Proceedings of The Institute of Acoustics

SPATIAL COHERENCE OF A SOURCE RECEIVED ON A SEISMIC TOWED ARRAY AFTER LONG RANGE PROPAGATION

A. Plaisant and S. Leroy

THOMSON SINTRA ASM, B.P. 53, 06801 Cagnes-sur-Mer, France

1 - INTRODUCTION

The exprimental results presented in this paper come from data collected during an experiment carried out in Central Atlantic where a towed powerful acoustic source transmitted long single frequency waves in the band 30-120 Hz which were received on a 96 channels standard seismic towed array after propagation to a distance up to 2000 kilometers.

The area was chosen for its regular deep bottom and low trafic in order to minimize propagation parameters variations and ambient noise. Both source and array were towed at low speed on straight divergent courses as shown in Fig.1 ; speed and headings were chosen to keep the source near the acoustic axis of the array. Single frequency pulses of 30 minutes duration were transmitted continuously, switching from one frequency to the other ; four frequencies were used, the same one appearing every two hours.

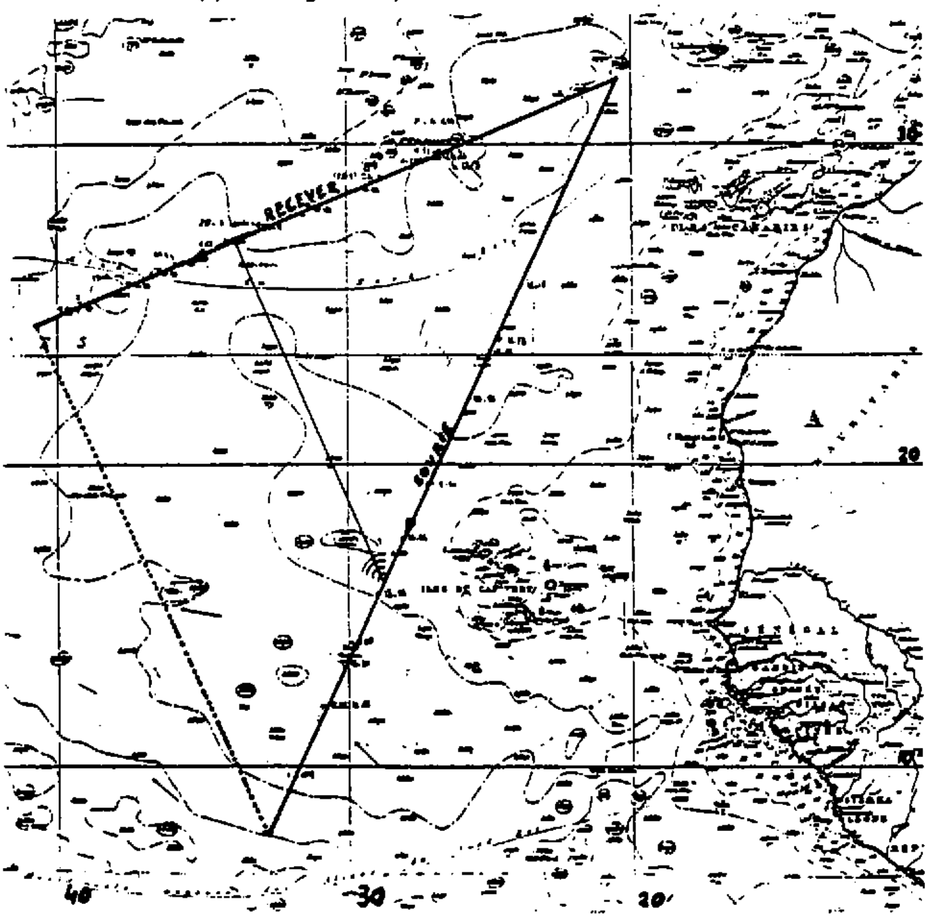


Fig. 1 - Ships courses during the experiment

SPATIAL COHERENCE OF A SOURCE RECEIVED ON A SEISMIC TOWED ARRAY AFTER LONG RANGE PROPAGATION

We discuss here results obtained with only one frequency : 82 Hz for 3 sequences of about 5 minutes duration corresponding to distances of 330 , 817 and 1790 km.

The distance between the 96 phase centers of the seismic array was 25 meters in most cases except for those array elements which were equiped by additional depth and compass sensors. The array was towed at a depth of 40 meters, the source at 60 meters. Velocity profiles were regularly measured from both ships using XBT's showing the presence of a surface duct of about 150 meters at the beginning of the experiment (northern latitudes), progressively decreasing in width as latitude decreases to about 55 meters at the lower latitudes reached by the source ship at the end of the experiment. The source was then just below the surface duct whereas the receiver remained in the duct during all the experiment.

We are interested in trying to evaluate the importance of fluctuations of the medium in array gain, depending of array length used and distance. This has been possible because good signal to noise ratio was achieved during most part of the experiment and particularly for the 3 sequences discussed here.

2 - SPATIAL COHERENCE

The medium can be responsible for array gain degradation by two different mechanisms : wave front curvatures and random fluctuations.

If the wave front is curved but stable, there will be a loss if the array processing is not adapted to the signal wave front, like for instance if one use classical beamforming which assumes the wave front is a plane wave whereas the actuel wave front is curved. In this case, it would be possible to recover the whole available array gain by correctly modeling the wave front, which might be very complicated since it depends of the unknown source position. If there is no fluctuation, the cross spectrum matrix Γ_S of the source is of rank 1 and the source will be considered as being perfectly coherent.

If the signal from the source suffers random fluctuations between sensors within the observation time, there will be also an array gain loss ; the cross spectrum matrix will not be of rank 1 and we say that the source is not perfectly coherent.

2-1 Classical beamforming

This type of processing is sensible to the two effects mentioned above.

The data corresponding to the three five minutes sequences at 330, 817 and 1790 km was processed using the double FFT technique with a frequency resolution of 1/16 Hz. A few bad sensors were removed but no correction was made to compensate for the non exactly constant distance between sensors and the fact that the 96 sensors were sampled not exactly at the same time but sequentially in two blocs of 48 within one sampling period.

For all sensors (except bad sensors), the signal to noise ratio achieved for the 3 sequences of interest was ranging from 10 to 23 dB.

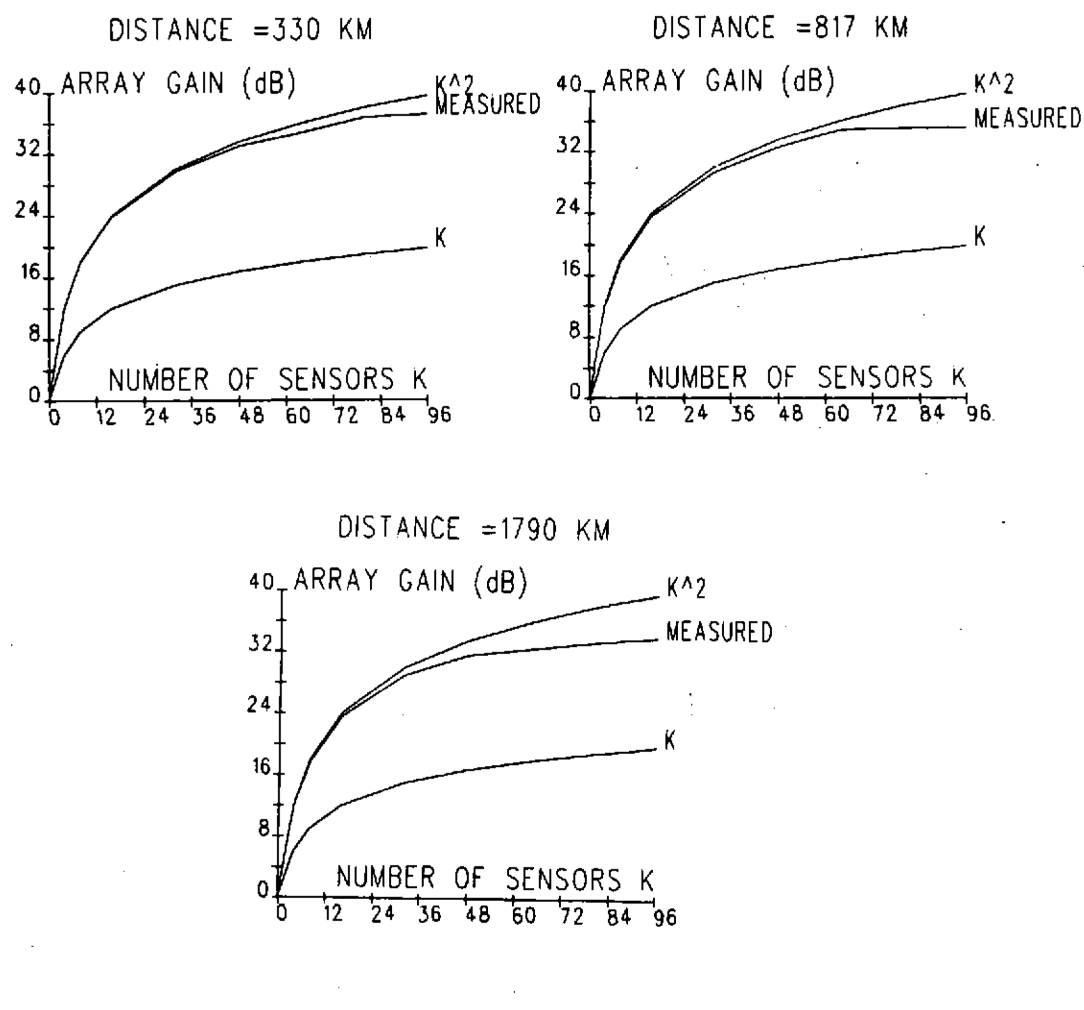
We define the classical array gain G_{cla} as the ratio between the power at the classical beamformer output to the power on one sensor, having before processing equalised this power for all sensors.

In the theoritical case where the signal is the same on all sensors, this gain equals K^2 where K is the number of sensors. If the signals from the source are completely incoherent, the gain equals K.

SPATIAL COHERENCE OF A SOURCE RECEIVED ON A SEISMIC TOWED ARRAY AFTER LONG RANGE PROPAGATION

The difference between the actual measured gain and K^2 is significant to the degree of curvature of the wave front and fluctuations, both effects alltogether.

Figure 2
Classical array gain versus array length



We have computed $G_{cla}(K)$ for different values of K from 4 to 96 corresponding to array lengths ranging from 75 m to 2375 m and results are shown on Fig. 2 ; the difference between theoritical and actual gain increases with array length and distance but remains relatively small, less than 6 dB.

SPATIAL COHERENCE OF A SOURCE RECEIVED ON A SEISMIC TOWED ARRAY AFTER LONG RANGE PROPAGATION

2-2 Optimum beamforming

We consider a processor which computes the quantity $\gamma_y = D^+ \Gamma_s D$ where + means transposed conjugate and D is a direction vector.
Γ_s is the crosspectrum matrix of the signals received on this array from the source (no noise).

If the elements of D are exponentials of regularly increasing delays, the processor is a classical beamformer. If one looks for a vector which maximizes the output γ_y under the constraint $D^+ D = K$, one finds :

$$D = \sqrt{K}\, V_1$$

where V_1 is the eigen vector associated with the maximum eigen value of Γ_s. The processor is then called optimum processor. It compensates for all stable wave front and array distortions and is sensible only to fluctuations. Of course, these distortions have to be known if one wants to find the source direction from the vector V_1.

If λ_i and V_i are the eigen values and eigen vectors of Γ_s, the matrix can be written as :

$$\Gamma_s = \sum_{i=1}^{K} \lambda_i V_i V_i^+$$

If we take $D = \sqrt{K}\, V_1$, we find the optimum processor output :

$$\gamma_y = K V_1^+ \Gamma_s V_1$$

$$= K \sum_{i=1}^{K} \lambda_i V_1^+ V_i V_i^+ V_1$$

$= K \lambda_1$ because the eigen vectors are orthogonal.

If there are no fluctuation, Γ_s is of the form

$$\Gamma_s = \gamma_s X X^+$$

γ_s being the source power in the analysis frequency band, on one sensor.

In this case, Γ_s is of rank 1, the only non zero eigen value equals γ_s and X is the associated eigen vector. We say in this case the source is perfectly coherent. The beamformer output is, in this case :

$$\gamma_{y\,coh} = X^+ \gamma_s X X^+ X$$

$$= K^2 \gamma_s$$

and we recover the theoritical gain K^2.

With the same definition as for the classical gain, the optimum gain is :

$$G_{opt} = \frac{K \lambda_1}{\gamma_s}$$

We have computed G_{cla} and G_{opt} for arrays of only 8 sensors with increasing length between sensors so that the total array length used ranged from 175 m to 2375 m.

SPATIAL COHERENCE OF A SOURCE RECEIVED ON A SEISMIC TOWED ARRAY AFTER LONG RANGE PROPAGATION

Figure 3
Gains with 8 sensors arrays of various length

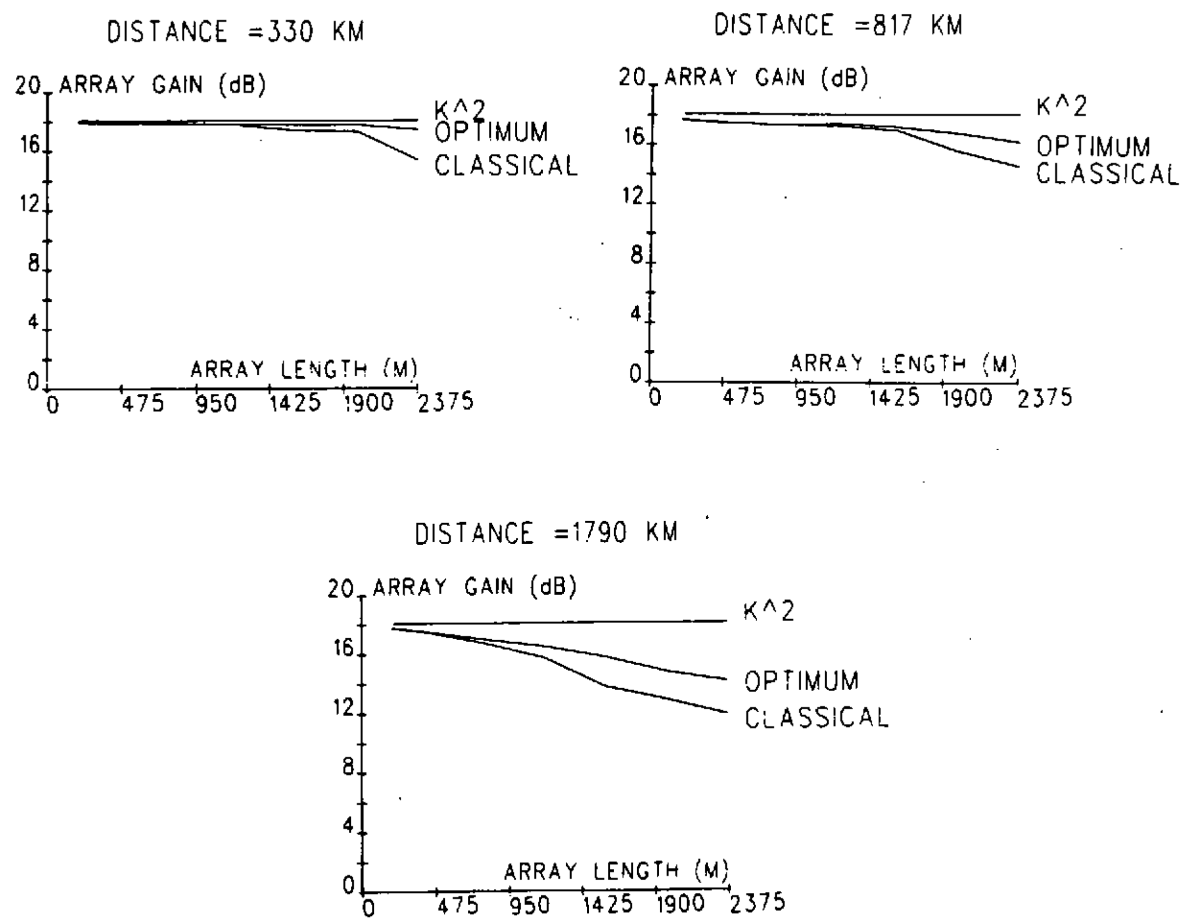


Fig. 3 shows variations of these gains with total array length and distance. One can see that optimum gain is always better than classical gain as expected and losses even with optimum processing are increasing with distance. This means that fluctuations are more important at long distances, and if one considers that at the end of the experiment, sea state conditions were better than at the beginning, keeping hydrophones movements in the array less important, one concludes that these fluctuations are due to the medium itself.

2-3 A measure of source spatial coherence

We would like to define the source spatial coherence by the ratio between outputs of the optimum beamformer in case of actual signals and perfectly coherent signals. As already seen, the output of the optimum beamformer is :

$$\gamma_y = K\ \lambda_1$$

with a perfectly coherent source one has

$$\gamma_{y\ coh} = K^2\ \gamma_s = \sum_{i=1}^{K} \lambda_i$$

so that

$$\frac{\gamma_y}{\gamma_{y\ coh}} = \frac{\lambda_1}{\sum_{i=1}^{N} \lambda_i}$$

This ratio measures the source spatial coherence loss but is impossible to evaluate correctly in real cases where noise is always present because the smaller eigen values become representative of noise rather than signal.

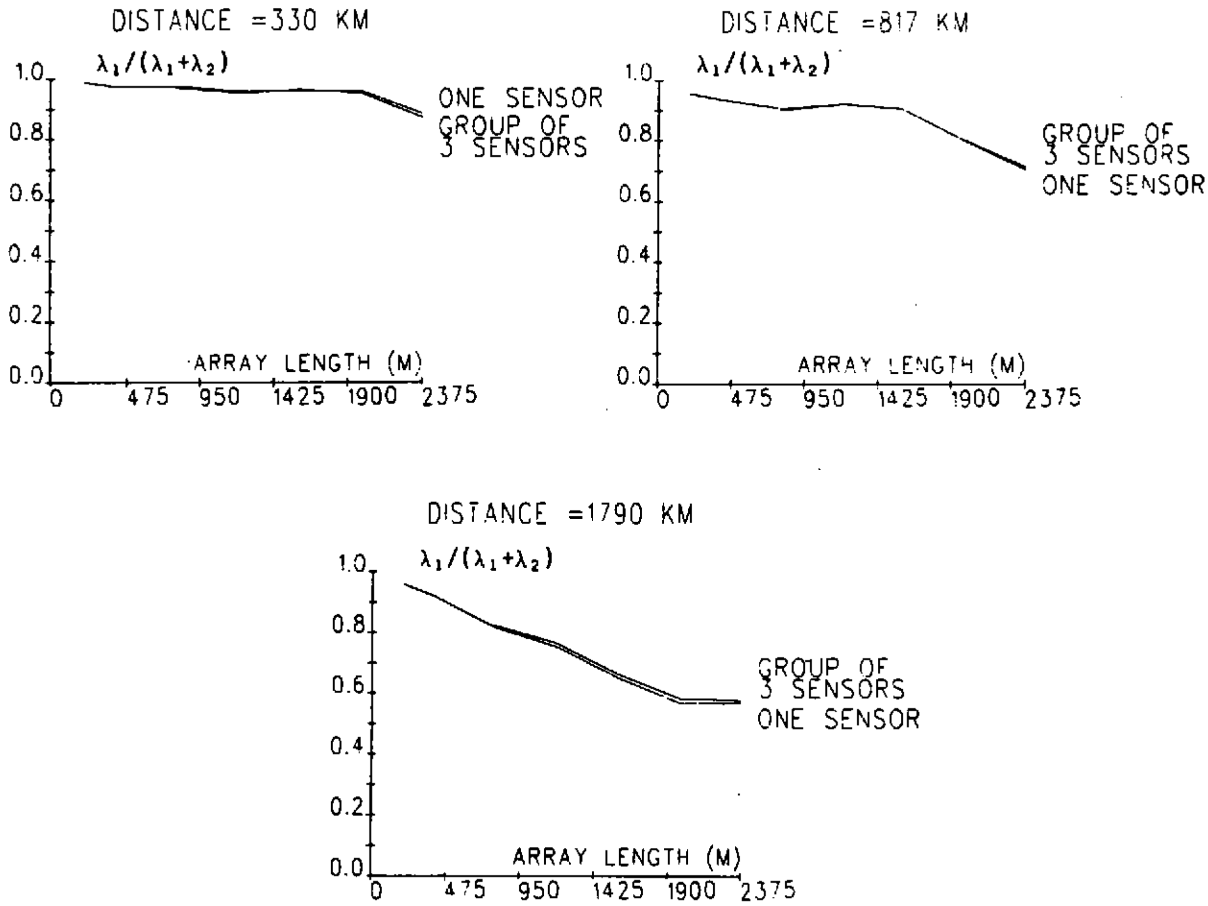
We have here chosen to use only the two highest eigen values and compute the ratio $\lambda_1/(\lambda_1+\lambda_2)$ function of array length both for sensors alone and by replacing one sensor by the sum of the sensor plus its two neighbours.

Fig. 4 shows the decrease of the ratio $\lambda_1/(\lambda_1+\lambda_2)$ with array length and distance. There is very little difference between sensors alone and groups of sensors.

SPATIAL COHERENCE OF A SOURCE RECEIVED ON A SEISMIC TOWED ARRAY AFTER LONG RANGE PROPAGATION

Figure 4

Ratio $\lambda_1/(\lambda_1+\lambda_2)$ for 8 sensors arrays of various lengths



SPATIAL COHERENCE OF A SOURCE RECEIVED ON A SEISMIC TOWED ARRAY AFTER LONG RANGE PROPAGATION

CONCLUSION

We have discussed in this paper experimental results about source spatial coherence obtained from a long range, low frequency propagation experiment using as a receiver a standard seismic towed array of acoustic length 2375 meters. We have analysed the effects of both wave front curvatures and fluctuations on classical and optimum beamforming array gains on the source signal. Results show a decrease of both of these gains with increasing array length and distance. The loss with respect to perfectly coherent signals after optimum beamforming reaches a maximum of 4 dB with the maximum array length used and for the largest distance considered : 1790 kilometers. In this case, the loss of classical beamforming compared to the non fluctuant plane wave response is also maximum and reaches 6 dB.

Two types of fluctuations are responsible for source spatial coherence losses : those due to the medium itself and those due to sensors movements. The two effects have not been separated but if one considers that sensors movements increases with sea state, it should have been less important, in our experiment, as distance increased, meaning that random fluctuations due to the medium increase with distance or spatial coherence decreases with distance.

ACKNOWLEDGEMENTS

The experiment was organized by the Direction Technique des Constructions Navales Laboratory GERDSM in Le Brusc (DCAN Toulon) and this work was supported by contract n° S.85.48.826.974 T.