BeBeC-2020-S10

CONTINUOUS-SCAN BEAMFORMING FOR IDENTIFICATION OF HIGHLY VARYING AMPLITUDE SOURCES WITH LOW SENSOR BUDGETS

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ABSTRACT

Continuous-scan beamforming (CSBF) is a technique that can improve array performance without increasing the physical number of sensors by employing virtual sensors. Previous CSBF studies have demonstrated the capability to perform high-resolution delay-and-sum (DAS) mapping of acoustic sources and identify almost an 18 dB difference in source level, which is not possible using conventional beamforming with an equal sensor budget. The current work further investigated the capability of CSBF by (1) conducting source localization with significantly reduced sensor budgets, (2) evaluating the effect of the number of partial fields obtained by reference sensors, and (3) combining CSBF with CLEAN-SC for further enhancement of source localization. Results based on a four-speaker noise test showed that CSBF using a low sensor budget (13 sensors) can perform identification of the locations and levels of multiple sources and can provide an accurate input to CLEAN-SC for further enhancement of the source map.

1 INTRODUCTION

Continuous-scan (CS) measurement is a technology that performs beamforming by employing continuously moving sensors tied to fixed reference sensors. CS technology has demonstrated the capability to improve array performance without increasing the physical number of sensors [1]–[3] by using fixed reference sensors and partitioning the time data acquired by continuously moving sensors with the goal of setting up virtual sensors.

In a recent study [2], the capability of CS technology was demonstrated using a four-source experiment in which the quietest source was 18 dB lower than the dominant source. The CS beamforming identified all four source locations and relative levels accurately. In this work, the capability of the CS technology has been further investigated with the goal of identifying the following characteristics:

1. Performance of CS beamforming using limited sensor budgets
2. Effect of varying the number of partial fields obtained by reference microphones
3. Performance of CS beamforming combined with CLEAN-SC

2 EQUIPMENT AND METHODS

2.1 Sixty-Channel Rotating Microphone Array

A sixty-channel rotating array used for continuous-scan beamforming (CSBF) is shown in Fig. 1. Low-cost microphones that were used in the proof-of-concept array in previous work [1] were used in this rotating array [2]. The center gearbox/motor assembly rotates the array in the counterclockwise direction when viewed from the front. This figure also shows the eight reference microphones used to acquire data at fixed positions for phase referencing. Note that the reference sensors are only used for phase referencing in the process of setting up virtual sensors in multireference CSBF (MRCSBF) and are not used in actual beamforming calculations. The right side of the figure shows the positions of the sixty microphones and the traces of all of them when one complete revolution is made. Each microphone has a different radial distance from the array center so that with one revolution the array can simulate a nearly complete 2-dimensional aperture.

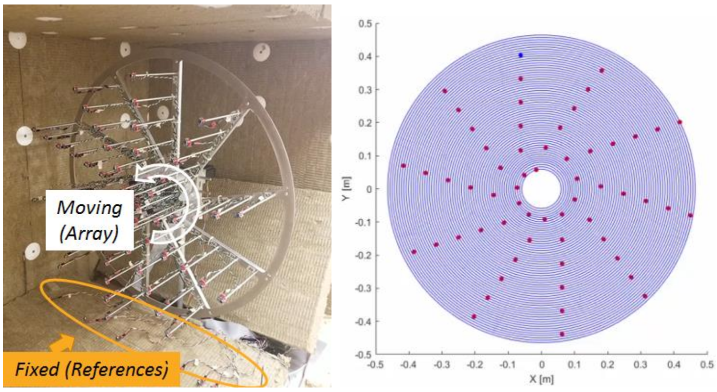

Fig. 1. Left: the manufactured array employing the moving and fixed sensors for CS measurements. Right: microphone locations at the beginning (red dots) and their traces with one rotation (blue lines).

2.2 Continuous-Scan Beamforming Methods

Conventional delay-and-sum (DAS) beamforming using sensors fixed in space (referred to as fixed receiver beamforming [FRBF] in this work) attempts to describe the source distributions, q_i, by “steering” the measured pressure signals, p_n, to account for the spherical decay and difference in reception time. The array output time history, $f_i(\vec{x}_i, t)$, on a source sphere of radius r_s originating at $\vec{x}_i$ is given by

$$f_i(\vec{x}_i, t) = \frac{1}{N}\sum_{n=1}^{N} \frac{l_{in}}{r_s} p_n(t + \tau_{in}), \tag{1}$$

where l_{in} and τ_{in} are the propagation length and retarded time from the ith source to the nth sensor. In the CSBF method, as opposed to FRBF, the sensors are allowed to move in a prescribed motion, and the trajectories of each sensor must be known precisely, such that

$$f_i(\vec{x}_i, t) = \frac{1}{N}\sum_{n=1}^{N} \frac{l_{in}\left(\vec{x}_i, \vec{\xi}_n(t)\right)}{r_s} p_n(t + \tau_{in}(\vec{x}_i, \vec{\xi}_n(t))), \tag{2}$$

where $\vec{\xi}_n(t)$ is the trajectory of the nth microphone. Similar to CSBF, the MRCSBF method employs N moving sensors; the main difference is that it employs an additional M fixed reference sensors. The primary use of the reference sensors is to perform phase referencing of the moving sensors in order to set up virtual sensors for subsequent beamforming calculations, thus improving the array performance without physically increasing the sensor count. The process of MRCSBF is briefly summarized as follows:

1) The overall spectral matrix of $M \times M$ of the reference sensors is computed over the entire duration and used as a datum for phase referencing.
2) CS time histories measured by the moving sensors are divided into K segments with the array assumed to reside at the segment midpoint (overlap can be used).
3) A transfer function matrix between the reference and CS sensors is computed for each scan sector, and based on the transfer function, the scan sectors are stitched together, providing $N \times K$ virtual sensors. The overall size cross-spectral matrix $\tilde{G}_{pp'}$ of the virtual sensors is therefore $(N \times K) \times (N \times K)$.
4) The high-resolution virtual array is projected back to the source plane using conventional DAS in the frequency domain.

3 EXPERIMENTAL SETUP

The performance of CS-based beamforming techniques was evaluated using a four-speaker test setup inside a soundproof chamber, as shown in Fig. 2. The array was placed 1.1 m away from the speaker source plane. A white-noise input was given to each speaker, and the inputs to speakers 2, 3, and 4 were reduced by −6 dB, −12 dB, and −18 dB, respectively, relative to speaker 1. See Lee et al. [2] for more details of the test configuration and data processing settings.

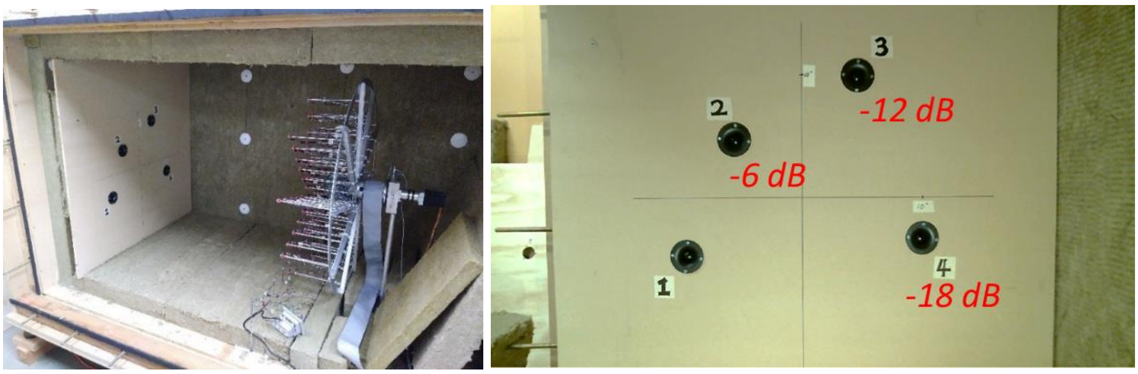

Fig. 2. Four-speaker test setup in ATA Engineering's soundproof chamber (left) and input levels of speakers 2, 3, and 4 relative to speaker 1 (right).

4 RESULTS

4.1 Low Sensor Budget Case

The localization results of the four-speaker measurement at 5 kHz from previous work is shown in Fig. 3. It is included here as a reference to show the virtual array setup by rotating a sixty-channel array as well as to show the comparison between FRBF and MRCSBF. There were 39 scan partitions used, which resulted in a virtual array sensor count of 2340 (60 microphones times 39 scan partitions). In the FRBF case, only the two loudest sources were detectable; other sources could not be identified due to the presence of side lobes (note that the contour scale is 20 dB). MRCSBF detected all four source locations and relative output levels of the speakers accurately.

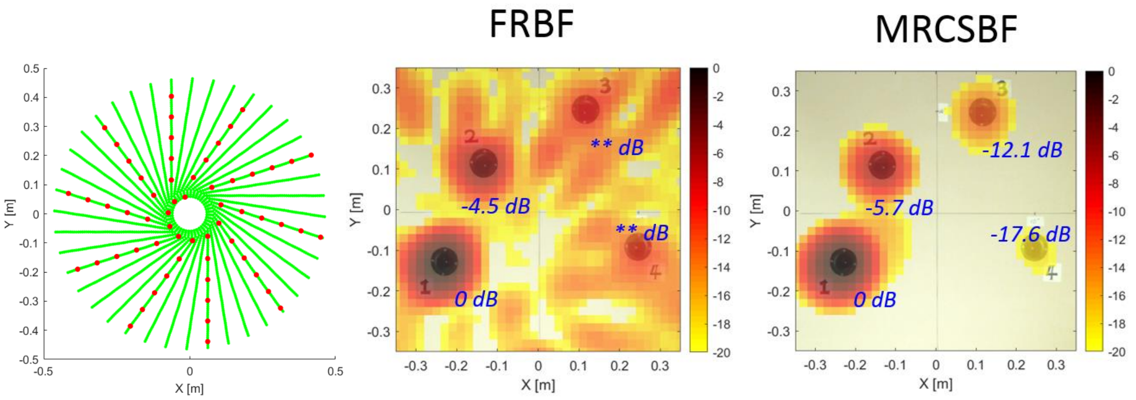

Fig. 3. Four-speaker experiment with varying amplitudes. Source localization at 5 kHz with Δf = 128 Hz.

To evaluate the performance of MRCSBF with a limited sensor budget, a case with thirteen microphones (five moving and eight reference) was set up. The 195-microphone virtual array produced by the five moving microphones and 39 scan partitions is shown in Fig. 4 (left). For comparison, the same sensor budget was used for FRBF. As shown, even with only thirteen physical microphones, MRCSBF obtains reasonably well resolved source locations and levels, whereas in the FRBF case, the sources could not be identified due to high levels of side lobes when the same 20 dB contour scale is used.

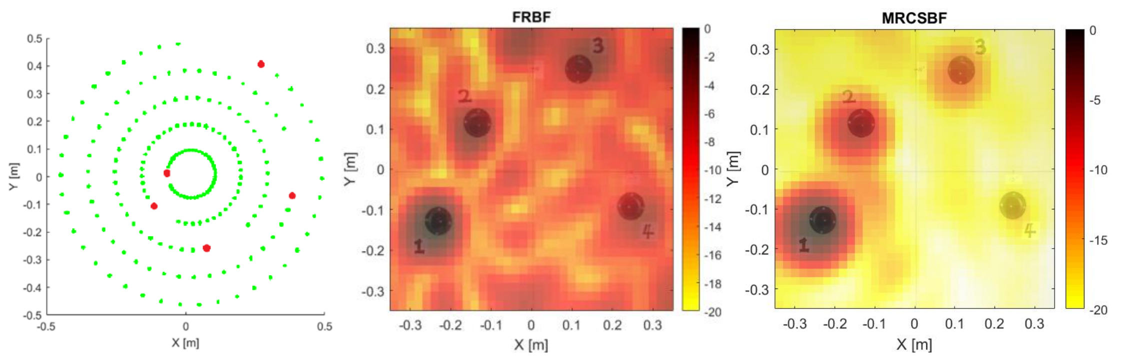

Fig. 4: Left: 195-microphone virtual array set up by five moving microphones (red dots). Center: FRBF with a total of thirteen microphones. Right: MRCSBF with five moving and eight reference microphone. Source localization at 5 kHz with Δf = 128 Hz.

4.2 Number of Partial Fields Using Reference Microphones

For MRCSBF, the role of the reference microphones is critical to maintaining accurate phase information when setting up virtual sensors. Using transfer matrices between moving and stationary sensors, the system is able to sew together partial fields of the sound sources. Each partial field is a fully phase-coherent sounds field, and the total number of partial fields that can be recovered is determined by the number of reference microphones. Generally, the choice of the number of reference microphones to use depends on the number of incoherent sources to be identified (see, e.g., [4], [5]). To evaluate how results change depending on the number of partial fields used, a case with fifteen moving microphones was set up, and results were obtained by varying the number of partial fields incoherently summed from eight to four to two to one, while keeping the processing parameters and the number of moving microphones the same. The virtual array created by fifteen moving microphones and eight reference microphones (not shown) is shown in Fig. 5.

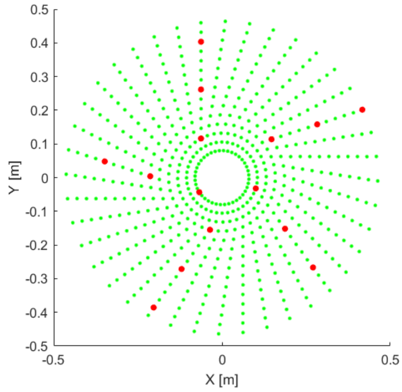

Fig. 5: 300-microphone virtual array (green dots) set up by fifteen moving microphones (red dots) and eight reference microphones (not shown). Three-hundred virtual microphones are generated by fifteen moving microphones × twenty scan partitions.

The results of four MRCSBF cases with different numbers of partial fields are shown in Fig. 6. The eight- and four-partial-field cases show comparable results, suggesting that having as many partial fields (or reference microphones) as there are incoherent sources is a reasonable minimum threshold. The one- and two-partial-field cases clearly show that the number of sources identified strongly depends on the number of partial fields sewed together. This dependence is fundamentally due to the ability to accurately reconstruct a virtual cross-spectral matrix, which is the starting point for DAS.

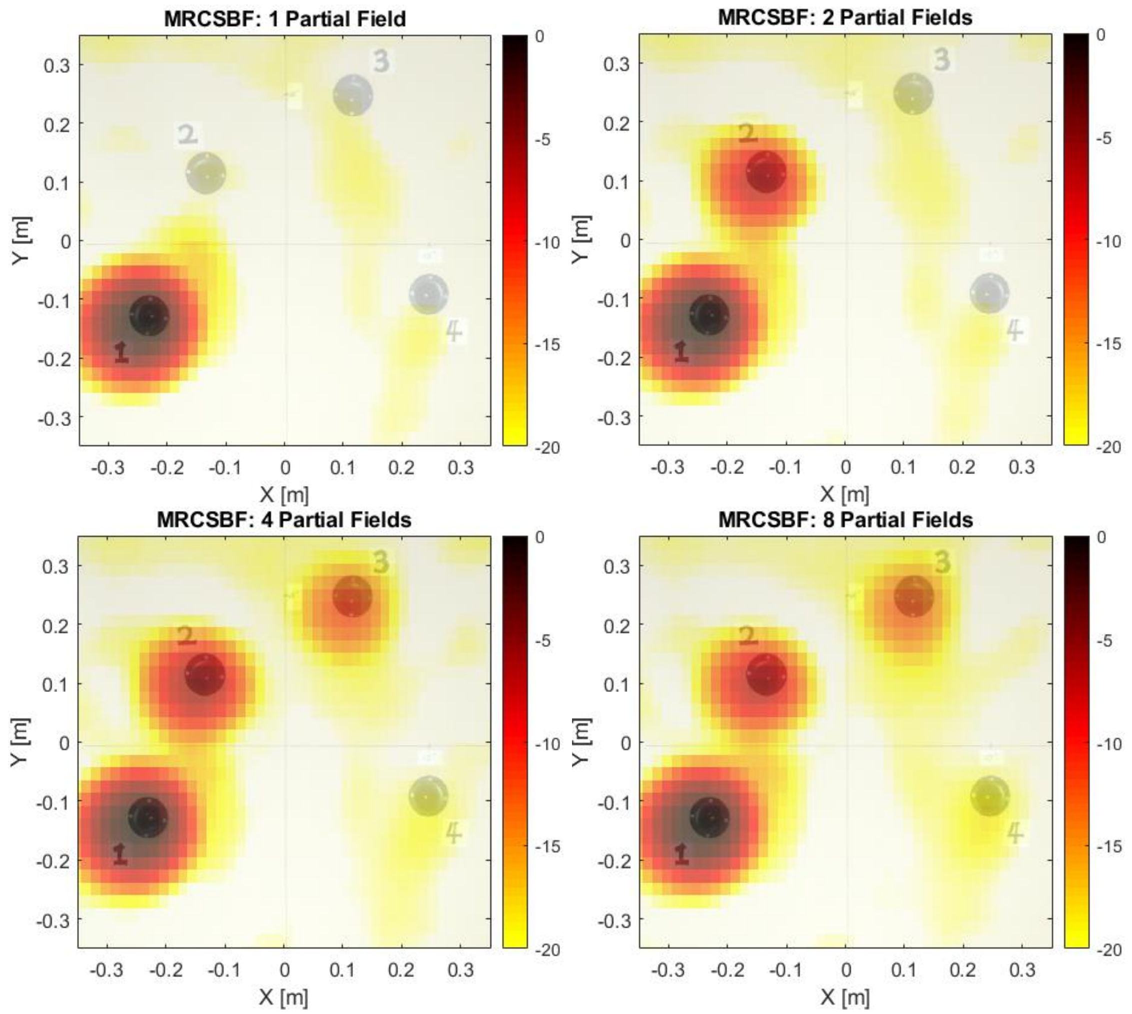

Fig. 6: MRCSBF cases with 1, 2, 4, and 8 partial fields at 5 kHz with Δf = 128 Hz.

4.3 MRCSBF with CLEAN-SC

CLEAN-SC [6] was employed to further improve the source map generated by MRCSBF. To compare FRBF and MRCSBF when used with CLEAN-SC, three cases employing different numbers—sixty, fifteen, and five— of moving microphones were considered. The results of FRBF and MRCSBF where each method is further processed using CLEAN-SC are shown in Fig. 7 to Fig. 9. As shown in Fig. 7, using 60 moving microphones, FRBF and MRCSBF results show comparable performance: the source locations and amplitudes of all four speakers are well identified. When the number of microphones is decreased to fifteen (Fig. 8), FRBF does not produce a clean source map, and thus subsequent CLEAN-SC results show erroneous source locations and amplitudes. By comparison, the results of MRCSBF and CLEAN-SC show that the source locations and amplitudes are still well identified.

Finally, the results of the five-moving-microphones case (Fig. 9) demonstrate the capability of MRCSBF to identify source amplitudes and locations even in a situation where the number of sensors available is extremely low and thus conventional beamforming results are unusable. Note that in the bottom right of Fig. 9, the quietest source identified has an amplitude of −22 dB, which is about 4 dB lower than the input level. This is considered to be due to the fact that MRCSBF did not clearly identify the quietest source, as shown in the bottom center of Fig. 9. Further improvement may be possible by selecting the five microphone locations optimized to a certain frequency range, which will be examined in future studies.

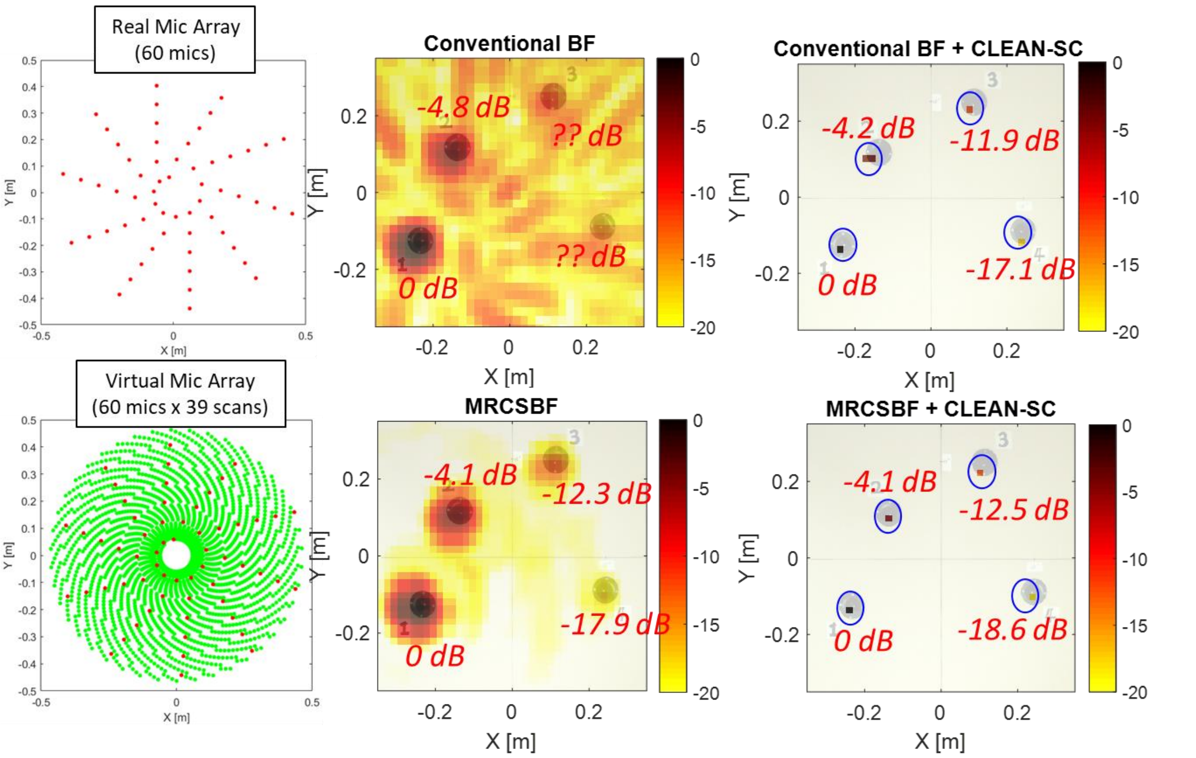

Fig. 7: Sixty-microphone conventional BF (FRBF) vs. MRCSBF cases along with CLEAN-SC at 5 kHz with Δf = 128 Hz, using 2340 virtual microphones set up by 60 moving microphones times 39 scan sectors.

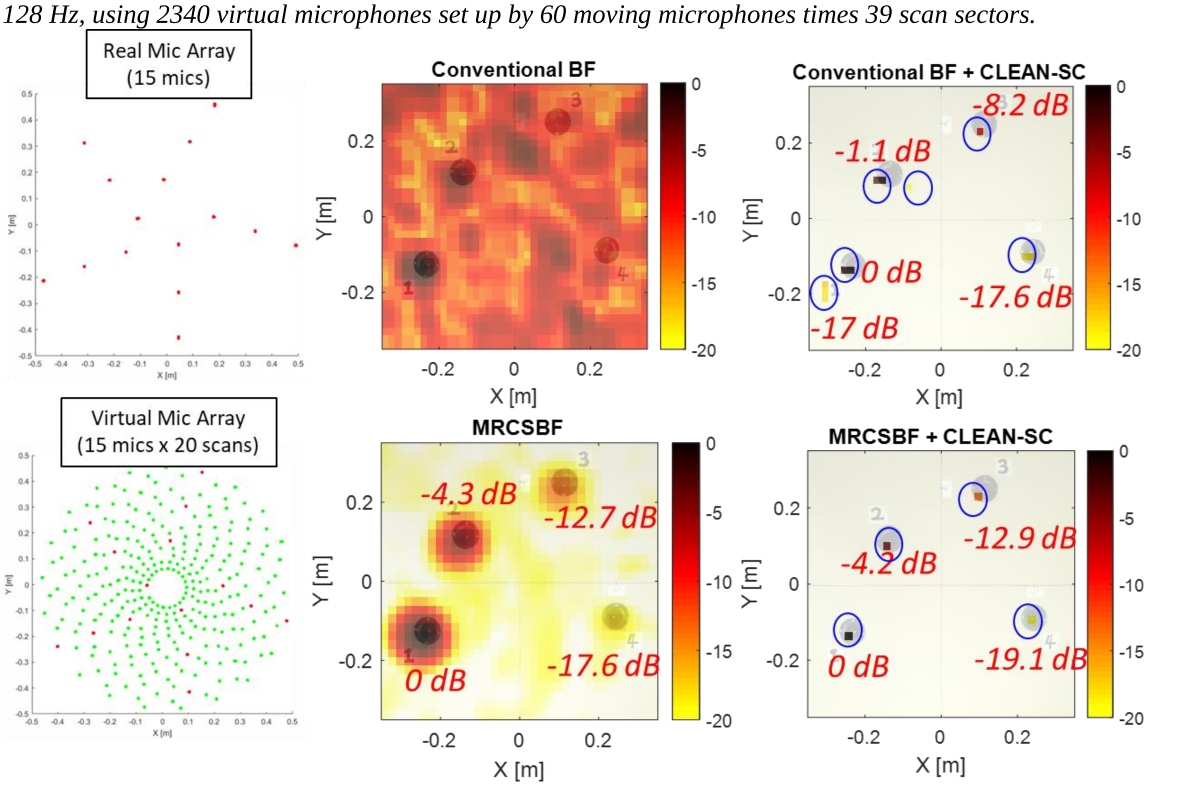

Fig. 8: Fifteen-microphone conventional BF (FRBF) vs. MRCSBF cases along with CLEAN-SC at 5 kHz with Δf = 128 Hz, using 300 virtual microphones set up by 15 moving microphones times 20 scan sectors.

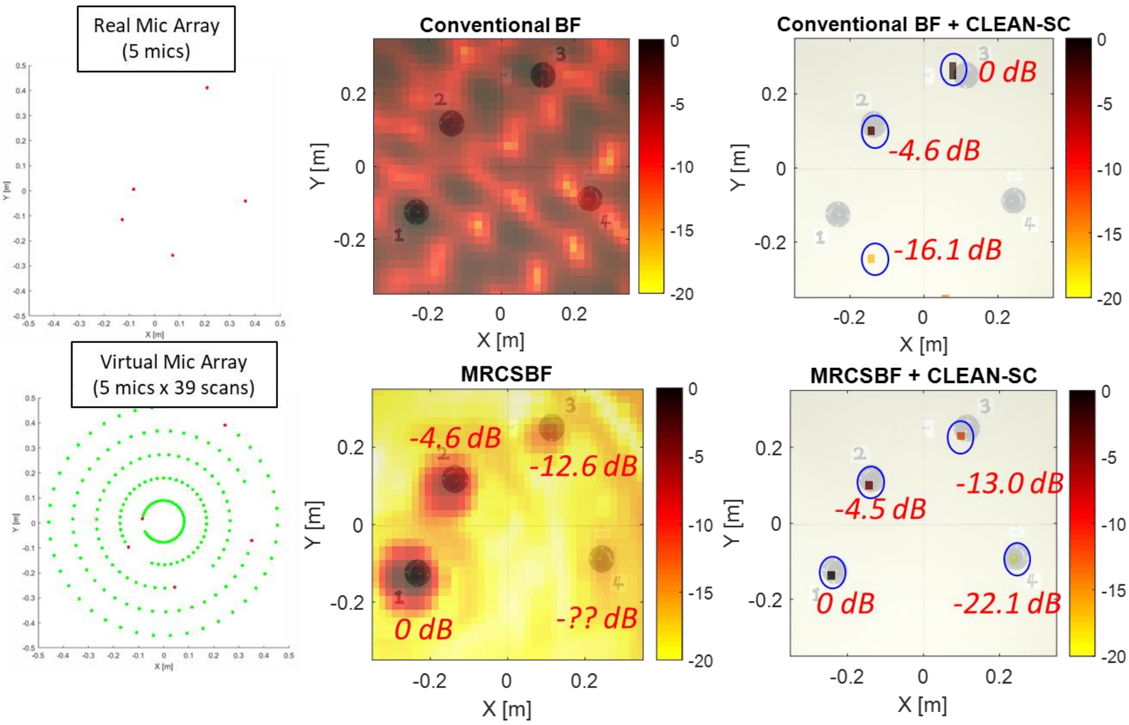

Fig. 9: Five-microphone conventional BF (FRBF) vs. MRCSBF cases along with CLEAN-SC at 5 kHz with Δf = 128 Hz, using 195 virtual microphones set up by 5 moving microphones times 39 scan sectors.

5 CONCLUSIONS

In this work, the capability of the CS beamforming (i.e., MRCSBF) technology was investigated using low sensor budgets that are not adequate for conventional beamforming. Even with a sensor budget of thirteen microphones (five moving and eight reference), MRCSBF was capable of identifying multiples acoustic sources of varying amplitude levels. The requirement on the minimum number of reference microphones was also investigated by evaluating the MRCSBF source map results generated by sewing together different number of partial fields; this investigation confirmed that the number of reference microphones needed generally depends on the number of incoherent sources to be identified. Combined with CLEAN-SC, further improvement was possible, and results showed that all source levels and amplitudes were reasonably well identified.

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