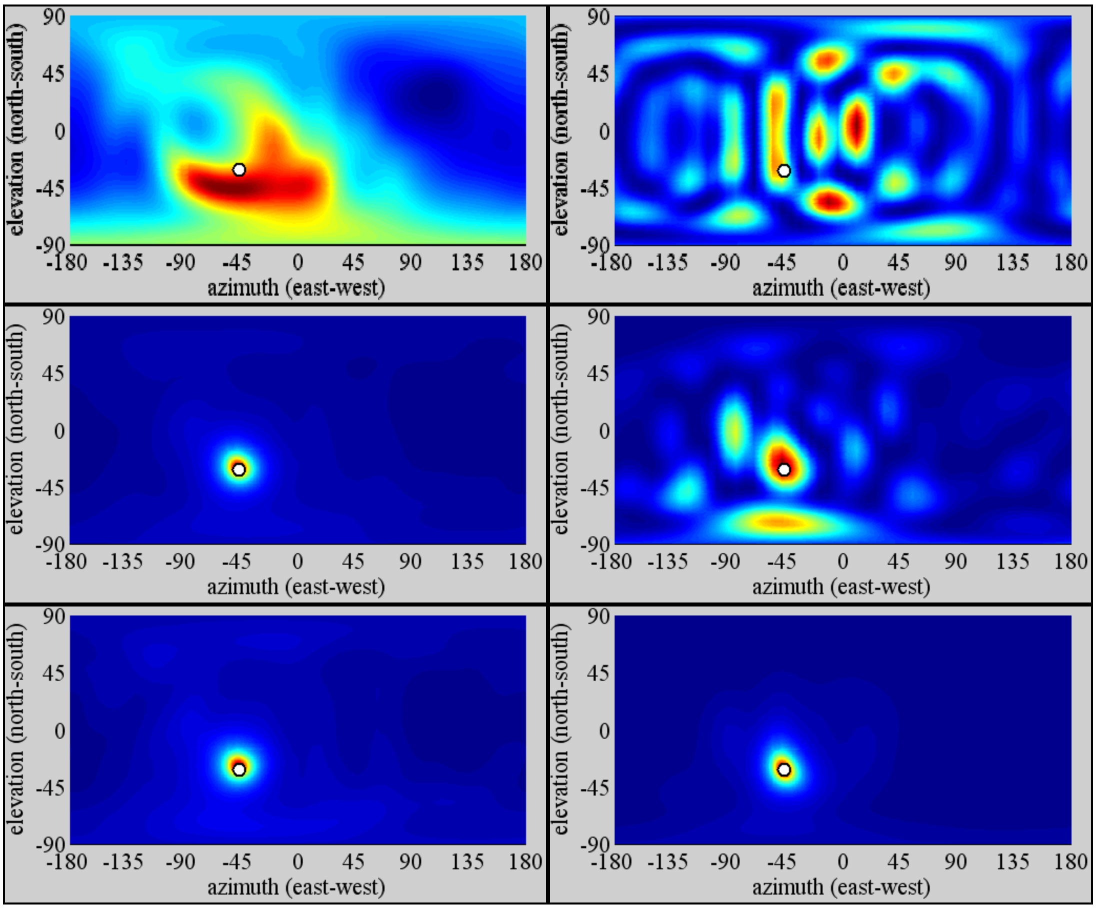

Figure 4: Localization of a single source using the AVS Quad (100-5000Hz). *Left top: Capon using the sensor grid positions. Right top: Conventional beamforming using the sensor grid positions. Left middle: Capon using localized sensors, error 1.2°. Right middle: Conventional beamforming using localized sensors, error 3.7°. Left bottom: Eigenvalue method, error 2.8°. Right bottom: MUSIC error 0.6°. The true source position is depicted by the small white circle.*

Figure 5 depicts the results of the velocity gradient setup. At 2.2 degrees, the error of the Capon method is roughly the same as the error of the AVS Quad. Due to the smaller size of the array, the peaks of both the Capon method and conventional beamforming are less sharp. This is an indication that its spatial resolution is limited if multiple sources are present.

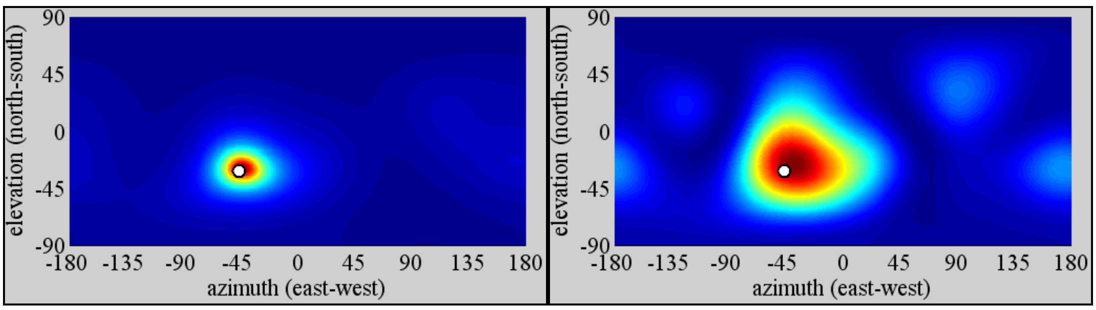

Figure 5: Localization of a single source using the velocity gradient setup (localized sensors). *Left: Capon, error 2.2°. Right: Conventional beamforming, error 8.3°.*

The final setup is the acoustic camera. Its results are depicted in figure 6. Although the angle error of the Capon method is only 1.6 degrees, the peak is more smeared out than it is in the case of the AVS quad and large side lobes occur for conventional beamforming. This problem is caused by some particle velocity sensors which have been localized inaccurately. By using the measured sensor locations instead of the localized locations, the peak is made sharp and the angle error becomes 0.4 degrees (see figure 6).

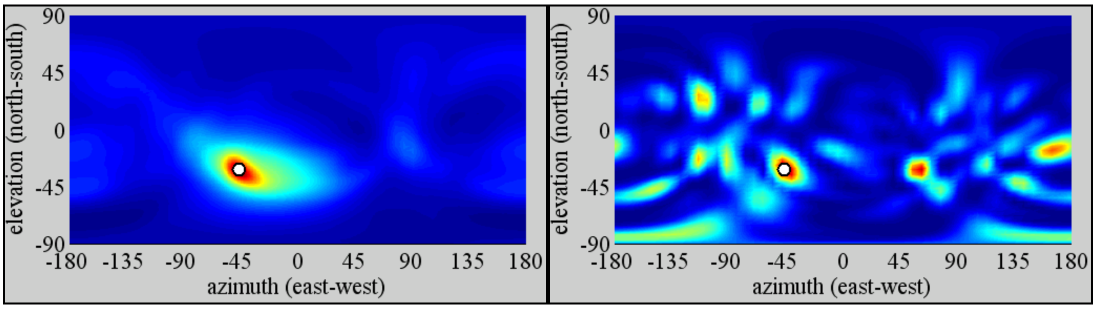

Figure 6a: Localization of a single source using the acoustic camera (localized sensors). *Left: Capon, error 1.6°. Right: Conventional beamforming, error 0.6°.*

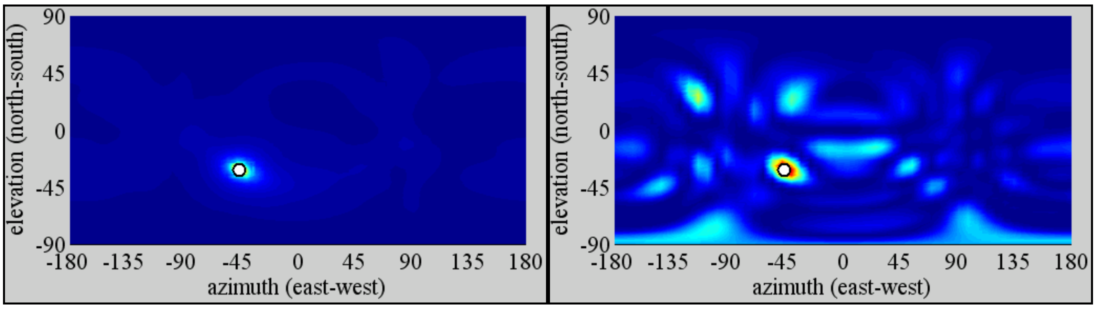

Figure 6b: Localization of a single source using the acoustic camera (sensor grid positions). *Left: Capon, error 1.0°. Right: Conventional beamforming, error 0.6°.*

Given the results of all considered methods and arrays, it is concluded that the Capon method has proven to have the most practical advantages because its results are clearer and often more accurate than the conventional beamforming method. The Eigenvalue and MUSIC methods have a similar accuracy but these methods require knowledge of the number of sources whereas the Capon method does not.

The use of sensor grid locations lead to bad results for the AVS quad but localized sensors lead to bad results for the acoustic camera. Detailed conclusions and recommendations can be found in[13]. In the next sections, localized sensors are used for the AVS quad and the velocity gradient setup. Sensor grid locations are used for the acoustic camera.

V. LOCALIZATION OF MULTIPLE SOURCES

This section studies the number of sources that can be localized using the different setups, and it is a continuation of the earlier papers by the authors[3,5]. The Capon method has been used in all cases and the frequency range is 100-5000Hz. Figure 7 depicts the results of the AVS quad. All seven sources are localized with an error below 4.5 degrees. In the case of twelve sources, there are no misrecognitions: each of the eleven local minima corresponds to a source. However, the two sources at an azimuth of 135 degrees yield a single, local maximum. If more sources are added, more sources are detected as a single ridge in the response.

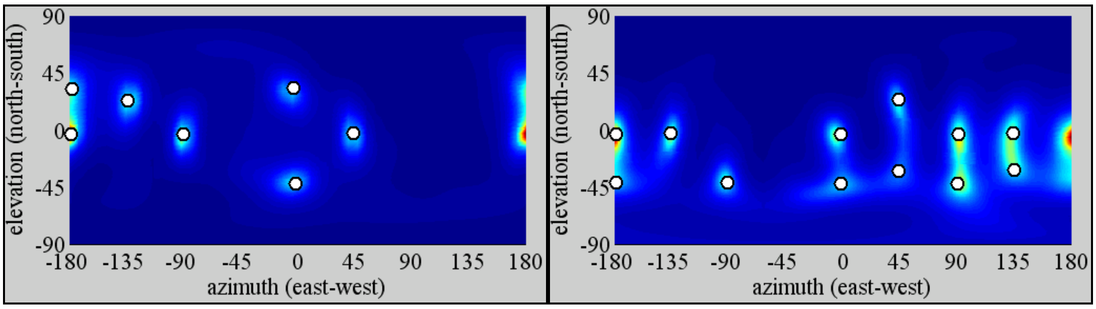

Figure 7: AVS Quad (localized sensors). *Localization of multiple sources using the Capon method (100-5000Hz). Left: seven sources. Right: twelve sources.*

The results of the acoustic camera are depicted in figure 8. Each of the seven sources is located with an error below 4.5 degrees. In the case of twelve sources, the top source at 135 degrees azimuth and 0 degrees elevation is not detected. There is a local maximum for all other sources but the errors can be as large as 10 degrees.

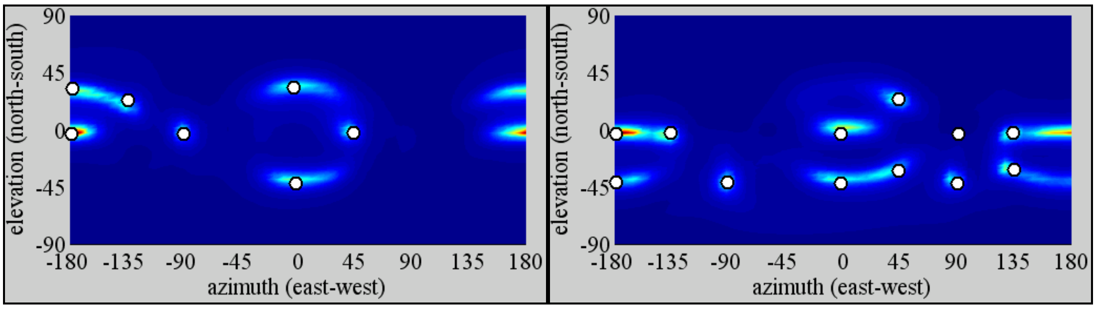

Figure 8: Acoustic camera: localization of multiple sources using the Capon method (100-5000Hz). *Left: seven sources. Right: twelve sources.*

The results of the velocity gradient setup are depicted in figure 9. Due to the smaller size and the smaller number of sensors of this array, the velocity gradient setup yields broader peaks than the other arrays. Six of the seven sources are localized within 5 degrees. The source at -180 degrees azimuth and 40 degrees elevation is not detected at all. In the case of 20 sources, all that can be said with any certainty is that there are no sources at an elevation above 45 degrees and that there are no sources below an elevation below -45 degrees.

Given the results presented in this section, it can be concluded that 7 sources have been localized at an accuracy of 4.5 degrees using the AVS quad and the acoustic camera. The velocity gradient setup struggles with this large number of sources and detects only six of the seven sources.

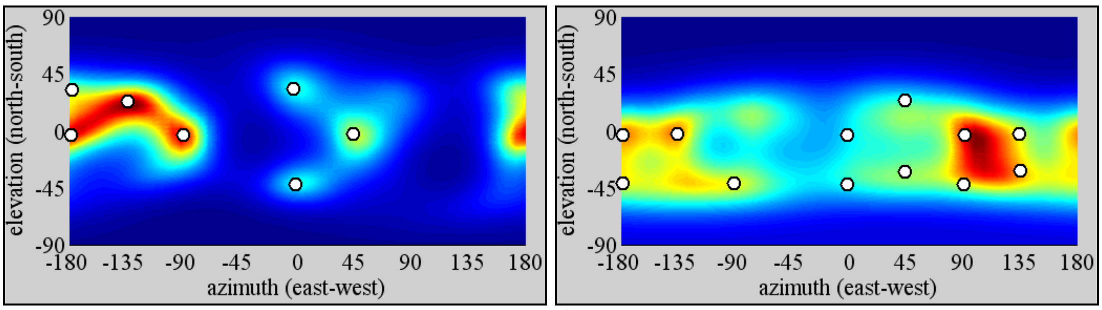

Figure 9: Velocity gradient setup. *Localization of multiple sources using the Capon method (100-5000Hz). Left: seven sources. Right: twelve sources.*

VI. COMPARISON BETWEEN P AND P-U BASED SOURCE LOCALIZATION

This section compares source localization using a pressure-based array with an acoustic vector sensor (AVS). By using only the four pressure elements of the AVS quad, we arrive at a four-element pressure array. This array is compared to a single AVS, which also consists of four channels: three particle velocity elements and one pressure element.

The response of an AVS to a plane wave is completely frequency independent, whereas the response of a pressure array consists of frequency-dependent phase differences. This can be a disadvantage for pressure-based source localization. In the low frequency range (200-300Hz for the current array), these delays are such small that small errors in the measurement data cause large errors in the detected source location. An example is given in figure 10 where pressure-based source localization yields an error of 18 degrees whereas AVS-based source localization yields 8 degrees. In the mid-frequency range, both approaches work well (see figure 11), but in the high frequency range (9000-9300Hz) aliasing occurs for the pressure-based source localization method. The AVS-based method does not exhibit aliasing. Although the error is large in this case (21 degrees), there are no peaks at the wrong locations.

Figure 13 depicts the results of source localization for two sources for the low frequency range. This result clearly shows that the two peaks can be distinguished using a single acoustic vector sensor whereas the pressure-based array only yields a single peak.

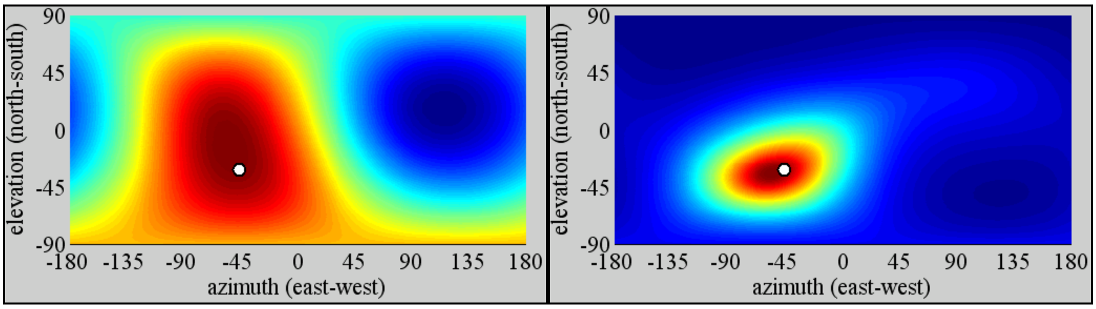

Figure 10: Comparison between a pressure array (left) and an AVS (right) in the low frequency range (200-300Hz). *Capon method.*

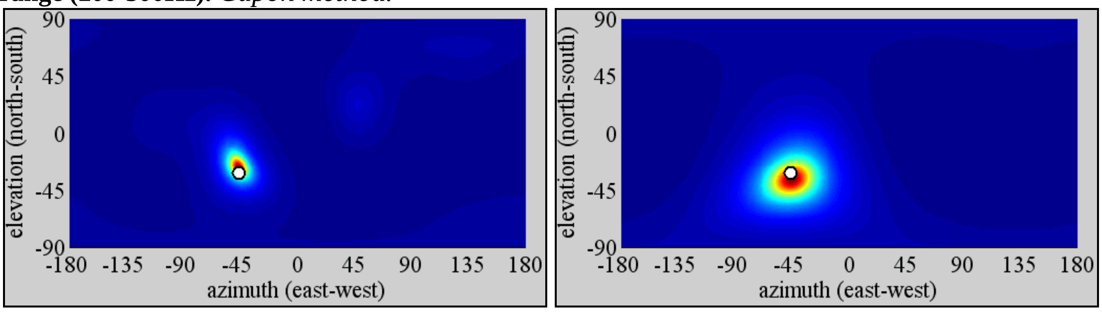

Figure 11: Comparison between a pressure array (left) and an AVS (right) in the mid frequency range (2100-2300Hz). *Capon method.*

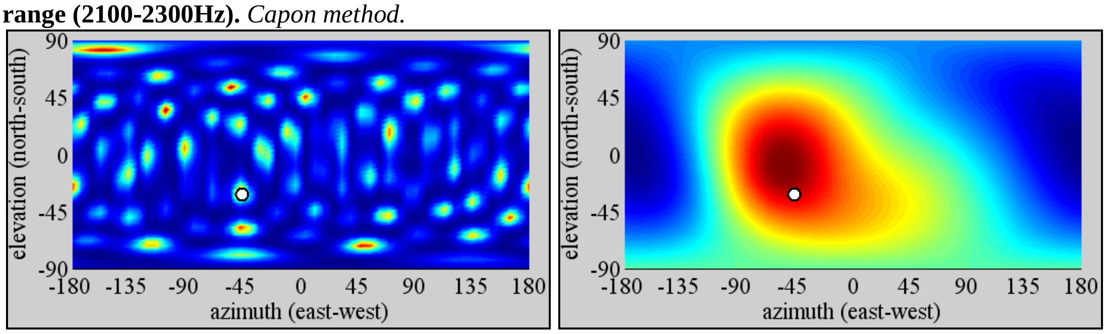

Figure 12: Comparison between a pressure array (left) and an AVS (right) in the high frequency range (9000-9300Hz). *Capon method.*

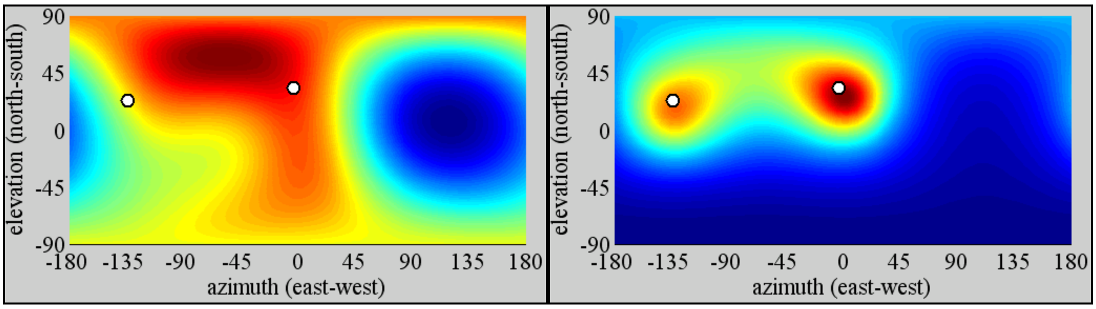

Figure 13: Comparison between a pressure array (left) and an AVS (right) in the low frequency range (200-300 Hz) for two sources. *Capon method.*

VII. CONCLUSION

This article considers acoustic source localization based on an array of pressure and particle velocity sensors. Using an experimental setup of 24 loudspeakers in an anechoic chamber, three array types and four source localization methods have been compared, for various numbers of uncorrelated sources and in multiple frequency ranges.

Three of the four source localization methods give similar results: the Eigenvalue method, MUSIC and the Capon method. The fourth method, conventional beamforming, has shown to yield broader peaks and inaccurate source locations. The Capon method, also known as the Minimum Variance method, is considered the most attractive because it yields accurate results and it does not require prior knowledge of the number of sources.

Of the three arrays, the 140mm diameter USP quad has proven to give the best results. The results are better than the velocity gradient setup, which is smaller and has redundancies. The USP quad is also considered more attractive than the acoustic camera, which requires more space and more channels.

A few examples of the differences between AVS-based source localization and pressure-based source localization have been presented in section 6. Although both methods yield accurate results in the mid frequency range, AVS-based source localization remains accurate in the low frequency range and it does not exhibit aliasing in the high frequency range. A clear example of this property is given in figure 13, where it is shown that a 4 channel microphone array cannot distinguish two sources whereas a 4 channel AVS can.

APPENDIX

This appendix lists the mathematical expressions used for source localization. Where possible, we conform to Johnson and Dudgeon for notation and nomenclature[3] because each of these source localization methods are thoroughly described in their book. The expression for conventional beamforming in the frequency domain is widely known. Let the measurement data be denoted as $\mathbf{y}(\omega)$ and let the modelled response of the array to sound coming from location $\boldsymbol{\zeta}$ be denoted as $\mathbf{s}(\boldsymbol{\zeta},\omega)$, then the beamforming map $Q(\boldsymbol{\zeta},\omega)$ is expressed as follows.

$$(1)\quad Q_B(\zeta,\omega)^2 = \left|\frac{\mathbf{s}(\zeta,\omega)'\mathbf{y}(\omega)}{\mathbf{s}(\zeta,\omega)'\mathbf{s}(\zeta,\omega)}\right|^2$$

For broadband signals, the response is integrated over the frequency range.

$$(2)\quad P_B(\zeta) = \int_W Q_B(\zeta,\omega)^2\, d\omega$$

Where W is the frequency band of interest. An alternative to conventional beamforming is the Minimum Variance Method, also known as the Capon method, which yields much sharper peaks at the source locations. This makes it possible to locate multiple sources accurately. Defining the spectral matrix $\mathbf{S}$ of the measurement data is

$$(3)\quad \mathbf{S}(\omega) = E\left(\mathbf{y}(\omega)\mathbf{y}(\omega)'\right)$$

Where E denotes the expected value. The response of the Minimum Variance Method can be expressed as

$$(4)\ \ Q_{MVM}(\zeta,\omega)^2 = \left(\mathbf{s}(\zeta,\omega)'\mathbf{S}(\omega)^{-1}\mathbf{s}(\zeta,\omega)\right)^{-1}$$

In this article, the response is not directly integrated over the source directly but determined as follows.

$$(5)\ \ P_{MVM}(\zeta) = \left(\int_W \frac{1}{Q_{MVM}(\zeta,\omega)^2}\,d\omega\right)^{-1}$$

Although the authors are not aware of the mathematical foundation of this equation, it has proven to improve the accuracy compared to direct integration of the response. The third method that is used in this article is the MUSIC method. Originally developed by Schmidt, this method requires knowledge of the number of sources *n.* A mathematical expression for the method is

$$(6)\ \ Q_{MUSIC}(\zeta)^2 = \left(\mathbf{s}(\zeta)^H\mathbf{Q}\mathbf{s}(\zeta)\right)^{-1} \quad ; \quad \mathbf{Q} = \sum_{i=n+1}^{N} v_i v_i^H$$

Where N is the number of sensors and v_i is the i^{th} eigenvector of **S**. For the broadband case, it is also written as

$$(7)\ \ P_{MUSIC}(\zeta) = \left(\int_W \frac{1}{Q_{MUSIC}(\zeta,\omega)^2}\,d\omega\right)^{-1}$$

The final method is the eigenvalue method. Its formulation is similar to the formulation of MUSIC, and identical if the noise is white. It is given by

$$(8)\ \ Q_{Eigenvalue}(\zeta)^2 = \left(\mathbf{s}(\zeta)^H\mathbf{Q}\mathbf{s}(\zeta)\right)^{-1} \quad ; \quad \mathbf{Q} = \sum_{i=n+1}^{N} \lambda_i^{-1} v_i v_i^H$$

Where λ_i denotes the i^{th} eigenvalue of **S.**

$$(9)\ \ P_{eigenvalue}(\zeta) = \left(\int_W \frac{1}{Q_{eigenvalue}(\zeta,\omega)^2}\,d\omega\right)^{-1}$$

This concludes the list of all formulations used for source localization in this article.

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