VARIATIONS IN SIGNAL PHASE AND BEAMFORMER GAIN DUE TO BUBBLE SCATTERING

R. Lee Culver[a], J. Daniel Park[a], Timothy G. Leighton[b], and David G. H. Coles[b]

[a]Applied Research Lab, Penn State University, PO Box 30, State College, PA 16804
[b]Institute of Sound and Vibration Research, University of Southampton, Highfield, UK S017 1BJ

Contact Author: R. Lee Culver, Applied Research Laboratory, The Pennsylvania State University, PO Box 30, State College, PA USA 16804, Tel. 814 865-3383, Fax. 814 863-1841, rlc5@psu.edu

Abstract: *We have investigated experimentally variations in the phase of acoustic signals propagating through bubble clouds and received at a three-element hydrophone array. The effect of bubbles in water to attenuate acoustic signals is well known, but the interest here is on the phase variation across the array introduced by bubble scattering, potentially decorrelating the signals across the array and reducing the gain that can be achieved by a beamformer. In this paper we report measurements made at the AB Wood acoustic water tank located at the Institute of Sound and Vibration Research (ISVR), University of Southampton, in June 2008. The distribution of signal phase among the individual hydrophones is seen to become more spread out as bubble density increases. As a result, beamformer gain is degraded. It seems that phase shifts caused by scattering from nearby bubbles are responsible for this effect.*

Keywords: *acoustic propagation in bubbly water, bubble scattering, beamformer gain degradation in bubbly water*

1. INTRODUCTION

It is well known that gas bubbles in water can scatter and attenuate sound and greatly affect acoustic propagation [1], [2]. The magnitude of these effects depends on the relationship between the acoustic wavelength and bubble radius as well as the density and size distribution of the bubbles. When hydrophones are used in the vicinity of gas bubbles, scattering by nearby bubbles can affect the phase and amplitude of the received signals. In fact, strong bubble scattering can cause the hydrophone signals to be less than fully coherent across the hydrophone array. Loss of coherence causes a reduction in the gain that can be obtained from beamforming, and that is the subject of this paper. Note that this effect is separate from the reduction in signal amplitude at all array elements due to attenuation; the latter affects signal amplitude but not array gain given sufficient signal to noise ratio. This paper reports measurement of the bubble density-dependent variation in signal phase and the resulting reduction in beamformer gain provided by a 3-element hydrophone array operating in bubbly water.

Array signal processing (or beamforming) exploits the spatial coherence of the signal and the spatial incoherence of the noise. Beamforming works when the signal arrives from one direction only and is therefore spatially coherent, while the noise or interference arrives from many directions and is therefore spatially incoherent. The main beam of the array can be steered toward the direction of the acoustic signal arrival either by physically changing the orientation of the array or by adjusting (delaying or advancing) each of the outputs from the individual elements in the receive array so as to align their phases. A measure of the performance of the beamformer is the array gain (AG), which is defined by comparing the linearly-expressed signal-to-noise power ratio (SNR) at the array output with that at the array input [3]:

$$\mathrm{AG} = 10\log_{10}\left\{\frac{\mathrm{SNR}_{\text{array output}}}{\mathrm{SNR}_{\text{single hydrophone}}}\right\}, \qquad \mathrm{SNR} = \frac{\text{signal power}}{\text{noise power}}. \tag{1}$$

This paper compares the phases of the received signals with and without bubbles nearby and demonstrates the effect of increasing bubble density on signal phase and spatial coherence across the array (i.e. the similarity between signals received by different hydrophones), as well as the gain available from beamforming.

2. BEAMFORMER GAIN MEASUREMENTS

In June 2008 a measurement of bubble scattering effects on a hydrophone array was supported by the Office of Naval Research in the US and the Institute of Sound and Vibration (ISVR), U. of Southampton (UK) using the A B Wood acoustic tank. An important capability at the AB Wood tank is the generation of small (10 µm - 400 µm) air bubbles such as those found in the ocean. For example, see Figure 5 of [4]. Air bubbles are generated using a venturi and then directed into a smaller tank approximately 1.2m x 2m x 1.2m deep which allows the larger bubbles to rise to the surface. Bubbly water (with larger bubbles removed) is then pumped from the smaller tank into the AB Wood tank and discharged through a diffuser placed at the bottom of the tank near the center. The discharged bubbles form a roughly conical cloud as they rise slowly to the surface. The bubble cloud is a statistically stationary feature, and the bubble density decreases with increasing distance from the center of the bubble cloud.

The AB Wood water tank measures 8m x 8m x 5m deep. Figure 1 shows the measurement hardware, which was positioned approximately in the tank center and directly over the bubble diffuser. A locally manufactured acoustic projector was placed approximately 3 m from the center of the bubble cloud and 1.9 m below the water surface. This projector provides a source level that varies by less than 15 dB from 25 kHz to 120 kHz. The projector beam was directed toward the center of the bubble cloud. A 3-element vertical line array of Neptune D140 hydrophones was located at the same depth as the projector and at a variable distance from to the bubble cloud center while keeping the distance from the source to the array constant. The hydrophones were spaced 0.025 m vertically, with the middle hydrophone placed at 1.94 m depth.

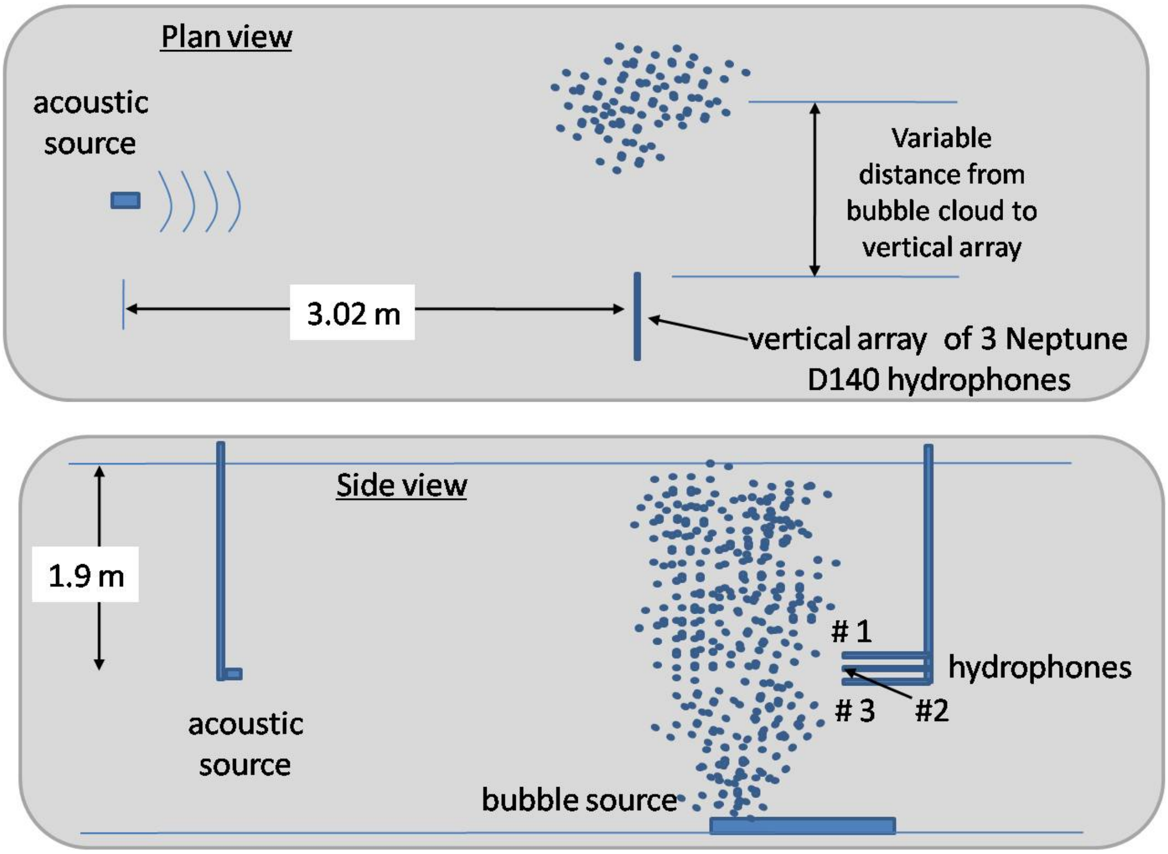

Figure 1: Geometry for beamformer gain measurements. The upper panel shows a view looking down on the tank and the vertical hydrophone array. Moving the hydrophone array closer to the bubble cloud center results in increased bubble density at the array. The bottom panel shows a side view of the geometry.

The measurement approach was to transmit a tone burst signal in the direction normal to a 3-element vertical line array. Signals were transmitted with the vertical array positioned at 4 different distances from the bubble cloud center: (1) 0 cm, (2) 30 cm, (3) 60 cm, and (4) 90 cm. The acoustic frequencies used in the measurement were 25 kHz, 30 kHz, and 35 kHz. Except for measurements made with no bubble present, about 120 transmissions were made at each position of the array and at each frequency. The signal was a 3 ms pulse composed of a 1 ms ramp-up, a 1 ms constant amplitude portion, and a 1 ms ramp down. Received signals were sampled at 250 kHz. The no-bubble measurements utilized 24 transmissions at 30 kHz only.

One set of acoustic measurements were made before introducing bubbles into the tank and with the hydrophone array positioned 60 cm from the center of the bubble cloud. When no bubbles are present, any difference in signal phase between two hydrophones is solely due to array tilt. In the presence of bubbles, phase differences could also be caused by superposition of bubble-scattered signals at the hydrophone, or possibly by differences in sound speed along the two paths. The latter is discounted because the hydrophones are quite close together (2.5 cm) relative to the path length (~2 m) such that sound propagating from the projector to adjacent hydrophones passes through virtually the same bubbly volume and thus is subject to the same propagation speed. Bubble scattering is considered the primary cause of phase differences. Since the bubbles are randomly distributed in space, phase differences induced by bubble scattering should average to zero. Thus the mean of measured phase differences, if non-zero, indicates that the array is tilted. This is consistent with the observation that the mean phase difference is seen to increase linearly across the array (this result is not shown in the paper).

Figure 2 shows examples of signals received with the array at two locations relative to the bubble cloud. With the array 60 cm from the center of the bubble cloud (left panel), the amplitude and phase of the signals are very similar for all three hydrophones. However, when the array is moved closer to the bubble cloud center (right panel), differences in amplitude and phase at the hydrophones are evident.

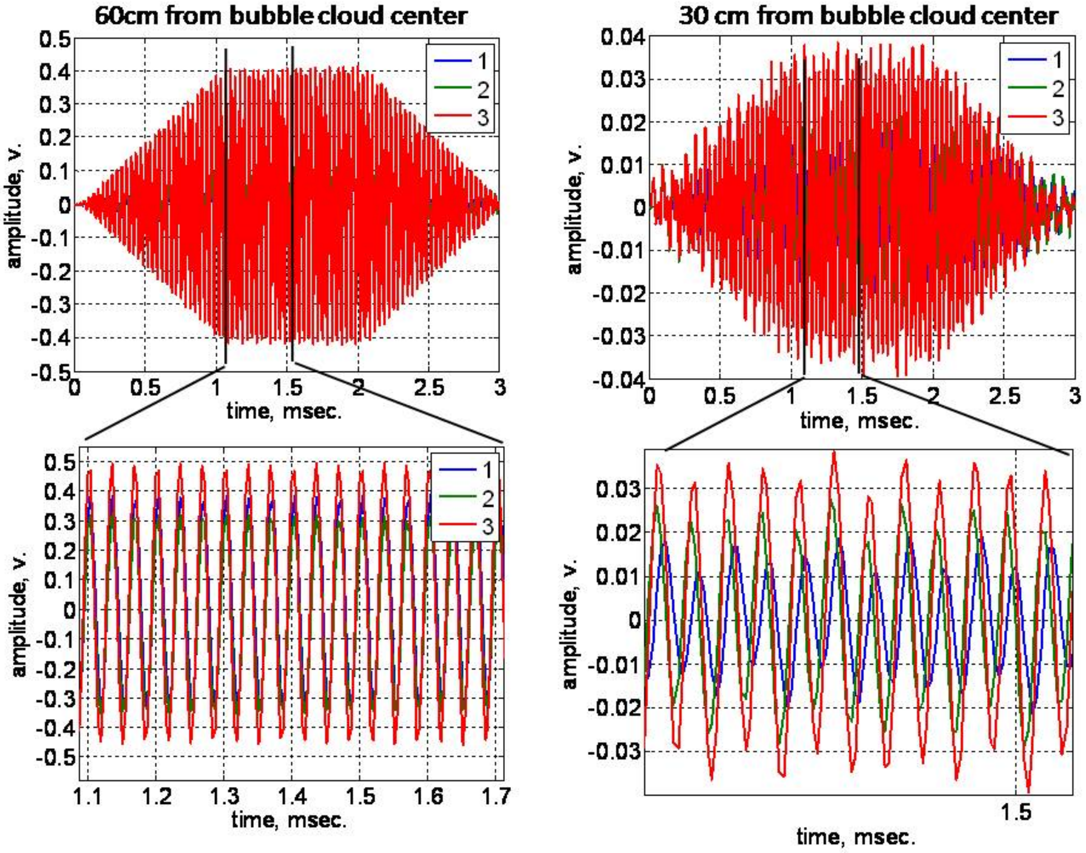

Figure 2: Signals received at hydrophones 1, 2 and 3 with the array at two different distances from the bubble cloud center. The right panel corresponds to a higher bubble density and displays larger amplitude and phase differences between the signals.

A measurement of maximum beamformer gain requires that the array be steered in the direction of the arriving signal. As shown in Figure 1, the hydrophone array was attached to a long rod suspended from rails laid across the tank opening. This arrangement resulted in the hydrophone array being tilted a few degrees from the vertical, which required that the individual signals be advanced or delayed in order to align their phases. It was therefore necessary to estimate the phase of each signal, and this was done using the constant amplitude 1 ms portion of the received signal.

The Discrete Fourier Transform (DFT) method was used to estimate signal phase for each transmission at each hydrophone using a 1-ms (250 point) sequence of data [5]. The complex DFT coefficient $X(m)$ taken from the proper frequency bin contains the signal amplitude and phase. The power at a single hydrophone is $\left|X(m)\right|^2$. The power at the beamformer output is $\left|X_1(m)+X_2(m)+X_3(m)\right|^2$, where the subscript indicates hydrophone number and signal phase alignment to account for array tilt is assumed.

The upper 4 panels of Figure 3 show signal and beamformer output power measured at 30 kHz for the no-bubble case. Panel (a) compares the power in the received signal for the 3 hydrophones with the (phase-aligned) beamformer output. There is no ping-to-ping variation due to high SNR and no interference from bubble scattering. Panel (b) shows the gain provided by beamforming, which is the difference between the two curves in panel (a). The measured value matches the theoretical prediction of $10\log_{10}\left(3^2\right)=9.5\,\text{dB}$. Panel (c) shows the hydrophone and beamformer output power measured 10 ms prior to the signal arriving. These levels represent the background noise present in the AB Wood tank. Note that the single hydrophone signal level is about 40 dB, and the single hydrophone noise level is about -40 dB, so that the SNR for a single hydrophone is about 80 dB for this no-bubble case. Panel (d) shows the beamformer gain against noise, again the difference between the beamformer output and the mean hydrophone power in panel (c). The beamformer gain against noise is quite variable and averages about 7.5 dB.

Eqns. (1) can be arranged to write

$$\text{AG} = 10\log_{10}\left\{\frac{\text{signal power @ array output / noise power @ array output}}{\text{signal power @ one hydrophone / noise power @ one hydrophone}}\right\}$$

$$= 10\log_{10}\left\{\frac{\text{signal power @ array output}}{\text{signal power @ one hydrophone}}\right\} - 10\log_{10}\left\{\frac{\text{noise power @ array output}}{\text{noise power @ one hydrophone}}\right\}$$

$$= \text{BG}_{\text{signal}} - \text{BG}_{\text{noise}}. \qquad \textbf{(2)}$$

where $\text{BG}_{\text{signal}}$ and BG_{noise} are the gains provided by the beamformer against signal and noise, respectively. If the noise is completely incoherent (i.e. the phase is random among the hydrophones), then the expected value of the beamformer gain against the noise is $10\log_{10}(\text{N})$, where N is the number of hydrophones. For a 3 element array operating in incoherent noise, $10\log_{10}(3)=4.75$ dB. Panel (d) of Figure 4 shows that $\text{BG}_{\text{noise}} \approx 7.8$ dB, indicating that the noise is not incoherent across the array. Using Eqn. (2), the mean AG calculated for the no-bubble case is (9.5 - 7.8) = 1.7 dB. The AG in incoherent noise would be (9.5 - 4.8) = 4.7 dB.

Note that the mean measured AG is less than the theoretically predicted value not because the signal is less than perfectly coherent across the array, but because the noise is not perfectly incoherent across the array. The source of coherent noise at 30 kHz in the AB Wood tank is unknown, but it is virtually unchanged for all of the measurements, with and without bubbles present and regardless of the array proximity to the bubble cloud.

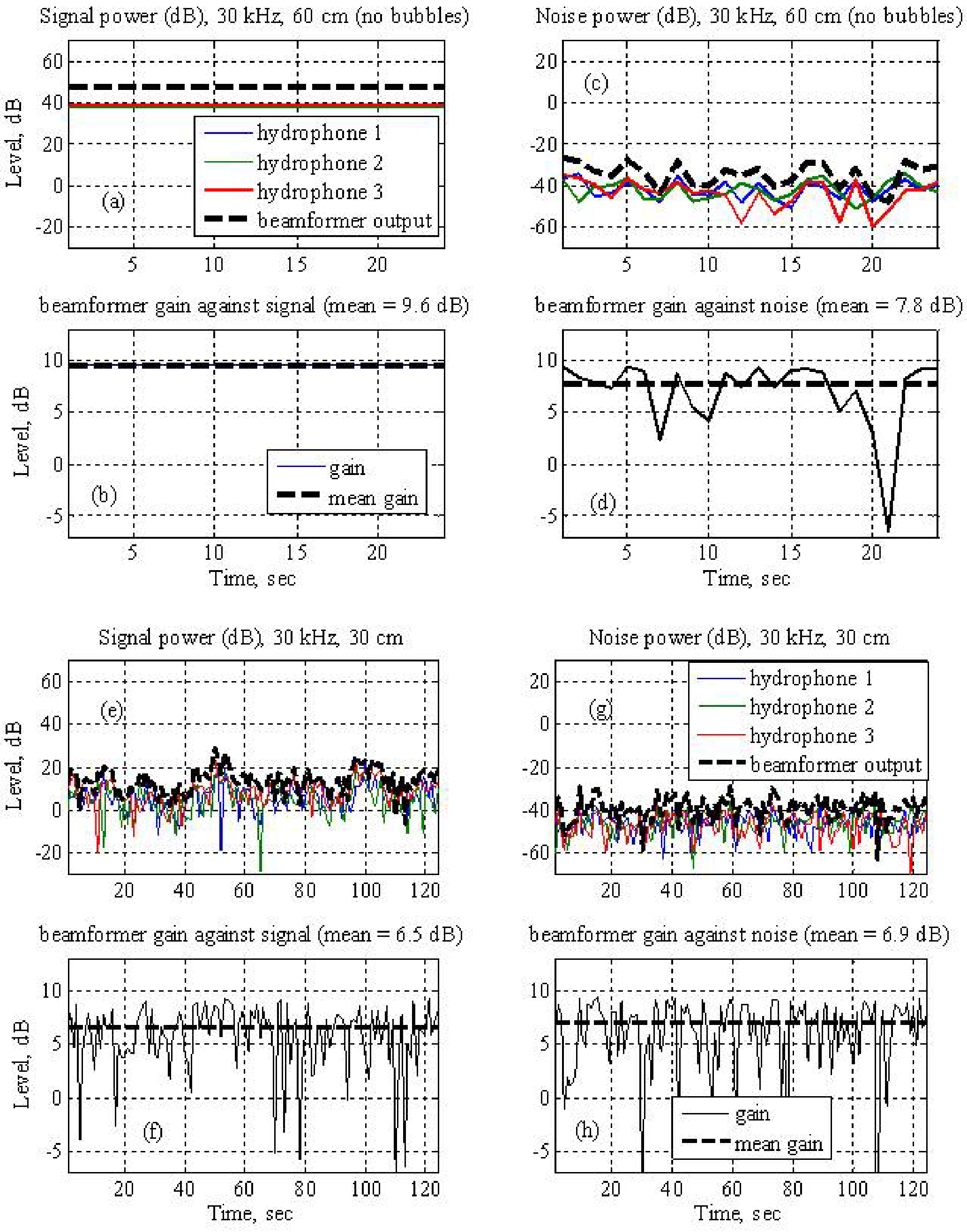

Figure 3: Signal and noise power at the individual hydrophones and at the beamformer outout for the no bubble case (panels a - d) and for the array 30 cm from the bubble cloud center (panels e - h). Panels (a), (b), (e) and (g) show signal and noise power at the hydrophones and beamformer output. Panels (c), (d), (g) and (h) show beamformer gain against signal and noise.

The lower 4 panels of Figure 3 show the signal and noise power and beamformer gains for 30 kHz with bubbles present and the array 30 cm from the bubble cloud center. The signal levels at a single hydrophone and at the beamformer output are significantly lower and more variable than for the no-bubble case, but the noise levels (single hydrophone and beamformer output) are not that different. The BG_{noise} is still about 6.9 dB, however the BG_{signal} has dropped to about 6.5 dB. While the presence of bubbles close to the array has not had much effect on the coherence of the ambient noise, it has caused a significant drop in the coherence of the signal across the array. The mean AG calculated for this case is -0.4 dB, which means that the beamformer is actually reducing mean SNR.

Histograms of BG_{signal} for single transmissions at 3 measurement frequencies and different bubble densities are shown in the upper half of Figure 4. The columns correspond to measurements made at (left to right) 25kHz, 30kHz, and 35kHz. The upper three rows correspond to measurements made with the array at (top to bottom) 30 cm, 60 cm and 90 cm from the center of the bubble cloud. The bottom panel is the no-bubble case. The panels show that as the array is moved closer to the center of the bubble cloud and thus the bubble density at the array increases, the distribution of BG_{signal} becomes more and more spread out. Also, the mean BG_{signal} drops from 9.5 dB, the maximum value for perfectly correlated signals, to approximately 6.5 dB as the array moves closer to the bubble cloud center.

The reduction in BG_{signal} is due to differences in signal phase among the hydrophones, histograms of which are shown in the lower half of Figure 4. The arrangement of the columns and rows are the same as for the beamformer gain histograms. Note that the mean phase difference is zero because the signals were aligned in phase.

The distribution of the phase difference is very narrow for the no-bubble case (bottom panel). As the array is moved closer to the bubble cloud center and the bubble density increases (moving up in the figure), the variance of the phase difference increases and the histograms flatten out. The phase difference approaches a uniform distribution in the top row, which corresponds to when the array was closest to the bubble cloud center.

3. ACKNOWLEDGEMENTS

Two of the authors (RLC and JDP) gratefully acknowledge support from Mr. Mike Vaccaro at the Office of Naval Research. The work of Paul Doust, DNV, UK to match the transducer and amplifier over a broad frequency range is appreciated.

REFERENCES

[1] **C. S. Clay and H. Medwin,** *Acoustical Oceanography: Principles and Applications***,** John Wiley & Sons, New York, New York, 1977. Chapter 6.

[2] **A. Ishimaru**, *Wave Propagation and Scattering in Random Media,* IEEE Press, Piscataway, New Jersey, 1997. Chapter 3, 4 and 6.

[3] **W.S. Burdick**, Underwater Acoustic System Analyis, Peninsula Publishing, Los Altos, CA, 2002. Chapter 11.

[4] **T. G. Leighton, D. C. Finfer, P. R. White, G. H. Chua, and J. K. Dix**, Clutter suppression and classification using twin inverted pulse sonar (TWIPS), *Proceedings of the Royal Society, 466:3453-3478, 2010.*

[5] **A. P. Martins,** A DFT-based phasor estimation method for power electronics converter control and protection under strong grid voltage perturbations, European Transactions on Electrical Power, 19(8):1082{1097, 2009

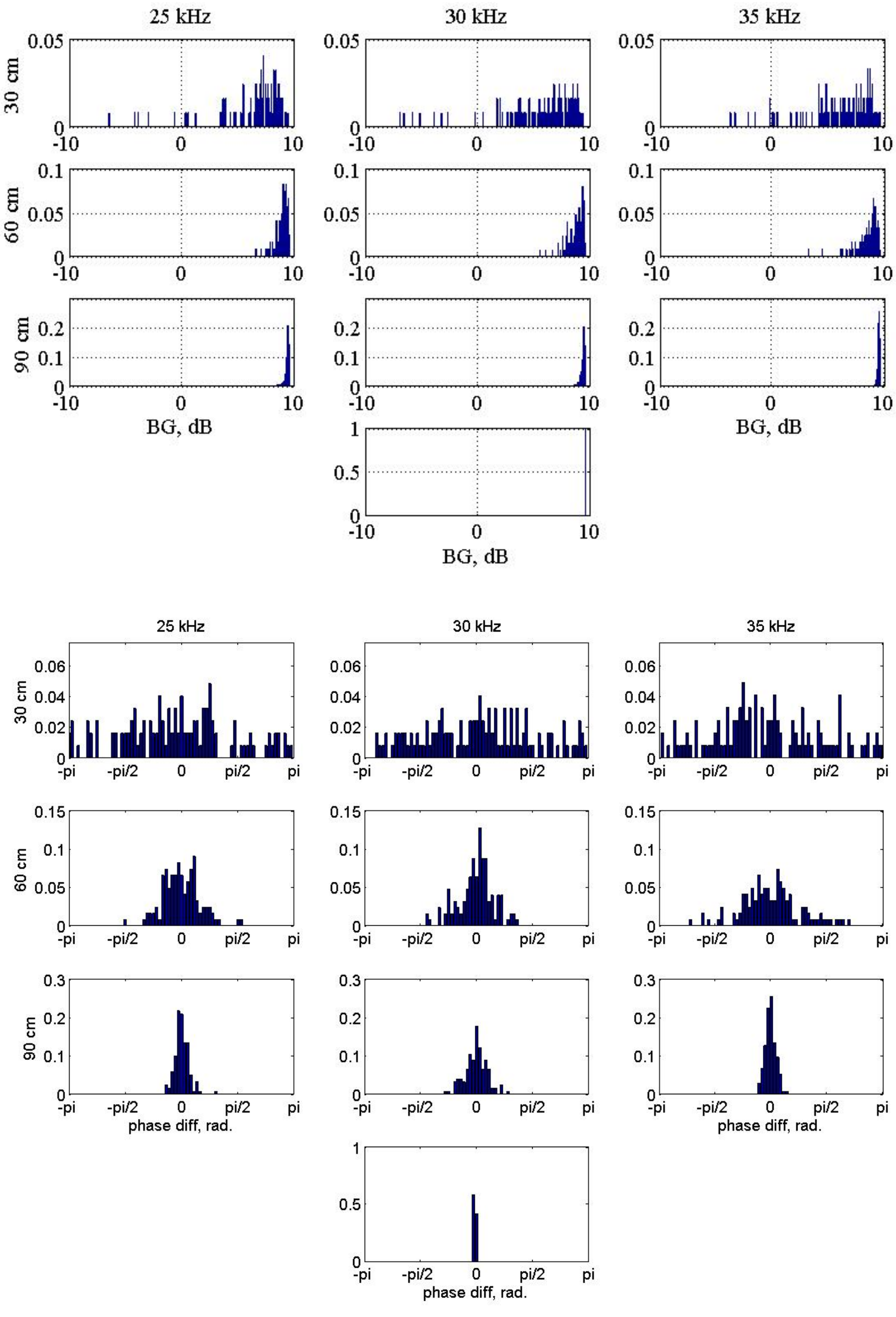

Figure 4: Histograms of BG$_{\text{signal}}$, the beamformer gain against signal (upper) and phase difference between signals received at hydrophones 1 and 2 (lower). The columns correspond to frequencies of (l to r) 25kHz, 30kHz, and 35kHz. The upper three rows in each set of panels correspond to measurements with the array at (top to bottom) 30 cm, 60 cm, and 90 cm from the center of the bubble cloud. The bottom row is the no-bubble case. Note that vertical scales are different among the panels.