THE JOURNAL OF THE ACOUSTICAL SOCIETY OF KOREA Vol.22, No.2E 2003. 6. pp. 78~86

Measurement of Horizontal Coherence Using a Line Array in Shallow Water

Joung-Soo Park*, Seongil Kim*, Young-Nam Na*, Young-Gyu Kim*, Teakhwan Oh**, Jungyul Na**
*Agency for Defense Development, P.O. Box 18 Chinhae, Kyungnam, 640-600, Korea
**Dept. of Earth and Marine Sciences, Hanyang University
(Received April 18 2003 ; revised May 2 2003; accepted June 4 2003)

Abstract

We analyzed the measured acoustic field to explore the characteristics of a horizontal coherence in shallow water. Signal spatial coherence data were obtained in the continental shelf off the east coast of Korea using a horizontal line array. The array was deployed on the bottom of 130 m water depth and a sound source was towed at 26 m depth in the source-receiver ranges of 1-13 km. The source transmitted 200 Hz pure tone. Topography and temperature profiles along the source track were measured to investigate the relationship between the horizontal coherence and environment variations. The beam bearing disturbance and array signal gain degradation is examined as parameters of horizontal coherence. The results show that the bearing disturbance is about $\pm 8°$ and seems to be affected by temporal variations of temperature caused by internal waves. The array signal gains show degradation more than 5 dB by the temporal and spatial variations of temperature and by the down-sloped topography.

Keywords: *Acoustic fields, Horizontal coherence, Internal waves, Beamforming, Bearing disturbance, Array signal gain degradation*

I. Introduction

Acoustic wave propagation in shallow water environment is greatly affected by sound speed structure in the water column and by the boundaries like sea surface and bottom. These factors are all functions of time, range, and azimuth. The temporal and azimuthal changes of these factors can influence many different applications of shallow water acoustics like source detection and localization. Recent studies have indicated that shallow water acoustic propagation and scattering are affected strongly by the spatial and temporal variabilities of water column, sea surface, and the spatial variabilities of the bottom and subbottom[1-5].

Corresponding author: Joung-Soo Park (js.park@add.re.kr)
Agency for Defense Development, P.O. Box 18 Chinhae, Kyungnam, 640-600, Korea

It is very difficult to examine the sound propagations in shallow water where the ocean environments are variable in time and space. A typical hydrographical feature shows the cold waters over the continental shelves and slopes along the east coast of Korea, which make sharp vertical density gradients. The sharp vertical gradients suggest that the internal waves could exist in this area[6]. Acoustic propagation in such environments is expected to have a strong propagation loss and complicated multi-paths. Consequently, the spatial and temporal coherence and correlation of acoustic signal can be degraded [7-10]. The degradation of the horizontal coherence causes the performance degradation of an array. Furthermore, the propagating direction of acoustic signal may be changed by internal waves when they move in some aspect between acoustic source and receiver.

In recent years, several studies concerning the line array have pointed out the importance of the variation of water column such as internal waves, tidal flows, and bottom topography[1,2,11,12]. The degradation of array signal gain in a downsloped bottom was found to be, on average, .5 dB[1]. And the short-time scale variability and azimuthal dependence of acoustic propagation are mainly caused by internal waves in some regions. The sound in such regions will be scattered and horizontally refracted [13].

In section II, we describe the sea experiment of measuring horizontal acoustic fields using a linear array in shallow water of the East Sea. The next section addresses a theory on the array signal gain to provide a quantitative description. In IV, we describe the results of array shape estimation, beam bearing disturbance, acoustic field response, and signal gain degradation.

II. Experiment

To measure horizontal acoustic field an acoustic experiment was performed using a bottomed horizontal line array and a towed sound source off the east coast of Korea in the summer of 2001 (Fig. 2). We used a 90 m long array that is non-uniformly nested with 25 hydrophones. The hydrophone sensitivity at the preamplifier is −193 dB re 1V//1 μ Pa. The array was deployed on the flat bottom at 130 m. The received signals from the sound source were autonomously conditioned, multiplexed, and transmitted by radio frequency telemetry through the surface buoy. The transmitted signals were received, de-multiplexed, filtered, amplified, and recorded on the Research Vessel (R/V) HAEYANG. A sound source, which transmits 200 Hz pure tone with the source level of 160 dB re 1 μ Pa @ 1 m, was towed at a normal depth of 26 m and a speed of 5~7 knots by R/V SUNJIN. The source depth variation due to inconsistent towing ship speed was negligible in this experiment. The bathymetry along the tracks was measured using depth recorder and the towing tracks of the acoustic source were monitored by Differential Global Positioning System (DGPS) on the R/V SUNJIN. Four towing tracks were accomplished with 45 degrees interval of azimuth angle. Track09 is over the straight course on the nearly flat bottom. Track03, Track05, and Track07 were on the downslope (Fig. 1).

To measure environmental variations, a thermistor chain was deployed near the line array and expendable bathythermographs (XBT) were dropped along each track. The temporal variations of temperatures near the line array were measured at every 10 seconds by the thermistor chain at the depth of every 10 m between 23 m and 73 m.

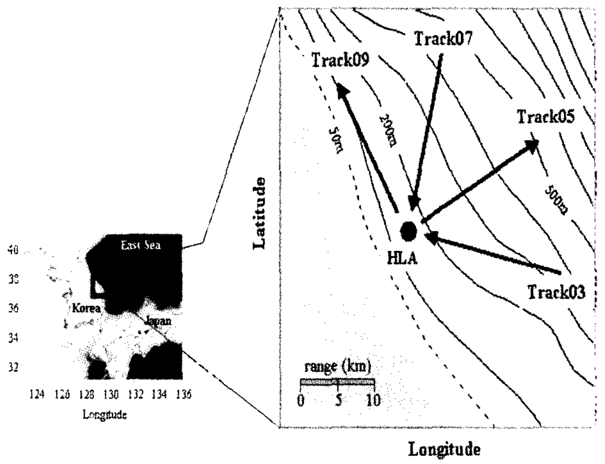


Figure 1. The position of the experiment and the geometry of the four source towing tracks. Horizontal line array (HLA) of 25 hydrophones was deployed at the ocean bottom.

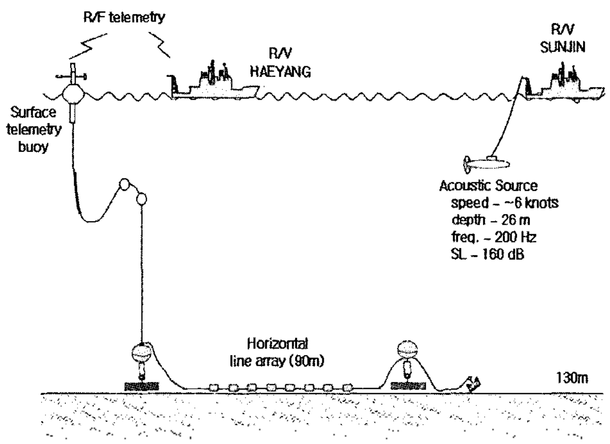


Figure 2. Configuration of the experiment.

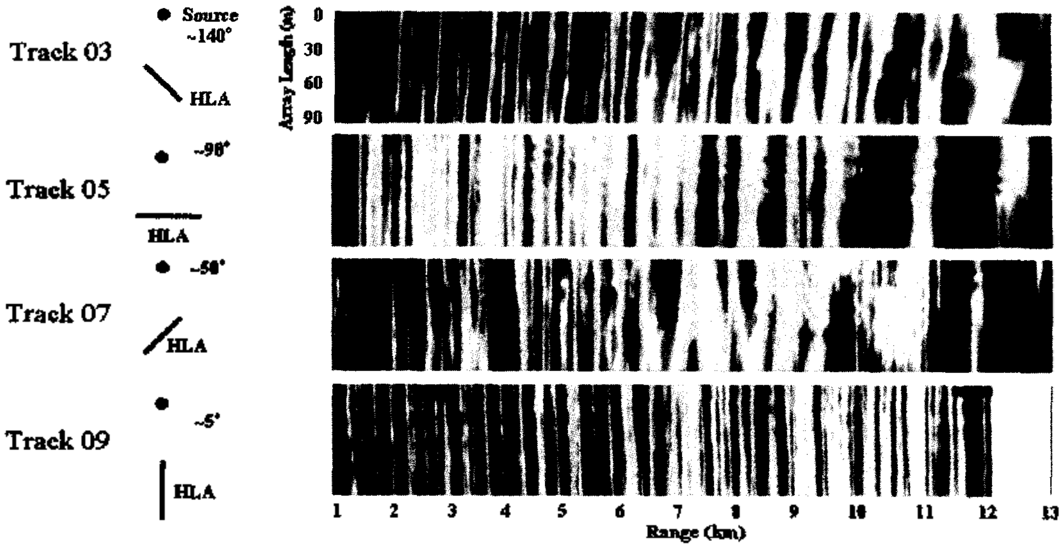


Figure 3. Source-receiver configuration (left) and acoustic fields (right) of each track measured by the 90 m long horizontal line array on the bottom. Acoustic source was towed up to 13 km.

The received signals at the line array were analyzed to examine the fluctuating characteristics of acoustic fields. The received signals were digitized with the sampling frequency of 1600 Hz for the further processing. Figure 3 shows the position configuration between the source and the horizontal array and the corresponding received signal intensities as range versus array elements of each track. The source angles are clockwise from the northwest to the endfire. The source was approaching from the broadside at the case of Track05 and from the endfire at the case of Track09. Besides the differences among the tracks, the acoustic fields show large fluctuations with time even along the same track, implying that there may exist path-to-path variations affected by shallow water environment. If the signals are coherent, the intensity lines at each range should be clear. However the disturbance of intensity lines gives the fact that the signals among the sensor elements are disturbed during their propagation from the source.

As mentioned in the introduction, the main environmental factors affecting coherence of acoustic fields include variations of bathymetry and water column. They generate refraction and deformation of horizontal wave fronts and result in coherence disturbance. As expected, the broadside approaching, i.e., along Track05, shows more variability with range due to the wide span in azimuthal angle and high energy loss crossing normal to the bathymetry. The endfire approaching of Track09, however, shows the least variability. Since the propagation paths between the source and each element may be assumed almost same, wave fronts arriving at the array are assumed to be more strait and coherent than those along other tracks.

III. Beamforming and Signal Gain Degradation

For more quantitative analysis, we examined the variations of array signal gain. The array signal gain can be measured from the measured array signal.

The complex acoustic field for the n-th hydrophone p_n can be written as

$$p_n = A_n \exp(i\theta_n) \tag{1}$$

A_n is the amplitude and θ_n is the phase of the field.

The voltage response of a plane-wave beamformer steered to the relative bearing θ_s is

$$Q(\theta,\theta_s) = \sum_{l=1}^{n} W_l A_l \exp(i(\theta_l - \theta_{sl})) \tag{2}$$

where,

$\theta_{sl} = 2\pi(l-1)(d/\lambda)\sin\theta_s,\ \lambda = C_0/f$

W_l is the weighting coefficient of the l-th hydrophone, d is the distance between hydrophones, N is the total number of hydrophones, C_0 is the sound speed, and f is the frequency in Hz. The signal power of the beamformer is

$$IP_s(\theta_s=\theta) = Q(\theta,\theta_s)\cdot Q(\theta,\theta_s)^*|_{\theta_s=\theta} = \left|\sum_{l=1}^{n} W_l A_l\right|^2 \to cN^2 \quad (3)$$

The c is constant. The mean hydrophone signal power is

$$\langle IP_{hs}\rangle = \sum_{l=1}^{n} W_l^2 \cdot A_l^2 / N \to c \quad (4)$$

Then, the signal gain (sg) may be written as

$$sg = IP_s(\theta_s=\theta)/\langle IP_{hs}\rangle = \left|\sum_{l=1}^{n} W_l A_l\right|^2 \Big/ \sum_{l=1}^{n} W_l^2 \cdot A_l^2 / N \to N^2 \quad (5)$$

The array signal gain degradation ($ASGD$)[2] is then

$$ASGD = 10\log(sg/N^2) \quad (6)$$

The $ASGD$ is a measure for the difference between theoretical and measured signal gains.

IV. Results

A. Array Shape Estimation

It is required to estimate the array shape for beamforming with linear algorithm. We estimated the shape of the horizontal line array using the travel time between the acoustic source towed by R/V SUNJIN and each hydrophone of the array deployed on the bottom. In measuring the travel time, we used the pulse signal of m-sequence with a carrier frequency of 400 Hz and the bandwidth of 100 Hz at every 10 seconds interval. The source was towed along the circled track of 500 m radius around the array. The received signals were transmitted by radio frequency telemetry from the surface buoy and then recorded on the R/V HAEYANG. Travel time of each transmission was extracted by demodulation and correlation of the received sequences. Then, the positions of each hydrophone were obtained using the travel times and the DGPS positions of the source. The singular value decomposition (SVD) was applied in the inversion algorithm. Figure 4 gives the source tracks around the array and the process estimating the array shape[14,15].

The mean variation of the estimated element position was about ±0.8 m (Fig. 5)[14]. Comparing the variation of the element position at 200 Hz with the wavelength of the signal frequency, we concluded that the array had a

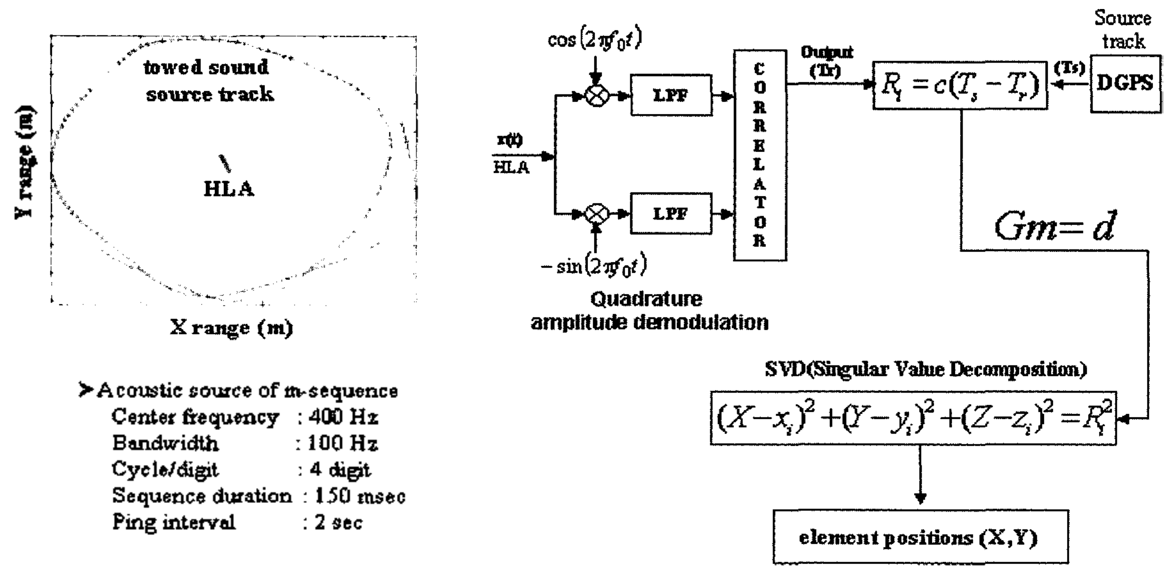


Figure 4. Source track (left) obtained by DGPS and process diagram (right) to estimate the element position.

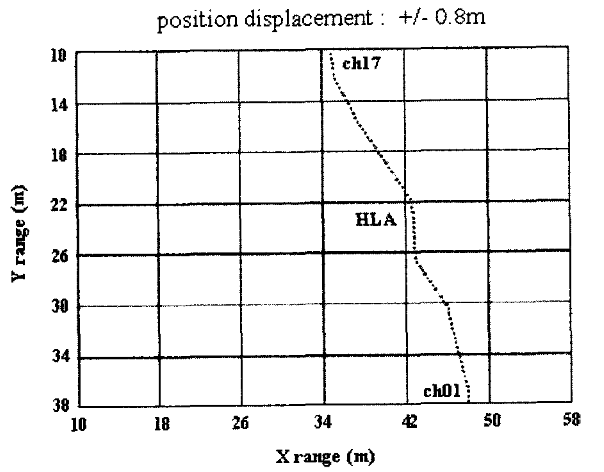


Figure 5. Estimated shape of the array consisted of 17 elements.

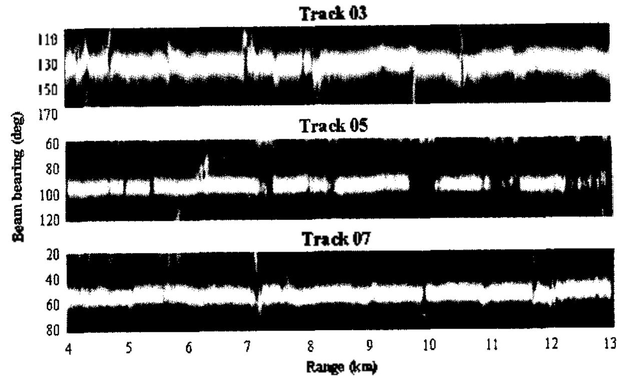


Figure 6. Beamformig results for the 45 m array module for the frequency of 200 Hz.

linear shape enough for beamforming without position correction.

B. Beam Bearing Disturbance

The received array signals were sampled more than four times of the considered frequency and consisted of a uniformly weighted spatial FFT. Peak-FFT bins, peak-beams and signal-plus-noise levels were employed to estimate the beam signal levels.

Figure 6 presents the beamforming output along the source track. This beamforming output shows the temporal variability of the coherence. If there is no temporal variability in the environment, the beamfoming output should be consistent. But there are a lot of temporal disturbance that causes an error in the source bearing estimation.

To explain the reason of bearing change, we compared towing track and beam bearing of the beamforming output. The depth changes of the source were less than +/-3 m along all tracks so that they might not influence much on the beamforming output. The towing tracks calculated using the DGPS show linearly smooth bearing change without any disturbance (Fig. 7). The beam bearing detected from the beamforming output, however, show the abrupt bearing change of 10-20 degrees time to time (Fig. 7). In addition to the abrupt bearing changes, there is a consistent fluctuation in the main lobe response that is shown to be larger at the Track03 to the amount of +/-8 degrees than the other tracks.

Figure 8 gives some examples of the main lobe response

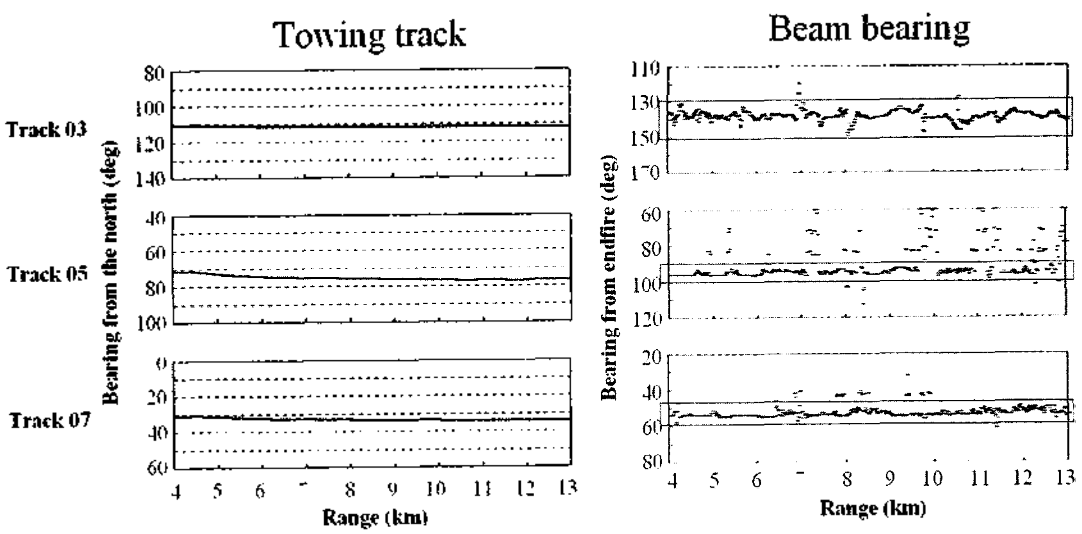


Figure 7. Towing track (left) obtained by DGPS and beam bearing (right) estimated from the array data.

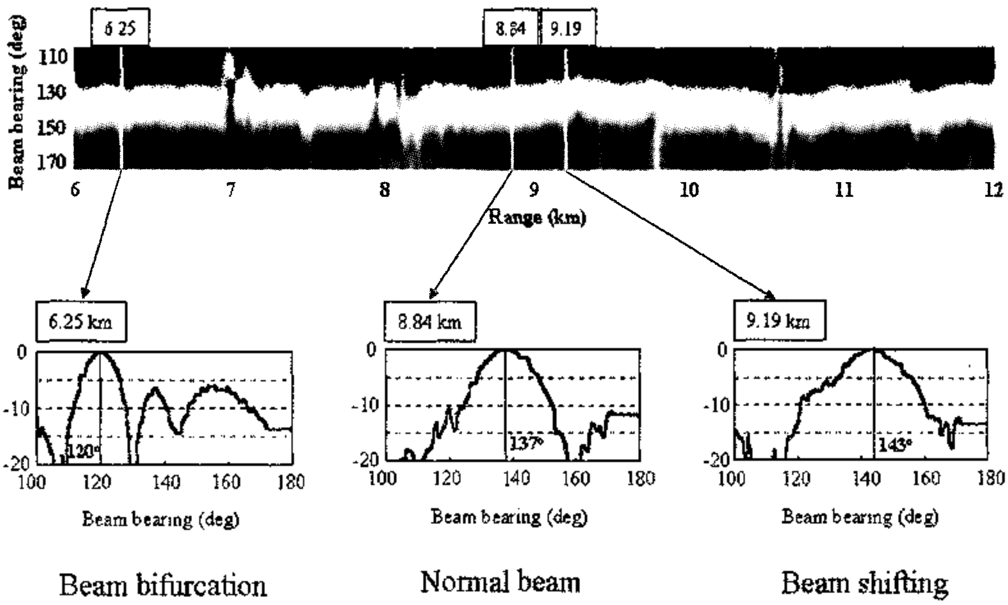


Figure 8. Examples of main lobe responses at three different ranges.

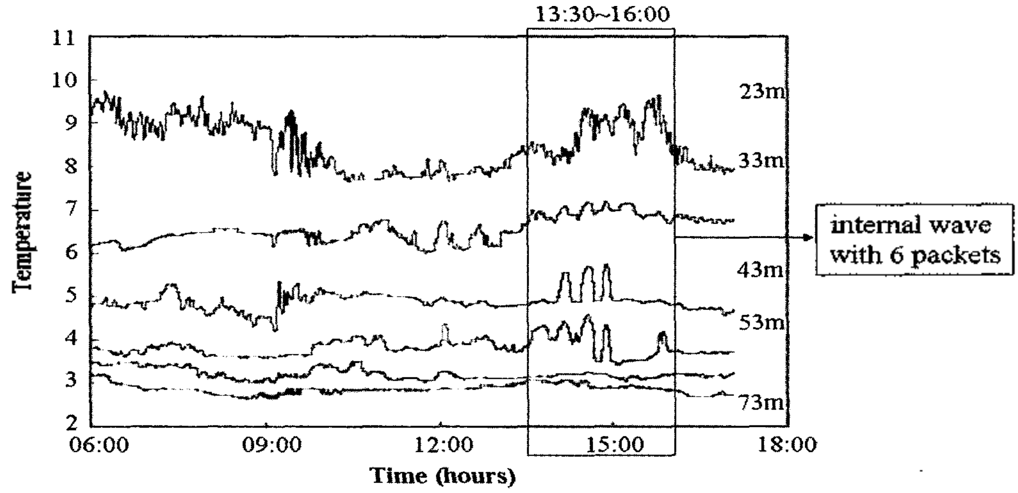


Figure 9. Time series of temperature variation measured by a thermister chain (TC-97) on Jun 17.

at three ranges in the case of Track03. At the range 8.84 km, the main lobe shows normal response. At the ranges showing the abrupt bearing change, however, the disturbance appeared as the beam bifurcation or beam shifting in the main lobe response.

C. Acoustic Fields Response to Environmental Fluctuations

To explain the acoustic fluctuation with the environmental change, we measured temporal variations of vertical temperature fields with a thermistor chain near the receiving array. Figure 9 shows the time series of temperature from 06:00 to 17:00 on June 17 at 6 depths. Temperatures at 23 m fluctuate from 7.7℃ to 9.6℃ during the period. But the fluctuations gradually decrease with depth. Especially, the temperature fluctuations in from 13:30 to 16:00 (designated as box) are considered as internal wave packets of 6 crests. These packets were observed in the upper layer at the thermocline zone. In this area, the generation source of the internal waves may be the near inertial current on the continental shelf or slope [6]. The group velocity of the internal waves, which propagate shoreward, is known as the range from 0.5 m/s to 0.7 m/s (mean 0.6 m/s). And the generation period of the internal waves is known as about 18.7 hours corresponding to nearly inertial period[6]. Thus, we assumed the bearing disturbance was affected by this internal wave

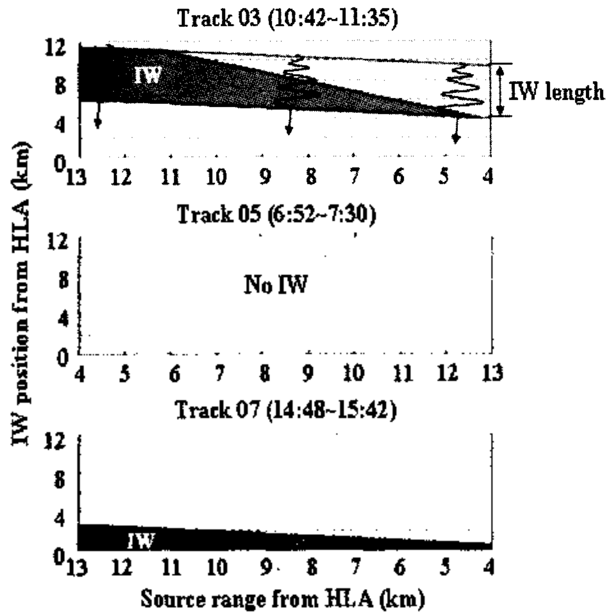
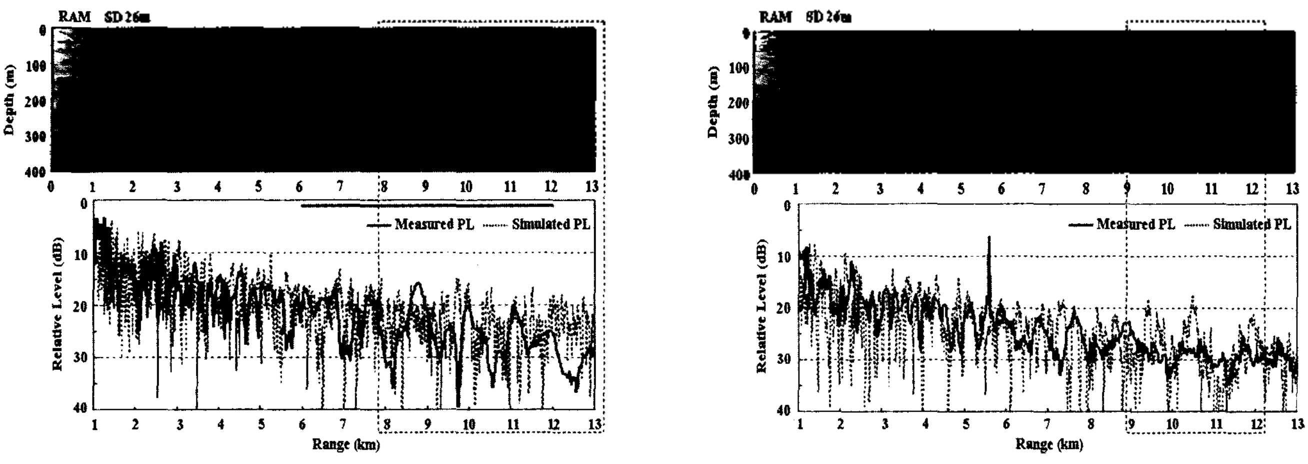


Figure 10. Positions of the internal wave (IW) between the bottomed receiver and the towed source. These are estimated with the group speed, the direction, and the length of the internal wave in this area.

activity as recently reported by many researches.

To investigate how the measured acoustic field was affected by internal wave, we estimated the spatial positions of the internal wave packets using the information between the towing source and the receiving array. Figure 10 presents the estimated positions of the internal wave packets along the three tracks. In the case of Track03, most of the time of the source towing, the acoustic source was crossing the internal wave packets. In the case of Track07, the packets were passing the receiving array. Therefore, we could note the measured acoustic fields at Track03 and Track07 were all affected by internal wave activity. However, as can be seen in Figure 7, the bearing disturbances along Track07 were relatively small compared to those along Track03.

We simulated propagation loss to explain the influence of bottom topography to the measured acoustic fields. In this simulation using Range dependent Acoustic Model (RAM), we did not consider any stochastic variations such as internal waves. Figure 11 shows the comparison between the measured and the simulated propagation loss in the case of Track03 and Track05. The calculated propagation loss in case of Track03 well explains the measured data between 1 to 8 km range (Fig. 11(a)). But, after 8 km, the propagation loss is lower than the calculated. This suggests that propagation after 8 km was affected by not only bottom topography but also other fluctuating environments. In conclusion, we assumed one of the fluctuating environments was internal wave. Because Track05 has steeper bottom slope and strong thermocline, the propagation was affected by bottom condition. The result in the case of Track05 shows good agreement between the measured and modeled propagation losses (Fig. 11(b)). Therefore, we could note deterministic environments affected the propagation in the case of



(a) Track03

(b) Track05

Figure 11. Comparisons of the simulated and the measured acoustic fields along Track03 and Track05. We used Ram (Range-dependent acoustic model) to simulate the PL (Propagation Loss).

Track05, not fluctuating environments. In many cases, steeper downslope topography results in the degradation of horizontal coherence.

D. Array Signal Gain Degradation

After beamforming, array signal gain was determined for the 45m-long array module with the frequency of 200 Hz. The mean hydrophone level was estimated from 11 hydrophones spaced over the array. The averaging time of array signal gain was 20 seconds, which is long enough to examine the environmental effects including internal waves.

Figure 12 presents the array signal gain degradation (*ASGD*) for the three tracks. In the figures, 0 dB of *ASGD* corresponds to the designed gain so that the graphs show the degree of degradation from that. The *ASGD* fluctuates with range at all tracks. In the case of Track03 and Track07, the array signal gains are degraded 0.4 dB up to 0.5 dB, and abruptly fluctuated to 3 dB. In the case of Track05, the array signal gain is degraded 0.6 dB up to 2 dB, and fluctuated over 5 dB. We note that the severe degradation of Track05 with the condition of no internal wave activity could be affected by strong thermocline layer and downslope topography.

The bearing disturbance and the *ASGD* are considerable and much larger than the results of previous works. For example, Carey and Bucker[2] measured the array signal

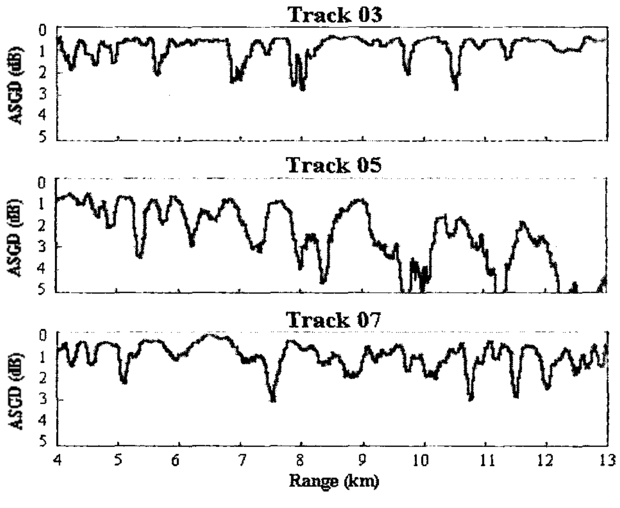


Figure 12. Variations of array signal gain with range for each track.

gains over the downslope topography in Gulf of Mexico and concluded that low-frequency signals could propagate coherently in downslope, bottom-limited regions with thick sediments. The results of this work, however, shows that even low-frequency signals could propagate incoherently in shallow water of the continental shelf.

V. Summary and Conclusion

An acoustic propagation experiment was performed using a horizontal array in shallow water site on the continental shelf off the East Cost of Korea. The experiment has produced a unique data set allowing the study of temporal and spatial variations of sound field affected by the internal waves and downslope topography. The experimental results show the close correlations between the variations of the received acoustic signals and the temperature fluctuations including the internal waves and the downslope topography. The deformation of horizontal wavefront by internal wave causes the bearing disturbance. The bearing disturbance increases when the acoustic source crossing the internal wave packets. However, the bearing disturbance is smaller when internal wave passing the receiving array. Also, the steeper downslope topography makes horizontal coherence degraded severely. In conclusion, it is found that the horizontal coherence is affected by internal wave activity and bottom topography in this area.

The interesting feature in the horizontal coherence is the difference with the position and approaching aspect of the internal wave packet. This is the subject of continued research.

References

1. W. Carey, I. Gereben, and B. Brunson, "Measurement of sound propagation downslope to a bottom-limited sound channel," *J. Acoust. Soc. Am.*, **81**, 244-257, 1987.
2. W. Carey, and H. Bucker, "Environmental acoustic influence on array beam response," *J. Acoust. Soc. Am.*, **104**, 133~140, 1987.
3. J. Lynch, G. Jin, R. Pawlowicz, D. Ray, and A.

Plueddemann, "Acoustic travel-time perturbations due to shallow water internal waves," *J. Acoust. Soc. Am.*, **99**, 803-821, 1996.
4. T. Duda, and J. Preisig, "A modeling study of acoustic propagation through moving shallow water solitary waves," *IEEE J. Ocean. Eng.*, **24**, 16-12, 1999.
5. D. Rubenstein, "Obserbations of cnoidal internal waves and their effect on acoustic propagation in shallow water," *IEEE J. Ocean. Eng.*, **24**, 346-357, 2000.
6. H.-R. Kim, "A study on the internal waves off the east coast of korea," Doctoral dissertation, Soul National University, 2001.
7. Q. Wang and R. Zhang, "Sound spatial correlation in shallow water," *J. Acoust. Soc. Am.*, **92**, 932-938, 1992.
8. Z. Gong, L. Xiao, P. Li, and L. Hao, "Experimental research on sound spatial correlation and time-variant characteristics in shallow water," *WESTPRAC VII*, **39** (1) -**39** (4), 2000.
9. Y.-N. Na, M.-S. Jurng, and T.-B. Shim, "Interference of acoustic aignals due to internal waves in shallow water," *J. Acoust. Soc. Kor.*, **18**, 9-20, 1999.
10. Y.-N. Na, Y.-G. Kim, J.-S. Park, E.-H. Kim, J.-H. Choi, "Considering of environmental factors affecting the detection of underwater acoustic signals in the continental regions of the East Coast Sea of Korea," *J. Acoust. Soc. Kor.*, **20**, 30-45, 2001.
11. M. Orr, and P. Mignerey, "Matched-field processing gain degradation caused by tidal flow over continental shelf bathymetry," *J. Acoust. Soc. Am.*, **111**, 2615-2620, 2002.
12. A. Shmelev, A. Migulin, and V. Petnikov, "Horizontal refraction of low frequency acoustic waves in the Barents Sea stationary acoustic track experiment," *J. Acoust. Soc. Am.*, **92**, 1003-1007, 1992.
13. M. Badiey, Y. Mu, J. Lynch, J. Apel, and S. Wolf, "Temporal and azimuthal dependence of sound propagation in shallow water with internal waves," *IEEE J. Ocean. Eng.*, **27**, 117-129, 2002.
14. T.-H. Oh, S.-T. Oh, J.-S. Park, and J.-Y. Na, "Positioning of hydrophone of line array deployed on the bottom using acoustic travel time," *J. Acoust. Soc. Kor.*, **20** (1s), 653- 656, 2000.
15. T.-H. Oh, J.-Y. Na, and D.-W. Suk, "Two-dimentional localization of array elements placed on a sea floor using m-sequence signal in multipath ocean," *J. Acoust. Soc. Kor.*, **21**, 686-694, 2002.

[Profile]

• Joung-Soo Park

Joung-Soo Park received the B.S. and M.S. degrees in earth and marine sciences from Hanyang University, Korea, in 1998 and 1990, and is working towards the Ph. D. degree from Korea Maritime University. He has been a research scientist at Agency for Defense Development since 1990 where he has specialized in underwater acoustics. His fields of expertise include: ocean reverberation, matched field processing, acoustic interaction with the ocean bottom and the medium fluctuation, and sonar system performance prediction.

• Seongil Kim

Seongil Kim received B.S. and M.S. degrees in the Department of Oceanography from Seoul National University, in 1986 and 1988 respectively, and Ph.D. degree in 2002 from the Scripps Institution of Oceanography in the University of California, San Diego. Since 1990 he has been working for the Agency for Defense Development. His research interests include ocean acoustics, signal processing and underwater communication.

• Young-Nam Na

The Journal of the Acoustical Society of Korea, Vol. 21. No. 2E.

• Young-Gyu Kim

Young-Gyu Kim received the Ph. D degree in oceanography from Seoul National University, Korea in 1996. He was a Postdoctoral Research Fellow at the Hanyang University, Korea during 1997-1998 and worked as Research Scientist of Underwater Acoustics Research Center and Research Associate of Research Institute of Oceanography in Seoul National University until 1999. Dr. Kim is a senior scientist of Ocean/Acoustic Environment Team in Agency for Defense Development of Korea.

• Teakhwan Oh

Taekhwan Oh received the B.S. and M.S. degrees in earth and marine sciences in 2000 and 2002, respectively, from Hanyang University, Korea. Presently, he is working toward the Ph. D. degree in the area of underwater acoustics in the Dept. of Earth and Marine sciences at the same institute. His research interests include mainly ocean acoustic inversion.

• Jungyul Na

Jungyul Na received the B. S. degrees in astronomy and meteorology in 1968 from Seoul National University, Korea, and the M.S and Ph. D. degree in oceanography in 1973 and 1976, respectively, from Florida State University, Florida. He is currently a Professor in the Department of Earth and Marine Sciences and Director of Institute of Natural Science and Technology at Hanyang University, Ansan, Korea. His current research interests include boundary scattering and ocean acoustic Tomography. Dr. Na has also served as the president of the Acoustical Society of Korea from 1996 to 1998.