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15 January 1983

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(Reprinted from Proceedings of ICASSP 82, IEEE International Conference on Acoustics, Speech and Signal Processing, held in Paris, France, 3-5 May 1982, Vol. 2. New York NY, The Institute of Electrical and Electronic Engineers, 1982: pp 811-4).

15 January 1983

This memorandum has been prepared within the SACLANTCEN Underwater Research Division as part of Project 21.

APPROVED FOR DISTRIBUTION

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Division Chief

VIRTUAL BEAMS FROM AN FFT BEAMFORMER AND THEIR USE TO ASSESS THE QUALITY OF A TOWED-ARRAY SYSTEM

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ABSTRACT

Linear towed arrays with sophisticated signal processing systems have become popular for passive sonar and seismic prospecting. This is due to the ease of mobility and the large spatial gains achievable. However, because these systems are mechanically and electronically complex and not constrained to remain linear, the potential for degraded performance is a constant problem. An onboard data-processing system has been developed to assess the performance of towed-array systems. This paper discusses an extension to that system in which the beams steered beyond endfire (virtual beams) can be used to determine the sidelobe suppression capability and self-noise of the sonar and to flag system degradation. This is illustrated by examples from recent ambient-noise measurement exercises.

INTRODUCTION

The information available from virtual (non-acoustic) beams has enabled the Ambient Noise Group of the SACLANT ASW Research Centre to measure undersea ambient noise with a towed-array system having sidelobe suppression levels consistently of the order of 50 dB. Twenty to 25 dB is usually considered normal for a towed array; 30 is considered excellent; 40 to 50 is unbelievable and is generally considered out of the realm of possibility. This paper describes techniques that can be used to achieve 40 to 50 dB sidelobe suppression levels and gives examples to illustrate the utility of the techniques and the reality of the improved performance.

BACKGROUND

The towed array is an important tool for undersea acoustic measurements. It has been widely used by the petroleum industry for seismic prospecting and by acousticians for undersea acoustic-propagation and ambient-noise measurements. It consists of a line array of hydrophones enclosed in a soft plastic oil-filled tube of up to 10 cm in diameter. The electrical response to the acoustic signals received at each hydrophone are sent up a cable to the towship and processed to extract the desired information.

To achieve good performance, such systems make use of a large number of channels and complex processing equipment; faults of any kind can happen at any time and a constant monitoring of the system's performance is important to detect the times of any resulting degradations.

A system in excellent condition should have low self-noise and sidelobes suppressed 40 to 50 dB. This can be monitored in real time through the use of virtual beams. If the system is not in excellent condition the virtual beams can be used to help "debug" it. This has been the case for the recent SACLANTCEN ambient-noise measurement exercises.

VIRTUAL BEAMS

Figure 1 illustrates the data acquisition and processing systems used by the Centre for ambient-noise measurements. Signals from 40 hydrophones in the array are digitized at 5 kHz (12 bits A/D). A fast fourier transform (FFT) is performed on each series to obtain complex frequency spectral components by a MAP-300 array processor. The 40 sets of complex spectral components are augmented by 24 zeroes and a second (spatial) FFT performed to produce 64 sets of complex spatial spectral components. The magnitudes squared of these latter spectra are proportional to the output powers of 64 beams. Such a beamformer was proposed by Williams <1> and at present enjoys popular acceptance.

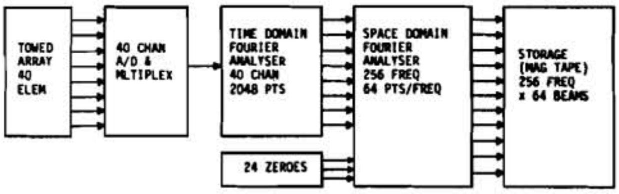

Fig. 1 Towed array data acquisition and processing system for ambient noise measurements

At frequencies below design frequency (which is 1500 Hz for the following figures), virtual beams will be produced automatically by the FFT beamformer. These are the beams that are formed by time delaying (in a time-domain beamformer) or phase shifting (in a frequency-domain beamformer - FFT beamformer for example) the signals from the array of hydrophones more than is necessary to form an endfire beam.

Since the virtual beams do not have main lobes in real acoustic space, they are usually ignored. However, it will be illustrated below that they contain energy from various incoherent sources of self-noise and coherent acoustic energy through sidelobes in the acoustic domain. Simple statistics calculated from the outputs of these virtual beams can be used to help determine the levels and sources of self noise, the operating condition of the system, and the levels of sidelobe suppression. These statistics can also be used to signal the existence of problems and to guide in locating them.

For a given frequency the FFT beamformer computes the beam data from the hydrophone data according to the formula:

$$B_j = \sum_{n=1}^{64} A_n H_n e^{-in\phi(j)} \qquad (1)$$

B_j is the complex amplitude of beam number j at frequency f.

A_n is an amplitude weight applied to hydrophone number n.

H_n is the complex amplitude of hydrophone number n at frequency f.

$\phi(j)$ is the difference in phase between adjacent phones to steer beam j at direction α_j; ϕ is given by :

$$\phi(j) = \frac{2\pi j}{64} = \frac{2\pi d}{\lambda}\cos(\alpha_j) \quad (\text{modulo } 2\pi), \qquad (2)$$

which can be simplified as:

$$\frac{d}{\lambda}\cos(\alpha_j) = \frac{j}{64} \quad (\text{modulo } 1). \qquad (3)$$

d is the distance between successive hydrophones, λ is the wavelength at frequency f.

At low frequencies, d/λ can be small and some of the beams may have a $\cos(\alpha_j)$ outside the window (-1,+1). These are the virtual beams.

The FFT beamformer produces beams with steering angles that vary with frequency and have beam spacings that increase away from broadside. Figure 2 illustrates the effect and the separation between real and virtual beams. The steering angle relative to the axis of the array is indicated on the diagram; the beams corresponding to numbers outside the circle are virtual beams. Note that at the design frequency of the array, the wavelength is twice the inter-element spacing and there are no virtual beams.

In Fig. 3 and subsequent figures beams have been renumbered so that beam 32 is broadside; beams

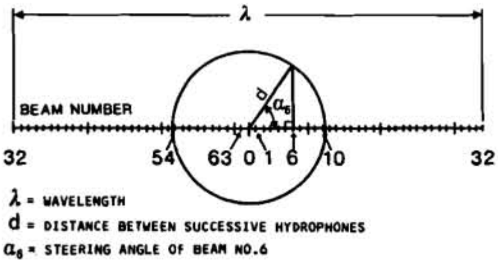

Fig. 2 Simple diagram to determine beam steering and whether the beams are real or virtual

with lower numbers are forward of broadside, those with higher numbers are aft.

There are at least three ways in which the virtual beams receive energy.

1. Virtual beams, like real beams, have sidelobes that extend into real space. If the sidelobe rejection of the beamformer is poor, strong sources from acoustic space can "leak" acoustic energy into the virtual beams
2. There could be energy propagation in the array at a speed lower than the speed of sound in the sea. This energy would appear on one virtual beam.
3. There is energy on the hydrophones that is not coherent from one hydrophone to another. This energy may be of acoustic (flow noise), electronic, or mechanical (shocks, vibrations) origin. These incoherent noises are spread among all the beams, real and virtual. However they are most easily spotted in the virtual domain because there is normally less energy there to mask them.

The energy in the virtual beams can therefore be invaluable for quality checking and "grooming" the towed-array system.

STATISTICS

Five statistics of the real and virtual beam power time series illustrated in Fig. 3 are used in

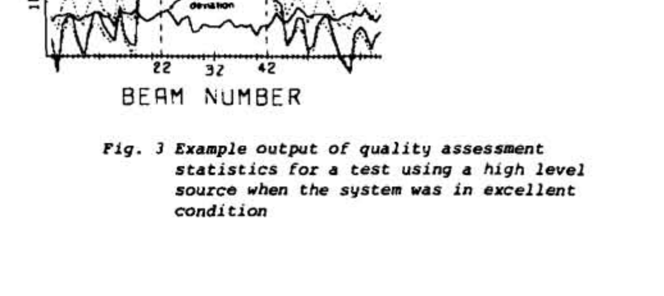

Fig. 3 Example output of quality assessment statistics for a test using a high level source when the system was in excellent condition

the quality assessment and grooming of the sonar system. They are the following:

For each beam
- average beam power level
- median level
- geometric mean power level (dB average)
- standard deviation

For beam pairs
- Spearman's rank correlation coefficient with associated confidence levels <2>.

Spearman's method estimates the degree of association between two series of measurements. Because it operates on the ranks of the observations (the order of occurrence in magnitude of the spectral estimate) and not on the magnitude, it is a distribution-free (non-parametric) statistic. The coefficients are entered into a matrix with rows and columns defined by beam numbers, such as in Fig. 3. This correlation matrix contains the correlation coefficients above the main diagonal and the significance levels on and below the main diagonal for a beam of the given column correlated with the beam of that row. Because of display limitations, only the even-numbered beams have been used in the matrix. If the significance levels are below three standard deviations (corresponding to a level of confidence of 99.73%) the values are replaced by zeroes. At the reduction level used on the figures, the areas of high correlation appear dark, below the main diagonal. Such a display facilitates rapid recognition of possible system problems, since it is generally desirable to have independence among the various beam power time series. The area above the main diagonal, which contains the correlation coefficient, is unimportant for the present discussions.

The rationale for choosing the above set of five statistics for monitoring system performance is the following. The average power detects high-level transients, the dB average detects drop-outs; the median is insensitive to any of these transients; the standard deviation measures the scatter in the beam output - too much or too little scatter indicates possible problems. Because these statistics are sensitive to different types of malfunctions, anomalous behavior of the system can be readily detected by monitoring their values and their differences. Finally, as mentioned previously, the correlation matrix indicates possible problems if there are large regions of correlation among the beams (a significant part of the area below the main diagonal is dark). Also, as will be illustrated below, the correlation matrix is useful in helping to determine the actual sidelobe suppression levels of the system.

RESULTS AND DISCUSSION

Figure 3 was obtained during a test of the sidelobe suppression of the system. A high-level source was used so that the virtual beams would be dominated by that source on their sidelobes.

The three power estimates for the beams (median, geometric, and power averages) all show an excellent dynamic range. The virtual beams are 43 to 53 dB lower than the maximum beam. The rank correlation matrix shows that all the virtual beams are correlated with that maximum beam, which means they are dominated by the strong source near forward endfire. It also shows no correlation between that source and the other real beams, which means that the real beams were dominated by the ambient noise received from azimuths within their main lobes, without interference from the high-level source. High variation from beam to beam in the virtual space, which is evident in this figure, is a characteristics of sidelobe domination.

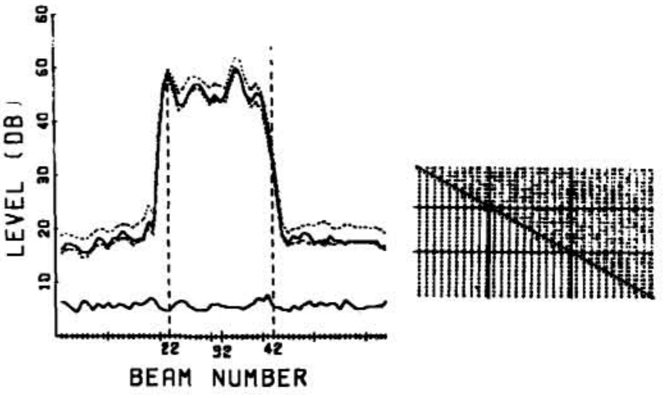

Fig. 4 Representative output of quality assessment statistics for normal ambient noise measurements when the system was in excellent condition

Figure 4 is a representative output from a normal ambient-noise measurement. The high-power source has been shut off; the matrix shows no correlations at all. The virtual part of the beam plot is flat. Here the self-noise of the system is incoherent from hydrophone to hydrophone and is spread uniformly over all the beams. The real beams are much higher in level, which means that they are dominated by the ambient noise since their self-noise is at the same level as that in the virtual beams. This illustrates that examination of the virtual beam levels is a fast way of determining whether self-noise is interfering with the measurement.

The average self-noise of a single hydrophone can be calculated from the average virtual beam level, which in this case is dominated by electronic and flow noise. The component due to flow can be easily determined by varying the tow speed and hence, the level of the flow noise.

Figures 3 and 4 were obtained with the sonar system in excellent condition, i.e. after the information from an analysis of the virtual beams had been used to debug it. This has always been necessary at the start of a measurement exercise. There have always been errors in the system. Some are difficult to detect even when it is obvious from the virtual beams that they exist. The next two examples illustrate the use of virtual beams as a diagnostic tool.

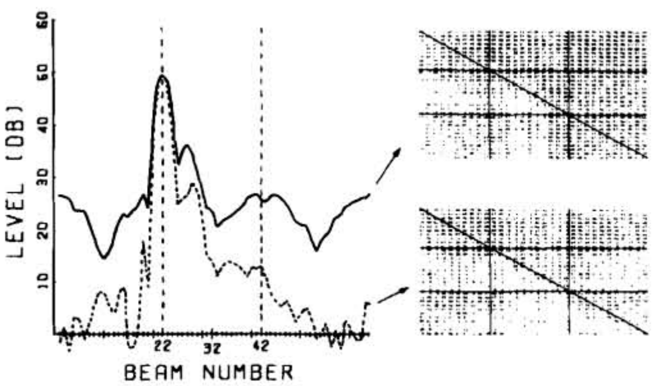

Fig. 5 Examples of quality assessment statistics with a noise source when the system has a fault (ch. 6 and 9 switched – solid curve and top matrix) and after fault correction (dashed curve and bottom matrix)

Figure 5 compares two cases, one bad and one good. They correspond to a similar situation as in Fig. 3: a strong source near forward endfire. The continuous plot illustrates a problem. Here, the virtual beams are only 25 to 35 dB down and have a peculiar pattern. The real beams aft of broadside are not significantly different from the virtual ones. The problem is also evident from the upper rank correlation matrix, where most beams are correlated with the source near forward endfire. In this condition the sidelobe suppression level of the system was 25 to 30 dB. For some measurements this may be acceptable performance. After extensive "trouble shooting" it was discovered that during a reconfiguration of the system the coaxial cables for channels 6 and 9 had been exchanged at the input to the beamformer. The sidelobes were 45 to 50 dB down once the cables were switched back to their correct positions, as is evident from the dashed curve in Fig. 5. The lower rank correlation matrix for this corrected case shows correlation only between the virtual beams and the main arrival, as would be expected from a perfect system.

The last case takes advantage of not only the virtual beam display but also the different statistical outputs of the system.

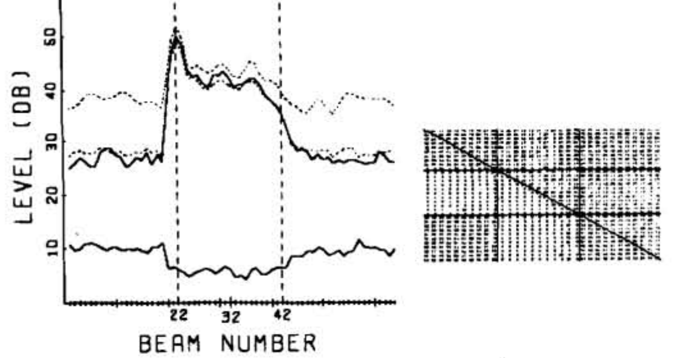

Fig. 6 Example of quality assessment statistics for a time period of mechanical shocks (sounds like "clonks") on the hydrophones

Figure 6 shows a beam-output plot obtained from time series of 50 successive noise samples acquired during a normal measurement period without a noise source. The power average is the top dashed curve followed by, in turn, the solid curve of the median levels, the dashed curve of dB averages and the solid curve of standard deviations. The large differences between the power averages and the median and dB averages of the virtual beams are indications of problems. The abnormally high standard deviations of the virtual beams also indicate that a problem exists. The corresponding rank correlation matrix shows that all virtual beams are correlated and their levels are approximately equal.

The source of the problem was mechanical shocks on the hydrophones. When listened to on the aural output the hydrophones had sounds that might be described as "clonks". They occurred on every hydrophone, but were not frequent enough to disturb the hydrophone statistics. This is because the hydrophone levels are dominated by the ambient noise most of the time. This form of self-noise was due to lack of oil in the array and became worse when bad sea conditions caused too much transverse motion of the cable and array. After the sea-state and subsequent array motion decreased, the hydrophones went back to normal.

SUMMARY

Towed-array sonar systems for undersea acoustic measurements are necessarily very complex. There is an almost unlimited number of possible faults that could degrade their performance. This might mean that the system could achieve only a maximum of 20 to 30 dB sidelobe suppression level. It has been shown that the virtual beams can be used to monitor system performance without interfering with normal operation; they can also provide clues to the possible sources of degradation. Once faults are found and corrected the measurements may continue with the system in nearly perfect operating condition. The utility of the virtual beams and the reality of such high-level performance have been demonstrated by results from recent ambient-noise measurement exercises by SACLANTCEN's Ambient Noise Group. Others could use the same techniques and expect improved system performance. In many cases their systems could achieve 40 to 50 dB sidelobe suppression levels as did the Centre's towed array system, which was not in any way particularly special.

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