MATCHED FIELD PROCESSING IN AN ARCTIC ENVIRONMENT

John M. Ozard(1), Michael Greening(2) and Peter Brouwer(3)

(1)Defence Research Establishment Pacific, FMO Victoria, B.C., Canada, V0S 1B0.
(2)Jasco Research Ltd, 9865 W. Saanich Rd, Sidney, B.C., Canada, V8L 3S1.
(3)Datavision Computing Services Ltd, 105-1030 Pendergast, Victoria, B.C., Canada, V8V 2X2.

1.ABSTRACT

Matched Field Processing (MFP) has been used as a method for remotely detecting underwater acoustic sources and estimating their positions. Alternatively it can be used to estimate environmental parameters if the location of a source is known. Performance that can be achieved depends critically on array configuration as well as signal and noise properties. To investigate MFP performance in the Arctic ocean an impulsive ambient noise model has been developed from the measured properties of the noise. This Arctic model, a classical surface noise model and a model corresponding to widely distributed fishing boats have been incorporated in a comprehensive computer code for MFP simulation. Realistic simulations have been carried out for horizontal and vertical arrays which show that ambient noise models have a significant impact on array performance and design. For the cases investigated, equispaced bottom mounted horizontal arrays outperformed equispaced vertical arrays that span the water column, achieving higher array gains, and higher peak-to-sidelobe and peak-to-standard deviation ratios in all three noise fields studied. Array gains were consistently higher for the Arctic noise than either of the other noise models.

2. INTRODUCTION

Anticipation of quieter targets has led to the investigation of Matched Field Processing (MFP) as a means of increasing array gain. MFP consists of matching the acoustic measurement against a realistic replica of the signal.[1] The signal replica is a better approximation than the conventional plane wave replica so that the maximum array gains are more likely to be limited by the propagation than by the plane wave approximation.

Gains also depend upon the noise models so that an improved noise modelling capability is required for realistic array gain predictions. As a basis for developing suitable noise models, Arctic ambient noise properties have been under investigation at Defence Research Establishment Pacific since 1953. Recently the directionality, as well as source level, and spatial and temporal distributions of the impulsive noise sources have been measured. Such noise sources constitute a significant fraction of Arctic ambient noise.

This paper compares the performance of horizontal arrays of varying length, and to a lesser extent the performance of horizontal and vertical arrays with the same number of sensors, for three noise fields. The first noise model provides a reference and is the classical field generated by a surface noise source distribution as described by Cron and Sherman[2]. It represents the noise field produced by waves on the ocean surface. By way of transition to a more Arctic-like noise, a model was developed for a finite number of continuous noise sources distributed 1 m below the ocean surface. This represents the noise that might be received from a distribution of fishing boats. The third noise field differs from the fishing boat model in that the noise sources are impulsive. These impulses are intended to represent thermal ice cracking, which is known to be the dominant noise mechanism in the Arctic during April and May.[3] Other noise mechanisms such as ridging[4] are even more anisotropic and thus are likely to provide conditions under which high array gains are possible.

The noise fields differ in the degree of anisotropy and in the cross correlations between sensors. To characterize the array performance, ambiguity surfaces and array gains are presented for each noise type.

3. THEORY

3.1 Noise Model

For the classical surface noise model the modelling was analytical and represents a surface noise distribution over a half space. To introduce statistical fluctuations into the analytic surface noise model a Cholesky decomposition was applied to the noise covariance and the received noise was reconstructed in the frequency domain with Gaussian distributed amplitudes.

In the case of the Arctic and fishing boat noise models the sound from the discrete noise sources was propagated with a normal mode model to the receiving array. For both models the acoustic sources were uncorrelated and were distributed at 1 m depth at random ranges and bearings. The distribution was uniform in range to 60 km and uniform in bearing.

Since the Fishing boat noise model has been described elsewhere under the name modal noise model[5,6] only the parameters for, and an outline of the model will be given here. For this model 100 sources are present for the duration of the covariance estimation. The source levels were uniformly distributed to a maximum level and normalized to give the desired signal-to-noise ratio (A Gaussian distribution gave similar results in simulations).

In the Arctic noise model the impulsive sources were present only for a single estimate. Based on experimental results[3] a lognormal distribution with a standard deviation of 12 dB was used to represent the thermal ice cracking levels. The lognormal distribution represents the source distribution seen at the receivers but under-represents weak ice-cracking events that contribute a few percent of the total noise energy. The lognormal approximation was used because it reduces the computational load for the simulations by many orders of magnitude. A measured source density of 0.0003 events/km^2/sec was employed.

The assumption is made in the Arctic model that a given impulse reaches all sensors in the array in the same time sample. This implies long samples, as is required for narrowband gain, otherwise impulsive noise sources near endfire are not correctly modelled. Near endfire sources would introduce more incoherent noise, which is also to be expected from other not necessarily acoustic sources. To account for this and other sources of uncorrelated noise a white noise component 30 dB below the signal was included in the simulations of this study.

3.2 Propagation Model
A normal mode model with unity single mode coherence was chosen for an efficient implementation for the Arctic and fishing boat noise models. This propagation model restricts the applicability of the noise model to situations in which the noise sources are several water depths from the array. For the Arctic model measured source positions satisfy this condition for a large fraction of the events.[2]

The same shallow water environmental model was used for both the Arctic and fishing boat noise models. It consisted of 527 m of water with an upward refracting sound speed profile (1437 m/s at 0 m to 1455 m/s at 527 m) over a bottom with a sound speed of 2000 m/s and an attenuation of 0.25 dB/km. The first 25 m of water was also given an attenuation of 1.13 dB/km to account for the effect of surface roughness at 24 Hz.

4. RESULTS OF SIMULATIONS

Matched field performance for bottom mounted equispaced horizontal arrays was simulated[6] for covariance estimates with three times as many samples as elements in the array to ensure fairly stable estimates of the covariance matrix. A normal mode representation of the signal was employed for forming the noise-free replica in this study while noise was added to form the simulation of the measurement. It is also important to sample modes 1 and 2 well with the array since these modes usually carry most of the signal energy. For the physical model of this study modes 1 and 2 give a 16 km null separation (the acoustic signal field for a point source has nulls separated by $\{2\pi/(k_1-k_2)\}$) which is the largest null separation for the waveguide. This suggests that arrays of equispaced sensors that span 16 km in the direction of propagation will adequately sample modes 1 and 2 regardless of the source range.

Figure 1 shows the Minimum Variance (MV) ambiguity surface in depth and range for a source at 25 km range and 150 m depth for the fishing boat noise field. The submerged -10 dB source at 25 km range and 150m depth is several dB above background reflecting an array gain of ~ 12 dB. The peak-to-sidelobe ratio is small but the ratio of the peak level to the standard deviation of the background is large, indicating that a flat background has been obtained from the noise through normalization.[6]

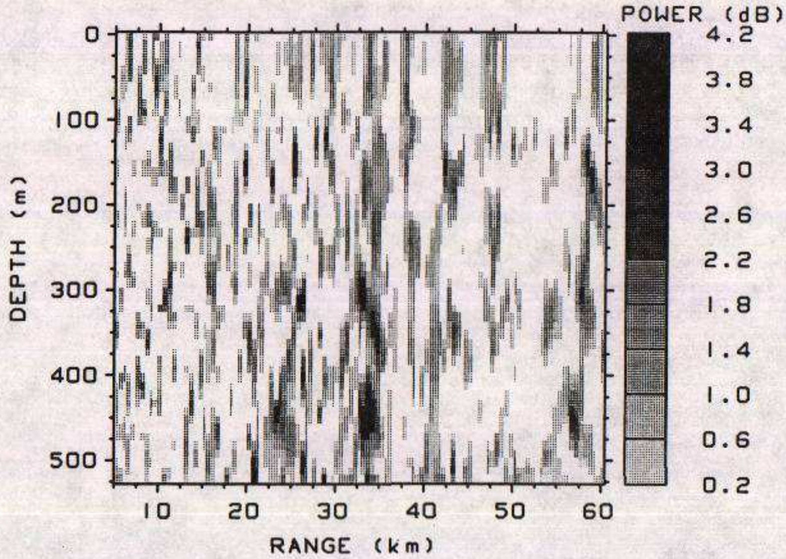

Figure 1. Minimum variance ambiguity surface for a 16 element equispaced 16-km long horizontal array on the bottom with a source at 45°, 25 km range and 150 m depth in fishing boat noise. The signal-to-fishing boat noise ratio was -10 dB and signal-to-white noise ratio was 30 dB for the 24 Hz source.

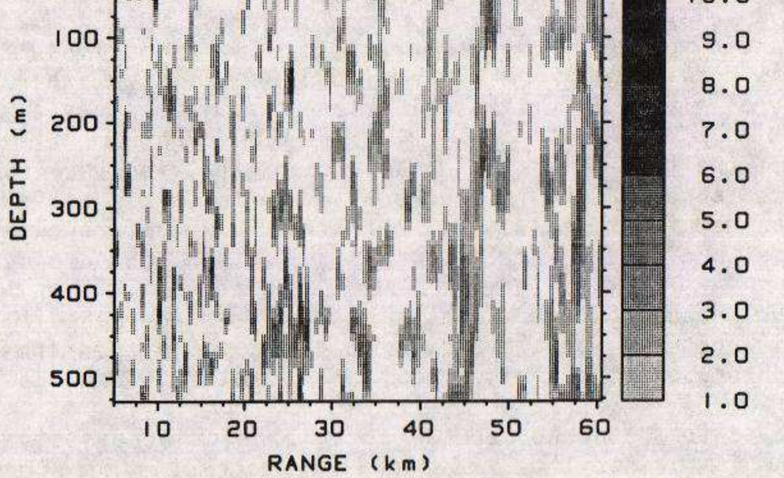

Figure 2. Minimum variance ambiguity surface for the same conditions as Figure 1 but for Arctic impulsive noise.

Figure 2 shows the ambiguity surface for the impulsive Arctic noise model where the ambiguity surface is clearly less ambiguous than for the Fishing boat noise model. The Arctic model differs in usually having one dominant source present in any one estimate so that there are few cross-terms generated between sources in the formation of the covariance matrix. This difference is reflected in fewer peaks in the noise background and higher array gains.

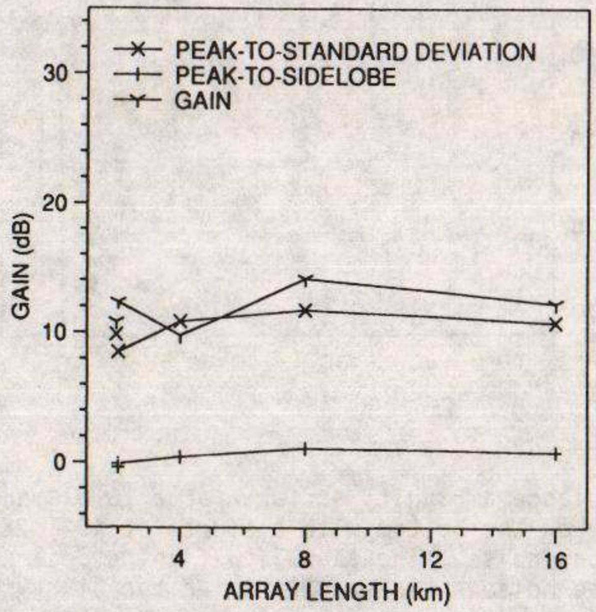

Figure 3. Array performance for the same conditions as Figure 1 but for fishing boat noise and varying array length. Performance in surface noise is shown as isolated points.

Figures 3 and 4 summarize performance estimates from simulations for the two noise models for arrays from 0.33 km to 16 km long. Within the statistical uncertainty of a few dB for these 16 element equispaced arrays performance is not noticeably dependent on array length. In all three measures of performance, the gain in Arctic noise exceeds that for the Fishing boat model. The gain predicted for the fishing boat noise model is and should be similar to that obtained for the classical surface noise model shown in Figure 3 and is 8 dB less than that in arctic noise. To obtain the same gain in both noise fields would require six times as many sensors in fishing boat noise as in Arctic noise. The additional cost that would be incurred, if the fishing boat noise model were used for the arctic noise scenario, confirms the importance of using a representative noise model to estimate performance.

Adding more sensors to a horizontal array should increase the array gain for measured data provided that the signal is correctly modelled in the signal processor. Figure 5 shows that the simulator does indeed demonstrate this effect for the 16 km array. The linear fit to array gain is however fortuitous as each gain estimate is subject to an uncertainty of a few dB.

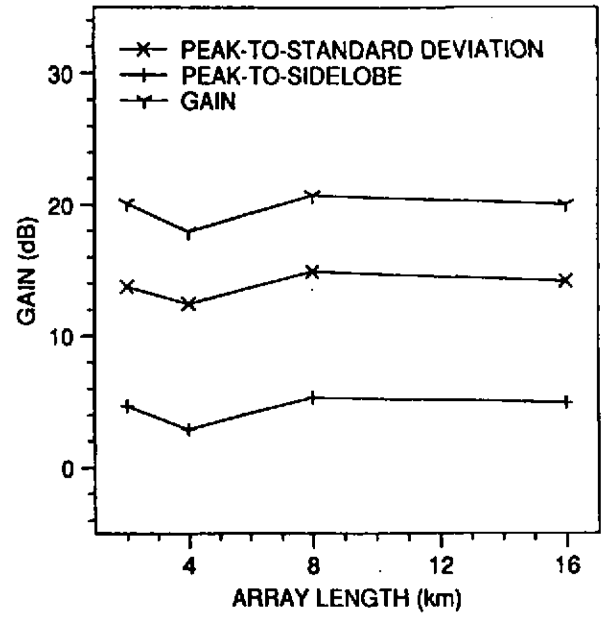

Figure 4. Array performance for the same conditions as Figure 1 but for Arctic impulsive noise and varying array length.

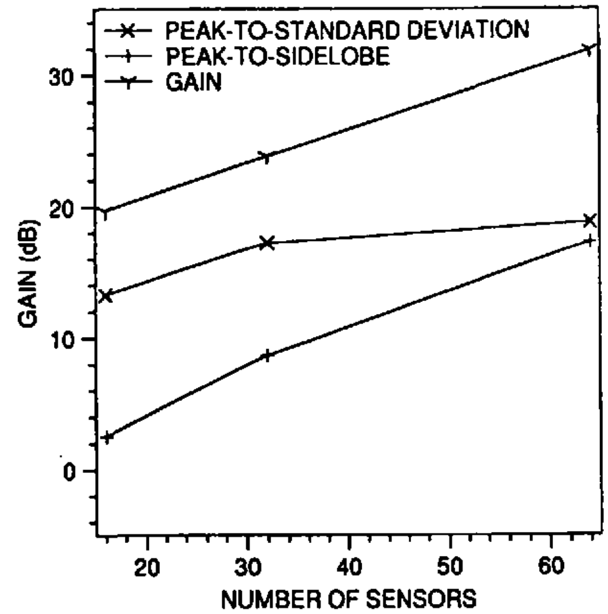

Figure 5. Array performance for the conditions of Figure 1 but for Arctic impulsive noise and a varying number of hydrophones in a 16 km long array.

Whether such gains can be achieved depends on whether the coherence of a single mode remains sufficiently high over 16 km as is required for the simulated gains to be achieved.

Performance for equispaced vertical line arrays that span the water column was compared with that of horizontal arrays with the same number of hydrophones. As for horizontal arrays the vertical arrays had gains that were highest for the Arctic noise model. However for all three noise fields, depth and range ambiguity surfaces were more ambiguous for the vertical arrays than for the horizontal arrays. Array gains, peak-to-sidelobe ratios and peak-to-background ratios were also consistently poorer for the vertical arrays.

5. CONCLUSIONS

Simulated performance for an equispaced horizontal array was found to be substantially better for the Arctic impulsive noise model than for classical isotropic surface noise models or for models representing a distribution of fishing boats in an environment otherwise the same. Improvements were seen in array gain, peak-to-sidelobe ratios and peak-to-standard deviation ratios in the range-depth ambiguity surface. Vertical line array performance was generally poorer than horizontal line array performance for all three noise fields. These gains are dependent on the single mode signal coherence remaining high over the array aperture and indicate a need to measure such coherence.

6. REFERENCES

[1] J M Ozard,"Matched field processing in shallow water for range, depth, and bearing determination: Results of experiment and simulation,"J. Acoust. Soc. Am. **89**, 744-753 (1989)
[2] B F Cron and C H Sherman,"Spatial-Correlation Functions for Various Noise Models,"J. Acoust. Soc. Am. **34**, 1732-1736 (1962)
[3] M V Greening,"Arctic Ambient Noise Modelling,"DREP Contractors Rep. Ser. 90-16 (1990)
[4] R S Prichard,"Sea ice noise-generating processes,"J. Acoust. Soc. Am. **88**, 2830-2842 (1990)
[5] J M Ozard,"Improving performance for matched field processing with a minimum variance beamformer,"submitted to J. Acoust. Soc. Am.
[6] G M Fricter, C. L. Byrne and C. Feuillade,"Sector-focussed stability methods for robust source localization in matched field processing,"J. Acoust. Soc. Am. **88**, 2843-2851 (1980)