A REAL-TIME SYSTEM FOR TOWED-ARRAY CALIBRATION AND PERFORMANCE ANALYSIS,
OR
HOW TO GET 50 dB SIDELOBES FROM A TOWED ARRAY

by

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ABSTRACT

Sidelobe suppression levels of 30 dB for a towed array are generally considered excellent; values above that are considered exceptional or unachievable. However, 40 to 50 dB suppression levels have been achieved and maintained throughout most of the measurements conducted within the last two years with SACLANTCEN's towed array and can be considered the norm rather than the exception. The key to achieving and maintaining this high level of performance is to keep the system free from faults and properly groomed. The techniques by which degraded performance is detected in real-time are discussed and illustrated by examples from past measurements. When the faults were repaired, the system performance returned to its usual high level. Similar techniques could be implemented by other researchers, with high expectations of receiving similar performance from their towed-array sonars.

INTRODUCTION

Sidelobe suppression levels of 30 dB for a towed array are generally considered to be excellent and 40 dB or above are considered the exception or unachievable. However, experience with SACLANTCEN's towed array demonstrates that it is possible for performance to be sufficiently high that sidelobe suppression levels of 40 to 50 dB can be the norm rather than the exception. This has been achieved and maintained throughout most of the ambient-noise measurements conducted by SACLANTCEN's Ambient Noise Group during six measurement exercises within the last two years.

There is nothing particularly special or unique about the Centre's towed array sonar system that achieved this high-level performance. If kept in perfect condition this sonar, like many others in use today, is capable of achieving and maintaining such performance. The key is to keep these systems free from faults and properly groomed. There is nothing new in the idea that good array grooming leads to improved performance. Achieving 40 to 50 dB sidelobe suppression continuously and the techniques that make this feasible in real-time, however, are new. The reality of such performance and the techniques for detecting degraded performance are discussed and illustrated by examples of faults that occurred during measurements.

1 BACKGROUND

In the past two years a towed array has been used extensively at SACLANTCEN. Six major measurement exercises have been conducted in the Mediterranean and in the eastern North Atlantic to measure ambient noise directionality and beam-noise statistics. A schematic of the system used for the series of measurements is shown in Fig. 1. Descriptions of the measurement techniques and the data analysis products are given in <1-3>. A summary of the measurements is given in <4>.

Experience prior to this series of measurements had suggested that it is vital to monitor the data from towed arrays in real-time. The towed-array sonar is a very complex system that, like any other sonar system, is subject to electrical and mechanical faults. It is even more vulnerable to degradation than other "conventional" sonars because it is not constrained to remain either linear or horizontal; deviations from either can degrade the system performance, even though it might be electrically and mechanically sound.

Because of the high potential for degraded performance by the towed array, techniques were developed to measure the system's performance and to assess the quality of the acoustic data. The techniques became more versatile and inclusive as experience was gained. This resulted in the present onboard analysis system, which can not only monitor the performance of the sonar system but is actually an onboard relative-phase-and-amplitude calibration system. In addition, the quality-assessment products generated by the system provide clues to faults that cause degraded performance. Once degraded performance is discovered it is usually not long before the fault is found and corrected. The measurements can usually be continued with a near-perfect system.

There were two discoveries that greatly enhanced the capabilities of the towed-array sonar analysis system. The first was that the towship could actually be used as a broadband sound-source to check the system. When the active rudder is idling it makes a terrible racket, up to 30 dB above the normal towship noise. It is thus an excellent source that is always available for a complete acoustic check of the system without the usual deployment problems of towed sources.

The second important discovery was that the virtual beams can be used to help judge the quality of the data and to assess the array performance because they provide information that is not otherwise available. These virtual beams are the beams that correspond to phase shifts or time delays greater than those corresponding to an endfire beam. They are produced by the FFT beamformer at all frequencies below design frequency. There are at least three ways in which the virtual beams can receive energy.

a. 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.

b. 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.

c. 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 (shock, vibration) 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. A more complete description of virtual beams and their use for system performance assessment is given in <6>.

2 APPROACH

The usual procedure for assessing the performance of the towed-array system is to collect time-series of beam levels from all beams produced by the FFT beamformer. Approximately 50 spectral samples per beam per frequency analyzed are considered adequate. Inverse FFTs are used to convey the beam data to analogous time-series of hydrophone data for all hydrophones of the array. Time-series of the phase relative to that of an "average hydrophone" are obtained from the hydrophone data. The following statistics are calculated from these three types of time-series data.

- Percentile levels of 10, 25, 50 (median), 75 and 90
- Average power levels
- Geometric mean power levels (dB average)
- Standard deviation of the decibel or phase-angle time-series
- Percentile deviation of the phase angles, which is the quartile spread normalized to give the same value as the standard deviation for a gaussian distribution
- Spearman's rank correlation coefficients and associated confidence levels for beams correlated with all other beams.

The above statistics are used to generate plots of:

- Beam level versus beam number or azimuth angle
- Hydrophone level versus hydrophone number
- Phase angle versus hydrophone number
- Spearman's rank correlation matrix

The combination of the towship noise and the virtual beams provides a very powerful tool to debug and calibrate the whole system. The statistical outputs used for checking data quality are:

- Hydrophone amplitude plots, which show power average, dB average, median and dB standard deviation of hydrophone power series versus hydrophone number. These can be used to detect anomalous behaviour of hydrophone channels.

- Hydrophone phase plots, which show the average, median, standard deviation and percentile deviation for the phases of the hydrophones relative to an "average" hydrophone, after removing the theoretical time shift for each hydrophone
- Beam level plots, which show power average, dB average, median, standard deviation and (power average - dB average) of the beam power series versus beam number. These give a measure of the sidelobe suppression on the self noise and can be used to detect actifacts in the beamformed outputs.
- Beam polar plots, which show median beam versus beam heading for real beams
- Spearman's rank correlation matrixes, examples of which are given as parts of Figs. 7, 10 and 11.

The top half gives 100 times the Spearman's rank correlation coefficient, which measures the correlations of the beam power time series for each set of two beams. Below the diagonal are the corresponding confidence levels, which are zeroed when the confidence level is low, and printed only if the confidence level is high enough that the beams are correlated.

3 THE TOWSHIP AS A NOISE SOURCE

The MARIA PAOLINA G., SACLANTCEN's research vessel, is neither particularly quiet nor noisy in normal operation, but has an active rudder that is very noisy when idling. The active rudder, consisting of an electric motor with a variable-pitch screw mounted on the ship's rudder, is used to manoeuvre the ship at low speeds. When idling, it rotates at high speed at zero pitch, generating cavitation and mechanical noise. The noise it creates is at medium frequencies; that is, around 500 Hz to 2 kHz. At lower frequencies, the source is so close to the surface that the Lloyd mirror effect reduces its output greatly.

The noise from the towship noise does not propagate to the array through a single path, as shown in Fig. 2 for deep and shallow water. In deep water, the direct path is usually dominant. In shallow water this is not so and many paths contribute significantly, the dominant one being usually the first bottom-reflected path. The total energy received on the forward endfire beam is greater by 15 to 12 dB in shallow water, and more beams receive the towship noise. Figure 3 gives the noise levels on the forward endfire beam for the ship in normal operation and with the active rudder idling, both for deep and shallow water. It shows that the active rudder can indeed be used as a good beacon to calibrate the system, as its level is well above the range of ambient noise levels, at least at high frequencies.

When such a single dominant beacon is available, the hydrophones all see the same signal, and a relative calibration can be performed. The active rudder has therefore been used as such a beacon at the beginning and end of each measurement, and also at any other time when the system quality needed to be checked. These array-performance tests delay the normal measurement by 15 minutes; they do not require any change in the acquisition or processing system.

4 RESULTS AND DISCUSSION

Figure 4 shows the hydrophone amplitude plots for three different types of averaging power average (upper dotted), dB average (lower dotted), and median (solid) at 750 Hz, for two situations.

The right side corresponds to a shallow-water measurement and shows excellent balance among the successive 40 hydrophones. The absolute level is high and the standard deviation (bottom curve) is the same for all the hydrophones. Apart from hydrophone N° 5 which has 1 dB more sensitivity than the others, the hydrophone plot looks almost perfect. The high level of the standard deviation is an artifact due to the randomness of the source level. The active rudder is very close to the surface and has a daisy directivity pattern caused by the surface. This pattern rotates with the sea surface and gives a very irregular level at the array. The left side shows the hydrophone plots in a deep-water location at the same frequency. Three hydrophones were malfunctioning due to bad contacts in the connectors of the array, and the performance was seriously degraded, as will be shown later.

In deep water, when a single path is predominant, the hydrophones can be calibrated in phase as well as in amplitude. The phase calibration is a bit delicate because the source is close to endfire and a phase unwrapping must be performed before doing any statistical analysis of the phases; in Fig. 5 the plot shows the average (dotted) and the median (continuous) phases of each hydrophone relative to a "reference" hydrophone. The "reference" hydrophone is not a physical one, but rather an "average hydrophone" for each acquisition. The right side shows a good array, with phase variations of 1° to 3° for the different hydrophones. This may be due to inexact positions of the hydrophones in the array, as the phase calculation assumes them to be exactly equidistant. A 3° degree phase error at 750 Hz corresponds to an error in position of 2 cm. The bottom curves show the phase standard deviation (dotted) and percentile deviation (continuous) of the phase with a 30° offset. If the phase had a gaussian distribution, the standard deviation and percentile deviation would be the same. Note that the bottom curves of the graph show that the phase distribution of the 50 successive measurements is not gaussian, as the PCDEV (standard deviation estimated from percentiles) is smaller than the standard deviation estimated by conventional methods.

The left side shows the same phase plot when hydrophones 6 and 9 had been interchanged by mistake. If the phase calibration is done, it will immediately spot such an error. However, the phase calibration is possible only when the signal is coming through a single path and is dominant on every hydrophone with a reasonable signal-to noise-ratio. The phase measurement shown here was for a beacon 15 dB above the omnidirectional noise level.

When the signal from the beacon reaches the array with multipath structure, the phase plots may not make any sense. The quality of the array can still be assessed by using the beam level plots. Figure 6 shows the beam level plots for two situations. Again, power, median, and dB averages are plotted together to help spot any abnormal distribution. On the right is the beam level plot for a near perfect array in deep water. Beam 17 is forward endfire, which receives the direct arrival from the towship. The bottom-bounce arrival is on beams 29 and 30. The virtual beams, 1 to 16 and 48 to 64 , receive the towship on their sidelobes and show the excellent sidelobe rejection of the array. The plot on the left shows a malfunctioning array. It corresponds to the left plot of Fig. 4 which had three bad hydrophones. The sidelobe rejection is not as good as is the previous example. The similar levels of virtual and real beams suggest that the system is seeing the towship on all beams, and does not see the ambient noise at all.

Figure 7 shows the median beam plots and the rank correlation matrixes for two active-rudder tests. The upper matrix corresponds to the continuous curve; they show that the sidelobe rejection is only about 25 to 30 dB. This curve corresponds to the case where hydrophones 6 and 9 had been interchanged. After correction, the lower matrix shows no correlation of the beams corresponding to real space. They really measure ambient noise, without being corrupted by towship noise. The virtual beams are still correlated with the beam towards the towship, but their levels are well below the ambient noise, as can be seen on the dotted curve. The sidelobe rejection capability of the array at that frequency is 45 to 50 dB.

In the example of Fig. 7, the error was found and the performance of the array fully restored. When the array is damaged, repair would sometimes take too much time and it is necessary to decide whether to continue. The virtual beams can be used to evaluate the degree of the degradation. If the performance of the array is not sufficient to ensure good data quality, then the bad channels can be replaced by a combination of their neighbours, providing sufficient, if not optimum performance. This is illustrated in Fig. 8. The phone plots showed two bad channels, 14 and 37. Channel 14 was dead due to a bad contact in one of the vibration-isolation modules in the array. Repair would have taken at least one day of work at sea, and would have precluded measurement at that site. The resulting beam plot appears at the centre and shows only 20 dB of sidelobe rejection, not enough to destroy the measurement, but marginal for the rest of the experiment, as any closeby source would blow up the entire field. Hydrophone 14 was therefore replaced by the average of 13 and 15, and the beam plot on the right resulted, showing 35 dB sidelobe suppression, adequate for continued measurement.

In shallow water, the phase is difficult to measure directly, because the towship noise reaches the array through many paths and the phase plots are often scrambled. An indirect estimation of the phase quality can still be performed by measuring the dynamic range of the beams. Figure 9 shows the beam plots for an active-rudder test in shallow water. Sound from the towship reaches the array through many paths, as evident on the polar plot (the forward beams are contaminated by the towship). The linear plot on the left shows the virtual beams to be down by 45 dB. If the sidelobe rejection of the system is 45 dB, it must have good phase match between channels.

While good sidelobe rejection is necessary it is not the only criterion by which to judge data quality. The system must also have low self-noise. This self-noise comes from two sources. One is the towship, whose noise is coherent, and can be cancelled by the spatial transient elimination techniques described in <1,2,7>. The other is the array self-noise, which can be of electrical or mechanical origin, and the flow noise. This type of noise is usually incoherent from hydrophone to hydrophone and is spread evenly among the different beams by the FFT beamformer. Thus the noises from the different channels always sum in energy; however they are delayed before the summation. To estimate this self-noise in the presence of noise of acoustic origin is trivial if the virtual beams are available, and if the sidelobe suppression of the system is sufficient. Figure 10 illustrates such a situation. The sidelobe-suppression capability of the system is over 40 dB and the Spearman's rank correlation matrix shows no correlation between beams. The level of the virtual beams looks reasonably flat and is free from contaminations from the acoustic space. The energy present on the virtual beams is the system's incoherent noise, which is electronic noise at that frequency. Figure 11 shows a different case. The rank correlation matrix shows a high level of correlation between all the virtual beams. The beam level plots show the power average level of the virtual beams to be 10 to 12 dB higher than the median and dB-average levels. This was due to mechanical impulse noise occurring randomly on the hydrophones, probably due to lack of oil in the array and oscillations caused by rough sea conditions.

The virtual-beam noise levels at low frequency can be used to monitor and measure flow-noise. The array used by SACLANTCEN is electronically noisy at low frequencies because it has prewhitening high-pass filters. At 4 kn, the electronic noise is dominant at all frequencies, but at 8 kn, the flow-noise component begins to be clearly apparent, as shown in Fig. 12. The noise measurements were all conducted at 4 to 5 kn to minimize the flow noise. At 300 Hz, the 50 dB level is below sea-state 0 noise, and the virtual beams permit measurement of the flow noise during ambient-noise measurements in 20 to 25 kn winds (Force 6).

The excellent quality of the towed-array system has demonstrated a curious artifact, as shown in Fig. 13. At 1460 Hz, during the active-rudder test, there is always a target following the towship, 25 dB down in level at 114° relative to the towship. This is believed to be due to part of the towship noise being guided in the array. In tests at other nearby frequencies the relative level stayed constant while the direction slightly rotated, indicating it could be caused by a grating lobe for a sound speed of 940 m/s in the array. At lower frequencies no such phenomenon has been observed, but the waveguide effect, if real, would obviously vary with the ratio of the wavelength to the array diameter. In this array no measure was taken to attenuate acoustic propagation in the filling liquid.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The real-time calibration and test system integrated in the ambient-noise measurement system has proven very useful during the six major noise measurement exercises conducted in the last 20 months. Without it, it would have been impossible to keep the array in good working condition. The constant monitoring also gave a very high confidence level in the data collected during these noise measurements. A new system is being prepared, which will expand the eight frequency measurements to 256 frequencies on a frequency/wavenumber display, with automatic tests in the system to give warnings when the data have anomalies. Users of towed-array systems might wish to integrate similar tests in their systems in order to monitor the quality of their data.

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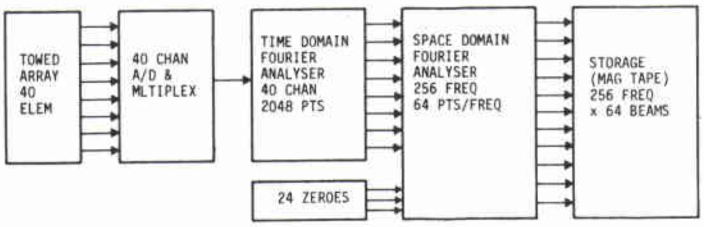


DATA PROCESSING AND REDUCTION

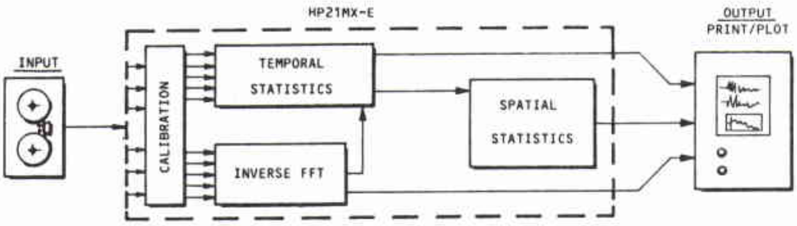


FIG. 1 THE DATA-ACQUISITION, PROCESSING, AND ANALYSIS SYSTEM

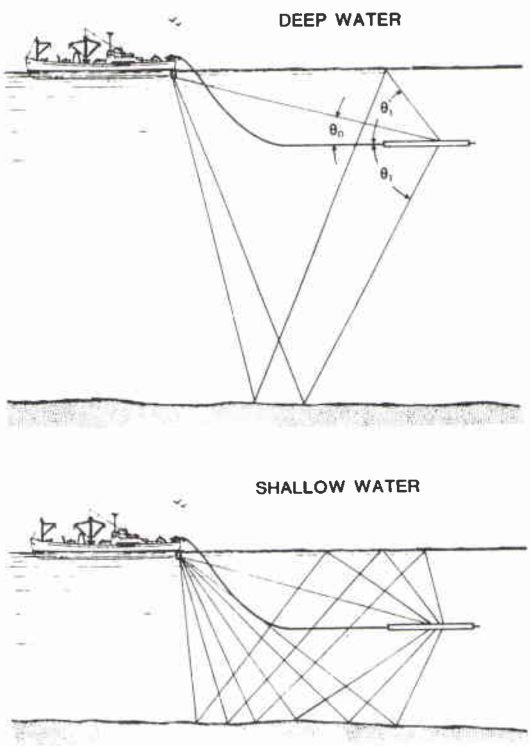


FIG. 2 *THE TOWSHIP-NOISE PROBLEM: ARRIVAL ANGLES OF TOWSHIP NOISE AT THE ARRAY*

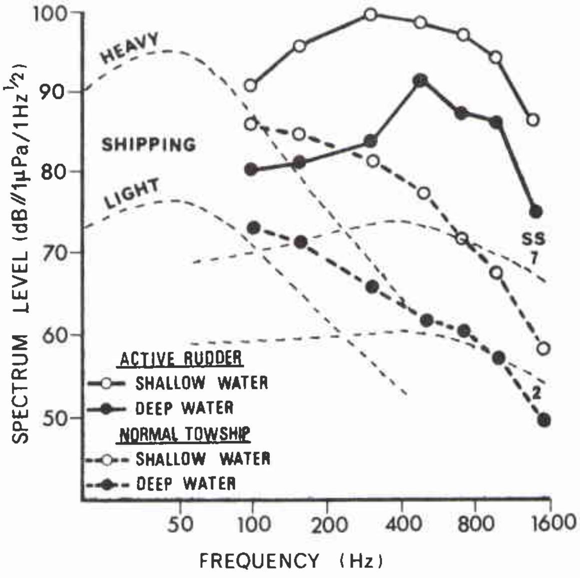
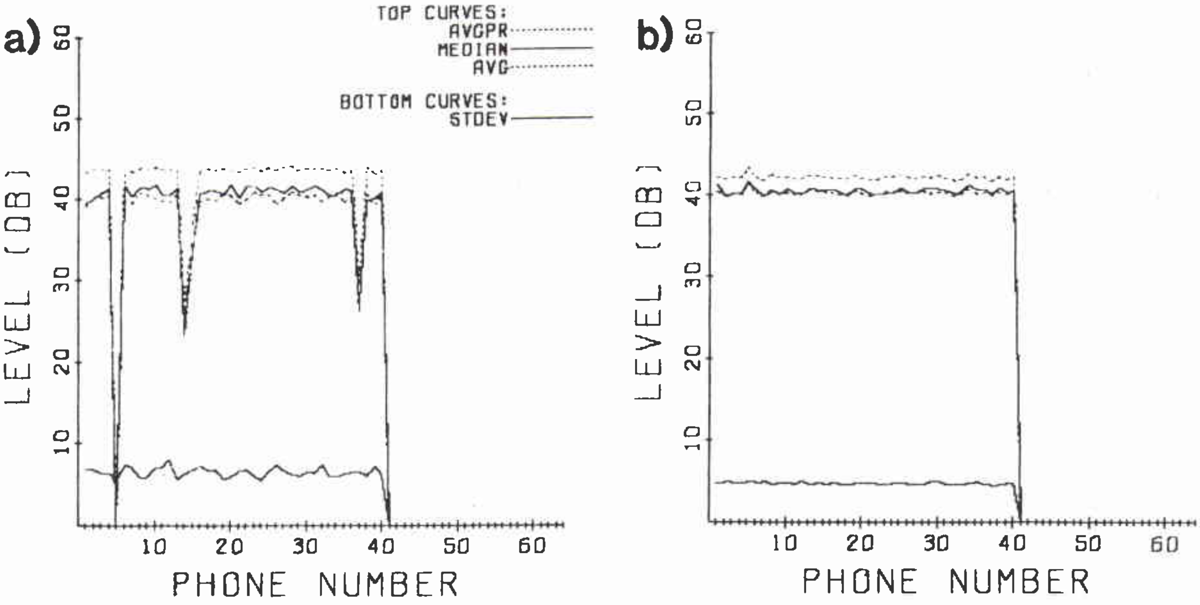
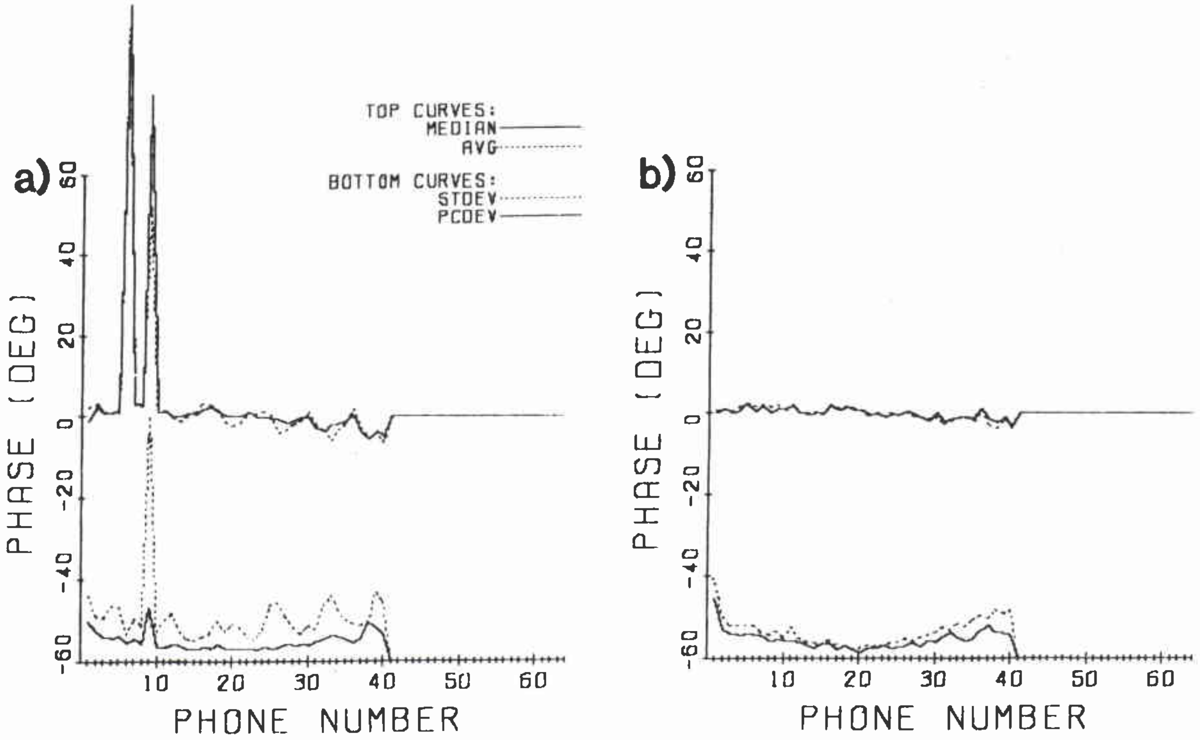


FIG. 3 *TOWSHIP NOISE LEVELS IN NORMAL OPERATION, AND WITH THE ACTIVE RUDDER IDLING, IN DEEP AND SHALLOW WATER*



FREQUENCY 750 Hz

FIG. 4 HYDROPHONE LEVEL PLOTS AT 750 Hz
a) Array with 3 bad channels
b) Properly functioning array



FREQUENCY 750 Hz

FIG. 5 HYDROPHONE PHASE PLOTS AT 750 Hz
a) Array with channels 6 and 9 interchanged
b) Properly connected channels

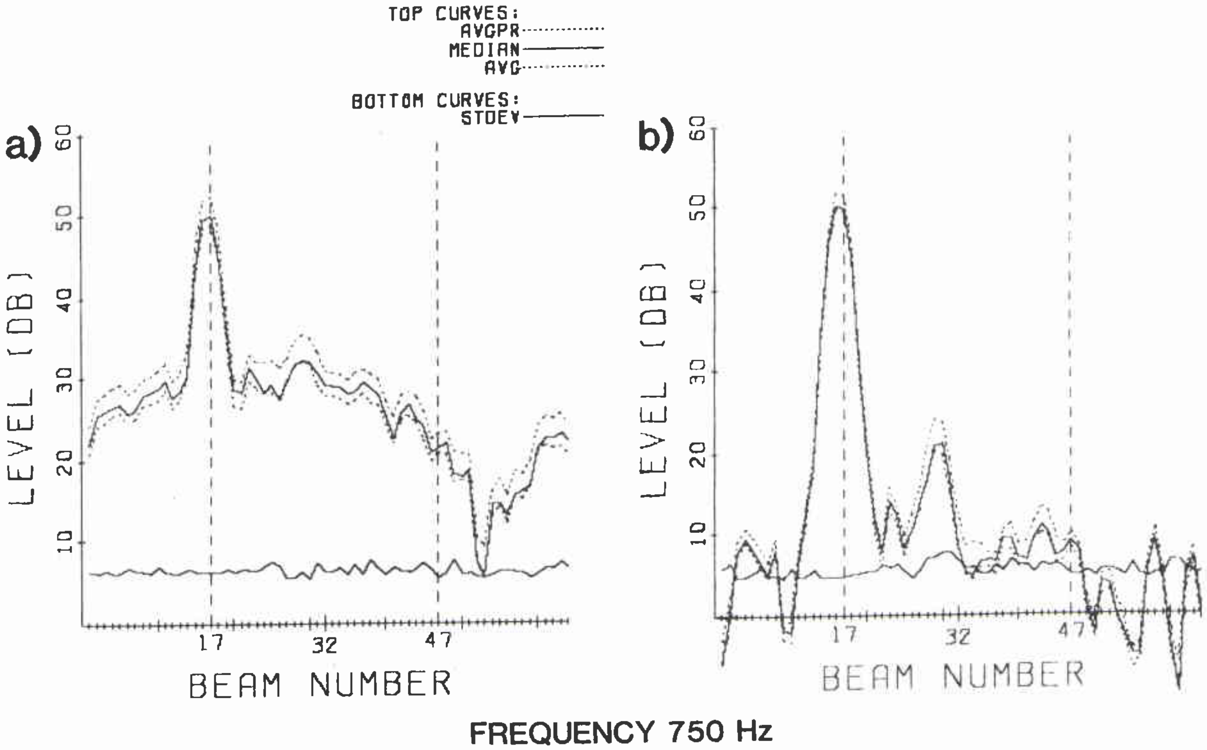


FIG. 6 BEAM LEVEL PLOTS
a) Array with 3 bad hydrophones
b) Properly functioning array

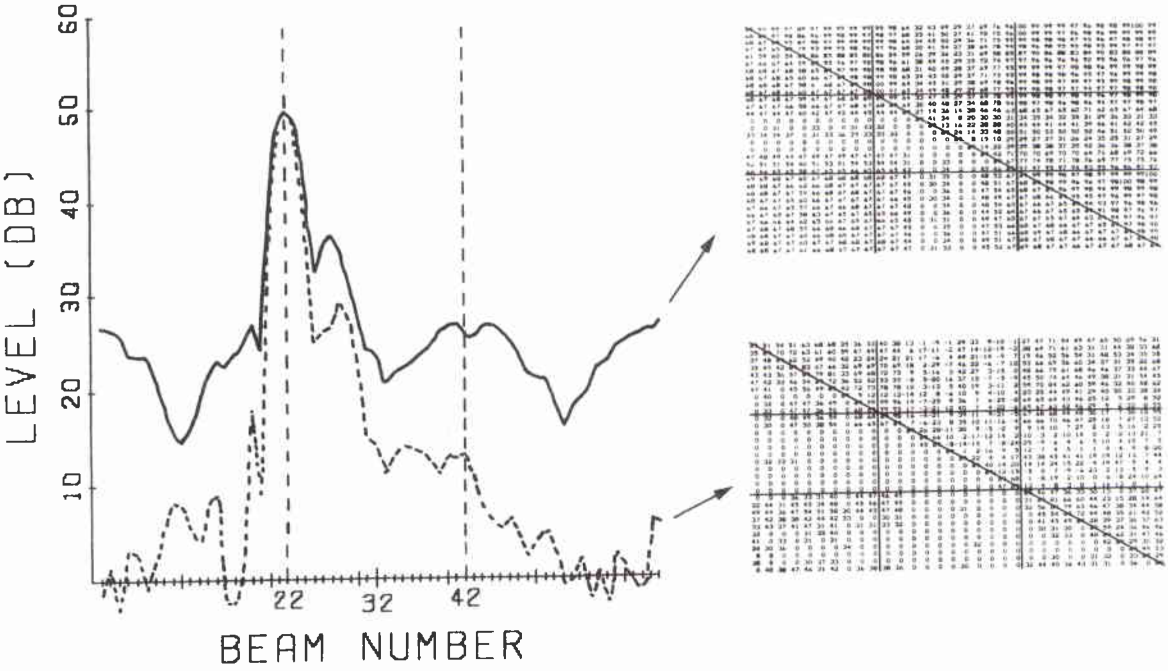


FIG. 7 BEAM LEVEL vs BEAM NUMBER PLOTS AND RANK CORRELATION MATRIXES FOR THE TWO CASES OF FIG. 5
Top curve and matrix: Channels 6 and 9 interchanged
Bottom curve and matrix: Array after correction

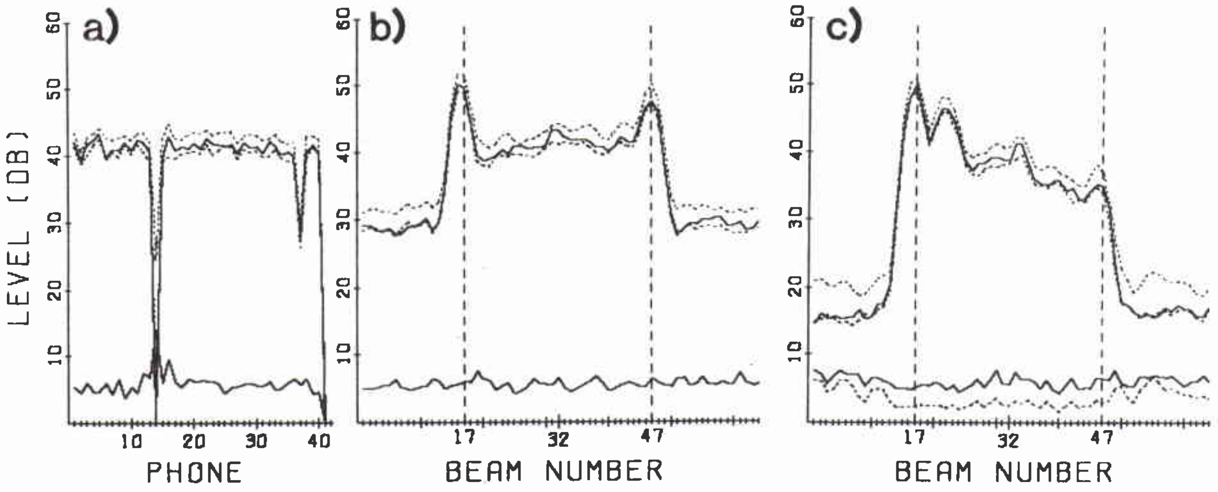


FIG. 8 PHONE LEVEL AND BEAM LEVEL PLOTS
- *a) Hydrophone plot showing malfunctioning channels 14 and 37*
- *b) Corresponding beam plots*
- *c) Beam plot after replacement of channel 14 by the average of 13 and 15*

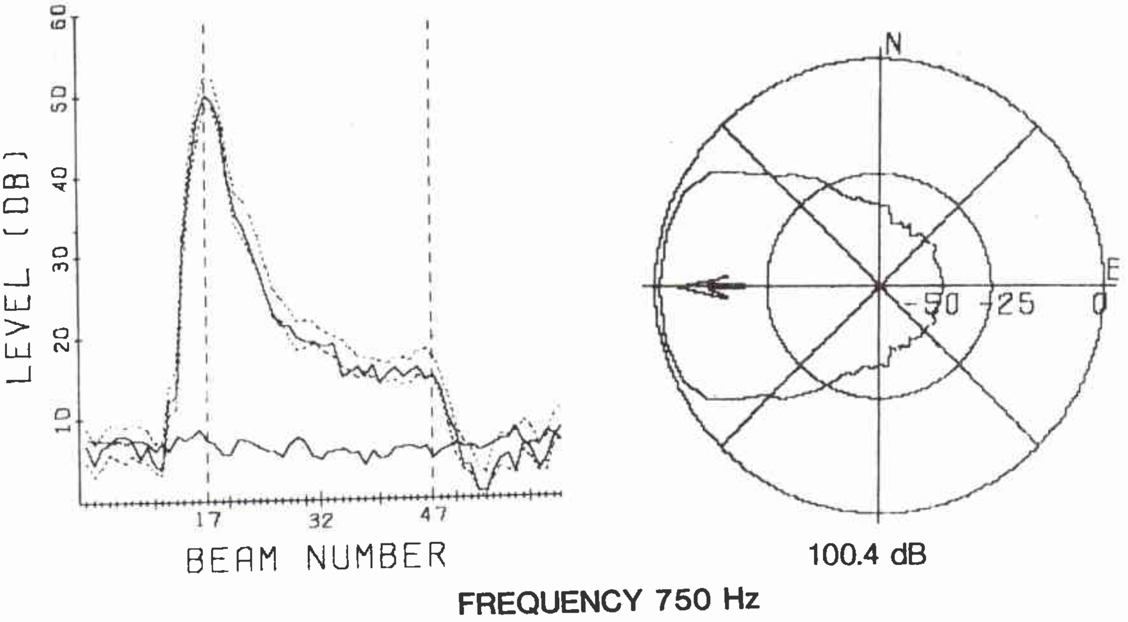


FIG. 9 BEAM LEVEL PLOTS FOR AN ACTIVE-RUDDER TEST IN SHALLOW WATER
- *a) Beam level vs beam number plot*
- *b) Polar beam level plot*

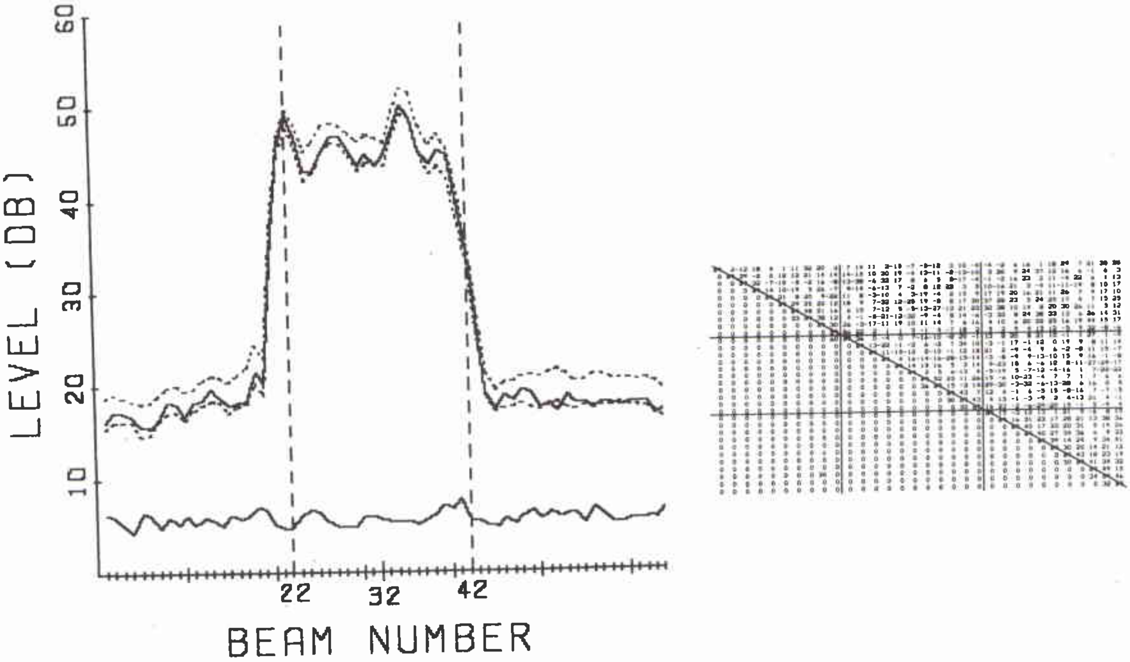


FIG. 10 BEAM LEVEL PLOT AND SPEARMAN'S RANK CORRELATION MATRIX FOR A MEASUREMENT AT 480 Hz, SHOWING ELECTRONIC NOISE ON THE VIRTUAL BEAMS

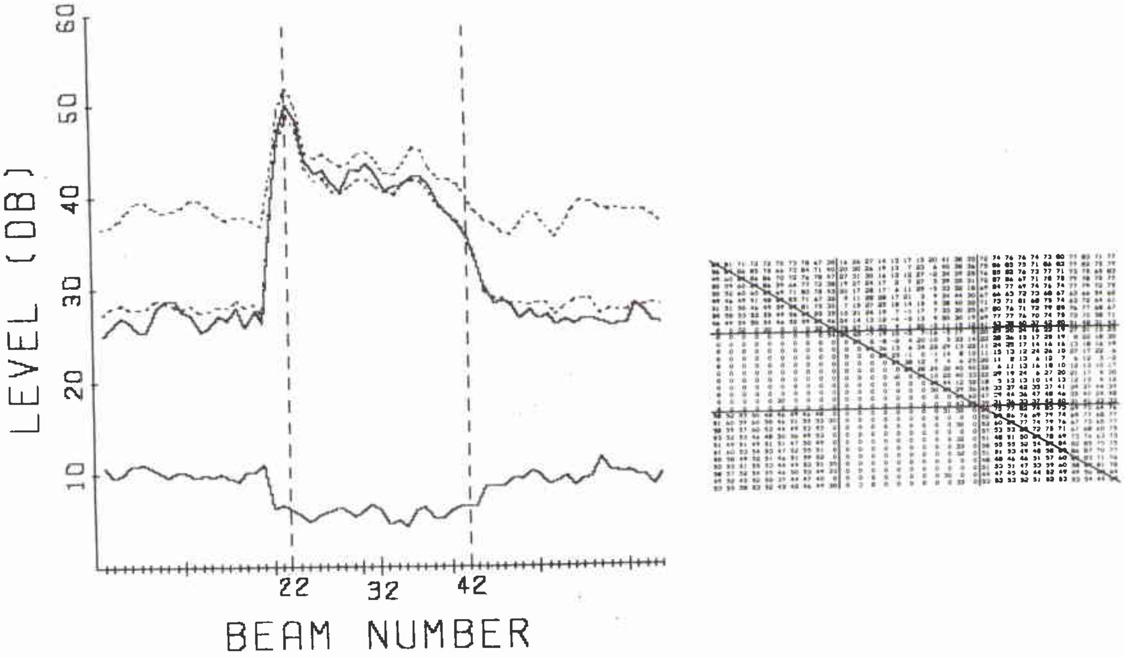


FIG. 11 BEAM LEVEL PLOT AND SPEARMAN'S RANK CORRELATION MATRIX FOR A MEASUREMENT AT 480 Hz, SHOWING THE EFFECTS OF RANDOM MECHANICAL HYDROPHONE IMPULSE NOISE ON THE VIRTUAL BEAMS

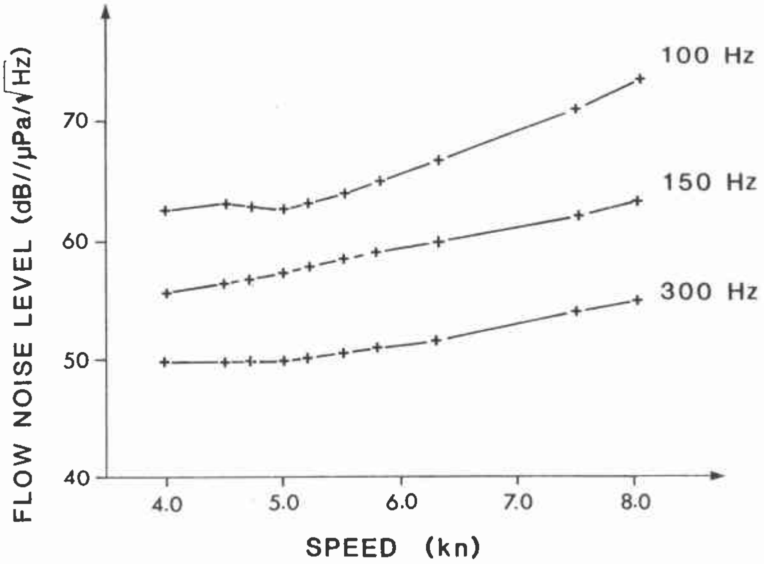


FIG. 12 SELF-NOISE LEVEL VERSUS TOW SPEED AT 100 Hz, 150 Hz AND 300 Hz

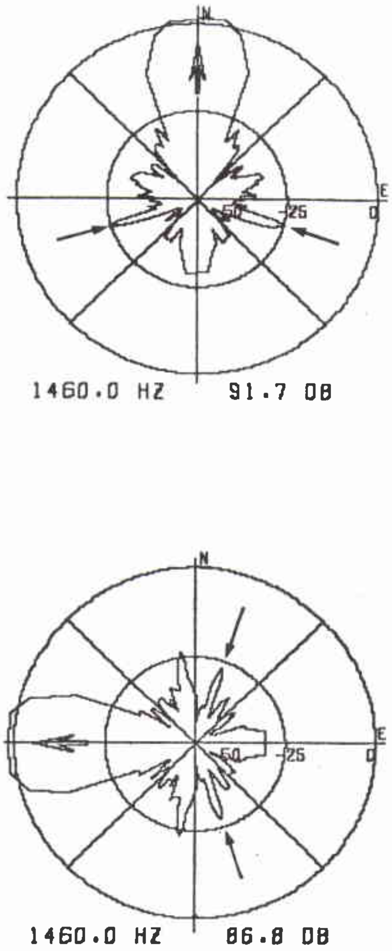


FIG. 13 POLAR BEAM LEVEL PLOTS FOR TWO ACTIVE-RUDDER TESTS AT 1460 Hz, SHOWING AN ARTIFACT AT 114° FROM FORWARD ENDFIRE