IS POWER AVERAGING THE BEST ESTIMATOR FOR UNDERSEA ACOUSTIC DATA?

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ABSTRACT

The power average is the statistic which is commonly used in all types of acoustic data processing. It is an excellent estimator for "well behaved" Gaussian distributions when the central or average value is desired. However, when there are "outliers" and errors or when the distributions are not Gaussian there are other statistics which are better estimators. In the case of ambient noise, the distributions are seldom Gaussian or free from "outliers" and errors. For this case the median and the geometric mean power level (dB average) are less sensitive to interference in the environment and to some of the minor system faults and are more powerful statistics.

INTRODUCTION

It is not a simple task to measure the undersea ambient noise and to process and report the results with a high level of confidence. The measurement itself is plagued with many potential hazards. The equipment is seldom in perfect condition and the noise environment is usually not cooperative. Nearby ships, seismic exploration, and countless other interferences have ruined many hours of otherwise good data. The measurement system has its own problems which increase the difficulty of achieving good results. Hydrophones can go bad as well as can the electronic components in amplifiers, preamplifiers, and filters which condition the acoustic signals. If the system is a towed array there is the additional problem of towship noise. In some cases, the noise from the towship is considerably more than the ambient which is to be measured.

Past experience in the measurement of ambient noise in many different areas, with different environmental conditions and noise source distributions, and with different measurement systems indicates that ambient noise data are generally not Gaussian distributed. The distributions tend more toward the shape of a log-normal or Rayleigh distribution. The distribution function in levels has a longer tail on the low noise level end than on the high noise level end. Most of the usual interferences, however, are distributed more toward the high-level end. This is intuitively obvious, since an interference of low level noise cannot reasonably interfere with the measurement.

The average power level is a commonly used statistic in ambient noise data processing. Because of the extremely high level of the interference, the average power level can be dominated even when the interference constitutes a relatively small percentage of the data. If a "persistant background" noise is desired from the measurement, the average power will not provide it. This is also true if trying to detect a target during times of high level noise interference, which is illustrated by the time series in Fig. 1. Two explosions were received from seismic prospecting during the measurement period. Three statistics have been calculated: the average power level, the decibel average (dB AVG), and the median level (MEDIAN). In this case, the average power level, being biased upward about 5 dB, is not a good estimator for what might be considered representative of the data. The other two seem reasonable. A target line would be masked if the averaging period contained one or more of these transient noise "spikes".

The selection of a best statistic is based on a very simple concept: for a source to interfere it must be of reletively high level. A lower level source does not interfere. The ideal statistic, then, is one which discriminates against high levels. This would not be the average power level. The average power can easily be captured and biased upward as in Fig. 1 when the high level interference constitutes a small percentage of the data. However, it is this statistic which is most commonly used in ambient noise processing. The geometric mean power level (dB average) and median levels, on the other hand, are relatively insensitive to interferences which constitute a small percentage of the data. A simple example illustrates this point. Consider a set of 50 observations. Let 45 be of 60 dB level and 5 of 100 dB level. The average power level of the 50 samples is about 90 dB. The dB average is 64 dB and the median is 60 dB. The differences between these latter two and the average power level are about 26 and 30 dB. If it is accepted that the five samples of 100 dB are a result of interference, then the dB average and median are better statistics than the average power level. These statistics have the obvious advantage that they give very good estimates without the need for deleting suspect data. This is important for automatic data processing. The advantage of course, decreases as the percentage of the contaminated data increases. Some examples will be given from measured data which illustrate the "power" of these two statistics for ambient noise measurement. The same concepts apply to other processes in acoustic measurement and signal processing. It will be left as a challenge to the reader to discover in which phases of analysis this simple concept can be applied to his situation.

RESULTS

During one ambient noise measurement exercise with the towed array, interference from seismic prospecting was received during the entire measurements. The range to the source was not known, only the azimuth. The level of the interference at the array was about 95 dB at 480 Hz. The

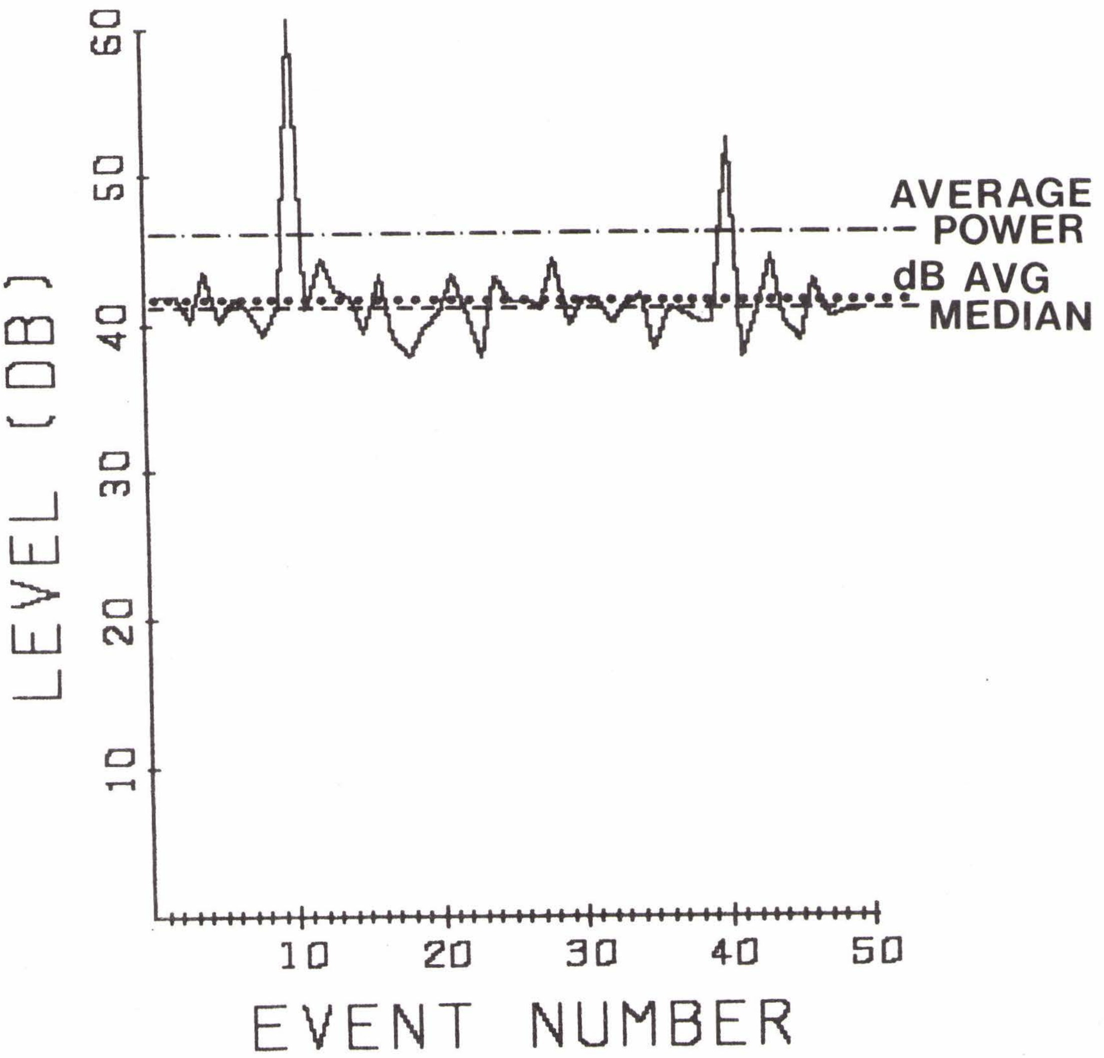


FIG. 1 EXAMPLE OF POWER AVERAGE LEVEL, DECIBEL AVERAGE, AND MEDIAN FOR A 50 POINT TIME SERIES OF ACOUSTIC NOISE DATA CONTAINING TWO SEISMIC PROSPECTING EVENTS

repetition rate was between 9 and 12 seconds and each explosion lasted about 2 seconds. The 480 Hz ambient noise without the interference was approximately 66 dB. The effects of these explosive sources on the data processing are illustrated in Fig. 2. There are three curves in each plot of Fig. 2. The dashed curves at the top are the average power levels for 50 spectral estimates. The next two curves are the for the median (solid) and the dB average (dashed) for the same 50 data points.

The explosions cause an interference pattern across the array in the hydrophone noise power average (top dashed curve). The mean level decreases about 5 dB across the array and has oscillations with an amplitude of about one decibel. Such effects could cause problems to many types of signal processing. The curves of the median (solid curve) and dB average (bottom dashed curve) register considerably different behavior. The median has about a 1.5 dB slope across the array with very little evidence of oscillations and the dB average is flat with no oscillations.

The reasons the median and the dB average give such excellent results are the following. The data points with the explosions are all above the median level. About half of them might have been below the median if there had been no explosions. Therefore, the median level is shifted in the ordering of the data by an amount equal to about half the number of explosions. If 4 explosions were received in the 50 samples the shift would be about two numbers but not more than four. The resulting change in the level of the median would be small and possibly none at all. As the number of occurrences increases in proportion to the total data, the affect on the median increases. The same is true for the dB average. However, the discrimination capability of the dB average, in addition, is affected by the relative magnitude of the difference between the good data and the interference. Estimates of the beam noise level and the noise field horizontal directionality could be made from the median and dB average beam noise levels; it could not be done from the average power levels without being biased by the explosions. The results in the beam noise plot Fig. 2b indicate the explosion, near beam number 13, which dominates the curve for the average power levels (top dashed line), but is not evident in the curves for the dB average and median. The discrimination level of the latter two is approximately 34 dB against the explosion.

Figure 3 illustrates the three different statistics on data from two other time periods. In each case the data base consists of sets of 50 beam noise spectral estimates. Figure 3a is for 1460 Hz when interference was being received from a source which was believed to be of biological origin, possibly snapping shrimp. The plot of average beam power levels shows the obvious effects of the interference. Judging from the other two curves (median and dB average) in the same plot, the average power level has been biased up by as much as 15 dB. The curves for the median (solid) and dB average (lower dashed curve) appear unaffected, with the anisotropy due to shipping noise being clearly evident.

The data for Fig. 3b were obtained when a different type of biological source was nearby. The noises received on the array sounded like carpenters hammering on a roof. The sources of the noise were most likely carpenter fish (Sperm whale). The average power levels (top dashed curve) are again "captured", being biased upward as much as 17 dB, while the

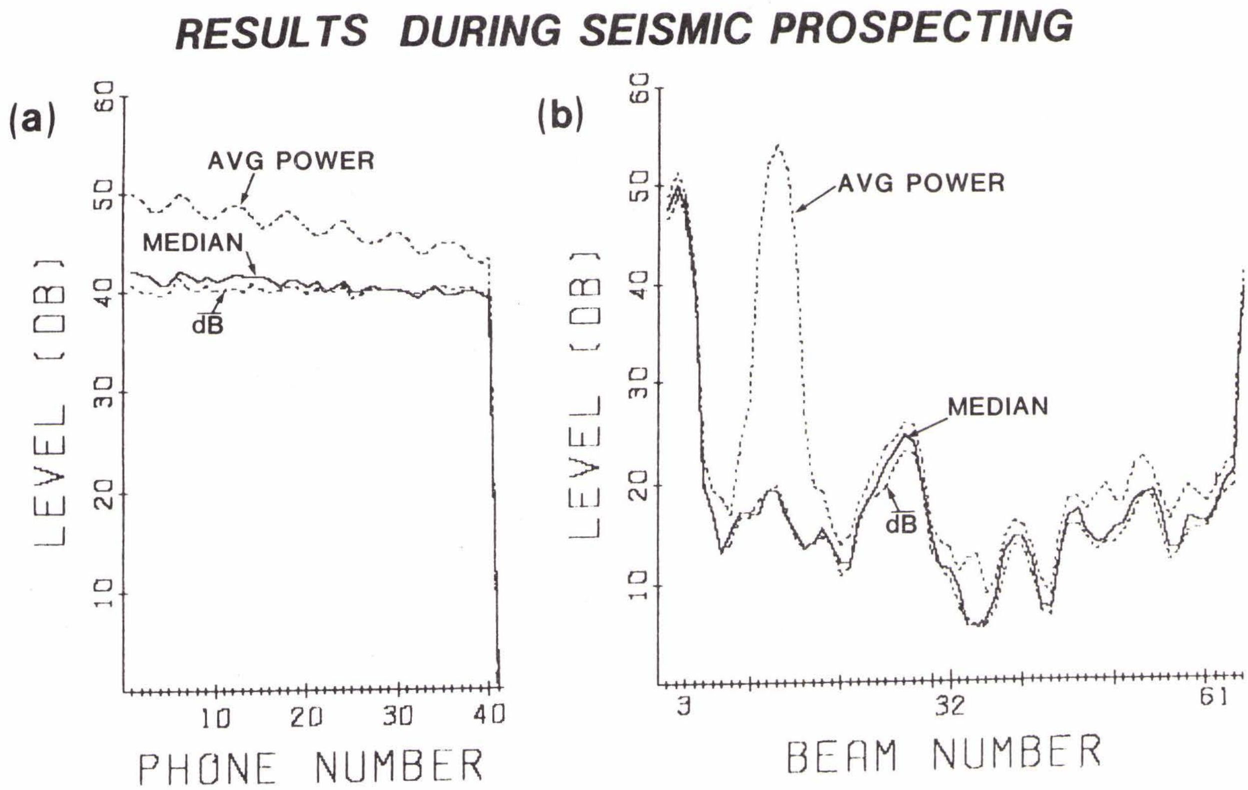


FIG. 2 NOISE LEVEL VERSUS HYDROPHONE NUMBER PLOT (2a) AND BEAM NOISE LEVEL VERSUS BEAM NUMBER PLOT (2b) FOR A PERIOD WHEN NOISE FROM SEISMIC PROSPECTING WAS BEING RECEIVED. POWER AVERAGE (top dashed curve), MEDIAN (solid curve), AND dB AVERAGE (bottom dashed curve)

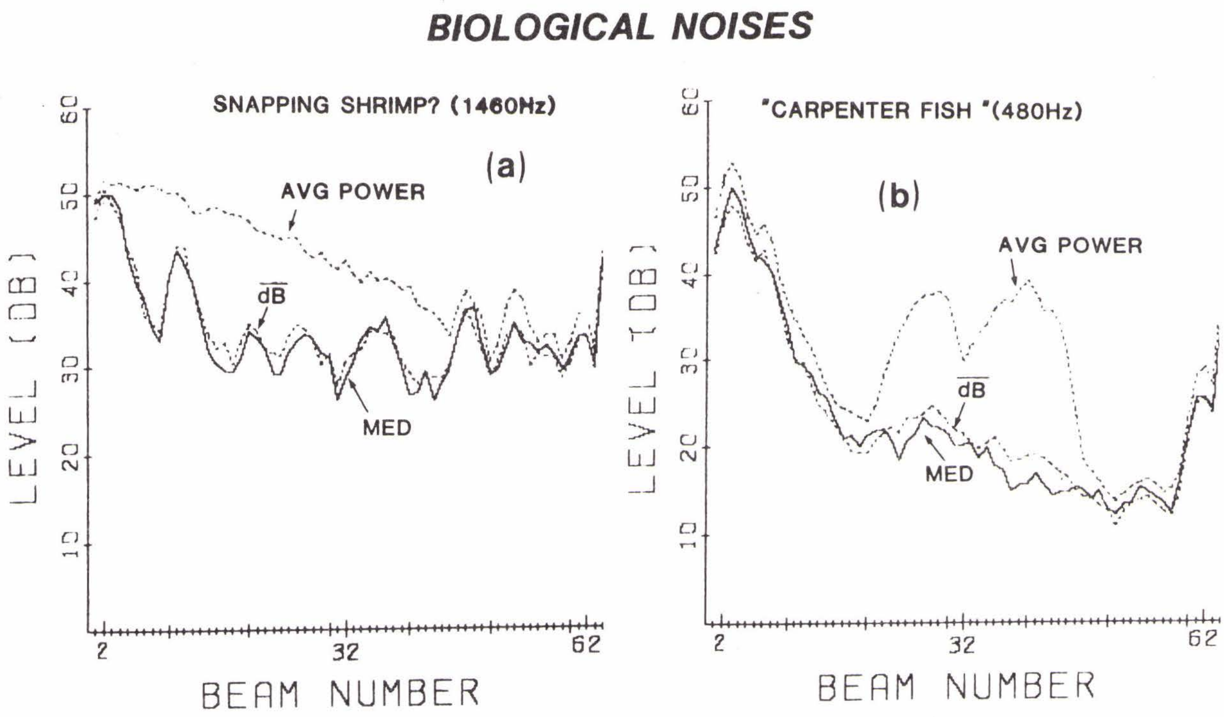


FIG. 3 NOISE LEVEL VERSUS BEAM NUMBER FOR TIMES OF NOISE INTERFERENCE FROM (3a) SNAPPING SHRIMP, AND (3b) CARPENTER FISH (Sperm whale). POWER AVERAGE (dashed curve), AND dB AVERAGE (bottom dashed curve)

curves for the medians and dB averages do not register any significant effects. Hence, in both sets of data in Fig. 3 the background shipping noise could be measured by the median and the dB average during the periods of interference, while it could not be measured with the power average. This might also have been true if instead the objective was to detect a target. The gain against the interference is the level differences between the power average and the other two statistics. The potential improvement is substantial.

The previous examples demonstrate that the median and the dB average can effectively discriminate against high level transient sources in the environment. Unfortunately, the environment is not the only source of bad data. The measurement system can also be a problem. Most of the present systems contain many components and are highly sophisticated. As the number of components increases, the probability of experiencing a mechanical or electronic failure also increases. In fact, past experience indicates there is always a defect in the measurement system. It is a challenge to minimize the deleterious effects of the defect and produce high quality results.

The median and the dB average can also be used to improve the data quality for some types of system faults. Consider, for example, the two plots in Fig. 4. The plot on the left is a strip chart recording of a hydrophone output from a towed array during a time of acoustic measurements. Noise "spikes" of about 18 dB above the background occur about every 10 seconds. The spikes are believed to be caused by the relative motion of the hydrophone in its fasteners. The affect the transient noise spikes in Fig. 4a have on data quality is illustrated in the beam noise plot of Fig. 4b. The beams from 22 to 42 are steered into real space and receive acoustic energy on their main lobes. The beams outside this range correspond to phase shifts greater than for endfire beams. They are virtual beams and receive acoustic energy only through the sidelobes which extend into acoustic space (see reference 1 for more detail). When the sidelobes are good the levels of these virtual beams are measures of the self noise of the system. For the case in Fig. 4b the sidelobes were in the neighborhood of 40 dB down at the time of this measurement but were masked by the "system" noises in Fig. 4a.

The self noise resulting from the noises illustrated in Fig. 4a are given by the levels of the virtual beams. Relative to the plot, the self noise is about 38 dB for the power average and about 28 dB for the dB average. The median is a few decibels below the dB average. These results indicate that for the power average the self noise of the system is about 4 to 6 dB below the acoustic levels on the beams. The lowest average power beam levels would most certainly be contaminated by the hydrophone noise spikes. The median and dB average beam levels, on the other hand, have a greater safety range. The differences between the acoustic and virtual beams is generally in excess of 12 dB for these latter two statistics.

The dB average and median can be used in the spatial domain as effectively as in the time domain. For example, consider the problem of estimating the omnidirectional level and horizontal directionality of the ambient noise from the beam outputs of a towed-line array. There are two major problems which must be solved to do this. The first is that the line array has an

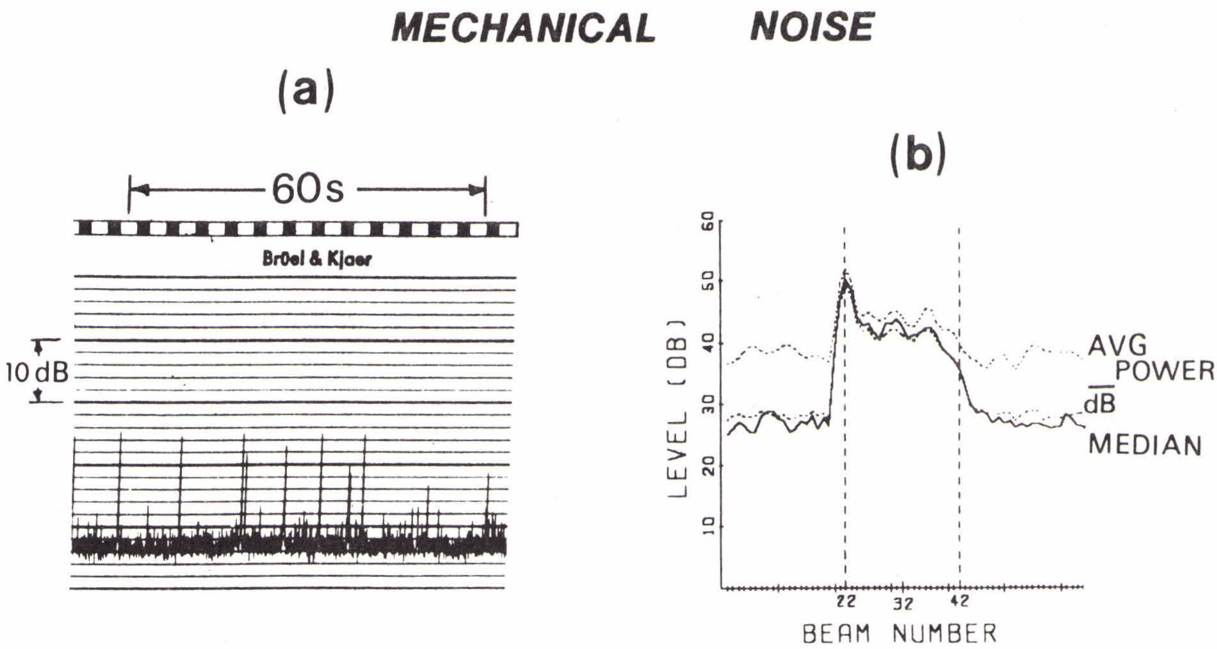


FIG. 4 STRIP-CHART RECORDING OF NOISES ON ONE HYDROPHONE CHANNEL (4a) AND THE EFFECTS ON THE BEAMFORMED OUTPUT (4b). POWER AVERAGE (top dashed curve), MEDIAN (solid curve), AND dB AVERAGE (bottom dashed curve)

inherent left-right ambiguity which must be resolved. This requires that measurements be made on different array headings. Unfortunately, the noise-field changes over the time required to do this. Hence, an exact solution is generally impossible. The second problem is caused by the towship. The noise received from it interferes with the measurement of the ambient. It can be as much as 30 dB above the ambient for the entire set of measurements.

The capability of the dB average and the median to discriminate against the high level transient noise can also be used to discriminate against the towship noise. When the measurements are performed on different array headings, the towship noise appears on a different true azimuth each measurement period. This constitutes a spatial transient. Hence, the transient discrimination capability of the median and the dB average can be utilized to discriminate against the towship in the estimation of the horizontal directionality of the noise field. Furthermore, the ambiguities in the beam noise measurements will be resolved in the same way. The true azimuth of a fixed source is not transient. The ambiguous azimuth, however, will vary with the array heading and this constitutes a spatial transient. It will, therefore, be discriminated against by the median and the dB average performed in the spatial domain. When the source does not remain on a fixed azimuth for the entire set of measurements, all true and ambiguous azimuths will be spatial transients. The median and dB averages will arrive at values which will be between the extremes. They will be good estimators of the noise field most of the time. The omnidirectional level can then be obtained by integrating the horizontal directionality pattern. Because of the discrimination capability of the median and the dB average, the omnidirectional level of the ambient noise can be estimated exceptionally well in the presence of masking by the towship and other high level moving or transient sources.

The spatial discrimination capability of the median and the dB average can be illustrated by estimating the horizontal directionality and omnidirectional level of the ambient noise for various levels of interference from the towship. This was done for simulated measurements in the Alboran Sea south of the shipping lane. The shipping surveillance data, obtained during the actual measurements were used in the RANDI II noise model <2> and the positions dead-recknoned from one measurement period to another. The measurements were made each hour for nine hours on nine array headings which were incremented 80 deg. each hour. Noise was added to the beams normally contaminated by the towship and the measurement was simulated again. This was done for towship noise levels received at the array equal to 74 dB and again for 114 dB. This latter level was about 40 dB above the ambient and 70 dB above the lowest beam noise levels (10 kt of wind at 480 Hz). The algorithm in reference 3 was used to obtain estimates of the horizontal directionality and the omnidirectional level of the ambient noise from the beam noise data for each level of towship noise contamination. This algorithm utilizes the dB average in the deconvolution of the beam data by an iterative approach and either the dB average or the median in space to resolve the ambiguities and discriminate against the towship.

Example polar plots of the beam data for three of the nine headings are given in Fig. 5a. Only a few of the forward beams are affected by the

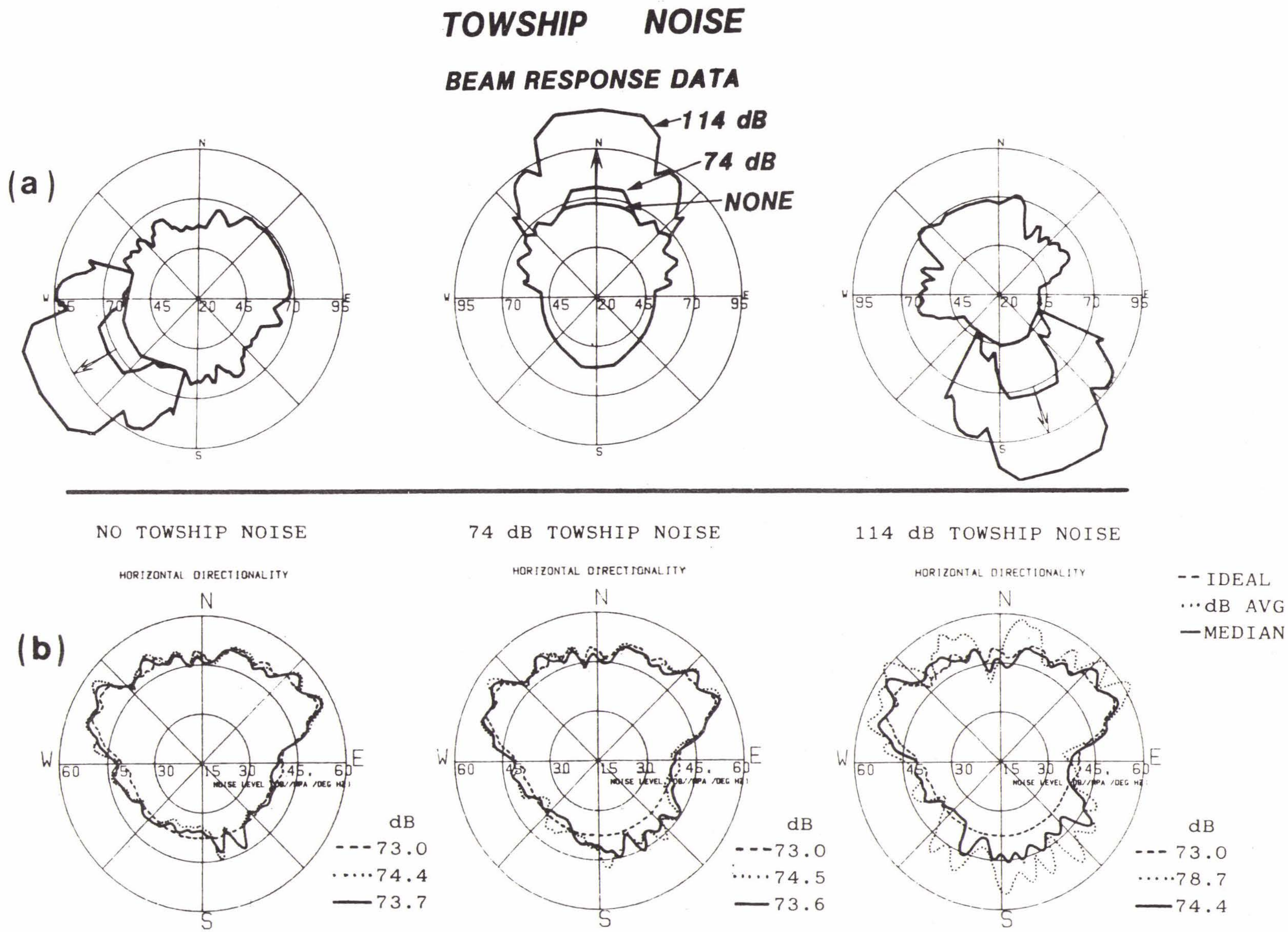


FIG. 5 TYPICAL SIMULATED BEAM NOISE POLAR PLOTS FOR VARIOUS LEVELS OF TOWSHIP NOISE (5a) AND THE RESULTING HORIZONTAL DIRECTIONALITY PATTERNS OBTAINED DIRECTLY FROM THE NOISE MODEL (IDEAL), BY dB AVERAGING, AND BY USING THE MEDIAN BEAM LEVELS (5b)

towship noise as is evident by the superposition of the beam noise plots for the cases of no towship noise, 74 dB towship noise, and 114 dB towship noise. The sidelobes have been reduced sufficiently to eliminate the system as a source of degraded results in order to concentrate only on the discrimination capabilities of the dB average and the median.

The directionality estimates and the corresponding omnidirectional levels are given in Fig. 5b. The dashed curve in each plot was obtained directly from the model. It is the unambiguous estimate (ideal) of the time averaged and spatially smothed noise field. It is not degraded by the towship noise or the ambiguities of the array. It is the quantity that the algorithm <3> is attempting to estimate. The solid curve in each plot is the estimated directionality pattern using the median. The dotted curve corresponds to the dB average processing. The plots from left to right are for no noise from the towship, 74 dB, and 114 dB from the towship. The omni-directional levels corresponding to each pattern are also included beside each plot.

In each of the three cases illustrated in Fig. 5b the median estimate agrees well with the ideal pattern except in the 90 deg. sector south of southeast. In this region the estimated levels are biased up by about 7 dB. The azimuthal extent of this region increases with the level of the contamination. The omnidirectional level of the median estimate is biased up about 1.4 dB when the contamination is 41 dB above the ambient. This is rather impressive suppression of the contamination. The dB average does not perform as well but still gives impressive results. The omnidirectional levels of the dB average estimates are biased up about 5 dB for the 114 dB contamination and 1.5 dB for 74 dB contamination. The excellent agreement between the patterns, especially for the first two plots of Fig. 5b, indicates that the dB average and the median are very effective in resolving the ambiguities and estimating the omnidirectional levels and the directionalities. The last two plots indicate that these statistics are also very good at discriminating against spatial transients, in this case the towship.

There is always a question of the validity of modeled results. The previous results are supported by measurements of a similar nature obtained in the Alboran Sea. The level of the towship noise was increased by switching on the active rudder of the towship. This increases the noise received from the towship by up to 30 dB. The exact amount depends on frequency. It is negligible at 100 Hz and 30 dB at 1000 Hz. Ambient noise measurements were made on nine different headings. Data were acquired on each heading with the active rudder off and another set with it on. The data were processed as two separate nine-sided polygons, one with the active rudder noise and one without.

Figure 6 illustrates the results for 750 Hz. The top row of plots are beam noise measured during three of the nine legs. The effective omnidirectional level was about 73 dB. The noise from the towship exceeds the ambient beam noise from 5 to 20 dB depending on array orientation. The second row of plots are for the same orientations but the active rudder is switched on. In these cases the noise from the towship exceeds the beam noise from the ambient by 30 to 40 dB. The omnidirectional levels were about 96 dB, 23 dB higher than without active rudder. The active rudder

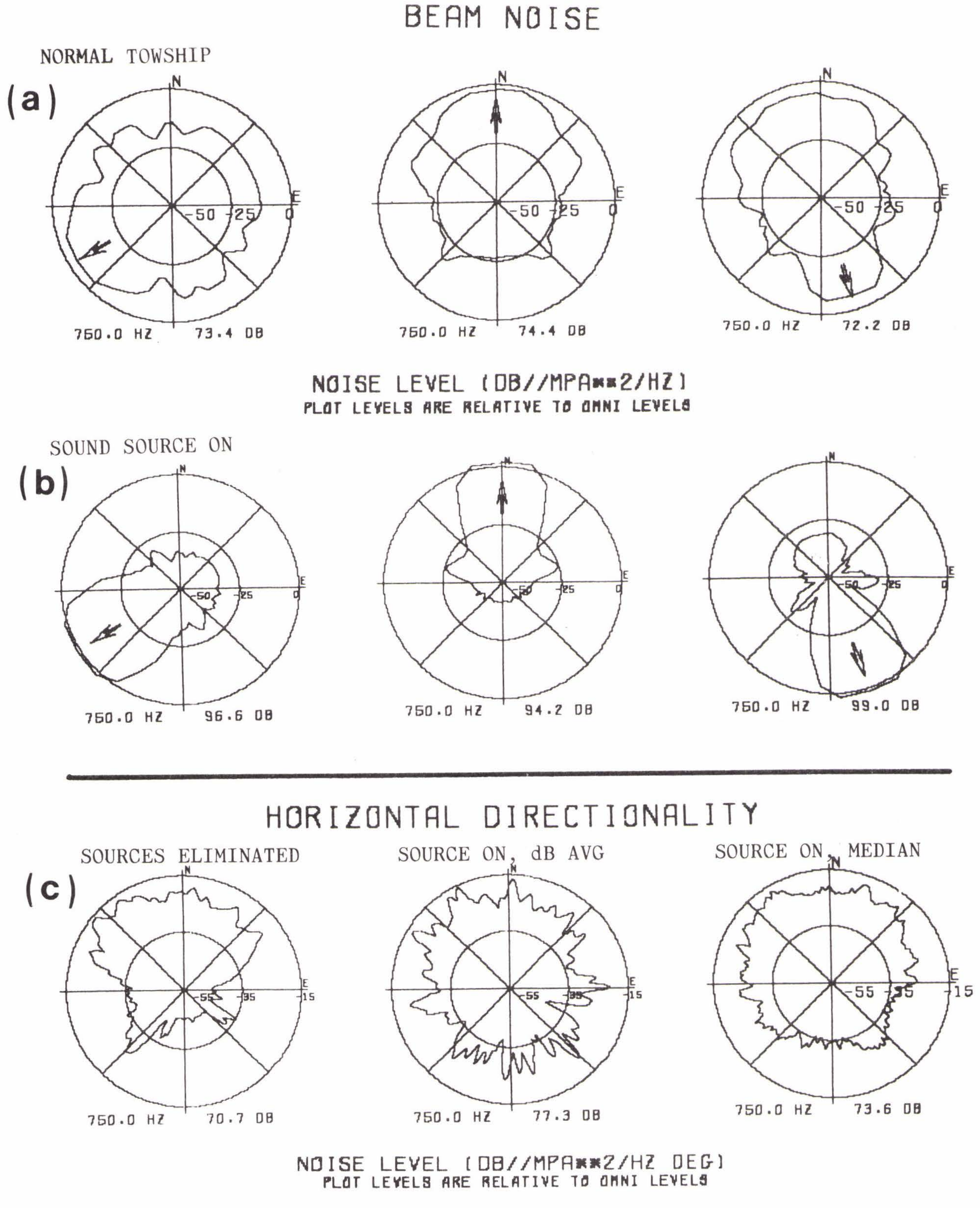


FIG. 6 MEASURED BEAM NOISE POLAR PLOTS SHOWING NORMAL TOWSHIP NOISE INTERFERENCE (6a), INTERFERENCE WHEN A HIGH LEVEL SOURCE IS OFF (left column) AND WHEN IT IS ON (center and right column) (6b) AND THE RESULTING HORIZONTAL DIRECTIONALITY PATTERNS OBTAINED BY dB AVERAGING AND THE MEDIAN (6c)

measurements for each leg were immediately preceeding or following the measurements without the active rudder on.

The final row of plots are the ambient noise directionality estimates from the beam noise data for 9 legs. The pattern on the left-hand side was obtained from the data sets without the active rudder and the beams containing the towship noise were eliminated from the processing. Hence, this pattern is completely free of contamination by the towship. It will be used to judge the effectiveness of the dB average and the median in discriminating against the towship noise. The omnidirectional level, printed below the plot, is 70.7 dB. The center plot is the directionality estimate from the active rudder data when dB averaging is used. The omnidirectional level is biased up 7 dB and the low levels in the southern half space have not been well reproduced. The results for the median in the third plot are much better. The omnidirectional level is biased up only 3 dB and the low levels have been reproduced much better. The median is clearly a more effective discrimination than the dB average.

The lowest levels achieved by the dB average and the median are not as low as when the active rudder is not used and the towship noise is eliminated in the processing. The main reason this is so is that the sidelobes of the array were not sufficiently suppressed during the measurements. The differences between the active rudder noise and the lowest beams were about 46 dB (96-50). This level of sidelobe suppression was not always achieved during the measurements.

As an example of discrimination in both the temporal and spatial domains consider the ambient noise horizontal directionality results which were obtained by a towed array at one site in the northeast Atlantic. During most of the measurement periods interference was being received every 9 to 11 seconds at levels in excess of 30 dB above the normal beam levels. The hydrophone time series data in Fig. 1 and the hydrophone and beam noise plots in Fig. 2 are from the same measurement time period but for different frequencies. The difficulty of estimating the ambient from the beam data was increased by a sea state of about ½. In such a case, the towship noise is the dominant source, not considering the seismic prospecting noise. It is much easier to estimate the ambient at higher sea states when the towship noise is a smaller part of the total and less discrimination is required.

This case is one in which there was interference in the time domain and spatial domain. The time domain interference consisted of explosive sources being received about every 9 to 12 seconds from an azimuth of approximately 333°. The spatial domain interference consisted of the towship on the forward beams. These two sources dominated the measurements. The seismic prospecting noises were discriminated against in the time domain by using the median beam outputs and the towship noise was discriminated against by using the dB average in the spatial domain. The resulting directionality patterns for 500 to 1500 Hz are included in Fig. 7. These patterns do not show evidence of either the seismic prospecting noise or the towship noise. They are obviously dominated by distant shipping. The two peaks in the northeast quadrant are along azimuths to a Port (72°) and a shipping lane (52°). Without having employed the median and/or dB average in both spatial and temporal domains, it is unlikely that such excellent results could have been achieved.

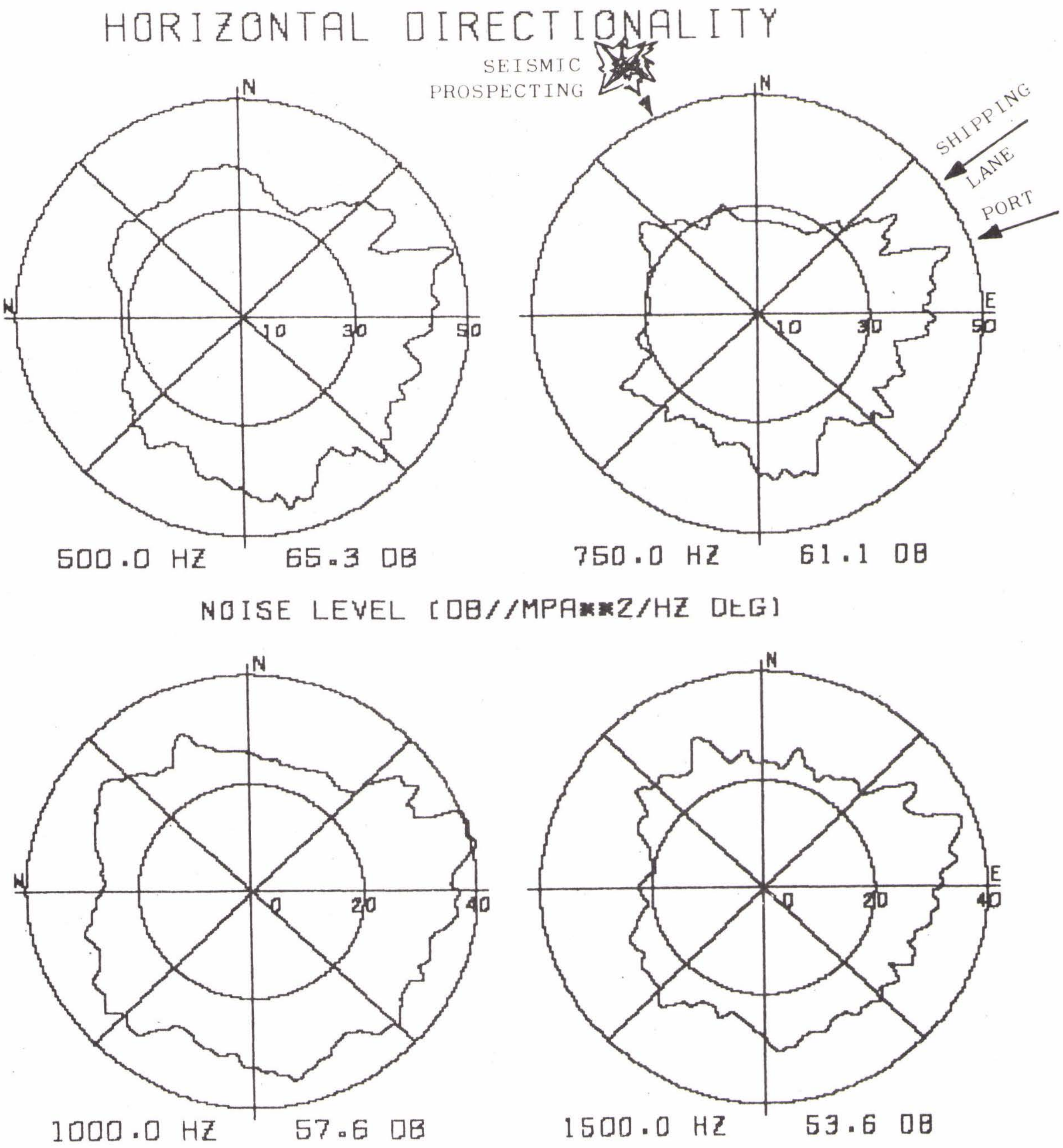
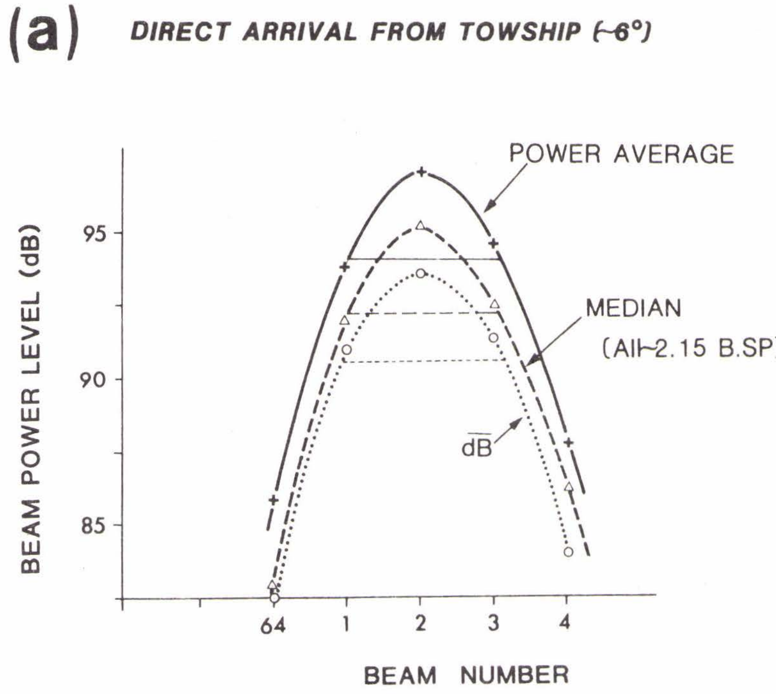


FIG. 7 EXAMPLE OF AMBIENT NOISE HORIZONTAL DIRECTIONALITY PATTERNS OBTAINED IN THE PRESENCE OF A VERY NOISY TOWSHIP AND SEISMIC PROSPECTING (about 333°)

In general the towed array has a variable geometry. As it is towed along it snakes through the water. The deviation from linearity often increases with increasing sea state and wind conditions. One of the effects of this on the acoustic performance is a degradation in the beamforming capability of the system. One measure of this degradaton is the deviation of the measured beamwidth from theoretical. Figure 8a illustrates the effective beam response of a towed array system to the noise from a source on the towship. The arrival angle was about 6 deg. from forward endfire. The results for the three statistics indicate the wiggling of the array over the 13 minute time period required to collect the data has had no adverse effects. All three statistics produce beam responses near theoretical. This is not the case near broadside where the effects of the wiggling are maximum. The bottom reflected arrival for the same time period was received 70 deg. from forward endfire. The results in Fig. 8b indicate that the effective beam response obtained by all three statistics has increased. The theoretical half-power beamwidth should be about 2.15 beam spacings. It is 2.4 for the median, 2.66 for the dB average and 2.95 for the power average. Hence, the median and the dB average have, in effect, "straightened" the array compared to the results for power averaging. The median, however, is the best statistic for this case.

CONCLUSION

It has been shown by example that the power average is not always the best estimator for underwater acoustic data. The median and the dB average are very effective in eliminating or discriminating against some of the sources of data degradation in the environment and in the data measurement and processing systems and give improved result over the power average. Tradition is probably the main reason the power average has been used so extensively by the underwater acousticians. If the power average is not vital to the processing technique the dB average, median, or some other statistic may provide significant improvement in the results. This has been the experience of the authors in the measurement and analysis of towed array data. The technique is sufficiently general that it could be applied to other situations, such as detection or signal processing, with similar results.



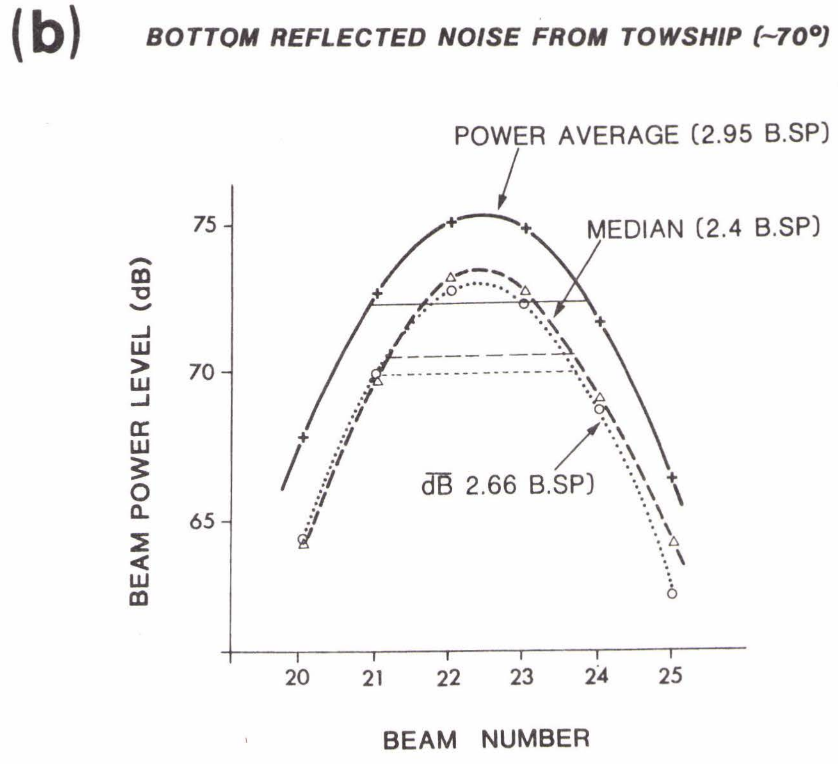


FIG. 8 BEAM RESPONSE TO A SOURCE (a) 6 DEG. FROM FORWARD ENDFIRE AND (b) 70 DEG. FROM FORWARD ENDFIRE

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