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USE OF THE TOWSHIP FOR ASSESSING TOWED-ARRAY PERFORMANCE AND ANALYZING DATA QUALITY

by

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RALPH R. GOODMAN
Director

Use of the towship for assessing towed-array performance and analyzing data quality

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A series of relatively simple tests are presented and discussed, which used in conjunction with the noise received from the towship, can be used in real time to assess the performance of a towed array and the quality of the acoustic data. One test constitutes a simple, yet thorough, relative amplitude calibration of the sonar system. Examples from actual measurement situations are given to illustrate the utility of these tests in indicating the existence of problems and providing clues to their sources. Results suggest that problems which affect array performance and degrade data quality occur more often than might be expected. Once the problem is corrected, however, measurements can ofttimes be carried out with a near-perfect system. Measured side-lobe suppression levels in excess of 40 dB and in some cases in excess of 50 dB are not uncommon.

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INTRODUCTION

The towed array is increasing in popularity with the petroleum industry as an important component in seismic prospecting and with the underwater acoustic scientists as a measurement tool. The reasons for this include its relative mobility, rapid deployment, and its high spatial gain characteristics. The towing platforms can be small off-shore supply vessels, large research vessels, or helicopters.

When the towing platform is a ship, the noise caused by its cavitating propellers and the various motors, generators, pumps, valves, and other noise sources are received by the array and can interfere with the measurements and reduce the quality of the data. This noise is generally considered to be a nuisance. Ofttimes considerable effort is expended in its elimination or reduction.[1,2]

The noise interference from the towship is not the only source of possible data quality degradation. There is the same potential for electrical and mechanical problems that exists with other complex acoustic systems as well as those unique to the towed array, i.e., the array is not constrained to remain linear, horizontal, or on a given heading. Furthermore, the towed array is a mobile system which must be deployed and retrieved each time it is used. This increases the hazard to the system. All of these factors can adversely affect the acoustic performance of the system and, consequently, the quality of the data.

The purpose of this paper is to demonstrate that the noise from the towship can be used to determine when problems affecting data quality exist and estimate the extent of the degradation (including the noise from the towship). If the assessment is performed onboard, during the measurements, the sources of degradation can often be found and corrected with subsequent improvements in data quality. Hence, a reasonably noisy towship can be considered a blessing rather than a nuisance. The ideal, of course, would be to have a silent towship and an easily deployed sound source. However, this is seldom possible.

The discussions presented herein are in the context of the towed array being utilized as a tool for the measurement of ambient noise. Most of the ideas and results presented, however, are sufficiently general to apply when using the array to satisfy other objectives. In fact, the techniques are sufficiently general to apply to measurement situations in which other types of arrays (vertical, bottom mounted, planar, etc.) are utilized and the high level noise is provided by a towed or moored source or a noisy "ship of opportunity" instead of the towship.

I. BACKGROUND

The towed array has been used in measurements of the characteristics of undersea ambient noise and acoustic propagation for more than ten years. When designing the experiments, array heading and equipment geometries are usually chosen, such that, the relevant data will be obtained from beams near and aft of broadside. Those near forward endfire are usually considered to be sufficiently contaminated by the noise from the towship to be of no value. The data processing would seldom involve data from these contaminated beams.

Often, the presence of the towship noise contamination precludes the use of certain processing techniques. In such a case, the contamination must be either reduced or eliminated prior to that processing or the processing technique must be modified or replaced by one which is insensitive to the contamination. Examples of noise reduction or elimination are replacing the towship with one which is quieter, installing an electrical or other quiet propulsion system, and applying noise reduction[1] or cancellation[2] techniques to the data. In the case of modifying or replacing the processing technique, for example, algorithms for the estimation of ambient noise horizontal directionality have been developed which would effectively discriminate against the towship contamination[3,4] because most techniques previously used would not.[5–7]

Perhaps the reason the noise from the towship has not been exploited for useful purposes in the past is that the emphasis has been too strong to eliminate or ignore it. On first consideration, it appears unlikely that the noise received from the towship would be anything but detrimental to towed array data collected to satisfy other measurement objectives. Experience gained by the principal author, in several experiments involving towed arrays, has indicated the need to monitor the acoustical performance of the arrays. The towship appeared to be the perfect source to do it, since it is an ever present relatively high level broadband source with no deployment problems. Such a conclusion is not unique to the authors; it was independently expressed by Dr. Samuel Marshall[8] after a series of experiments, jointly participated by him and the principal author, in which the results from a towed array appeared to suffer serious quality degradation. The cause and the extent of the apparent degradation, unfortunately, remained unknown although extensive effort was expended after the fact to determine it.

Using the techniques which are described herein, it is likely that in a similar situation, as previously mentioned, the data quality degradation would be readily detected and easily quantified. If these techniques had been applied onboard during the measurement, it might have been possible to correct the problem and continue the data collection with an improved system. This has been the approach taken by the authors during several recent ambient noise measurement experiments. The results indicate that the norm seems to be that in the beginning of measurements there are always problems which will degrade data quality. It is also evident that the problems can generally be corrected, permitting measurements to proceed with a nearly perfect system. Consequently, the system performance assessment and data quality analysis procedures outlined below have become part of the standard procedures for ambient noise measurements with the SACLANTCEN towed arrays. It has been possible to report the data with extremely high levels of confidence as a result of knowing that the system was generally providing side-lobe suppression levels in excess of 40 dB and in some cases in excess of 50 dB. It is highly unlikely that there can be anything seriously wrong with a system that can provide side-lobe suppression levels this large.

II. THE SYSTEM: SHIP, ARRAY, DATA ACQUISITION, AND PROCESSING

The system which is used for the towed array performance and data quality assessment has four major components: A. towship with high level broadband noise, B. towed array and signal conditioning electronics, C. data acquisition, and D. data processing.

A. Ship

The ship used by SACLANTCEN to tow arrays is the R/V MARIA PAOLINA G. It is an 80-m-long cargo ship converted into a research vessel. One characteristic of this ship, which makes it highly desirable as a towed-array ship, is its extremely noisy active rudder. An active rudder has a propeller which is driven by an electric motor. This is one way of increasing a ship's maneuverability at slow speed. With the main engine providing propulsion and the active rudder idling, the noise level at the array is up to 30 dB greater than the noise from the towship when the active rudder is off. Spectra are included in Fig. 1 for the noise from the towship, which is received at the array, with and without the active rudder operating. The normal range of ambient encountered in recent measurements is also included as the shaded region. The equalities in level of the noise for the towship with and without the active rudder at frequencies below 150 Hz could be a result of the surface image effect (or surface decoupling) and not a characteristic of the active rudder or ship source spectra. As might be suspected from the results in Fig. 1, the active rudder is a convenient broadband source without the usual deployment problems.

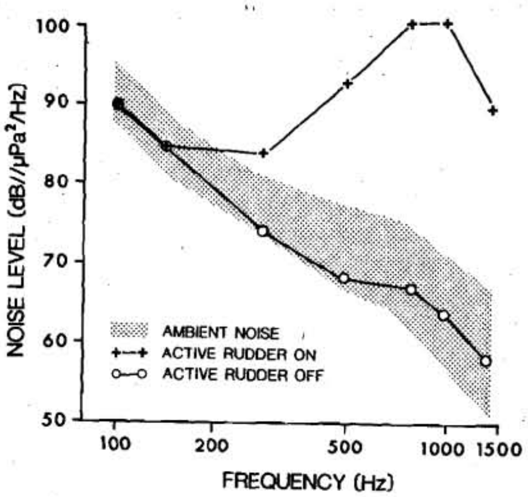

FIG. 1. Noise level of towship, received by the array, with and without the active rudder noise compared to the maximum and minimum ambient noise levels (shaded area) measured during recent cruises.

B. Array

There is nothing particularly unique about the array which is most commonly used by the Centre. It consists of approximately 950 m of tow cable, 35 m of vibration isolation modules (VIM) preceding the array, a depth and heading sensor module (about 2 m), the 128 hydrophones with preamplifiers and prewhitening filters centred in a 90-m section, a depth sensor module (about 2 m) followed by 35 m of VIM, and finally a thick (about 6-cm-diam) polypropylene rope of 100-m length for a drogue.

Because of constraints imposed by the limited number of wires in the towcable and the onboard electronics, the array is subdivided into two arrays of 40 hydrophones each, one with 49-cm spacing and the other with 147-cm spacing. These give half-wavelength frequencies of approximately 1500 and 500 Hz, respectively. Hence, data processing is generally confined to frequencies below 1500 Hz.

C. Data acquisition

Onboard, 40 channels from the array were amplified and filtered with 2-kHz low-pass antialiasing filters. These channels were then converted to 12-bit digital streams, sampled at a rate of 5000 Hz, multiplexed into one digital bit stream and then sent to a minicomputer (HP 21 MX-E). These data were demultiplexed in the computer and stored until the MAP 300 array processor could accept them. In the MAP 300, the 40 channels were Hann weighted in time and

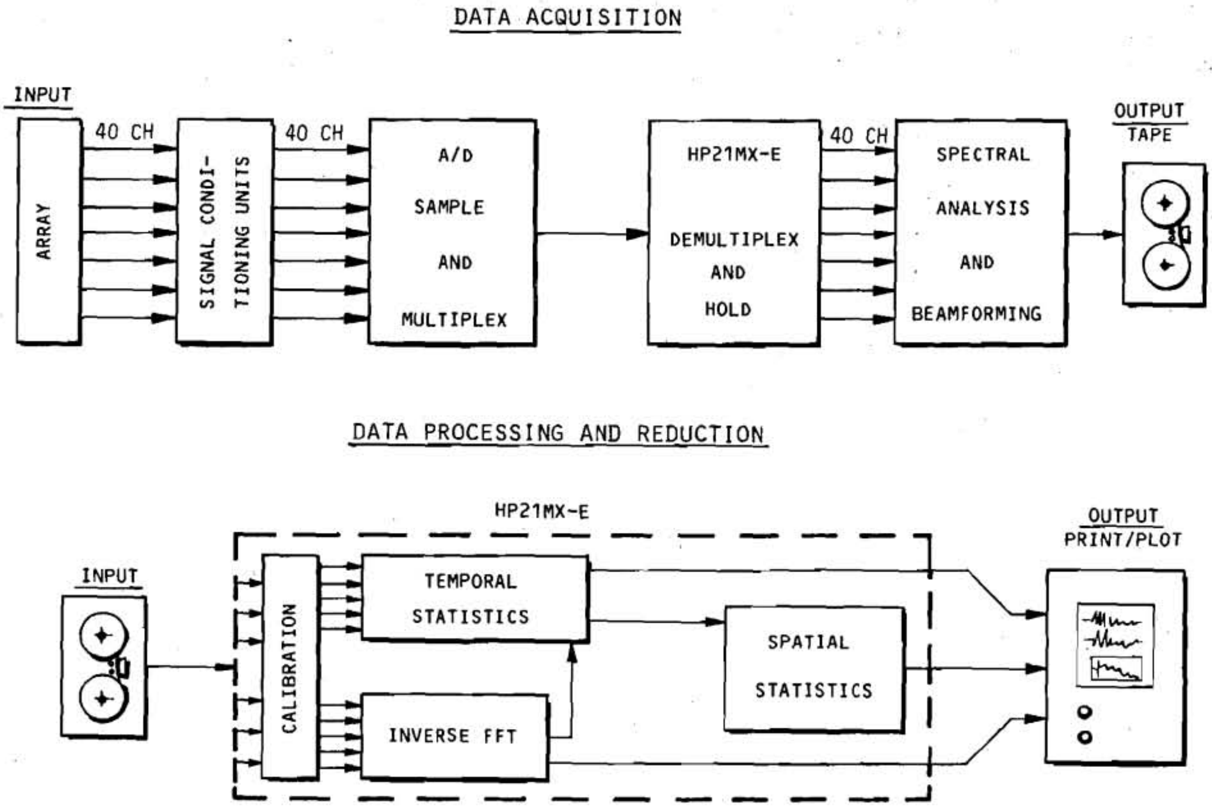

FIG. 2. Block diagrams of data acquisition system and data processing and reduction system.

spectrum analyzed by a 2048 point Fast Fourier Transform (FFT) giving an approximate bandwidth of 2.5 Hz for each frequency bin. The 40 spectral estimates in each frequency bin were then augmented by 24 zeros. The resulting 64 channels for each frequency bin were Hann shaded and transformed into 64 beam output levels by a second (spatial) FFT. The resulting beam output noise levels were then stored on magnetic tape with header information containing the important data acquisition parameters. A block diagram of the data acquisition system is given in Fig. 2(a).

D. Data processing

The magnetic tape from the data acquisition system which contains the array beam-noise output data is manually transferred to a tape drive unit connected to another minicomputer (HP 21 MX-E) for data processing and reduction. The first step in this process is to apply the calibration corrections. An inverse FFT is then applied to the calibrated beam-noise data to give calibrated hydrophone data. This yields 40 hydrophone outputs and 24 sets of zero output corresponding to the input to the spatial FFT in the beamformer. The resulting beam noise and hydrophone data time series are for a time-bandwidth product equal to one. A block diagram of this system is included as Fig. 2(b).

This beam data processing and reduction system has been developed over a period of several years to facilitate the study of undersea ambient noise and to assess array acoustic performance and data quality.[9] Although many of the products produced by this software package can be used to satisfy both of the above objectives, only in the context of satisfying the latter one will any be discussed. The products which will be discussed are the following:

(i) hydrophone noise level versus hydrophone number plots,

(ii) geometric mean intensity level and average power level plots,

(iii) plots of standard deviation of beam and hydrophone levels,

(iv) beam noise level versus beam number plots,

(v) rank correlation matrix.

With the exception of the rank correlation matrix, all of the above products rely on one or more of the following well-known simple relationships:

noise power of jth spectral estimate $= n_j$,

noise power level of jth spectral estimate.

$$N_j = 10 \log n_j, \tag{1}$$

average noise power level for a series of spectral estimates

$$R_p = 10 \log \frac{1}{J} \sum_{j=1}^{J} n_j, \tag{2}$$

geometric mean intensity level for a series of spectral estimates

$$R_G = \frac{1}{J} \sum_{j=1}^{J} N_j, \tag{3}$$

standard deviation of a series of spectral levels

$$S = \left(\frac{1}{J-1} \sum_{j=1}^{J} (R_G - N_j)^2 \right)^{1/2}, \tag{4}$$

where J is the number of spectral estimates in a beam or hydrophone noise time series.

The rank correlation matrix contains Spearman's rank correlation coefficients[10] for pairs of beams and the associated confidence levels of the correlation coefficients. 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 the magnitude, it is a distribution free (nonparametric) statistic and does not depend on any assumptions concerning the probability distribution of the values in either time series. This coefficient is calculated by the following:

$$r_s = 1 - \left(6 \sum_{j=1}^{J} d_j^2 / J(J^2 - 1)\right), \tag{5}$$

where d_j = the difference between the ranks of corresponding spectral estimates in the two temporal sequences. r_s can have values between $+1$ and -1 and is symmetrically distributed about 0. For sample sizes greater than 20, the distribution is sufficiently close to normality that the normal area table may be used to find the probabilities. Typically, the test for significance is applied to test the null hypothesis that the rank correlation coefficient in the population is zero, or the observations in the population are independent. If the correlation coefficient is not sufficiently close to zero the null hypothesis is rejected in favor of correlation with a given level of significance. The significance level in terms of standard deviations is given by the following:

$$Z = r_s(J-1)^{1/2}. \tag{6}$$

The correlation matrix contains the correlation coefficients, Eq. (5), above the main diagonal and the significance levels (if above an arbitrarily high value) on and below the main diagonal.

III. PROCEDURE

Many techniques could be used in the aquisition and analysis of the towship noise. The one mentioned here has proven successful when a modest onboard data processing capability is available.

At the beginning and the end of the measurements and at other times of opportunity, the active rudder is turned on for about 15 min. During this time, sufficient data are collected to form time series of the 40 hydrophones and 64 beams of about 50 spectral estimates in 256 frequency bins. Only a few frequency bins are selected from the total for further processing. The processing is generally completed about 1½ h after data acquisition has finished. The measurements to satisfy the main experiment objectives, of course, begin immediately at the termination of the towship noise data acquisition in order to conserve time. If the towship noise results indicate an unacceptable level of data quality degradation, the measurements would be terminated and the problem corrected, if possible. The measurements then resume, as before, starting with the towship noise measurements. With time permitting, the towship (active rudder) noise measurements are repeated at convenient times during the course of experiment and always at the end of a series of measurements. The minimum number of these towship noise measurements which should be made is two, one immediately after deployment of the array, when it has stabilized, and one just prior to retrieval. More would obviously be desirable since data quality degradation caused by transient phenomena, such as array nonlinearity, may occur but not be present at the beginning or the end. The data would be adversely affected just the same.

With more onboard computing power or more efficient data handling than the present system has, it would be possible to monitor the array acoustic performance and data quality in real time simultaneously with the acquisition of the ambient noise data. Another possible deviation from the procedure above for ships which are too quiet and do not have a noisy active rudder, is to use a noise source with high level source lines (or broadband noise) at frequencies of interest.

IV. RESULTS AND DISCUSSION

Some examples will be given below which illustrate the utility of the methods and products introduced previously. Unfortunately, these products, in general, do not determine the cause of problems. They merely indicate the existence of them and quantify their effects. In some cases, the cause can be inferred with reasonable confidence but this is not guaranteed. The problems which can occur with a system as complex as a towed array is almost limitless. The number of tests one can perform to assess system performance and data quality, however, must necessarily be small and executable in a reasonable amount of time. Once the existence of a problem has been determined, trouble shooting procedures, determined by the effect, can be initiated. At this point the procedures and products previously mentioned have fulfilled their main function.

The first product produced by the system in Fig. 2 is the hydrophone noise level versus hydrophone number plot. Figure 3(a) illustrates a typical example for 480, 750, 1000, and 1460 Hz. Channels 41 through 64 have no output, since they were merely zeros to extend the 40 live channels to 64 to facilitate the spatial FFT which forms the beams. With the exception of hydrophone number 5, which is about 1 dB high, the variation in the amplitude across the array is within a few tenths of a decibel. From an amplitude only consideration, one would expect good beamforming results from these data. However, phase is also important when beamforming and the results in Fig. 3(a) say nothing about the phase relationships between the hydrophones.

This is a very convenient and effective method for performing a relative amplitude calibration. One important advantage of this method is that the entire system is calibrated including the hydrophones, preamplifiers, tow cable, signal conditioning units, and even the data acquisition and processing systems. Usually, only the hydrophones and preamplifiers in the array are calibrated at a calibration facility.

Figure 3(b) illustrates a problem with channel 24 at another time. The abnormally high level at the lower frequencies (100 and 150 Hz) could be expected to present problems when beamforming. A degradation in the side lobes could be expected as a result. Results from trouble shooting indicate the problem to be electronic noise in the array in preampli-

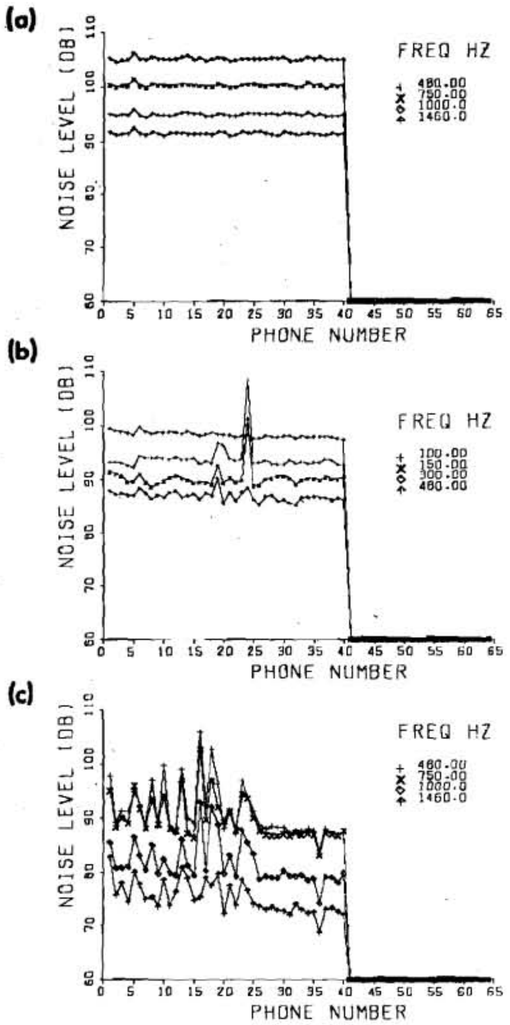

FIG. 3. Hydrophone noise level (first 40 only) versus hydrophone number plot for (a) a near-perfect array, (b) channel 24 bad, and (c) noise of nonacoustic origin.

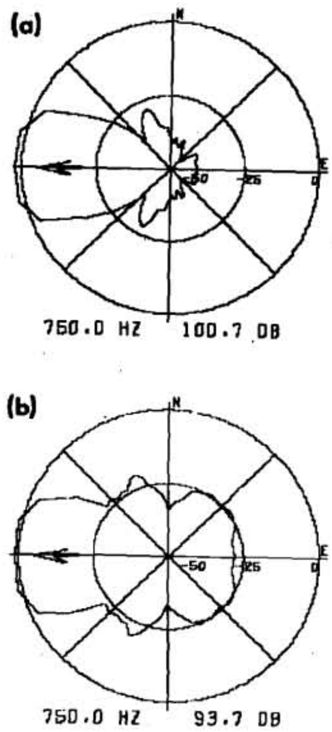

FIG. 4. Beam noise level versus (apparent) azimuth plots for the active rudder operating when (a) the system is performing excellently, and (b) when channels 6 and 9 are switched. Beam noise levels are relative to the total received level (below plot).

fier number 24. When the array is first turned on the problem is not present but gradually grows in level and increases with frequency as time progresses. After about 9 h, the level of noise at 100 Hz is 20 dB above that on other channels.

Figure 3(c) illustrates hydrophone data from a different experimental array than was used to obtain data for the previous two plots. The erratic behavior of the majority of the channels in the first half (left-hand side of the plot) of the array appeared to be sensitive to the towing speed. In this case the speed was 6 kn, which is not considered excessive. The abnormally high levels measured over the front part of the array are not of acoustic origin or all would be high. It is believed to be due to a fault in a connector which was probably sensitive to vibration. Good beamforming results would not be expected from such data and, indeed, they were not.

Figures 4 and 5 are examples of beam noise level versus azimuth plots and rank correlation matrices. Used together, these displays enable estimation of the side-lobe suppression capability of the system and give a rough check on the phase accuracy of the system.

The plot scale of the beam noise polar plots is relative to the total received level printed below each plot, following the frequency. The concentric circles are 25 dB apart with the outer circles being 0 dB and the origin − 50 dB. These plots are symmetric about the array heading arrow as a result of the left–right ambiguity inherent in the conical beams of the line array. Domination by the towship (active rudder) is clearly evident in the angular sector within 45° of forward endfire (array heading arrow). The levels in other directions are from approximately 25 dB less than the main towship noise arrivals [Fig. 4(b)] to more than 40 dB [Fig. 4(a)]. If the noise from these directions is due to the towship noise from side lobes in the direction of the towship, then the plotted levels are the side-lobe suppression levels of the system. At least, they are the side-lobe suppression levels of the system to noise from the towship. They are also reasonable estimates for the side-lobe suppression capability of the system to sources from other directions as well. If, however, the noise measured on these lower level beams is due to the ambient, then the side-lobe suppression capability of the system exceeds the dynamic range of the measured data. In Fig. 4(a) the dynamic range is about 40 to 45 dB. Whether the noise measured on the low level beams is due to side-lobe contamination or due to the ambient may not be important. The dynamic range measured indicates the side-lobe suppression capability of the system is at least 40 dB and that is generally more than adequate for most applications. It also indicates that the phase accuracy of the system is excellent, otherwise, the side-lobe suppression levels should not be this good.

The situation is different in the case of Fig. 4(b). The dynamic range of 25 dB indicates that either the system is degraded or the ambient noise is relatively high. The peculiar "butterfly" pattern which is roughly symmetric about

(a)

AFT ←|→ FORE

	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	65	66
17	69	100	95	73	41	31	31	32	19	12	2	9	26	22	25	45	28	24	38	35	27	43	62	39	34	37	18	39	55	56	42	100	100
18	69	69	97	71	39	29	29	32	19	12	2	11	25	20	24	45	27	22	39	38	29	45	61	36	34	38	19	40	56	57	41	100	99
19	65	67	69	55	27	28	25	36	27	19	8	20	24	19	25	44	23	17	37	42	38	51	60	27	32	39	18	40	61	61	43	94	94
20	50	49	38	69	78	23	26	7	-11	-13	-20	-18	7	6	4	25	33	34	34	24	9	27	44	36	29	29	21	18	12	11	7	74	71
21	0	0	0	54	69	31	34	3	-9	-14	-23	-35	-14	-10	-8	1	27	38	29	13	9	21	27	21	25	28	22	12	-6	-16	-24	42	40
22	0	0	0	0	0	69	53	19	13	7	1	1	-6	-5	3	19	20	15	12	-1	-2	7	21	30	2	8	1	3	-5	-14	-12	31	28
23	0	0	0	0	0	36	69	31	6	6	2	3	-1	5	23	27	1	5	13	-11	-14	-4	17	23	33	5	-2	24	25	11	-2	30	28
24	0	0	0	0	0	0	0	69	81	74	64	57	29	-8	-8	15	0	-4	-6	5	4	7	15	12	19	14	-10	3	17	24	23	32	32
25	0	0	0	0	0	0	0	56	69	95	81	51	21	-9	-10	4	1	-6	-7	12	16	9	6	4	-2	6	-6	0	4	6	7	19	19
26	0	0	0	0	0	0	0	51	65	69	93	54	22	-6	-7	3	-5	-13	-10	9	13	5	2	-2	-10	-4	-5	0	2	-3	1	12	13
27	0	0	0	0	0	0	0	44	56	64	69	64	22	-5	-7	1	-10	-9	-6	6	11	5	2	-7	-9	-10	-3	2	4	-5	2	2	2
28	0	0	0	0	0	0	0	39	35	37	44	69	62	7	-9	3	-16	-4	11	16	11	6	0	-12	4	7	-2	10	27	30	39	9	10
29	0	0	0	0	0	0	0	0	0	0	0	42	69	59	18	13	7	15	16	28	20	1	2	5	-3	3	6	23	27	38	53	26	28
30	0	0	0	0	0	0	0	0	0	0	0	0	40	69	70	41	21	11	20	43	24	3	3	4	-18	-7	10	17	19	27	35	21	24
31	0	0	0	0	0	0	0	0	0	0	0	0	0	48	69	79	38	13	31	43	24	13	12	6	-10	-5	1	22	18	16	23	24	26
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34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	69	65	21	16	25	39	24	20	20	21	16	-3	-3	6	24	24
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37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	69	76	46	13	-9	2	2	11	12	5	-1	26	25
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40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	69	24	18	-17	20	22	12	10	39	38
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	69	71	34	37	48	37	18	34	32
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43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36	69	44	17	16	4	18	18
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	69	75	48	20	38	38
45	38	38	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	33	0	0	51	69	82	44	53	54
46	38	39	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	56	69	80	55	56
47	0	0	0	0	0	0	0	0	0	0	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	55	69	41	42
65	69	69	65	51	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	30	42	0	0	0	0	0	36	38	0	69	100
66	69	68	65	49	0	0	0	0	0	0	0	0	0	0	0	31	0	0	0	0	0	0	42	0	0	0	0	0	37	38	0	69	69

FORE ←|→ AFT

BEAM NUMBER

(b)

AFT ←|→ FORE

	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	65	66
17	69	100	99	96	98	95	85	55	34	27	21	38	67	83	78	83	89	92	90	89	92	97	97	97	98	99	99	99	98	99	98	100	99
18	69	69	100	96	98	95	86	55	34	28	20	37	67	83	78	83	90	92	90	89	92	97	97	97	98	99	99	99	99	99	98	100	99
19	68	69	69	93	97	93	86	55	35	29	21	35	65	83	79	84	89	92	89	88	92	96	97	96	97	98	98	98	98	98	96	98	97
20	66	66	64	69	97	96	87	62	39	25	13	36	68	81	77	82	89	89	88	91	94	97	95	96	96	97	98	97	97	96	98	96	96
21	67	67	67	67	69	97	88	56	38	30	21	42	74	82	77	83	88	88	87	90	93	98	97	96	96	98	98	98	97	97	98	98	97
22	65	65	64	66	67	69	91	62	46	36	25	45	72	78	78	84	87	85	87	91	93	97	94	94	95	95	96	96	95	95	97	96	96
23	58	59	59	60	60	63	69	71	47	46	33	38	64	68	72	79	77	76	77	84	89	87	82	82	85	87	86	87	85	85	88	86	86
24	38	38	38	42	38	42	49	69	61	32	23	30	34	41	50	55	57	55	55	63	69	60	53	58	61	59	59	60	60	58	62	55	60
25	0	0	0	0	0	31	32	42	69	65	14	18	37	35	40	40	36	28	37	45	48	40	30	36	40	37	35	37	38	37	37	34	36
26	0	0	0	0	0	0	31	0	45	69	62	30	41	35	30	30	26	18	27	35	32	27	22	26	30	30	26	27	27	27	25	28	26
27	0	0	0	0	0	0	0	0	0	42	69	64	31	23	14	17	15	13	20	25	19	16	17	19	19	20	16	20	18	19	19	21	20
28	0	0	0	0	0	31	0	0	0	0	44	69	64	34	28	28	28	24	35	40	36	37	38	38	37	35	35	37	34	36	38	38	42
29	46	46	45	47	51	49	44	0	0	0	0	44	69	74	52	49	58	53	58	65	65	69	68	67	68	67	67	68	65	65	68	68	71
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32	57	57	58	56	57	58	54	38	0	0	0	0	33	49	61	69	92	83	74	74	82	84	84	85	84	85	84	84	85	84	82	82	80
33	61	62	61	61	60	60	53	39	0	0	0	0	40	56	54	63	69	92	79	80	84	89	93	93	92	92	92	92	92	92	90	89	89
34	63	63	63	61	60	58	52	38	0	0	0	0	36	54	54	57	63	69	90	82	85	89	91	92	93	92	92	94	94	94	91	92	90
35	62	62	61	60	60	60	53	38	0	0	0	0	40	52	50	51	54	62	69	92	83	85	87	90	92	90	89	91	91	91	89	90	89
36	61	61	60	63	62	63	58	43	31	0	0	0	45	54	50	51	55	56	63	69	91	89	89	90	90	90	91	90	90	90	91	90	91
37	63	63	63	65	64	64	61	47	33	0	0	0	45	53	56	56	58	58	57	63	69	96	90	92	92	93	94	94	93	92	95	92	92
38	67	67	66	67	67	67	60	41	0	0	0	0	47	54	54	58	61	61	58	61	66	69	96	95	96	97	99	98	97	97	97	97	97
39	67	67	67	65	67	65	56	36	0	0	0	0	47	58	53	58	64	63	60	61	62	66	69	99	97	98	98	98	98	98	96	97	97
40	67	67	66	66	66	65	56	40	0	0	0	0	46	58	54	58	64	63	62	62	63	65	68	69	99	98	98	98	99	98	97	97	97
41	67	67	67	66	66	65	58	42	0	0	0	0	47	58	54	58	63	64	63	62	63	66	67	68	69	99	98	99	99	99	97	98	98
42	68	68	67	67	67	65	60	40	0	0	0	0	46	58	54	58	63	63	62	62	64	67	67	67	68	69	99	99	99	99	98	99	98
43	68	68	67	67	67	66	59	40	0	0	0	0	46	57	54	58	63	63	61	63	65	68	67	67	67	68	69	100	99	99	99	99	98
44	68	68	67	67	67	66	60	41	0	0	0	0	47	57	54	58	63	65	63	62	65	67	67	67	68	68	69	69	100	99	99	99	98
45	67	68	67	67	67	65	58	41	0	0	0	0	45	58	54	58	63	65	63	62	64	67	67	68	68	68	68	69	69	100	98	98	97
46	68	68	67	66	67	65	58	40	0	0	0	0	45	57	54	58	63	65	63	62	63	67	67	67	68	68	68	68	69	69	98	99	98
47	67	67	66	67	67	67	60	42	0	0	0	0	47	54	52	56	62	63	61	63	65	67	66	67	67	67	68	68	67	67	69	98	98
65	69	69	67	66	67	66	59	38	0	0	0	0	47	57	53	56	61	63	62	62	63	67	67	67	67	68	68	68	67	68	67	69	99
66	68	68	67	66	67	66	59	41	0	0	0	0	49	56	51	55	61	62	61	63	63	67	67	67	67	67	67	67	67	67	67	68	69

FORE ←|→ AFT

BEAM NUMBER

FIG. 5. Rank correlation matrices corresponding to the same time periods as the data in Figs. 4(a) and (b). The rank correlation coefficients times 100 are above the main diagonal and the significance levels of the coefficients in standard deviations times 10 are on and below the main diagonal. Only the shades of gray below the main diagonals are of interest here, not the values of the numbers.

broadside was evident in data at other frequencies as well. Such patterns would lead one to suspect a problem with the system. However, by themselves, these patterns are not conclusive evidence that a problem exists. High level noise sources positioned appropriately in azimuth could produce the same patterns.

Spearman's rank correlation matrices are produced by the analysis program and used in conjunction with the beam noise polar plots to facilitate system performance and data quality assessment. Figure 5 contains two of these matrices which correspond to the same data as for Figs. 4(a) and 4(b).

The first column and the top row of each plot contains the beam number in increasing order (and increasing angle aft of forward endfire) from top to bottom (column) and left to right (row). The numbers above the main diagonal (top-left to bottom-right) are the Spearman's rank correlation coefficients times 100 (for display purposes). The numbers on and below the main diagonal are the confidence levels of the correlation coefficients in standard deviations times 10 (also for display purposes). Confidence levels less than three standard deviations (30 in the matrix) corresponding to 99.73% have been replaced by zeros. This facilitates spotting regions of high level correlation because the two-digit number blacks out more of the paper than does the single digit zero. Hence the correlation matrices can be used as gray scale indicators of correlation. This is illustrated by the two rank correlation matrices in Fig. 5. For the present discussion it does not matter if the numbers in these matrices have been reduced beyond recognition. The nearly total light gray area below the main diagonal of the matrix in Fig. 5(a) indicates an absence of strong correlation among the beams. Used in conjunction with the beam noise plot of Fig. 4(a), it is evident that the noise in most of the low noise level beams is due to the ambient and not to the side lobes of the system. In this case, only the broadside beam and four others aft of broadside show significant correlation. (The last two rows and columns are for selected hydrophones and should not be considered).

The correlation matrix in Fig. 5(b) is for the same data as Fig. 4(b). In this case the area below the main diagonal is "blacked out" except for four beams in the forward sector. These are the beams which receive a strong noise arrival from the towship after reflecting from the relatively shallow bottom [the peak at about 60° from forward endfire in Fig. 4(b)]. These beams do not correlate with the beams near forward endfire, which receive the towship direct arrival, because of the pathlength difference and the correlation calculation is for zero time lag.

The high percentage of dark area below the main diagonal of the correlation matrix of Fig. 5(b) indicates that a single source is dominating the system output on all beams except those receiving the towship noise which is reflected from the seabed. If the corresponding beam noise plot was Fig. 4(a), this would most likely be considered acceptable performance because it would indicate the side-lobe suppression level to be about 40 dB or better. However, since the corresponding beam noise plot is Fig. 4(b) instead, it indicates the side-lobe suppression was only about 25 dB and the "butterfly" pattern was caused by the system and not the ambient.

The beam noise polar plot used in conjunction with the rank correlation matrix conclusively established the existence of a problem which had gone undetected in the normal system checks prior to the acoustic measurements. The "butterfly" pattern was used as a clue in the trouble shooting which eventually found coaxial cables for channels 6 and 9 switched at the input to the beamformer. The ship had been used on a previous cruise for a nonacoustic experiment. During reconfiguration for the cruise which utilized the towed array, the cables were incorrectly connected. An upside-down 6 looks like a 9 and vice versa. However, the system still had 40 good channels to pass the normal system checks.

Figure 6 illustrates another problem, the effect of which

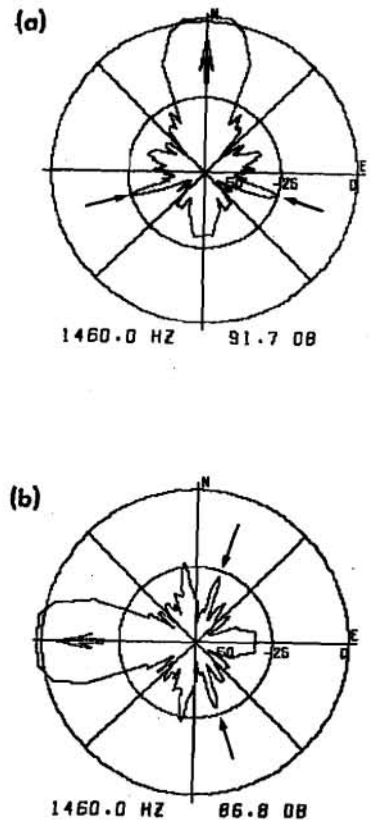

FIG. 6. Polar plot of beam noise measured while the active rudder is operating showing an artifact at 110° aft-of-forward endfire (arrows). Beam noise levels are relative to the total received level (below plot).

was readily detected in the beam noise data for the towship noise tests. The relatively high level noise at about 110° aft of forward endfire [about 20°, Fig. 6(b), and 160°, Fig. 6(a) on the plots] was always present and always at the same relative angle. This is illustrated by the two 1460-Hz beam noise polar plots for two different measurement locations. The water depths were different, which gave different bottom reflected towship noise arrivals, approximately 68° and 80° aft of forward endfire for Figs. 6(a) and (b), respectively. Trouble shooting failed to find a cause. However, low speed sound propagation in the array is one possibility. If there is low speed propagation of noise from the towship in the tubing containing the array (the speed of sound of the fill fluid is about 1100 m/s) the abnormally high noise at 110° aft-of-forward endfire could be a grating lobe of a beam steered toward the towship. This is analogous to making measurements above the design frequency of the array. The principal author has observed similar results in data for other arrays. However, the present data processing system was not available to investigate them and they remained a mystery. This artifact could be a problem for array performance and data quality if the apparent source, the towship noise, is more than 25 to 30 dB greater than the levels to be measured along the azimuths of the affected beams.

Figure 7 presents an additional example of the utility of the polar plots of beam noise levels obtained during towship noise measurements. The water depths during the measurements were about 2800, 500, and 140 m for the data in Figs. 7(a), (b), and (c), respectively. The array depths were about

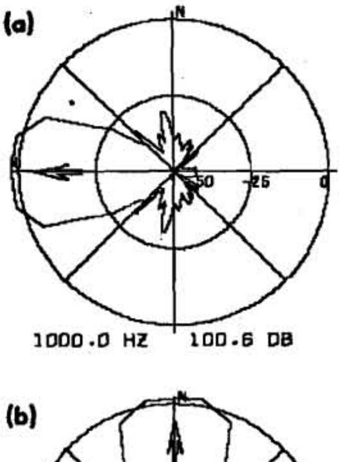

FIG. 7. Examples of towship noise contamination on beams near forward endfire (arrow) and closer to broadside [(a) and (b) only] for water depths of approximately (a) 2800 m, (b) 500 m, and (c) 140 m. Beam noise levels are relative to the total received level (below plot).

100 m with 900-m cable scope for the first two, and 80 m depth with 500-m cable scope for the last one. These results show the towship noise suppression for the aft-of-broadside beams to generally be in excess of 40 dB for the first two plots and for some beams to be in excess of 50 dB. The rank correlation matrices indicated no correlation between most of these beams and those containing the direct arrivals from the towship. Therefore, the actual side-lobe suppression levels in these two cases were in excess of the differences in the levels measured (more than 40 or 50 dB). Both amplitude calibration and phase accuracy must be very good to achieve this level of performance.

The situation is different in the case of Fig. 7(c). The noise levels for beams aft of broadside are only about 27 dB below the main arrival. The Spearman's rank correlation matrix for these data indicated significant correlation among the beams. This suggests degraded system performance. During the experiment that it occurred this level of performance was still within the range of acceptability. The following day, when the system was tested again for additional measurements at a deep-water site, the side-lobe suppression capability had increased to about 40 dB. Since no repairs had been made in the system between the two deployments and all other system checks were good it was concluded that the degradation was probably a result of the local conditions in that shallow water area and not due to the towed array system. Whatever the cause, the techniques quantified the effects and it is the effects which the researcher must live with or due something to change.

The plots in Fig. 7 serve another useful purpose. They indicate the levels and the arrival angles of the noise received from the towship. For example, distinct angles of bottom reflected noise from the towship are evident at 80° and 45° aft-of-forward endfire for Figs. 7(a) and (b), respectively at 30 and 25 dB down from the direct arrival. The main arrivals affected the beams within about 35° of forward endfire. These azimuths of towship noise contamination could present serious problems for some measurements. The extent of the probable degradation would depend on the differences in level between the levels of the towship noise contamination and the levels of the signals or noises that are to be measured along these azimuths. In the case of Fig 7(a), for example, at 80° aft-of-forward endfire, the level to be measured should not be more than 25 dB below the noise received from the towship (assuming a signal to contaminating noise ratio of 10 dB to be adequate). In the case of 7(c), the region of possible degraded results extends all the way to aft endfire and may be very sensitive to the water depth and local bottom conditions. This could have a significant affect on the measurements to satisfy the exercise objectives.

The geometric mean intensity level (dB average), Eq. (3), and the average power level Eq. (4), are two other products which are useful in the assessment of array performance and data quality analysis. When used together, they indicate the presence of abnormally high or low levels in the time series.

A simple example is given to illustrate that this test might be worthwhile. Consider a beam or hydrophone noise level time series consisting of 48 normal samples of 50 dB each and two abnormal ones of 100 dB. The decibel average for this data set would be 52 dB. The average power level, on the other hand, would be approximately 76 dB. The difference between the two of 24 dB is significantly above the value normally expected (up to 4 dB). This test is less sensitive to abnormally low levels, hence, a greater percentage of the low levels would be required to appear significant. Differences in these two types of averages in excess of 30 dB have been observed in both towship noise measurements and in ambient noise measurements. In the former case the problem is the sonar system, in the latter it could be the noise field (i.e., seismic prospecting or a nearby ship entering or leaving the beam coverage sector during the data acquisition period).

If the time series is one dominated by the direct arrivals from the towship or some other relatively stable source, the cause of the abnormal data is probably a problem in the towed array system rather than in the acoustic field. An example of a problem which was detected by these products is a series of high level "pops." Only about five or ten occurred during the 50 time periods required to acquire the time series. The geometric mean intensity level was relatively unaffected by the presence of the relatively few high levels. The average power level, however, was about 8 dB higher than the dB average. A difference of less than 4 dB would be considered normal for such measurements. Figure 8(a) illustrates this case.

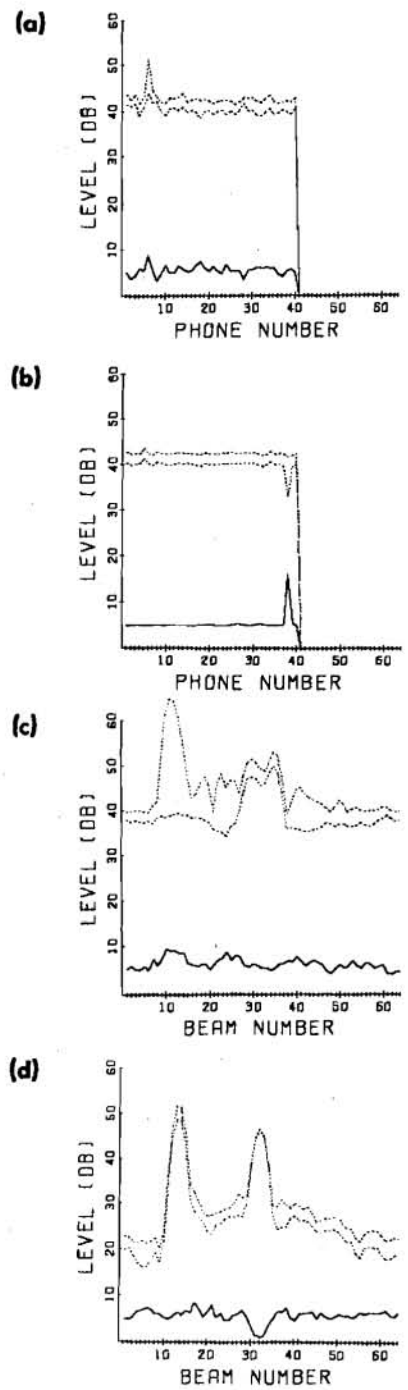

FIG. 8. Example plots of average power level (top dashed curves), geometric mean intensity level (bottom dashed curves), and standard deviation of decibel levels (solid curves) for hydrophone [(a) and (b)] and beam noise data with two magnetic tape parity errors (c), and electronic (common mode) noise (d).

The highest dashed curve in the plots of Fig. 8 are the average noise power levels. The lower dashed curves are the geometric mean intensity levels (dB averages). These curves have been normalized for display purposes. The solid curves are the standard deviations of the decibel time series. The top two plots [Figs. 8(a) and (b)] are for hydrophone data and the bottom one is for beam noise data.

The popping noise, which is transient in nature, increased the separation between the two curves. This is a definite indication of problems. The problems indicated here are of a different nature than the preamplifier problem which caused the abnormally high level of hydrophone 24 in Fig. 3(b) which would not have a large difference between the two different types of averages.

The data in Fig. 8(b) illustrates results for "dropouts" on channel 38. Even though the average power level remains relatively unaffected, the occurrence of these abnormalities could seriously degrade some types of processing and analyses which utilize the individual data points.

The curves in Fig. 8(c) are for beam noise data measured when the data acquisition system was not functioning properly. The first indication of a problem was when the data processing computer experienced two parity errors, at one point, while reading the data tape. Whether this could constitute a problem that would adversely affect the data was unknown until the data quality programs were run. Figure 8(c) was the result. The difference in the two types of averages ranged from about 3 to 28 dB and covered a wide range in beam numbers (azimuth). This was a clear indication that certain types of data processing would be adversely affected by the tape error. When the bad data point was eliminated and the data reprocessed, the curves for the two different types of averages (dashed curves) followed each other within about 3 dB. This is dramatic evidence of the adverse affect one point can have on the average power level, which is commonly used in signal processing. It also illustrates the power of the data quality test which uses the differences between these two types of averages.

The two types of averages behave differently on the two sources in Fig. 8(d). The source at beam number 12 is the towship noise. The two averages (dashed lines) for it have a normal spread of about 3 dB. The corresponding spread for the other (broadside) source at beam 32 is a fraction of a decibel. Such stability is not indicative of an acoustic source. Electronic noise is a strong candidate.

The standard deviation of the decibel time series of beam or hydrophone noise is the final product which will be discussed. In the case of the present processing system, the standard deviation of the noise from the direct arrival of the towship is normally between 5 and 6.5 dB. A larger or smaller value would indicate degraded performance. Some electronic noise, for example, has standard deviations less than 5 dB. A channel which is completely dead would have a standard deviation of 0 dB. One dominated by a power source line at 60 Hz, for example, could also have a very small standard deviation. The dB average and average power level, however, used in the previous test could be close in level and the problem would not be detected by that test. It is also possible to have an abnormally broad distribution of beam noise levels which have relatively similar values for the dB average and the average power level. The apparent degraded system performance may not be detected by the previous test but it would be by observing the standard deviation. Standard deviations as high as 11 dB have been observed when values of the order of six are normal for a time-bandwidth product of one. In a plotted format with standard deviations for other hydrophones and beams, the abnormalities are easily spotted. The solid curves in the plots of Fig. 8 are some examples.

The abnormally high standard deviation in Fig. 8(b) is a result of "dropouts" on channel 38 as discussed previously. The unusual behavior of the noise of the broadside beam (number 32) in Fig. 8(d) is evident in the standard deviation. It is about 1-dB broadside and 5 to 7 dB for beams which are not near broadside. Such a low standard deviation is an indication that the beams near broadside are dominated by electronic noise. Since it is in phase on all channels it appears on the broadside beam and is sometimes called "common mode" noise. This is not an uncommon occurrence. Anderson[11] indicates that common mode noise plagued his 100-Hz vertical-array data. Had such a diagnostic tool as Fig. 8(d) been available to him in real time, the problem might have been discovered immediately and corrected at sea. This was the experience of the authors as a result of Fig. 8(d). The trouble shooting that was prompted by this figure led to the discovery of "ground loops" which were introduced during system configuration. The problem was corrected and subsequent data were free of this artifact.

In the present data acquisition, processing and reduction system at SACLANTCEN (see Fig. 2), the testing for problems and levels of side-lobe suppression or towship noise domination is done manually by "eyeballing" the data. It is a simple matter, however, to establish thresholds for each test and have the data processing and reduction system perform the tests and print out a signal with appropriate details when a test is not passed. This will probably be implemented in the future at SACLANTCEN to aid those scientists who are not familiar with the many problems a complex system like the towed array can have and the affect those problems can have on their data.

V. CONCLUSION

An approach has been suggested to permit real-time relative amplitude calibration, assessment of performance, and data quality analysis for towed array systems. The necessary data can be acquired in as little as 15 min and requires no special noise sources, provided the towship noise is relatively strong compared to the ambient background noise. Examples have been given in which the techniques discussed have found problems with the sonar system that normal system checks prior to the acoustic measurements have failed to detect and provides clues to their causes. This is not to say that tests could not have been performed which could have detected the problem. It merely emphasizes the fact that only a reasonable number of the many possible tests to check out the system will be performed. Since the possible problems are far more than the number of tests that can be reasonably performed, some problems will not be detected. However, when the test is an acoustic one involving a known high level source, such as the towship, the number of problems which can go undetected with the approach introduced herein is significantly reduced.

These techniques have been used by SACLANTCEN for several towed array ambient noise measurement exercises. The results and past experience indicate that having some sort of problem with the system is the norm rather than the exception. This experience also suggests that once the problems are detected they can ofttimes be corrected and measurements continued with a near perfect system. Measured side-lobe suppression levels in excess of 40 dB and many times 50 dB are evidence that this is the case. Finally, the tests presented herein are easily automated by comparing the products with reasonable threshold levels.

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