ARRAY PERFORMANCE AND VARIABILITY AT SHORT RANGE NEAR VESTFJORDEN

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Abstract An experiment was conducted in October 1989 in shallow water near Vestfjorden in support of low frequency active sonar system research at SACLANTCEN. This report addresses some acoustic measurement results from that test related to array performance and variability at short range. The received signal level varied by as much as 10-15 dB across the array on a single ping, as well as from ping to ping. This variability and changes in the multimode arrival structure are shown to be caused by small (1 m) changes in array depth. Average array signal gain degradation is less than 1 dB, so the array performance is nearly perfect, despite moderate tow-ship course variations and an unexpected "hole" in the acoustic field.

1. Introduction

In October, 1989, an experiment (OCT89) was conducted near Vestfjorden, to investigate submarine detection in shallow water with the SACLANTCEN Low Frequency Active Sonar (LFAS) System. The experiment was one in a series dating back about 10 years to investigate the feasibility of LFAS systems to detect, track and localize targets under various environmental conditions. This report discusses one environmental-acoustic phenomenon that impacts overall LFAS system capability; i.e. array performance and acoustic variability for one-way propagation paths in shallow water.

The paper is organized as follows. First, there is a discussion of the experiment, including the equipment and the environment. Second there is a section covering the acoustic observations of multi-mode propagation variability and array beamforming performance. Next, there is an analysis section, wherein a deep null in the acoustic field is described. Then, acoustic field predictions are shown in a modelling section. Finally, the major conclusions are reviewed in a summary section.

2. Experiment, Equipment and Environment

The data analyzed in this paper are 46 pings (0.5 sec LFM from 340-345 Hz) from Run 14 of the OCT89 Cruise. The signals were emitted from a source mounted on a submarine at a depth of 35 m, a speed of 5 kn, a range of about 13 km and a bearing near broadside to the receiving towed array. The ping repetition rate was once a minute, so this analysis covers 46 min. The ping transmission times were known so the absolute range could be determined.

The Research Vessel Alliance towed a hydrophone array at a depth of about 40 m and a speed of about 5 kn. A set of 59 hydrophones, equally spaced at 2 m, were selected for analysis. This yields a 116 m aperture, or 27 wavelengths at 342.5 Hz. The array contained 3 non-acoustic sensors - a compass and pressure gauge 2 m forward of the first hydrophone and another pressure gauge 12 m aft of the 59th hydrophone. Throughout the run, on-line readings from the depth sensors showed a mean depth difference of about 1 m between the front and back of the array (implying a mean tilt of less than 1 deg).

At the beginning of the run, the water depth was 275 m under the source and 290 m under the receiver, but 320 m at mid-range in between. At the end of the run, the water depth was 250 m under the source and 315 m under the receiver and also 315 m at mid-range. The sediment consisted of silty-clay with thickness greater than 100 m under the source track but only 0-5 m under the receiver track. The range dependence of the environment, which changes from ping-to-ping, may contribute to some of the unexpected acoustic results described at the end of this report. The sea was calm with winds of 5 kn and sea state of 1.

3. Acoustic Results

The 59 hydrophone signals were first match filtered against a computer-generated, noise-free replica of the transmitted signal to improve the signal-to-noise ratio (SNR). The correlation function was computed using circular correlations in the frequency domain. The envelope was extracted and normalized so that a perfect correlation yields a value of 1. The time-compressed results were examined to determine the multi-mode arrival structure in shallow water and the arrival time of each pulse, at each hydrophone, for each ping.

An example of the replica envelope correlation is given in Fig. 1 for Ping, 12 for hydrophones 1 (forward), 20, 39 and 58 (aft). The time axis is relative to an arbitrary time and spans about 2.8 sec. The average signal-to-noise ratio (SNR) across the array is 18 dB; however, there are variations in SNR across the array of +/- 5 dB which will be shown and discussed later. The absolute coherence levels are slightly affected by noise contamination. The purpose of Fig. 1 is to show the arrival structure along the array, not the absolute coherence. This example is for a moderate SNR situation; however, the variability is representative of high SNR cases, as well.

The upper left curve (hydrophone 1) shows one dominant arrival at 26.15 sec with a correlation of 0.7 and a width of about 250 ms at the half-power point, which is approximately equal to the resolution of the pulse, or one divided by the bandwidth (1 / 5Hz = 200 ms). A secondary arrival group occurs about 1/2 sec later and finally a third arrival is seen near the end of the display. The middle arrival appears to be a group of arrivals superimposed, because the time spreading is much greater than the resolution width of the pulse.

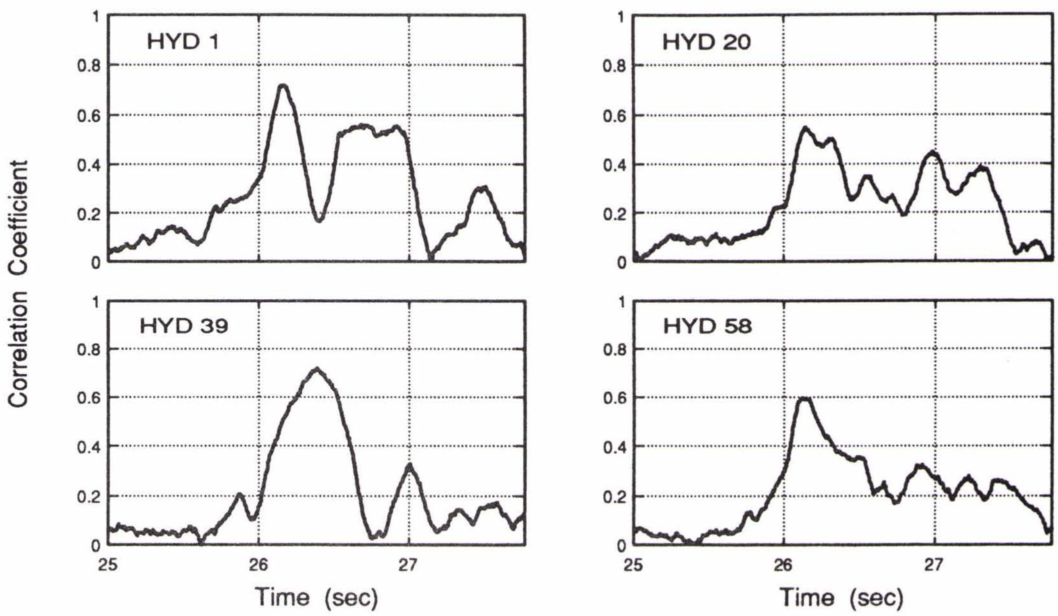

Figure 1 *Replica correlation for hydrophones 1, 20, 39 and 58 for Ping 12 (Run 14; OCT89 Cruise).*

The other 3 curves show different correlation functions which implies different arrival structures. The correlation in the upper right with phone 20 shows a reduced correlation and a smearing of the arrivals over 1.5 sec with no clear separations. The correlation in the lower left with phone 39 shows a wide peak with good correlation centered at the time between the first 2 peaks of hydrophone 1; i.e. an offset of 200 ms from the first peak of hydrophone 1. The large width indicates that some arrivals have been combined, as observed in the second group of hydrophone 1. The correlation in the lower right with phone 58 shows a smeared structure similar to that of hydrophone 20.

In some situations arrival time differences can be caused by array shape distortions. This is not possible for this data because the 200 ms delay seen on hydrophone 39, relative to the other three hydrophones, would imply a shape distortion of 300 m, or 3 times the length of the array. The time shift is probably caused by the constructive and destructive interference between several modal arrivals.

The variable modal arrival structure on individual hydrophones over 116 m on a horizontal aperture is surprising for a distant source at broadside, because the ray paths to each hydrophone are nearly identical in range extent and in environmental conditions. There may be cause for concern because the variability could reduce beamforming gain by reducing spatial coherence over the aperture.

Acoustic performance was examined by studying the array response patterns for the 46 pings. Each ping was beamformed in the frequency domain and averaged across all frequencies in the 5-Hz band. No shading was applied. An example of this result is given in Fig. 2 for Ping 3, which is representative of the average performance over all 46 pings. The solid curve is the measured array response and the dotted curve is the theoretical response, assuming perfect spatial coherence and normalized to the average hydrophone intensity. In this case, the measured response is 1.1 dB down from the theoretical; this amount is the array signal gain degradation (ASGD). The beam noise levels are also shown, as circles, and the output SNR is about 40 dB in the broadside direction, so the ASGD and beamwidth estimates have high confidence.

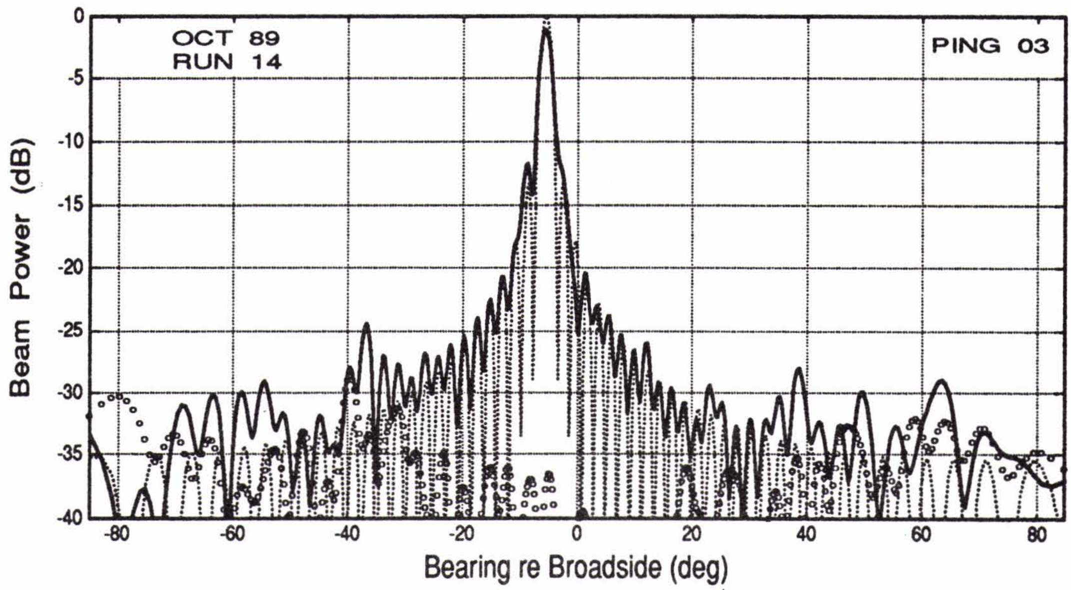

Figure 2 *Array response for ping 3 (Run 14 of the OCT89 Cruise).*

In order to show the results from all 46 pings simultaneously, a contour plot of the array responses from -20 to +20 deg around the maximum response is given in Fig. 3. There is an azimuthal variation in the apparent bearing of the beacon source of about +/- 6 deg around broadside (near 0 deg), despite the nearly constant relative geometry between the source and receiver. This oscillation has a period of 12 min and has been shown to be caused by array orientation changes induced by tow-ship course variations. The largest responses (darkest shades), indicate highest performance. The pings with highest performance are not uniformly distributed over time. For example, there are low levels at Pings 4-9, 12-19, and 33-37.

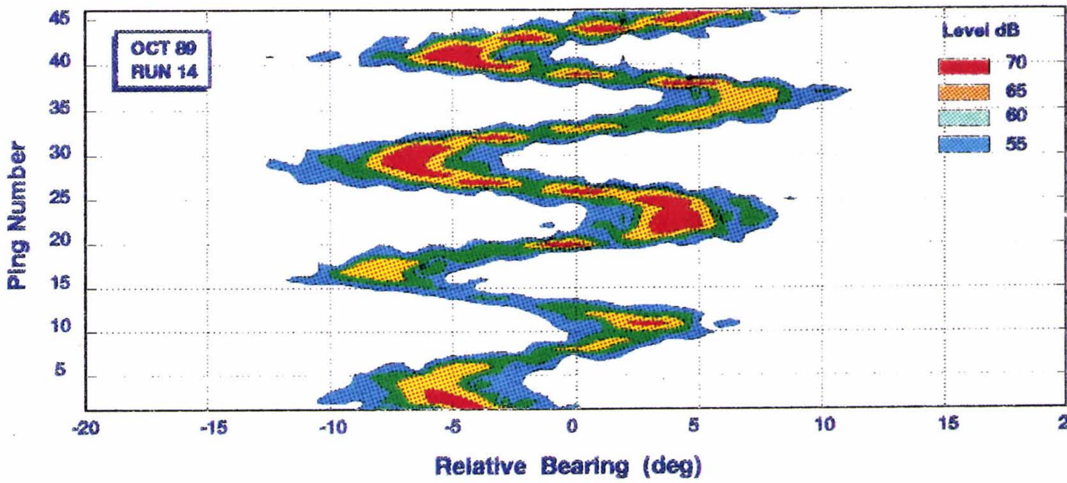

Figure 3 *Array response contours for 46 pings (Run 14 of OCT89 Cruise). The peak varies by +/- 6 deg with a period of 12 min.*

Next, the responses were aligned according to the bearing of the peak, to allow averaging (in dB) with and without correction for array wandering. These averaged results are given in Fig. 4, with alignment (dashed) and without alignment (solid). The theoretical response is also presented (dotted). There is a 15 dB maximum difference between the two averaged responses. It is somewhat remarkable that the sidelobe structure of the aligned response is so clearly defined. This indicates that throughout the 46-min time period the array was nearly always straight, and the spatial coherence was high. Therefore, this 27-wavelength array should provide nearly perfect acoustic performance (as measured by signal gain) on each individual ping.

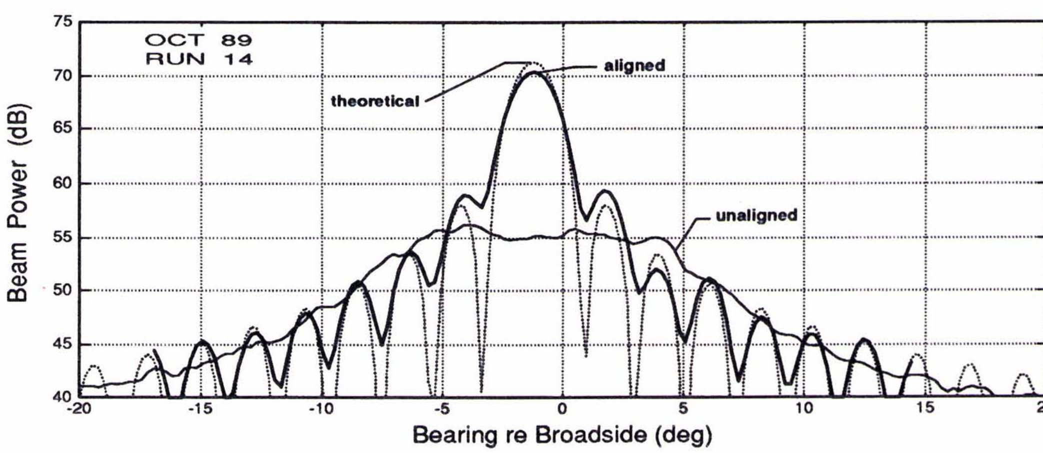

Figure 4 *Average array response with and without alignment for array heading variations caused by ship heading changes (Run 14 of the OCT89 Cruise).*

The 15 dB difference in average responses emphasizes the need to account for array orientation correction. Of course, the magnitude of the effect depends on the amount of array variation, but even under highly controlled ship steering conditions there will be some array movement and therefore some improvement to be gained with correction for orientation.

For each ping, several quantities were calculated from the individual array responses in order to see the time variability and to compute performance statistics. These results are given in Fig. 5. The upper left shows the hydrophone power (averaged over all 59 hydrophones and over the 5-Hz frequency band before converting to dB) and also the power through the beamformer. The hydrophone power is relative to an arbitrary constant. For perfect spatial coherence and a straight array, these 2 curves would be offset by a constant amount equal to the array signal gain [ASG=20log(59)=35.4 dB], and the array gain in isotropic noise would then be 10log59=17.7 dB. Variations in the hydrophone levels are due to changes in propagation loss. There is a close correlation between changing hydrophone levels and the beam response; therefore, the first-order variations in beam level are caused by changes in propagation loss and not by changes in spatial coherence or array shape distortion.

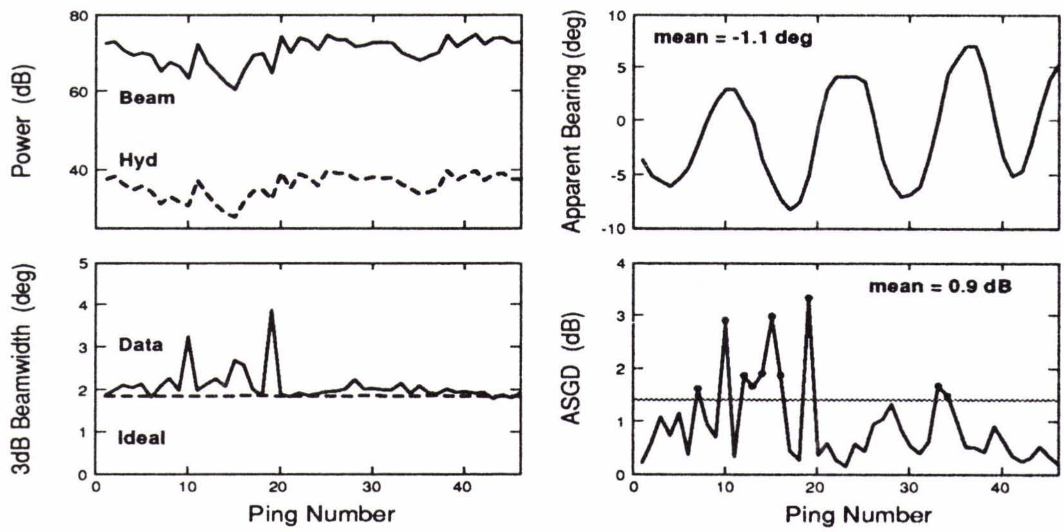

Figure 5 *Array response statistics for Run 14 of the OCT89 Cruise.*

The upper right curve in Fig. 5 shows apparent bearings to the source based on the peaks from Fig 3. These bearings change nearly periodically by +/- 6 deg over a 12-min period. As mentioned earlier, this variation was caused by changes in the ship track which caused changes in the array orientation. If the unusual trajectory caused array distortions, then one would expect a corresponding loss in performance, as measured by beamwidth and signal gain. These results are seen in the lower 2 plots of Fig. 5.

The lower left shows the 3 dB width of the measured beam responses along with the theoretical value of 1.85 deg. The average width for the data is 2.09 deg, which is only 13% wider than the theoretical. The highest values occur between Pings 7 and 19, when the hydrophone levels were at their lowest.

The lower right shows the ASGD. The average value is only 0.9 dB, so the array performance is nearly perfect, despite the ship track and array variations and the changes in propagation loss. Therefore, in isotropic noise, the array gain would be reduced by less than 1 dB, to about 16.8 dB. There are several instances when the loss in gain exceeds 2 dB, but these represent only 11% of the data. A line is drawn on the ASGD data at the arbitrary level of 1.4 dB in an attempt to separate some instances of poorer performance from those with better performance. There are 10 pings with ASGD greater than 1.4 dB and these are highlighted with circles. Possible reasons for the poorer performance during these 10 pings will be described later in the analysis section of this report.

But first, an interesting result is shown in Fig. 6 where the apparent bearings are displayed as a histogram. The distribution is bifurcated around the correct (mean) bearing of -1 deg, because during the quasi-sinusoidal ship maneuvers, a line normal to the array points either fore or aft of the source essentially all of the time. Opportunities for observing the source at the correct bearing are limited, and in this case there are no occurrences of the correct bearing. Of course, in a real system, there would be corrections for array orientation and this bifurcation would not be a problem.

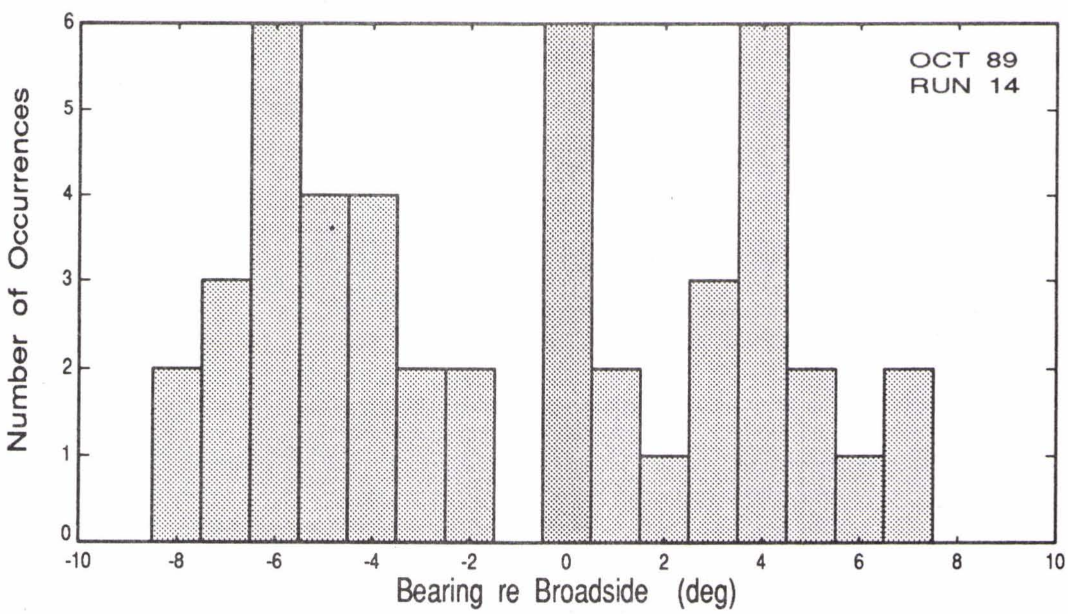

Figure 6 *Histogram of apparent bearings from Run 14 of the OCT89 Cruise.*

4. Acoustic Analysis

The main issues requiring analysis and explanation are the variations in arrival structure across the array during a single ping and the changes in propagation loss during the run, given that the geometry was fairly constant. Two important parameters to consider are the time-varying range to the target and the array depth. These are shown in Fig. 7.

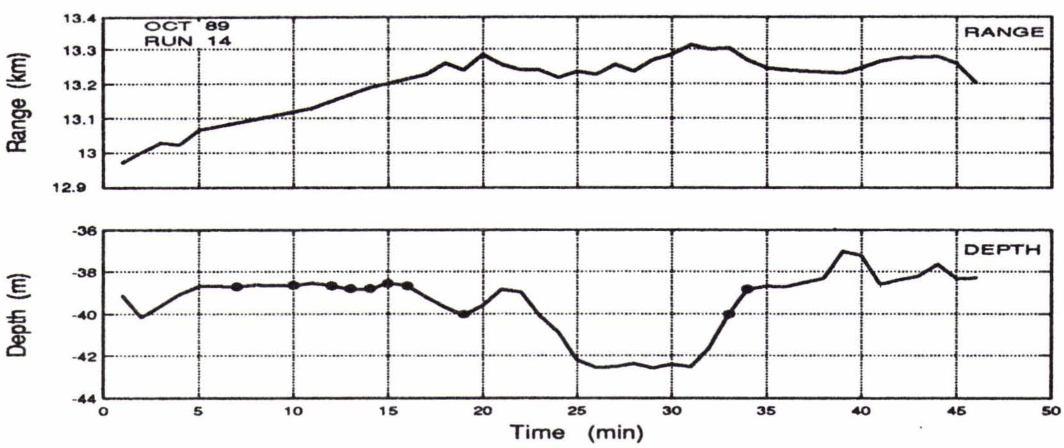

Figure 7 *Range to source (upper) and depth of array (lower) for Run 14 of the OCT89 Cruise. The circles represent pings (times) when array signal gain was degraded by more than 1.4 dB.*

The upper curve is the range to the source measured acoustically from the ping arrival times, and the lower curve is the mean array depth, calculated as the average between the 2 pressure gauges. The circles represent pings (times) when the array performance was degraded by more than 1.4 dB. There was degradation between pings 7 and 19 and again at pings 33 and 34. Pings 1-19 correspond to a period when the range was opening from 13 to 13.25 km (by 250 m), and the mean array depth was nearly constant between 38.6 and 40 m. From ping 19 to 34 the range is nearly constant at 13.25 km and the array depth increases by 3.5 m for 5 min and then recovers. Note the 2 degraded pings (times) at the end of the depth recovery, again in the depth interval of 38.6 to 40 m. From ping 35 to 45 the range was stable and the depth fluctuated between 37 and 38.6 m.

It is clear from Fig. 7 that variations in depth (not range) are the cause of the degraded performance because the range was changing during Pings 7-19 while at a constant depth, and as soon as the depth changed, the performance improved, only to degrade again when crossing the previous bad depth interval. Consider the performance in 3 depth intervals - less than 38.6 m, between 38.6 and 40 m, and greater than 40 m. We have the interesting result that 10/10 pings in the upper interval and 11/11 pings in the lower interval have nearly perfect performance (ASGD < 1.4 dB). However, only 14/25 pings in the middle interval have the same high performance.

Fig 8 shows how the ASGD varies with mean array depth and received signal levels. The upper data show that the higher degradation occurs strictly in a depth interval between 38.6 and 40 m. The degradation is always less than 1.4 dB when the array depth is less than 38.6 m or greater than 40 m. On the lower plot, it is clear that the higher values of ASGD occur when the hydrophone levels decrease. In particular, 34/37 data points have the higher performance when the signal level is above 33 dB, but only 1/8 below 33 dB have the higher performance. From Fig, 08, we see that ASGD is affected by both mean array depth and by signal level. Therefore, it is interesting to examine the relation between receiver depth and signal level in the next figure.

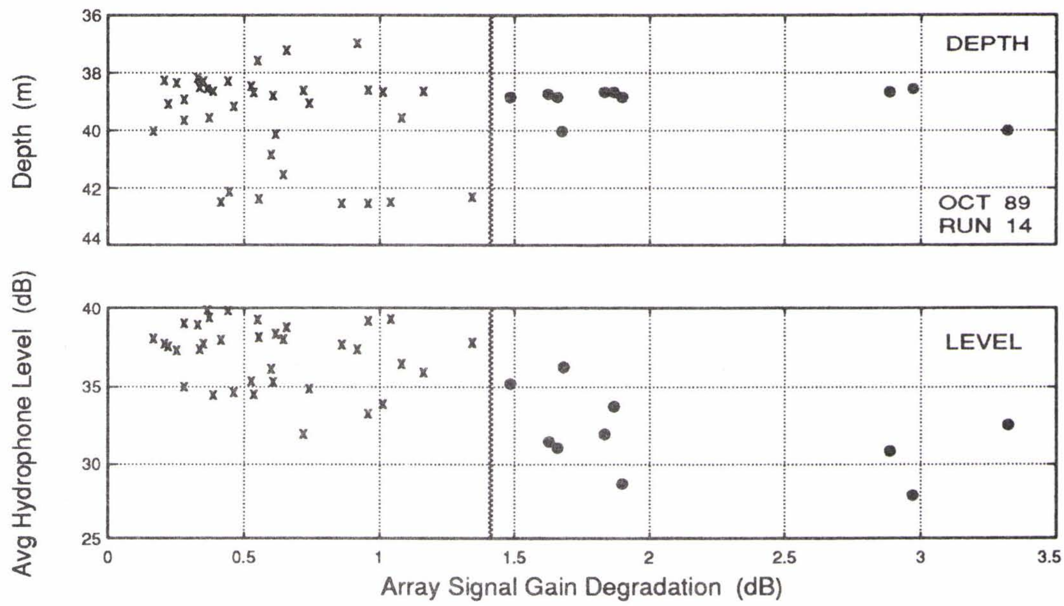

Figure 8 *Relation between ASGD and array depth (upper), and average hydrophone signal level (lower) for Run 14 of the OCT89 Cruise. A line has been inserted at the arbitrary value of ASGD = 1.4 dB to separate better from poorer performance. Those occurrences of ASGD greater than 1.4 dB are given by circles.*

Fig. 9 shows the relation between the mean array depth and the signal level (averaged over the array). We have the somewhat surprising result that most of the data points between 38.6 and 39 m are in an acoustic hole. It appears that the propagation changes by as much as 10 dB when the mean array depth is changed by as little as 1 m. On the average (in dB), the hydrophone levels in each 1 m interval from 37 to 43 m are 38.4, 34.6, 36.2, 36.2, 37.9, and 38.5, respectively, so the average variation is not so great. However, it should be remembered that most arrays will have some tilt and therefore cover some depth interval. For this data set, with a nominal 1 m depth difference, the hydrophone intensity, and undoubtedly the arrival structure, varied considerably due to depth extent. This could explain the variability along the array shown in Fig 1.

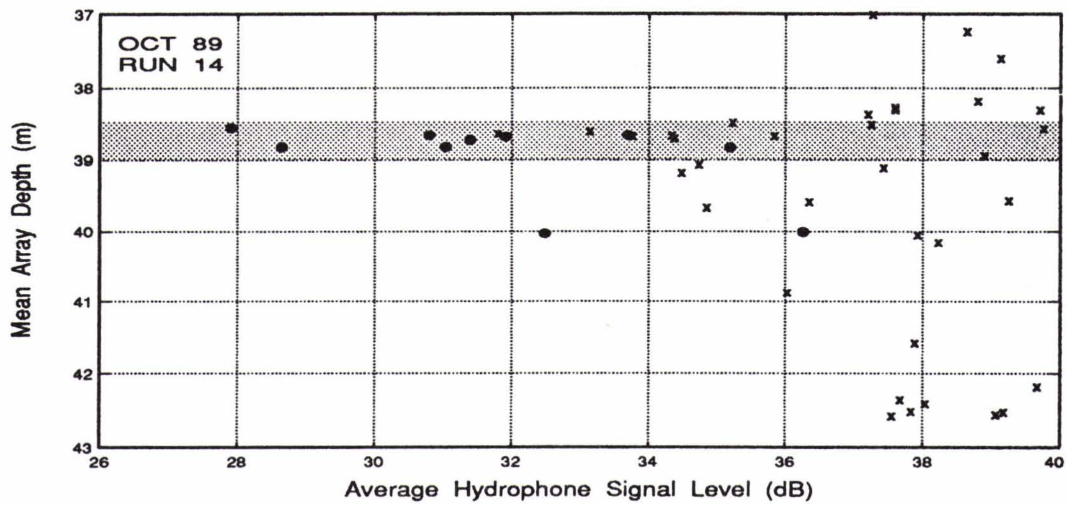

Figure 9 *Mean array depth vs average hydrophone signal level showing a band of low intensity (high propagation loss) between 38.6 and 39 m during Run 14 of the OCT89 Cruise. The pings with ASGD greater than 1.4 dB are shown as circles.*

It would not be surprising for the ASGD to drop when the signal level decreases, if the SNR also decreased to unacceptable levels, because noise will degrade estimates of signal coherence and signal gain. To investigate, the SNR as a function of ping number is presented in Fig. 10, with the poorer performance pings indicated with circles. The average SNR is 21.1 dB, with a minimum of 12.8 dB and a maximum of 25.9 dB. The SNR is relatively lower between Pings 7 and 19 than at later times. Most of the lower ASGD values occur between pings 5 and 19 so it appears that the ASGD estimates are slightly corrupted by noise during this time period, even though the SNR is greater than 12 dB.

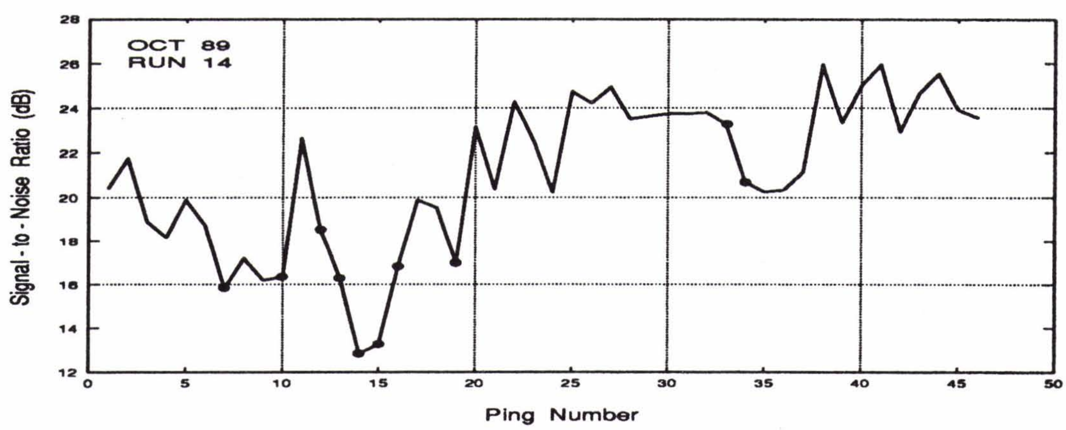

Figure 10 *Average signal-to-noise ratio across the array as a function of ping number (time) for Run 14 of the OCT89 Cruise. The pings with ASGD greater than 1.4 dB are highlighted by circles.*

It is curious that some adjacent pings, with similar SNRs have different ASGD. This is in contradiction to the hypothesis that only increased noise causes a higher value of ASGD. It is of interest to examine the variability of the received signal level across the array for individual pings. Two adjacent pairs are examined in more detail in Fig. 11 where the signal levels are plotted as a function of hydrophone number. The upper curves represent a low SNR case (Pings 9 and 10) and the lower curves represent a high SNR case (Pings 32 and 33). The average SNR was about 16 dB for the upper curves and about 23.5 dB for the lower curves. Notice that the vertical scales are different for the upper and lower parts of Fig. 11 when making comparisons.

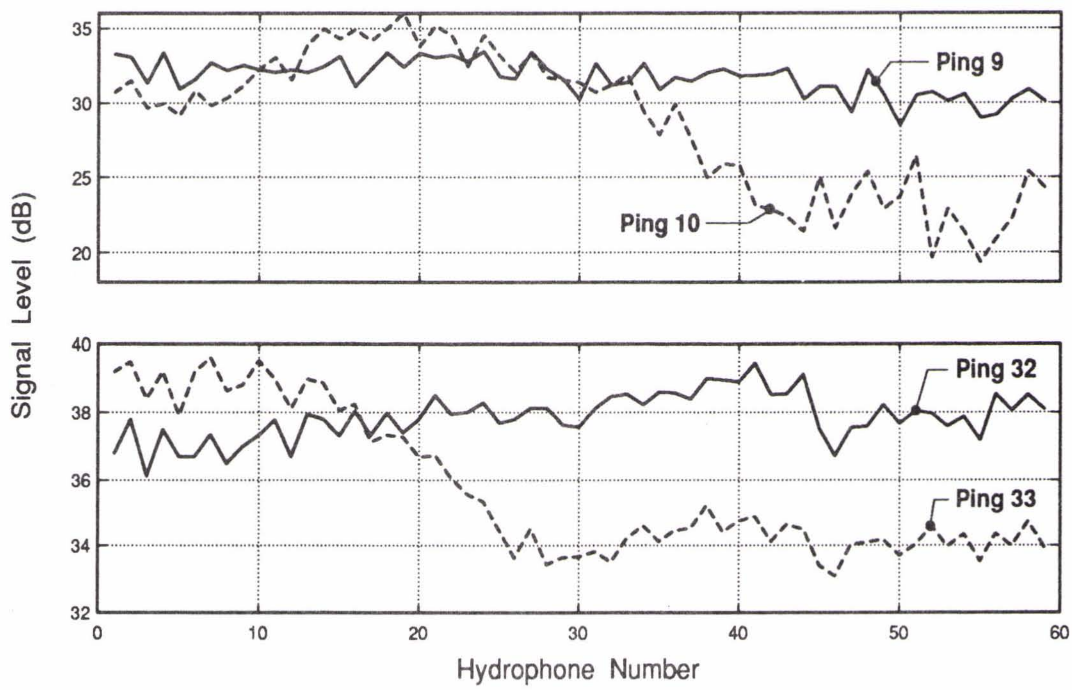

Figure 11 *Signal level across the array for Pings 9 & 10 at low SNR (upper), and for Pings (32 & 33) at high SNR (lower). Pings 9 & 32 show relatively stable levels across the array and have good performance (ASGD < 1.4 dB), while adjacent Pings 10 & 33 show variable levels across the array and have worse performance (ASGD > 1.4 dB).*

In these cases, the pings with a relatively stable signal level across the array (solid curves in Fig. 11) produce the better beamforming performance, for both low and high SNR. Signal levels vary by about 3-4 dB across the array for Pings 9 and 32; when the ASGD was less than 1.4 dB. However, the signal level variation across the array is 15 dB for Ping 10, and 7 dB for Ping 33, when the ASGD was greater than 1.4 dB. The hypothesized explanation for the level variation is that the array is always operating near the acoustic hole, and from ping to ping, it is possible for part of the array to encounter the deep null due to minor depth excursions and a small time-varying tilt of the array.

5. Propagation Modelling

It is difficult to accurately model broadband, pulse propagation in this range-dependent environment, especially since the environment changes along the track during the 46-min period. However, since the bandwidth is only 5 Hz and the water depth variability is not too great, range-independent CW propagation calculations were performed using the SNAP normal mode model. The geoacoustic description for the silty-clay sediment was based on independent geophysical experiments conducted within a few km of the test site. Several environmental descriptions of the area were input to the model, each of which was within reasonable limits of the actual environment, based on the geophysical test data.. SNAP calculations were made for each of the possible environments, with qualitatively similar results.

A sound speed profile for the area was obtained from a CTD measurement about 2 hr before the acoustic data were collected. Several XBTs were taken later in the day and converted to sound speed. Estimates of sound speed were also obtained from the submarine during a diving period. To first order, all of these independent estimates of sound speed were in agreement. A smoothed version of the CTD data is given in Fig. 12. The sound speed channel is the result of mixing between fresh water running into the sea from the fjord in the upper layer overlaying warmer, more saline summer water. Since the source and receiver were in the depth range of 35-40 m, propagation was mostly in the sound channel and this will minimize the effect of range-dependent bottom interactions.

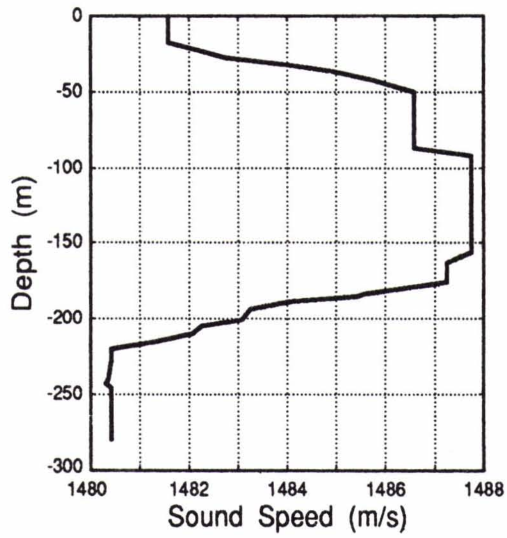

Figure 12 *Sound speed profile at the test site near Vestfjorden for Run 14 of the OCT89 Cruise.*

A typical propagation modelling result is shown in Fig. 13 as contours of sound intensity over an expanded depth and range interval (20-50 m and 12.5-14 km, respectively), surrounding the expected geometry of the experiment. There is a predicted region with very low intensity, centered at 35 m and 13.6 km, which could be the cause of the measured results of this report. Reasonable changes in the geoacoustic properties and in the water depth (as model inputs) caused a small change in the exact position and shape of the low-intensity region, but by only a few meters in depth and a few hundred meters in range.

Each color contour represents 3 dB of propagation loss, so the SNAP prediction shows the possibility of greater than 10 dB changes in level for depth changes of a few meters with a range extent of several hundred meters. Although not exactly the form nor the location implied by the acoustic measurements, the agreement between the sea data and the model calculations is quite good, considering the complicated environment. This high loss feature is probably caused by the multimode interference pattern produced by the low-bandwidth pulse. If so, then broader-bandwidth signals normally used in LFAS systems, may not experience the deep acoustic fades seen in this data set.

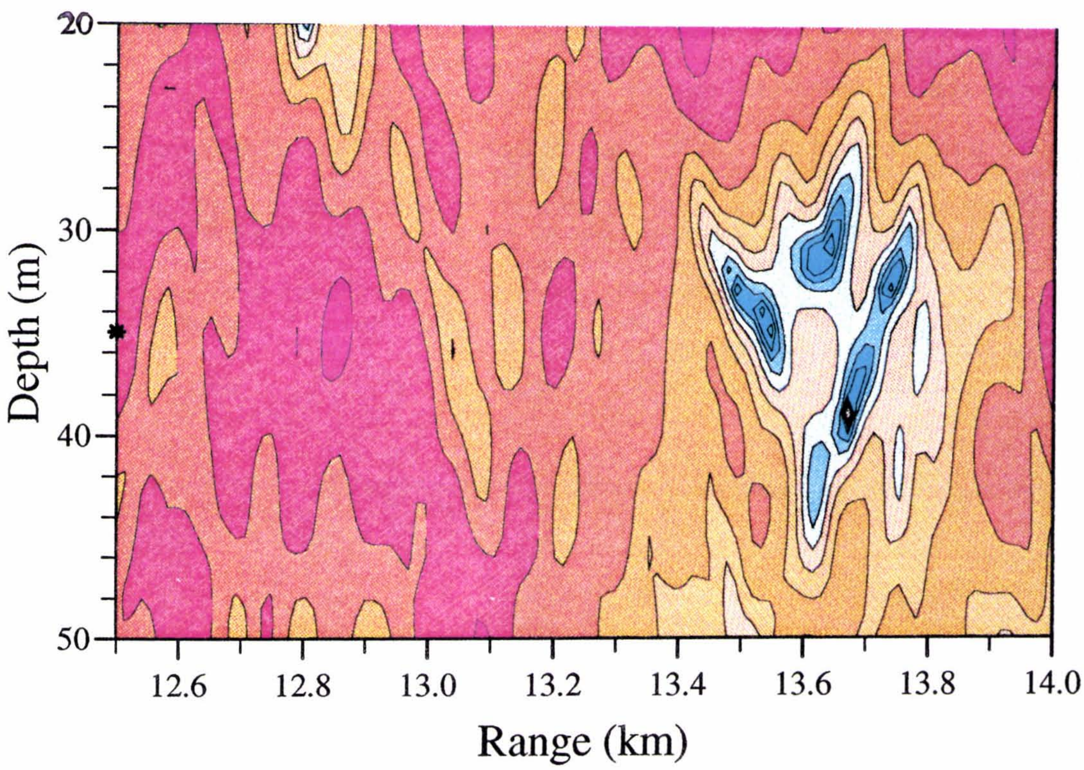

Figure 13 *SNAP acoustic prediction at 342 Hz in 250 m of water with the expected geoacoustic properties at the experimental site near Vestfjorden.*

6. Summary

In October, 1989, an experiment was conducted near Vestfjorden in support of the low frequency active sonar (LFAS) project at the SACLANTCEN. This report discusses measured one-way propagation data in shallow water from a beacon source at a range of about 13.2 km from the LFAS towed array. The signals (0.5 sec LFM pulses from 340-345 Hz) were processed on 59 hydrophones (2-m spacing) for 46 min. The water depth was between 250 and 320 m and the source was approximately broadside to the array.

The acoustic arrival structure varied considerably along the array, for a given ping, even though the broadside geometry would suggest equivalent propagation paths and therefore, similar arrival structure. In addition, the arrival structure changed over time, as the range increased slightly from 13 to 13.25 km.

The apparent bearings to the source varied by +/- 6 deg with a 12-min period due to ship course changes. The array response patterns were averaged with and without regard to the shifted bearings. With alignment, the maximum response was 15 dB higher than without alignment, thus pointing to the need to apply array orientation corrections.

Despite the spatial variability across the array during each ping and the ship course changes, the array performed within 1 dB of perfect, as measured by the average array signal gain. Thus, in isotropic noise, the array gain would only be degraded by about 1 dB on the average. The resolving power of the array, as measured by 3 dB beamwidth, was degraded by only 13%.

The acoustic variability was shown to be caused by changes in the mean depth of the array during the run and probably by depth extent of the array (tilt) at each time. The mean array depth changed by +/- 3 m during the run and the average tilt was less than 1 deg, based on the forward and aft pressure gauges, These amounts (+/- 3 m and <1 deg) seem small, but the propagation conditions in the area produced an acoustic hole in signal intensity (supported by model predictions) in a small, 1-m horizontal layer, which seemed to exist throughout most of the entire 250 m source-receiver range interval spanned by the test.