TITLE

SIREM: An Instrument to Evaluate Superdirective and Intensity Receiver Arrays

SIREM: AN INSTRUMENT TO EVALUATE SUPERDIRECTIVE AND INTENSITY RECEIVER ARRAYS

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Abstract -Pressure gradient arrays have been in use within the acoustic community for several decades. Historically most underwater acoustics measurements employing pressure gradient arrays have used the superdirective array whereas air applications have relied on the intensity array approach. Intensity arrays based on pressure sensors require the same hardware (and equally rigorous hardware tolerances) as superdirective arrays. The difference between the two methods lies in how one processes the received signals. One obtains the intensity by *multiplying* pressure and pressure gradient signals; The superdirective solution is obtained by *summing* the pressure and the pressure gradient signals. The measurement objective dictates which solution is better for a given experiment. The Defence Research Establishment Atlantic (DREA), in collaboration with Guigné International Ltd., has developed a 6-channel hydrophone array which will be used to explore the processing advantages of both methods. Two configurations of the system will be examined: a tri-axial array of dipoles enabling measurements along the x, y, and z axis, and a 6-channel linear array configuration enabling measurement of gradients up to 5th order along a single axis. In this paper, the array configurations will be outlined and the impact of system noise on the processing methods will be described.

I. INTRODUCTION

Pressure gradient arrays have been in use within the acoustics community for several decades. As the name implies, these arrays compute the gradient of the pressure field rather than just its magnitude and this offers two advantages: First and foremost, computing the pressure gradient allows one to obtain the direction of propagation of a pressure wave. Secondly, estimating the gradient requires inter-element spacings that are a small fraction of an acoustic wavelength; Thus by its nature, the array is much more compact than a conventional array.

Two realizations of the pressure gradient array shall be examined in this paper. The first is the intensity array and the second is the superdirective array. Both devices require the same hardware ñ and equally rigorous hardware tolerances. The difference between the two lies in how one processes the received signals. One obtains the intensity by *multiplying* pressure and pressure gradient signals; The superdirective solution is obtained by *summing* the pressure and the pressure gradient signals.

The Defence Research Establishment Atlantic (DREA), in collaboration with Guigné International Ltd., has developed a 6-channel hydrophone array known as SIREM (Superdirective/Intensity Receiver Evaluation Module). The device will be used to explore the processing advantages of superdirective and intensity receivers in a variety of acoustical environments. Moreover, two configurations of the system will be examined: a tri-axial array of dipoles enabling intensity and superdirective measurements along the x, y, and z axis, and a 6-channel linear array configuration enabling measurement of gradients from 0th to 5th order along a single axis. In this paper, the array configurations will be outlined and the impact of system noise on the processing methods will be described.

II. THE SUPERDIRECTIVE/INTENSITY RECEIVER EVALUATION MODULE (SIREM)

Conventional line arrays form acoustic beams using the principle of time-delay-and-sum[1] to align the signal received at each sensor. This causes the (coherent) signal to reinforce and the (incoherent) ambient noise to average out. This design benefits from large inter-element spacings since the signal tends to have a greater coherency length than does the noise. In contrast, superdirective and intensity hydrophone arrays estimate pressure gradients of various order by taking the difference between signals received a pairs of sensors and normalizing by the sensor spacing Since this latter technique approximates the gradient, the inter-element spacing must be much less than a wavelength. Thus, by its very nature the superdirective intensity array is much more compact than the conventiona array. Superdirective and intensity arrays based o pressure sensors require essentially the same hardwar specifications; The difference between them lies in hov one processes the received signals [2]. One obtains th intensity by *multiplying* pressure and pressure gradien signals; The superdirective solution is obtained by *summin* the pressure and the pressure gradient. The measuremer application dictates which solution is better for a give experiment. It is interesting to note that in a conventiona array, gain occurs against ambient noise if the noise i *incoherent* since it will then average out; However, in difference array, gain occurs only against *coherent* noise. One achieves gain against ambient noise with the difference array because at small inter-element spacings the ambient noise is coherent.

The principle disadvantage of these “difference arrays” that theoretical gains are difficult to achieve due to their susceptibility to uncorrelated noise. That is to say, the very process of taking the difference between the acoustic signals at two sensors means that the signal to noise ratio (SNR) must degrade. Noise sources include pre-amplifier voltage noise, inter-channel imbalance in gain and/or phase, sensor spacing errors, acoustic scatter and hydrophone self-noise due to hydrodynamic flow past the sensors. Voltage noise and inter-channel imbalance can be minimized through careful design of pre-amplifiers and modern digitization techniques. Sensor position errors are reduced by compliantly mounting the hydrophones to stiff mounting rods. Flow noise can be reduced by enclosing the hydrophones in an acoustically transparent shroud such as open-cell foam. Finally, noise resulting from scatter can be minimized by ensuring that hardware in the vicinity of the hydrophones is sufficiently low-profile in design. This last constraint is perhaps the most difficult to quantify and it is oftentimes the quality of the data which determines if the design requirement has been met. Modeling[3] indicates that in the absence of sensor noise, a six-hydrophone array with an aperture of 0.8 m will provide approximately 15 dB gain against three-dimensionally isotropic ambient noise.

III. THE SIREM HARDWARE

There are two configurations for the SIREM hardware: A three-dimensional (volume array) arrangement in which 3 pairs of hydrophones are arranged symmetrically along the Cartesian axis, and a linear arrangement in which all six hydrophones are aligned with a single axis. Both of these configurations are described below.

A. The Volume Array Configuration

Fig. 1 shows a schematic of the sensor layout for the volume array configuration. Horizontal rods (not shown) are used to set the transverse spacing to either 8 cm or 19 cm depending on the frequency band of interest. Each hydrophone pair is aligned with its respective Cartesian axis and the geometric center of the array corresponds to the point (x, y, z) = 0. The hydrophones, denoted (X1, X2), (Y1, Y2), and (Z1, Z2), are compliantly coupled to stiff stainless steel mounting rods which sets the vertical alignment. Wires run from the hydrophones to a set of preamplifiers approximately 2 m away. The pre-amplifier container is physically separated from the hydrophones to reduce acoustic scatter and diffraction effects. Care must be taken to ensure that the wires are immobilized to prevent electronic pick-up from contaminating the signals.

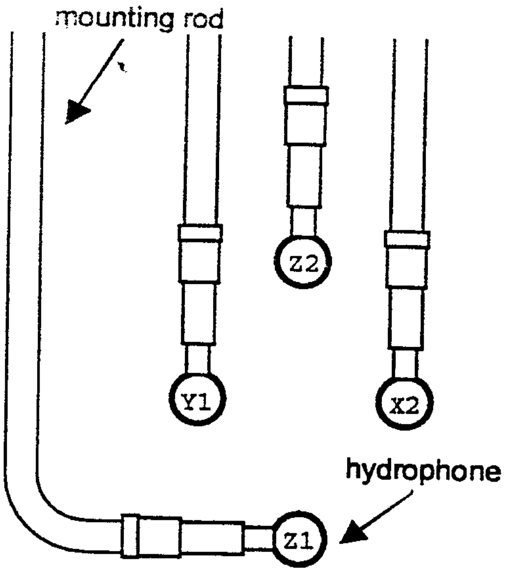

Fig. 1: Cross-section of sensor layout for volume array. Hydrophones Z1 and Y1 block the view of Y2 and Z2, because the section is taken at 45°.

B. The Linear Array Configuration

Fig. 2 shows a schematic of the linear array configuration. Inter-element spacing is maintained by mounting the hydrophones to a pair of wire-rope strength-members held in tension. This assembly is wrapped in open-celled foam and encased in a polyurethane hose. The foam serves to compliantly couple the sensors to the hose wall, which in turn maintains the axial symmetry of the array and provides mechanical protection. The hose is open-ended to eliminate scatter from the endcaps. The entire assembly is connected via metal stand-offs to a length of aluminum channel which allows the array to be attached to a variety of structures. The hydrophone wires run along the wire-rope to a pre-amplifier can located outside the hose. As with the volume array, care must be taken to ensure that the wires are immobilized to prevent electronic pick-up from contaminating the signals.

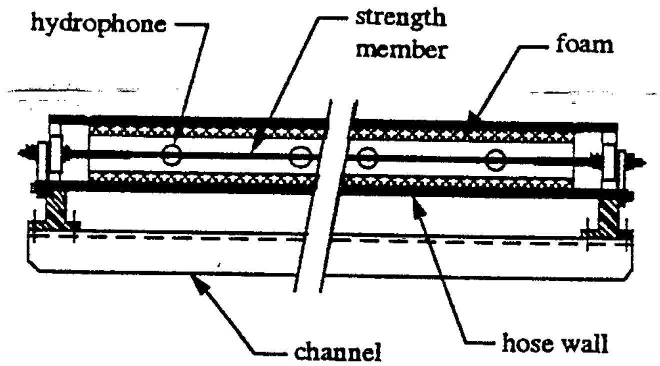

Fig. 2: Cross-section sensor layout for linear array. Only four of the six sensors are shown.

C. The Pre-amplifiers

The SIREM is a six channel difference array receiver used in DREAís Wide Band Sonar (WBS) system []. The hydrophones have a nominal acoustic sensitivity of -200 dB re $1V/\mu Pa$. The pre-amplifiers were custom-built. The pre-amplifiers have a 12 dB fixed gain at the input stage with 60 dB additional gain selectable in 12 dB increments. The dynamic range of the pre-amplifier varies from a high of 150 dB at the 12 dB gain setting to a low of 100 dB at the 72 dB gain setting. At 1 kHz, the pre-amplifier noise (referred back to the input) is less than -165 $dBV/\sqrt{Hz}$ all gain settings. Fig. 3 shows the inter-channel relative phase matching of the pre-amplifiers as a function of frequency. The five curves represents the relative phase of 5 of the pre-amplifiers to the 6th (the Z2 pre-amplifier). A phase difference of 0° means that the channels are perfectly phase matched. Phase matching between all six pre-amplifiers is better than ±.3° across the frequency band. For the volume array configuration, the pre-amplifiers were paired to minimize the phase mismatch along each axis. For example, the dashed curve shows the relative phase of the (Z1, Z2) pair. The two solid curves are the (X1, X2) pair and the dash-dot curves are the (Y1, Y2) pair. Phase matching between pairs is better than ±.05° across the frequency band.

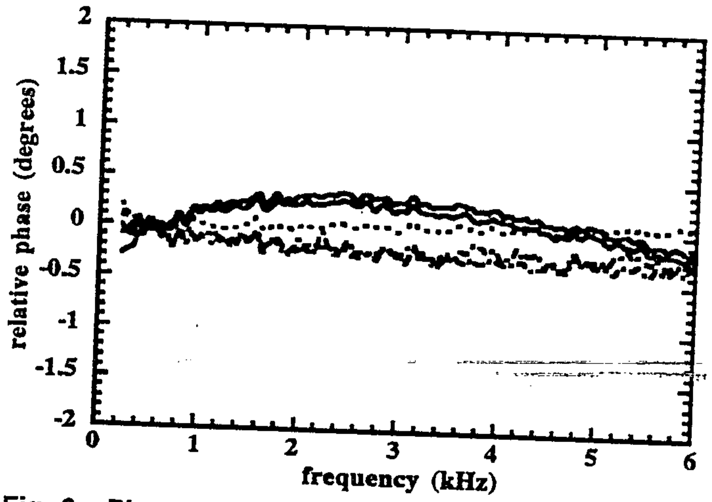

Fig. 3: Phase matching of five of the pre-amplifiers relative to the sixth.

Fig. 4 shows the inter-channel relative gain matching of the pre-amplifiers as a function of frequency. The five curves represents the relative gain of 5 of the pre-amplifiers to the 6th (the Z2 pre-amplifier). A gain difference of 0 dB means that the channels are perfectly matched in gain. The dashed curve shows the gain of the (Z1, Z2) pair. Gain matching between all six pre-amplifiers is better than ±.3 dB and matching between two co-axial pre-amplifiers is better than ±0.1 dB. The line designations are the same as in Fig. 3.

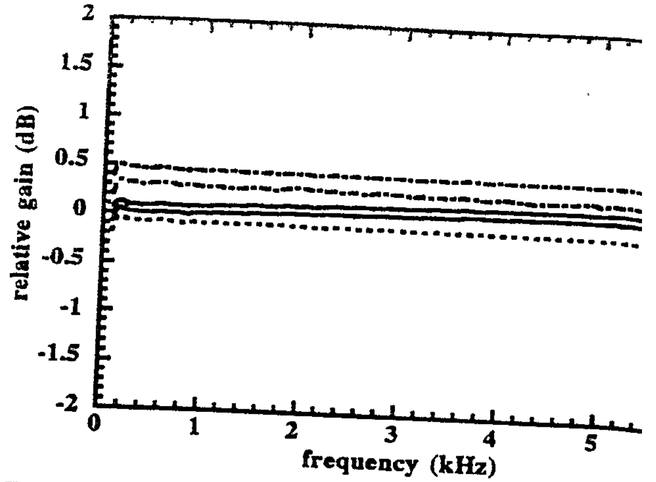

Fig. 4: Gain matching of five of the pre-amplif relative to the sixth.

IV. SYSTEM NOISE AND ITS IMPACT ON ARRA GAIN

In this section we examine the effect of system noise array gain for the linear array and for one axis of the volu configuration. The degradation occurs because form the gradient reduces signal amplitude while leav uncorrelated system noise unchanged. System no includes pre-amplifier voltage noise, inter-chan imbalance in gain and/or phase, sensor spacing err acoustic scatter and hydrophone self-noise due hydrodynamic flow past the sensors. In SIREM, volta noise limits the arrayís performance. Since t superdirective and intensity arrays both employ the gradi approach, the impact of system noise will be similar for t two processing techniques. For brevity, remarks will limited to the superdirective configuration.

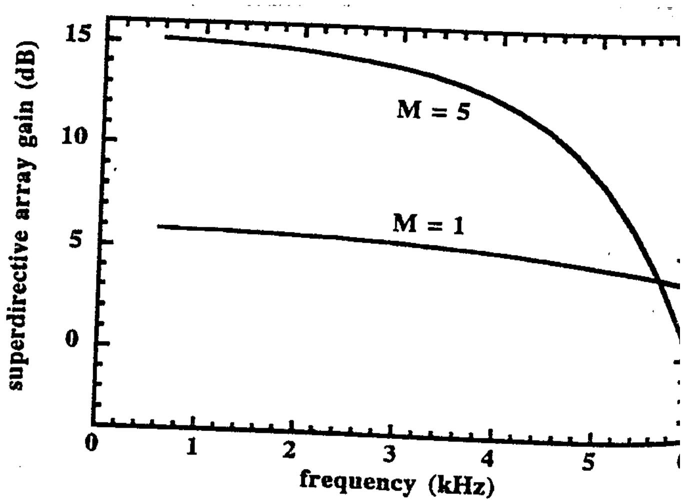

Fig. 5: Ideal gain for a 2-hydrophone (M = 1) and for 6-hydrophone (M = 5) superdirective array.

Figure 5 shows the array gain (*AG*) in decibels for a 1st order (2-element) and a 5th order (6-element) superdirective array [3]. The model assumes a three-dimensionally isotropic ambient noise field, an inter-element spacing of d=0.16 m, and zero system noise [5]. The array gain decreases with increasing frequency because the approximation to the gradient degrades; This defines the high frequency operating limit of the superdirective array. The low frequency limit of the superdirective array arises when one includes the effects of uncorrelated system noise. To quantify its effect we note from [3] that the degradation in array gain *AD* due to uncorrelated noise can be written as:

$$AD = 1 + \frac{N_{sn} AG}{N_o} \tag{1}$$

where N_o is the ambient noise power and N_{sn} is the system noiseand we have normalized to unity signal gain. The system noise at the output of a superdirective line array is given by:

$$\begin{aligned} N_{sn} = N_s \left\{ \left[\sum_{i=1}^{\underline{M/2}} \frac{w_{2i}\,{}_{2i}C_i}{W(-p^2)^i} \right]^2 + 2\left[\sum_{i=1}^{\underline{M/2}} \frac{w_{2i}\,{}_{2i}C_{i+1}}{W(-p^2)^i} \right]^2 \right\} + \ldots \\ N_s \left\{ 2\left[\sum_{i=1}^{\overline{M/2}} \frac{w_{2i-1}\,{}_{2i-1}C_i}{W(-1)^{i-1} p^{2i-1}} \right]^2 + 2\left[\sum_{i=2}^{\overline{M/2}} \frac{w_{2i-1}\,{}_{2i-1}C_{i+1}}{W(-1)^{i-1} p^{2i-1}} \right]^2 \right\} + \ldots \end{aligned} \tag{2}$$

where N_s is the system noise power of an individual pre-amplifier, ${}_aC_b$ is the binomial coefficient for the (b+1)st term, $W = \sum_{n=0}^{M} w_n$. is the sum of the gradient weights, w_n. , and $\underline{M/2}$ and $\overline{M/2}$ represent the summation taken to the floor or ceiling of the fraction, respectively.

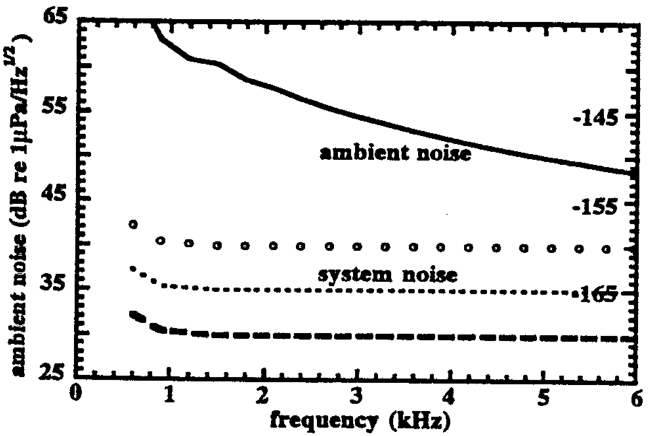

Fig. 6: Sample noise floor for pre-amplifier (dotted line) and noise floor 5 dB quieter (dash line) and 5 dB noisier (open circles). The noise curves are compared to the pre-amplifier response to ambient noise (solid line).

In order to quantify the effect of voltage noise on array performance, one must first compute the voltage response of the hydrophone/pre-amplifier for a specific ambient noise data set. This is compared to the voltage noise of the pre-amplifier. By way of example Fig. 6 shows ambient noise collected on Western Bank off the coast of Nova Scotia (solid line) []. The data were collected in water 60 m deep during winds of 20 knots. The measured data are limited to below 2 kHz; The data have been extrapolated to 6 kHz by assuming a roll-off of 6 dB/octave. The left vertical axis shows the data in units of dB re 1μPa/$\sqrt{Hz}$ whereas the right vertical axis provides the conversion to dBV/$\sqrt{Hz}$ using the SIREM hydrophone sensitivity. Also plotted in the figure is the voltage noise background (N_s) of an individual SIREM pre-amplifier (dotted line) and curves representing a 5 dB reduction in pre-amplifier noise (dash line) and a 5 dB increase in pre-amplifier noise (open circles). Using Fig. 6, and Equations (1) and (2) one can estimate the array degradation as a function of frequency and from that, adjust the theoretical array gains shown in Fig. 5 to obtain the corrected receiver array gain.

Figs. 7 and 8 show the array gain in decibels for a 6-element and a 2-element array, respectively, for the ambient noise and pre-amplifier noise of Fig. 6. The line conventions for array gain correspond to the line conventions for pre-amplifier noise in Fig. 6. For comparison, the ideal gain curves are re-plotted from Fig. 5. The four curves are well separated for the 6-element array but all four curves overlay one another for the 2-element array. Clearly, system noise has a much more severe impact on higher-order difference arrays. This occurs because the finite-difference method of computing higher order gradients successively reduces the signal (in this case ambient noise) while maintaining the same system noise background.

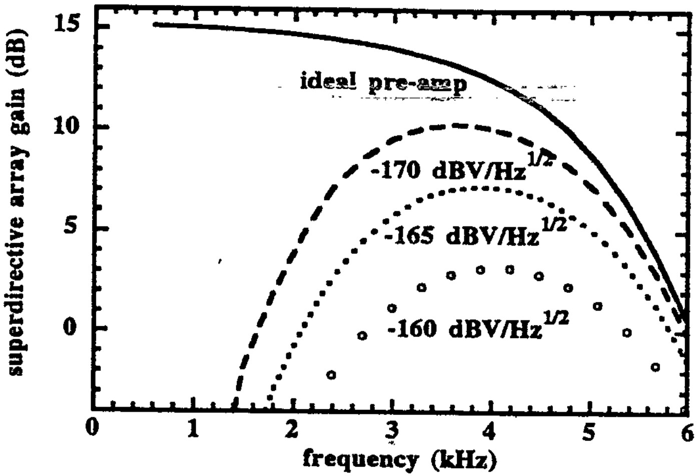

Fig. 7: Array gain for 5th order superdirective array for three pre-amplifier noise floors with the ambient noise conditions given in Fig. 6. The solid line is the ideal gain re-printed from Fig. 5. The other three curves correspond to the pre-amplifier noise curves shown in Fig. 6.

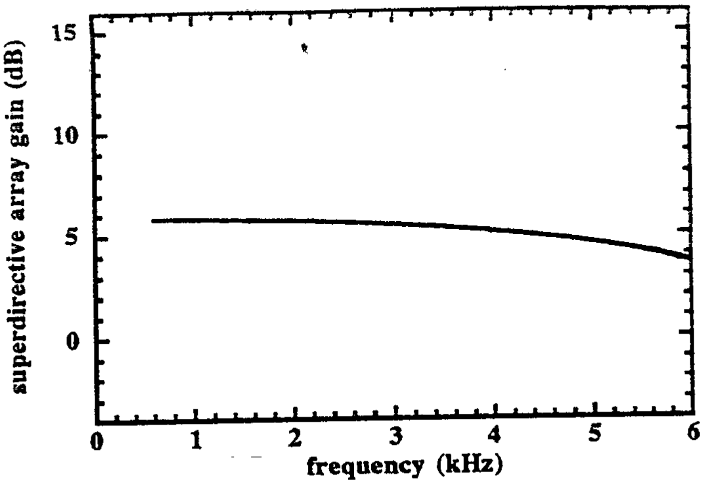

Fig. 8: Array gain for 1st order superdirective array for three pre-amplifier noise floors and the ideal gain re-printed from Fig. 5. Note that all four gain curves overlay one another. The four gain curves were computed using the ambient noise conditions given in Fig. 6.

V. CONCLUSIONS

SIREM is a 6-element receive array designed to examine the processing gains of two pressure-gradient processing techniques ñ the superdirective array and the intensity array. The system can be configured as either a 6-element linear array or a tri-axial array of dipoles. The array was designed to operate from approximately 1 kHz to 5 kHz.

The pdnciple disadvantage of pressure-gradient arrays is that theoretical gains are difficult to achieve due to their susceptibility to uncorrelated noise. This problem becomes more pronounced as one calculates higher-order gradients. For example, with the present hardware specifications, the 6-element linear array achieves a maximum gain of approximately 7 dB, some 8 dB below the theoretical limit. Improving pre-amplifier noise performance by 5 dBV/(Hz)$^{1)2}$ results in a maximum gain of approximately 10 dB. In contrast, the dipole array reaches its theoretical gain of 6 dB not only using the current pre-amplifier specification but also using a pre-amplifier that is 5 dBV/(Hz)$^{1)2}$ noisier.

VI. REFERENCES

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4 Paul C. Hines, W. Cary Risley, and Martin P. O'Connor, "A Wde-Band Sonar for Underwater Acoustics Measurements in Shallow Water," Proceedings: Oceans'98, Nice, France, Sept. 29Nov. 1, 1998.

5 To obtain Fig. 5, a gradient weighting scheme optimized for 2-dimensionally (i.e., horizontally) isotropic noise was chosen due to its robustness in the presence of self-noise and channel imbalance. As it happens, optimizing the weights for a 2-D isotropic noise field, and employing them in a 3-D isotropic noise field results in less than a 0.5 dB reduction in array gain.

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