

Considerations of Environmental Factors Affecting the Detection of Underwater Acoustic Signals in the Continental Regions of the East Coast Sea of Korea

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Abstract

This study considers the environmental factors affecting propagation loss and sonar performance in the continental regions of the East Coast Sea of Korea.

Water mass distributions appear to change dramatically in a few weeks. Simple calculation with the case when the NKCW (North Korean Cold Water) develops shows that the difference in propagation loss may reach in the worst up to 10dB over range 5km. Another factor, an eddy, has typical dimensions of 100-200km in diameter and 150-200m in thickness. Employing a typical eddy and assuming frequency to be 100Hz, its effects on propagation loss appear to make lower the normal formation of convergence zones with which sonars are possible to detect long-range targets. The change of convergence zones may result in 10dB difference in received signals in a given depth. Thermal fronts also appear to be critical restrictions to operating sonars in shallow waters. Assuming frequency to be 200Hz, thermal fronts can make 10dB difference in propagation loss between with and without them over range 20km. An observation made in one site in the East Coast Sea of Korea reveals that internal waves may appear in near-inertial period and their spectra may exist in periods 2-17min. A simulation employing simple internal wave packets gives that they break convergence zones on the bottom, causing the performance degradation of FOM as much as 4dB in frequency 1kHz. An acoustic experiment, using fixed source and receiver at the same site, shows that the received signals fluctuate tremendously with time reaching up to 6.5dB in frequencies 1kHz or less.

Ambient noises give negative effects directly on sonar performance. Measurements at some sites in the East Coast Sea of Korea suggest that the noise levels greatly fluctuate with time, for example noon and early morning, mainly due to ship traffics. The average difference in a day may reach 10dB in frequency 200Hz. Another experiment using an array of hydrophones gives that the spectrum levels of ambient noises are highly directional, their difference being as large as 10dB with vertical or horizontal angles. This fact strongly implies that we should obtain *in-situ* information of noise levels to estimate reasonable sonar performance. As one of non-stationary noise sources, an eel may give serious problems to sonar operation on or under the sea bottoms. Observed eel noises in a pier of water depth 14m appear to have duration time of about 0.4 seconds and frequency ranges of 0.2-2.8kHz. The 'song' of an eel increases ambient noise levels to average 2.16dB in the frequencies concerned, being large enough to degrade detection performance of the sonars on or below sediments.

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An experiment using hydrophones in water and sediment gives that sensitivity drops of 3-4dB are expected for the hydrophones laid in sediment at frequencies of 0.5-1.5kHz. The SNR difference between in water and in sediment, however, shows large fluctuations rather than stable patterns with the source-receiver ranges.

Keywords: *Sonar performance, Figure of merit, Eddy, Thermal front, Internal waves, Ambient noise, Geoacoustic property*

1. Introduction

In general, shallow waters are defined to mean shallow water in which there exist vertical boundaries influencing acoustic conditions. Acoustically, the problem of wave propagation depends on the dimensionless parameter kh , k being the horizontal wave number and h the water depth. Small to moderate kh values (for example $kh \leq 10$) often occur in coastal or continental shelf areas, whereas large values are typical in deep waters[1]. Shallow waters always have some degree of horizontal variability along the propagation paths, range dependence, which strongly influences the acoustic field patterns. The range dependence makes most shallow water environments have larger reverberation levels and higher propagation loss levels than deep waters. Typical shallow water environments affecting the acoustic wave propagation include water mass variation, bottom sediment distribution, and topography.

In detecting submarines using sonars in coastal waters, ambient noise or reverberation is another limiting factor for the sonars to give designed performance. The measure of sonar performance, figure of merit (FOM), is defined as a function of source level, ambient noise level (reverberation level), target strength, and sonar design parameters. The signal excess, which makes it possible for the sonars to detect some targets, occurs when the FOM is greater than the propagation loss between target and sonar. That is,

$$\begin{aligned} FOM &= SL - AN - (DT - DI) \geq PL \text{ for passive sonars,} \\ &= SL - RL(AN) - (DT - DI) + TS \geq 2PL \\ &\quad \text{for active sonars,} \\ SE &= FOM - PL(\text{or } 2PL) \geq 0 \end{aligned} \quad (1)$$

where, SL =source level of target or own sonar,
 AN =ambient noise level,
 DT =detection threshold,
 DI =directivity index of sonar,
 RL =reverberation level,
 TS =target strength,
 PL =propagation loss.

In this study, we consider only environmental factors affecting propagation loss and FOM . Propagation loss in shallow water is controlled by the propagating media, water column and bottom properties. Like deep-water problems, shallow water still gives the sound-speed layering with depth.

Another environmental factors are ambient noise and reverberation, which contribute negatively to the FOM . Unlike the deep-water situation where the shipping component of ambient noise is based on the average of a large number of sources that tend to give general characteristics, the shipping component of ambient noise in coastal waters is ever shifting in directionality and frequency characteristics.

In conducting anti-submarine warfare (ASW) in the shallow water regions, the hottest issue is the effects of the poorer propagation conditions. Poorer propagation implies that the contacts that are tracked will be at shorter ranges and thus have higher bearing rates. The shorter propagation ranges also mean short reaction times and short in-contact times. These short in-contact times require that the systems provide rapid classification and location estimates.

This paper considers the environmental factors affecting propagation loss and then examines the effects of ambient

noise on deciding the sonar performance. In the low frequency of less than 1kHz, ambient noise is more critical factor than reverberation in operating passive sonars. Therefore this study focuses on ambient noise from nature, ships and biology. The interested area is restricted to the East Coast Sea off Korean peninsula. As main factors affecting propagation loss, the oceanic phenomena eddies, thermal fronts, and internal waves will be considered. Bottom properties will also be adopted to estimate their effects on the propagation. Ambient noise effects are employed to estimate the *FOM* variations and thus detection ranges. When a sonar system is deployed on or under the bottom, the biological noise may play an adversary role in detecting the 'signals'. We had a chance to record low frequency noise of an eel at a pier. The noise is basically transient pattern but its levels are high enough to prevent sonars from detecting or localizing underwater targets. We deliver the characteristics of biologic noise in brief.

II. Oceanic Factors Affecting Propagation Loss

2.1. Water Mass Variation

The East Coast Sea of Korea is a region where different water masses interact and their relative distributions vary greatly in time and space. The water masses include the East Korea Warm Water (EKWW) of high temperature and salinity, North Korean Cold Water (NKCW) of low temperature, and East Sea Proper Water of low dissolved oxygen[2]. The vertical or horizontal variations of the water masses cause so called 'range dependent' environments for acoustic waves to propagate within them. Most typical variation occurs of course seasonally, most homogeneous in winter and most heterogeneous in summer. In addition to this seasonal variation, short-term variation, say within two weeks, is reported to be large enough to make the sonar perform differently[3].

The left picture of Fig. 1 shows the variations of water column over five months at one site near Donghae city of Korea. The time plot of vertical temperatures gives very complicated structure and the isothermal line of 5°C, regarded as the upper limit of the North Korean Cold Water[4], shows very dynamic changes with time. That is, with the strength variation of water masses, EKWW and NKCW, dramatic changes are led in vertical structure of temperature (or sound speed). The right two pictures show vertical distributions of temperature gathered at May 14 and May 26, respectively. Two distributions give strong

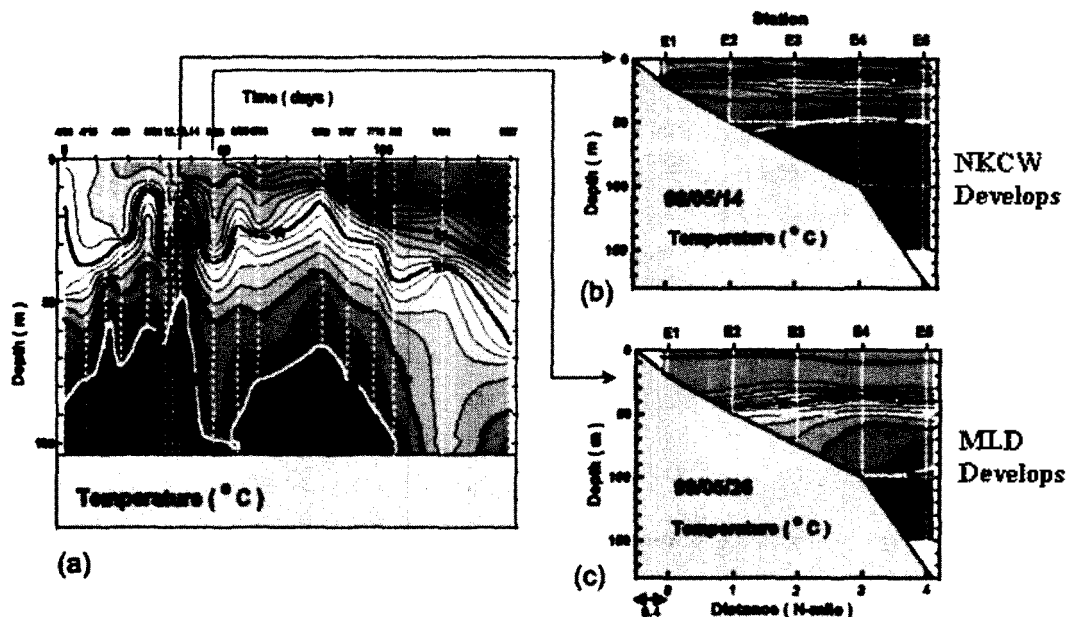


Fig. 1. Short-period variation of water masses, (a) Temporal variation of station E4, April 8 ~ August 27, 1999, (b) Temperature section of May 14, (c) Temperature section of May 26.

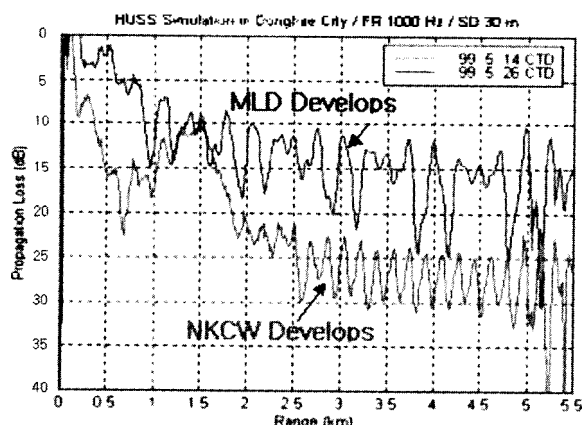


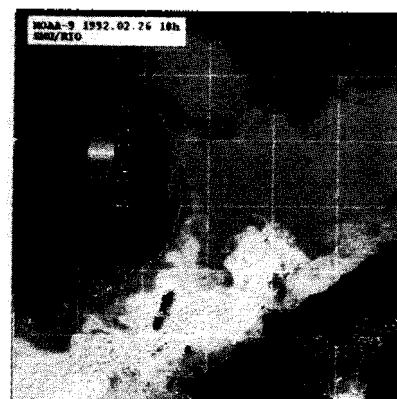
Fig. 2. Propagation loss variations for the two cases of temperature sections in Fig. 1. The source is assumed to be located at depth 30m and to have frequency 1kHz. The levels are relative values and the receiver depth is 10m.

changes at two points. One is the change of the thermocline. It is intensified at May 14 but weakened at May 26, when surface mixed layer develops well and results in lowering of the thermocline. The other point is the fluctuation of NKCW strength. At May 14, the NKCW having temperature of less than 5°C is intensified up to 50m but weakened down to 100m in 12 days later. This example implies that the environmental conditions can be changed dramatically in a few weeks in the East Coast Sea of Korea.

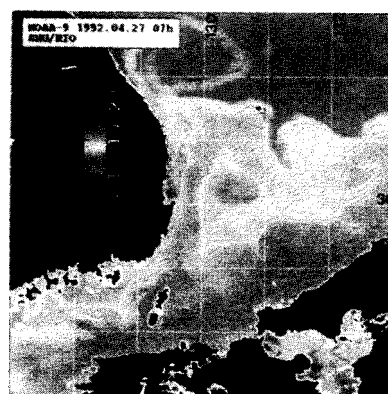
With the big changes of temperature distribution, the acoustic fields are also believed to respond to them. Fig. 2 gives the results of propagation loss for the two extreme cases in Fig. 1. The calculations are made for frequency 1kHz, source depth 30m, and maximum range 5.5km. The comparison of the two curves reveals that the loss abnormally increases when the NKCW develops (May 14), the difference reaching almost up to 10 dB at receiver depth 10m. This simple result is saying that the performance of sonars operating near surface is highly dependent on water mass distributions in the regions where they are subjected to search targets.

2.2. Eddies and Thermal Fronts

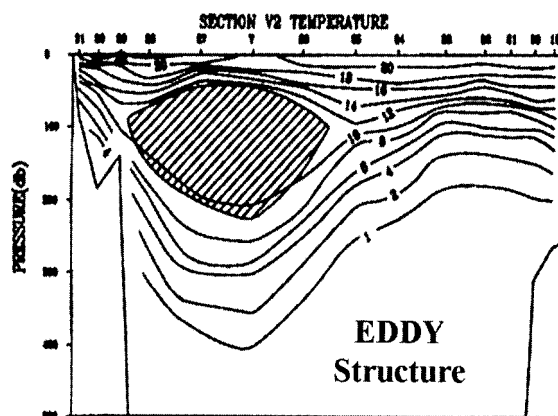
Besides making the vertical fluctuations of thermocline, water masses also form strong horizontal gradients of temperature called eddies and fronts. The first two pictures in Fig. 3 shows the typical distributions of sea surface



(a) February 26, 1992.



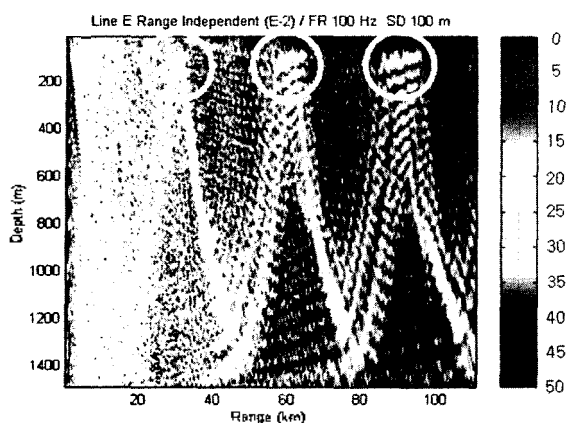
(b) April 27, 1992.



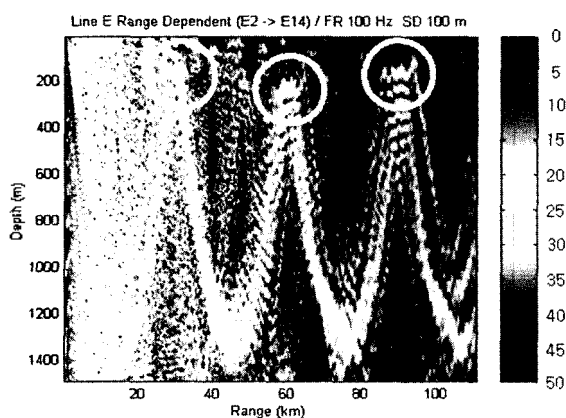
(c) Example of eddy structure.

Fig. 3. Sea surface temperatures obtained through satellites and typical eddy structure in the East Sea of Korea.

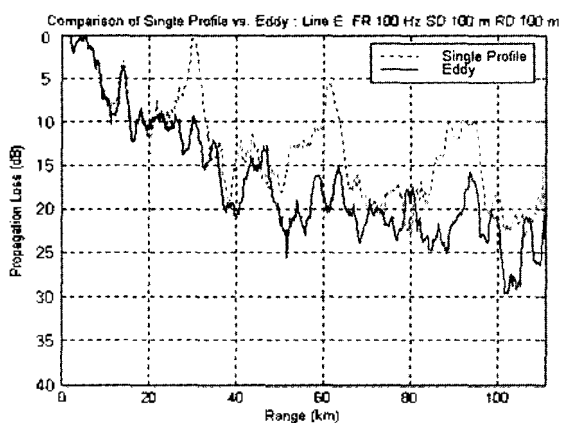
temperature from a satellite in the East Sea. The water masses, NKCW, EKWW, Thushima Warm Current (TWC) and cold water from the north part interfaces together, generating many eddies and fronts on their boundaries. The third picture gives the typical pattern of eddy in the East



(a) Depth-range distribution without any eddy.



(b) Depth-range distribution with eddy centered at the range 60km.



(c) Comparison of loss with and without the eddy at receiver depth 100m.

Fig. 4. Propagation loss variations with and without eddies. The levels are relative values and the source is assumed to be located at depth 100m with the frequency 100Hz.

Sea. It has the diameter of 100-200km and vertical thickness of 150-200m[2,5].

Employing a real eddy, we can estimate its effects on

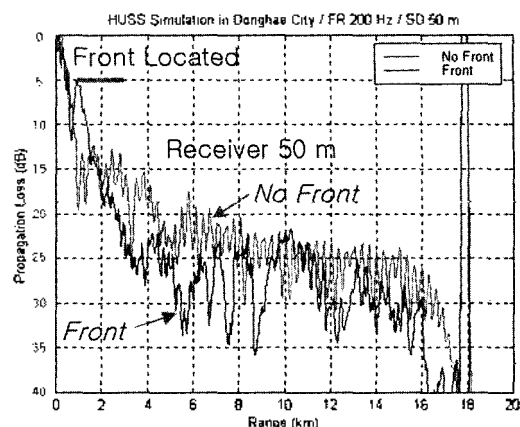
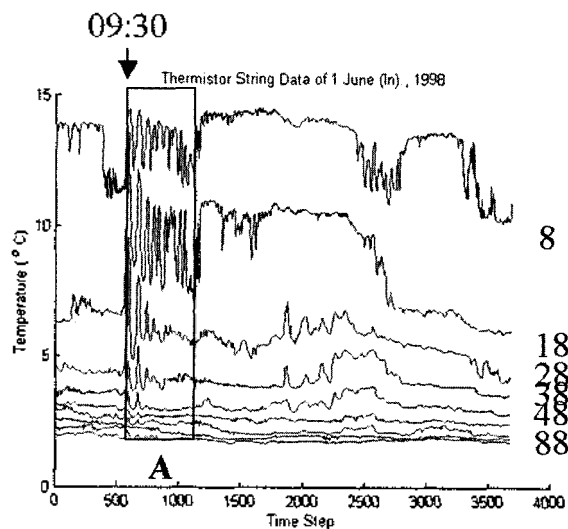
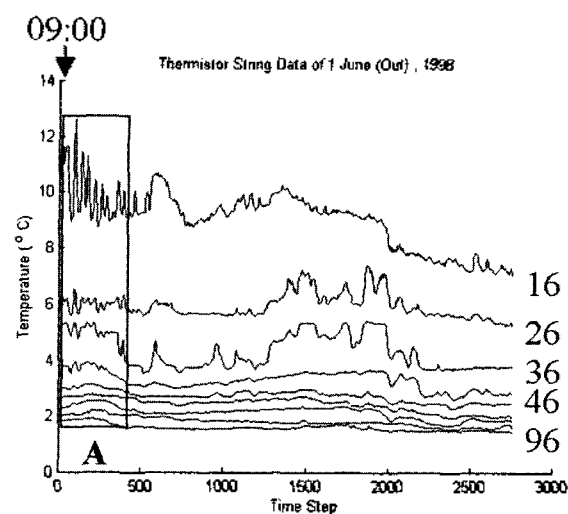


Fig. 5. Propagation loss variation with and without fronts. The front is assumed to be located at the range 1-3km and the source to produce 200Hz signals at depth 50m. The levels are relative values.

acoustic waves propagation. Fig. 4 shows the calculated loss distributions with and without eddy between source and receiver, the eddy being assumed to be centered at range 60km. The source is assumed to be located at depth 100m and to have frequency 100Hz. The range-depth distribution of loss shows noticeable difference between the two cases, without (Fig. 4a) and with (Fig. 4b) the eddy. When the eddy exists on the way of acoustic waves propagation, the second main traveling axis near surface (or *convergence zone*) is lowered down to depth 200m, which normally develops near the surface. If we notice that the eddy is centered at range 60km, we can see that it makes the changes in loss distribution. When we cut slice from the range-depth distribution at receiver depth 100m (Fig. 4c), we can estimate the eddy effects more quantitatively. With the eddy, the convergence zones, which make it possible for sonars listen to very distant sound, actually disappeared. The loss differences on the convergence zones reach up to 10dB. Hence, whether an eddy exists or not may be absolute criteria for sonars to succeed or not in detecting long-distance targets. Some researchers are also emphasizing the very strong focusing property of an eddy by calculating the angular energy distribution at a receiver [6,7]. An eddy concentrates a high percentage of the incoming energy at small angles, so called 'lens effects'. As the ring moves from the source towards the receiver fluctuations in intensity of up to 30dB are observed. The amplitude fluctuation appeared to be related to phase



(a) Jun. 1, 1998, TR-1 (onshore)



(b) Jun. 1, 1998, TR-2 (offshore)

Fig. 6. Time series of thermistor string data. The numbers in the figures denote the measurement depths and one time step corresponds to 10 seconds.

variations and interference effects, rather than amplitude changes along each ray[7].

The thermal front effects to propagation are also cleared from Fig. 5. The simulations are made assuming a source of frequency 200Hz at depth 50m and an environment of very steep topography varying from 800m (source located) to 50m over range 20km. In the figure, the solid horizontal bar denotes the location of thermal front. With the front, the loss curves fluctuate greatly at ranges 2-10km, the differences reaching up to 10dB. This result shows that fronts may be main obstacles for sonars to guarantee designed performance in coastal areas where different water masses exist together and thus form strong fronts.

2.3. Internal Waves

Internal waves (IWs) and internal tides are characterized by temperature and current velocity fluctuations with periods of tens of seconds to several hours, and are important mechanisms for mixing in deep ocean[9]. Whenever a sufficient vertical density gradient exists, oscillations restored by buoyancy can occur. Acoustically, the temperature fluctuations cause changes in the speed of sound, which in turn lead to fluctuations in travel time of acoustic signals.

The East Sea of Korea is supposed to have IWs because it has strong thermocline in summer. Calculations with historical CTD data show that IWs may exist with the periods from a few minutes to 20 hours, where the maximum varies with latitudes[10]. A series of oceanographic experiments were conducted at a site in the East Coast Sea of Korea from 1997 to 2000, where the water depth varies between 130-140 m. Thermistor strings were deployed to investigate the IWs characteristics. In order to examine acoustic wave responses to fluctuating media, an acoustic experiment was performed in the same area in 1998 and 2000. The acoustic experiment used a sound source and a vertical array of hydrophones, each being moored for several hours and placed a few kilometers away.

The time series example of thermistor string data observed in 1998 (Fig. 6) show dramatic fluctuations in the upper layer up to 48m. In particular, the group marked as 'A' shows clear pattern of IWs, of which the temperature variation reaches almost 5°C (18m, TR7-1) and the phases are very coherent over the water column. Comparing the two figures reveals that the event 'A' starts at 09:00 at TR7-2 and follows at 09:30 at TR7-1 (TR7-1 is located offshore and about 1.3km away from TR7-2), implying the propagation of the IWs from sea to coast. The current data observed for long period suggest that the IWs

appear in near inertial period, 18.7 hours [18]. An analysis using the wavelet transform shows that the highly nonlinear wave packets have spectra in broad-band periods from 2 to 17 minutes[11].

To distill the acoustic observation down to a simple estimate of received energy, the CW signal can be incoherently averaged over the water column. That is, the depth-averaged intensity at some time t , $I(t)$, is calculated by the following formula,

$$I(t) = \sum_z E(z, t) - \overline{E}, \quad \overline{E} = \sum_z \sum_t E(z, t). \quad (2)$$

Here, the square of sound pressure level is given by $E(z, t) = 10 \log(p(z, t)^2)$ and $p(z, t)$ is pressure signal at each hydrophone at depth z and time t . The summation includes the average across the domains concerned, time t and depth z . The intensity $I(t)$ would not fluctuate if the source and receiver were fixed in a non-fluctuating ocean.

Fig. 7 shows the depth-averaged intensity $I(t)$ during the experiment. The horizontal arrows in the figures denote the time zones where exceptionally strong interference occurs. They begin a little before the time step 2500 and lasts for more than 500 seconds. The magnitude of zone increases with frequency so that it reaches more than 1000 seconds at 1 kHz. In the experiment, the weather conditions were very good so that the source and receiver could suffer no considerable horizontal or vertical motions. Consequently, this frequency-dependent pattern of the zone magnitude is thought to be due to the fluctuations of medium, the water column. The medium fluctuations initially cause tremendous signal changes at 250 Hz (about 6.5 dB) but make the longest effects at 1 kHz. Especially it can be pointed out that the nearly same time scale of the interference and IWs packet observed by thermistor string suggests that the acoustic wave propagation can be interfered by IWs. Simulation example employing simple IWs in shallow waters shows that IWs may cause breaking of convergence zones and thus the degradation of FOM as much as 4dB[11].

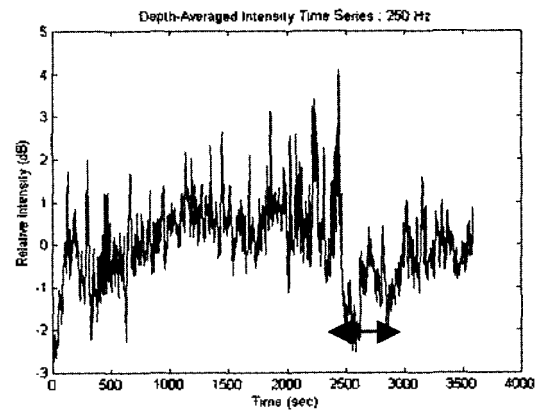
Concerning IWs effects on the acoustic waves propagation in the East Coast Sea of Korea, the following studies should be followed.

1) Specification of the IWs including their spatial dis-

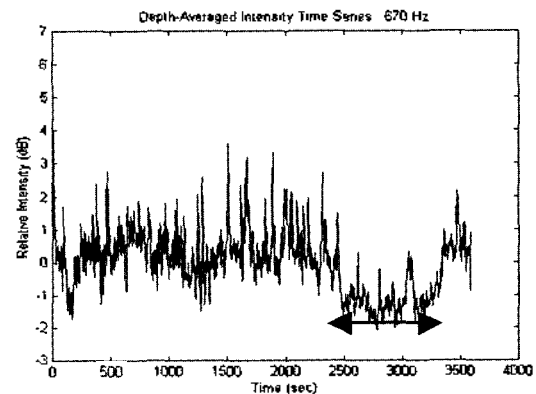
tributions, propagating direction, wavelength, typical number of packets, and their periods.

2) Generation, development and dissipation dynamics to describe the behaviors of IWs considering classical or modified KdV model[12].

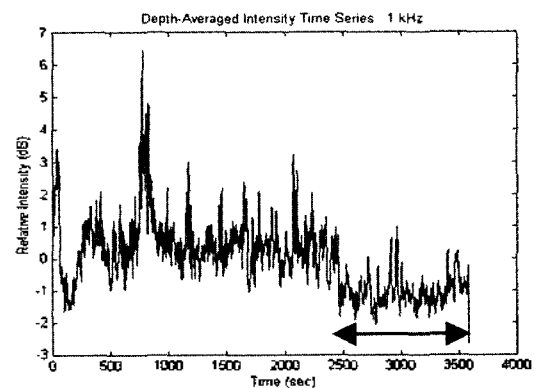
3) Dissipation, bathymetric steering, scattering and hori-



(a) 250Hz.

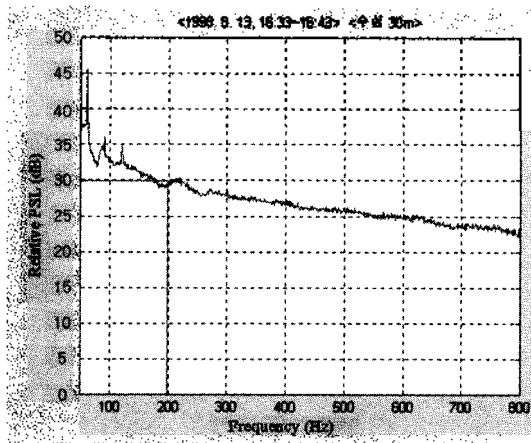


(b) 670Hz.

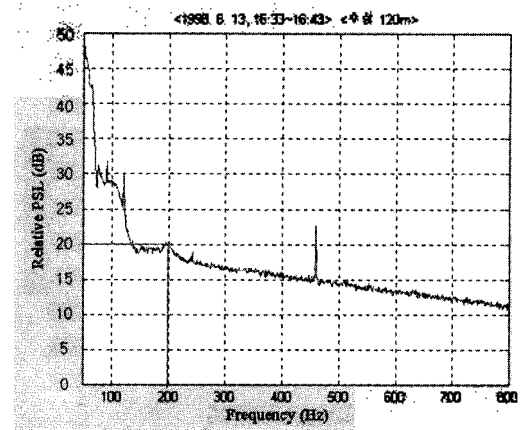


(c) 1kHz.

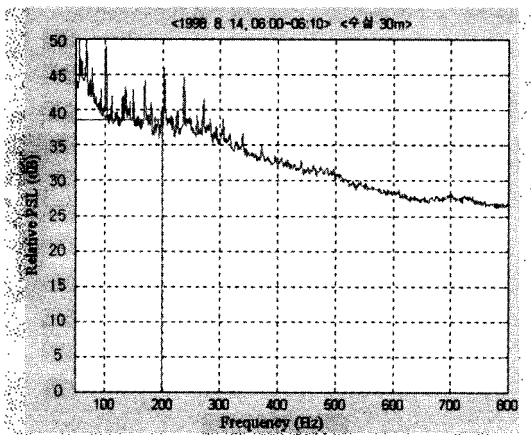
Fig. 7. Depth-averaged intensities of the received signals through an array of hydrophones during the experiment.



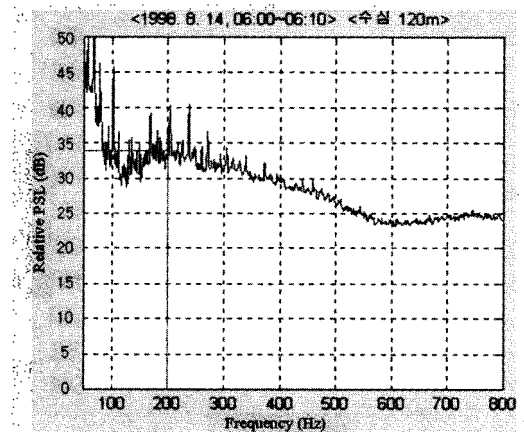
(a) Noon, depth 30m



(b) Noon, depth 120m



(c) Early morning, depth 30m



(d) Early morning, depth 120m

Fig. 8. Ambient noise patterns at a site of East Coast Sea of Korea in 1998, where the levels are relative values.

zonal refraction in IWs dynamics.

- 4) Effects of 2- or 3-dimensional IWs on the acoustic waves propagation including both along and across the IWs crests.

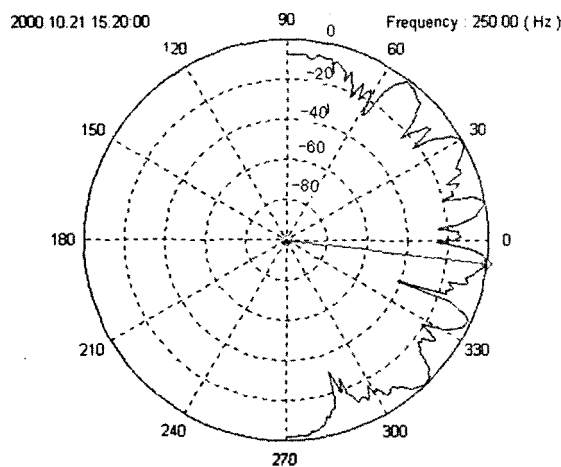
III. Ambient Noise Affecting the FOM

3.1. Stationary Ambient Noise

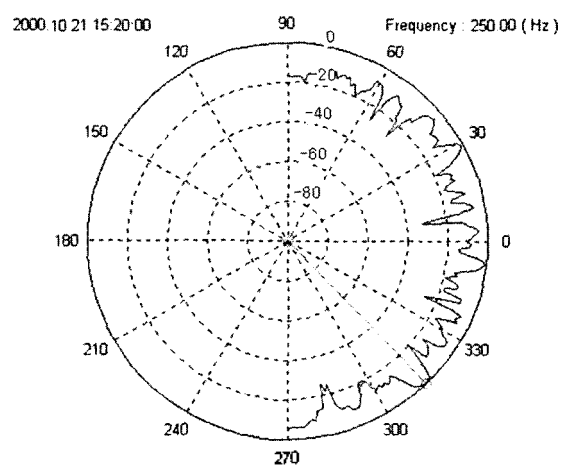
Statistically, a stationary random process means that its mean is constant (independent of time t), and the functions of correlation and covariance are dependent only on the specified time difference, say $t_1 - t_0$ [13]. In this study the noise from nature and ships is assumed to be stationary

because its statistical properties mentioned above are valid within a few minutes for which sonars would possibly detect signals or noises. Meanwhile, the biological noise from say an eel should be *non-stationary* because it happens for very short time, typically less than one second. Its pattern is rather intermittent or transient than steady with time.

Fig. 8 gives examples of ambient noise patterns at a point of East Coast Sea of Korea in August, 1998. In the figures, the signals are averaged for 10 minutes and the denoted levels are relative values. Two distributions of spectrum level (Fig. 8a,b) are obtained from two hydrophones moored at depths 30m and 120m, and the difference reaches up to 10 dB for example at frequency 200Hz. This fact shows that there may be large variation of noise levels with depth. The first two cases correspond to the normal



(a) Horizontal distribution, 250Hz.



(b) Vertical distribution, 250Hz.

Fig. 9. Ambient noise patterns measured using an array of hydrophones at a site of East Coast Sea of Korea in 2000, where the levels are relative values.

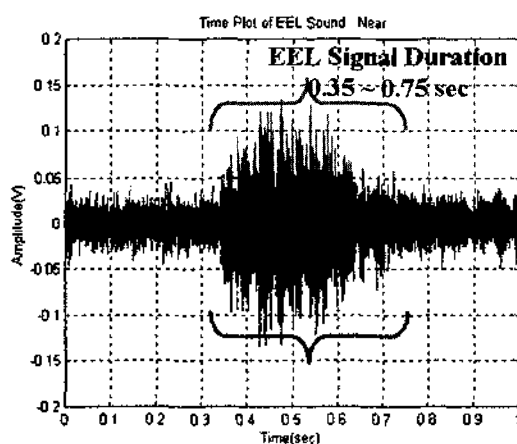
conditions where there exist a few ships within the radius of 10nm. Other two distributions (Fig. 8c,d) show examples at another time, very early morning, when tremendous number of fishing boats (usually more than 100) are observed within a radar range. Unlike the former, these spectrum levels give many narrow-band tones from fishing boats. The broad-band noise levels are higher than the former, the difference being about 8dB at 200Hz. The levels at lower depth, 120m, are still lower than those at 30m, say, about 5dB at 200Hz.

Fig. 9 shows examples of vertical and horizontal patterns measured using an array of 22 hydrophones. Here, the signals are beam-formed to give spectrum levels with

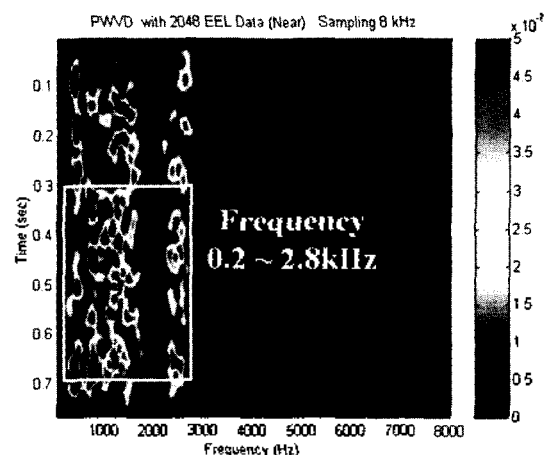
angles, where the levels are again denoted with relative values. Both the vertical and horizontal patterns show large fluctuations caused by multi-path effects of acoustic waves and anisotropic distributions of noise sources themselves. The distributions are revealing that the spectrum levels may be different as large as 10 dB with vertical or horizontal angles.

3.2. Non-Stationary Biological Noise

By intermittent or non-stationary noise sources we mean those noise, while at times occasional and irregular in occurrence. Such sources of noise may be divided into



(a) Waveform



(b) PWVD coefficients

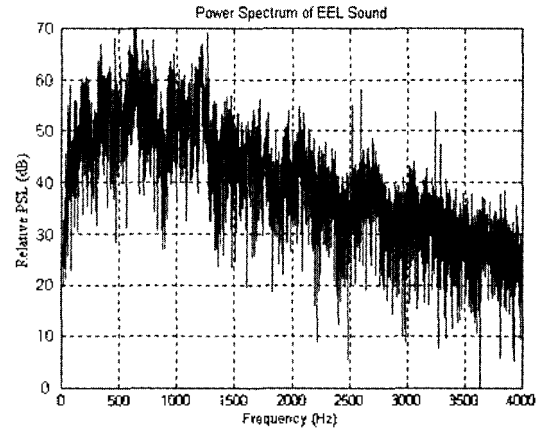
Fig. 10. Waveform and PWVD coefficients of eel noises near the acoustic sensor.

biological noises caused by marine animals and non-biological noises, such as the underwater noise made by rain from above and earthquakes from below. Three main biological sources of noise are: (1) whales, dolphins and porpoises, (2) croakers or drum-fish, and (3) snapping shrimp[14]. These animals produce noises of frequencies ranging from a few tens of Hz to kHz, covering almost all frequencies of sonars. These are called as transient noises on which operators should classify quickly in operating sonars. However, when an acoustic sensor is laid under the bottom sediment in shallow water, noises near it may make major troubles. In this study, we give an example of eel 'song' as one of biological noises by which sonar operators may be upset during their mission. The noises near the sonars absolutely give negative effects on listening to very silent or cautious targets.

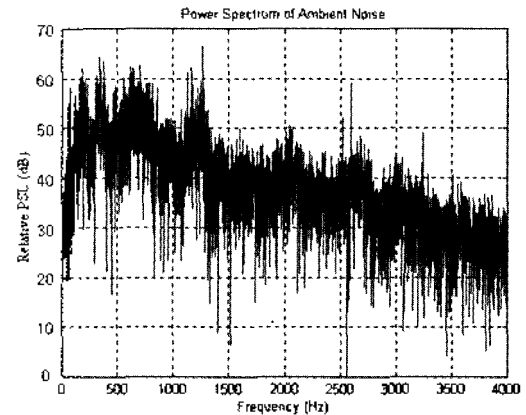
Fig. 10 gives waveform and PWVD (Pseudo Wigner-Ville Distributions) coefficients of eel noises near the acoustic sensor. The PWVD is a kind of time-frequency distributions and is known to be suitable for analyzing transient or other non-stationary phenomena[15]. The distribution is obtained by taking FFT (Fast Fourier Transform) after local correlations are calculated with the time data, guaranteeing four times of frequency resolution than conventional FFT. The experiment was designed to examine the difference in characteristics between in-water and in-sediment sensors responding to underwater noises. For this, divers jumped into the 14m-depth water and installed the two acoustic sensors 0.6m above and below the sediments, respectively. The waveform is from the eel below the sediments during the experiment, typically persisting for 0.4 seconds or more. The PWVD coefficients of the eel sound (Fig. 10b) give spectrum patterns in the ranges of time 0.35-0.75sec, frequency 0.2-2.8kHz. The problem is that this frequency band overlaps that of radiated noises from midget submarines, and thus makes problems towards both sonars and operators.

Power spectrum levels of eel noise are compared with those of ambient noise where there is no eel noise (Fig. 11). The two spectrum distributions seem to show almost same patterns but their difference clearly gives that the levels with eel noise are higher particularly in the frequency range 0.2-2.5kHz. The average of the difference is +2.16dB

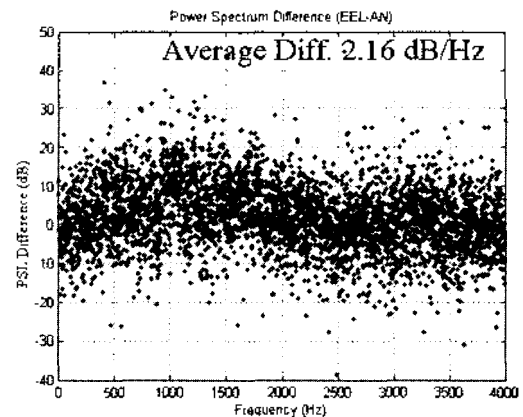
per Hz, implying that the eels may cause serious degradation of detection performance when the sonars are to be operated on or below sea bottoms. As shown in sonar equations (Eq.(1)), noise levels contribute negatively to the



(a) Levels with eel noises.



(b) Levels without eel noises.



(c) Level difference.

Fig. 11. Comparison of power spectrum levels with and without eel noises. The levels are relative values.

FOM. Considering very high propagation loss between source and receiver, unexpected high levels of noise may be dominant factor in deciding detection probability or range.

IV. Ocean Bottom Effects on Sound Propagation

4.1. Effects of Geoacoustic Properties on Propagation Loss

Recent efforts to model the propagation loss of sound in shallow waters have realized the importance of the geology of ocean bottom. Although the sound speed profile continues to be the single most important environmental parameter in determining the interaction of sound with the geologically controlled ocean bottom, the bottom far surpasses the oceanographic controlled sound speed profile in complexity and lack of knowledge. The main issues of geological factors regarding propagations loss are (1) bottom bathymetry (structure), (b) sediment types, (c) geoacoustic modeling.

As for the bottom bathymetry, there may exist situations where the targets approach the sonars from the water of deeper (up-slope) or shallower (down-slope) or same (flat). In general, if other environmental or tactical conditions are assumed to be the same, the down-slope environment

appears to give best performance for sonars and the up-slope the worst. Although ocean bottoms are flat within an area, their inner structures are often very complicated with sediment depth as well as with range. These kinds of structure do not permit the propagating environment to be range-independent. In some cases, for example, the high variability of propagation loss (70 -100dB in 40km) in shallow waters has been reported to be due to the range and depth dependent sediment properties, and not to changes in the water column[16]. Seismic profiling records have shown the buried geological structures within the thin sedimentary layer which block low frequency sound in sediments. The bottom structures often decide what frequencies are preferable with lower loss. That is, some measurements show the preferential propagation of low frequency (for instance less than 400Hz) and other measurements show high frequency. Another interesting results happened when the bottom consisted of a thin layer of sand overlaying semiconsolidated sediment[17]. In this environment, the large difference appeared in the measured low-frequency attenuation of the first normal mode for the two propagation paths, which could be accounted for the variations in the thickness of the surface sand layer. Another example showed that the propagation loss differs by 40dB at a distance of 30 nautical miles between two sections, the frequency being 63Hz[18]. It seems impossible to account for this large acoustic difference by the nature of the water column and the general nature of the bottom. The sound speed profiles in the sub-bottom sedi-

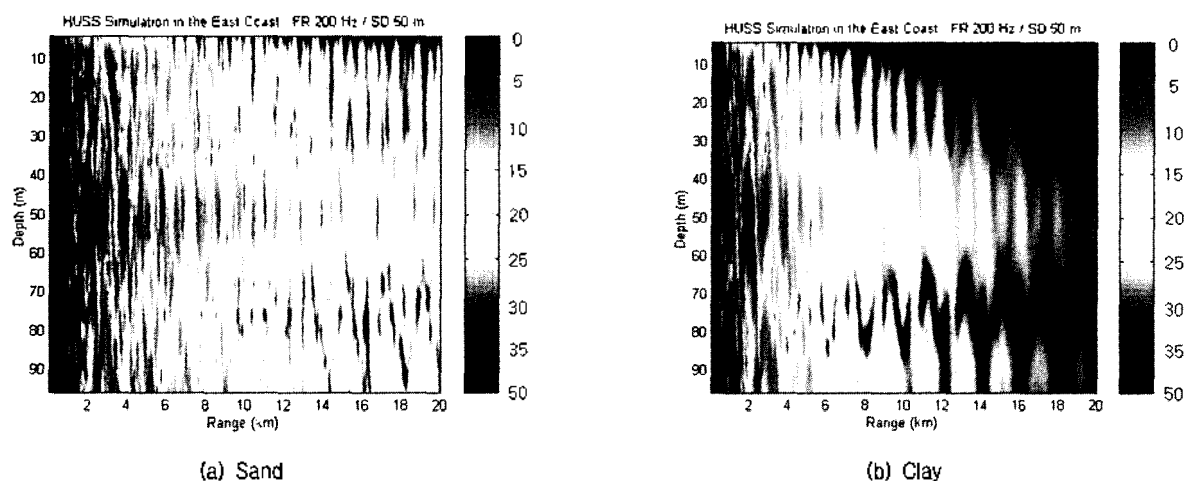


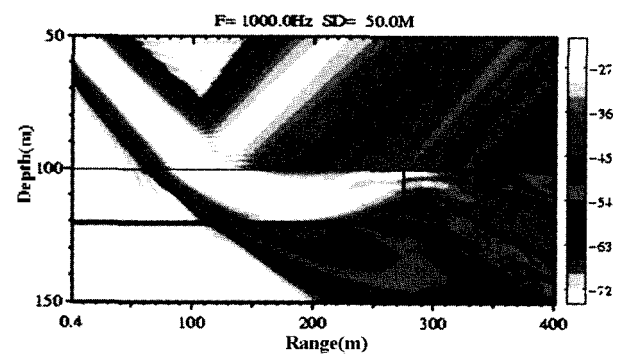
Fig. 12. Comparison of propagation loss distributions with typical bottom properties. The levels are relative values.

ments at the two sites were somewhat different. That is, the difference in sound speed profiles was the answer to the incredible loss difference. The above two examples give the importance of sediment structures for acoustic propagation in shallow water. Hence, we absolutely need to know the details of bottom structures of the areas in which (particularly fixed-type) sonars are to be operated.

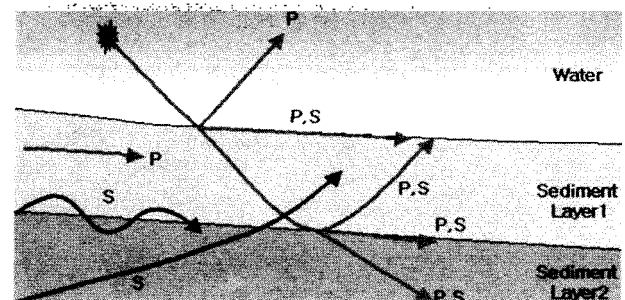
As acoustic waves travel in the water column of shallow water, they inevitably interact with seafloor of which properties vary very much from place to place. Many different types of materials, such as clay, silt and sand, are encountered in continental shelf and slope environments. The typical geoacoustic properties, which affects directly on propagation loss, include sound speed, density and attenuation coefficient with sediment depth. Among these, the attenuation of bottom materials is tree-to-four orders of magnitude more lossy than water. Thus, at 100Hz for example, the attenuation in seawater is about 0.004dB/km, whereas the compressional wave attenuation in bottom materials varies between 2dB/km in basalt to around 63dB/km in silt[19]. The vastly different material compositions and stratifications encountered in ocean seafloor are essentially meaning that specific geoacoustic model must be established for any given geographical area. Fig. 12 gives an example of loss distributions with typical sand and clay bottoms in the East Coast Sea of Korea. In the simulations, the source is assumed to produce CW of 200Hz at 50m, and sound speed of the water column to be of the winter. Comparing the two distributions, we can see that the loss with clay seafloor is much more lossy than sand with range.

Bottom sediments are often modeled as fluids meaning that they accommodate only a compressional wave. If the rigidity of sediment is considerably less than that of a solid, such as rock, the *fluids* assumption may be a good approximation. In reality, however, the sediment must be modeled as *viscoelastic* meaning it supports both compressional and shear waves, and also lossy. Fig. 13 gives schematics of acoustic wave propagation in sediments. Arriving at the interface of water-sediment, the acoustic energy reflected into water and transmitted into sediment (Fig. 13a). There may exist many propagating paths in sediment

from compression to shear waves and from refracted to interface waves (Fig. 13b). A geoacoustic model is defined as a model of real seafloor emphasizing measured, extrapolated, and predicted values of those material properties needed for the modeling of sound propagation. In general, a geoacoustic model details the true thickness and properties of sediment and rock layers within the seabed into which acoustic waves penetrate. The information required for a complete geoacoustic model should include the following depth-dependent material properties: the wave speeds of compressional and shear, the attenuations of compressional and shear, and the densities. Moreover, information on the variation of all of these parameters with geographical position is required. The construction of a detailed model for a given area is a tremendous task, and the amount of inaccurate information used is the primary limiting factor on the accurate modeling of bottom-interacting sound propagation in the ocean. If the highly sensitive sonars, particularly fixed ones, are to be operated in shallow water, the accurate geoacoustic model should be set up for estimating their 'real' performance.



(a) Seismo-acoustic propagation in sediment [19]



(b) Propagating paths in water and sediment

Fig. 13. Schematics showing propagating behaviors in sediment.

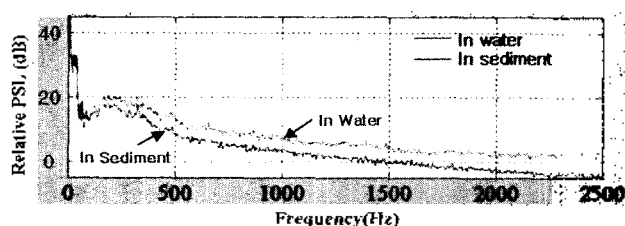
4.2. Sensitivity of Acoustic Sensors Laid Under Sediments

For operational purposes, when acoustic sensors are to be laid under sediments, they are expected to show somewhat different characteristics as in water column. Among the characteristics, primary interests would be directed to sensitivity and signal-to-noise ratio (SNR) of the sensors under sediments.

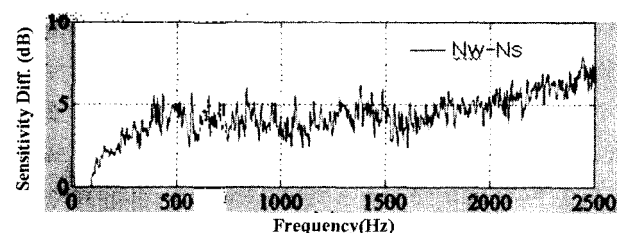
There are few measurements to conclude what differences in characteristics would be induced with the sensors in sediments. In an experiment using a three-component geophone and hydrophone placed on the bottom, the hydrophone or pressure sensor had a SNR of about 5dB that is roughly the same at all frequencies between 20-300Hz [20]. The hydrophone was designed to be insensitive to acceleration and it was indeed a pressure-sensor. The vertical geophone signals were generally buried in noise at nearly all frequencies. The two horizontal geophone components had a SNR of 10-15dB in 30-50Hz, much better than the hydrophone. The extraordinary high SNR in the geophones is implying sound sources must have traveled principally in the bottom as waves having horizontal particle motion and therefore not coupled to the lossy water medium. What is likely to have happened was that

the waterborne sound, on striking the bottom, became converted into earthborn sound traveling in the sediments [20]. Although the hydrophone was placed on the bottom, very interesting thing is that it gives stable SNR throughout the frequency ranges 20-300Hz.

In order to examine the patterns of sensitivity and SNR of the sensors under sea bottoms, an acoustic experiment was performed in shallow waters in October, 2000. Five hydrophones were put into the bottom (about 1.3m), and other two were placed 1.0m above the bottom simultaneously. To estimate precise SNRs of hydrophones with range, a sound source transmitting multiple tones was towed on a vessel. The environmental conditions were as follows: The water depth is around 15m, the wave height is 2-2.5m, and the bottom type is fine sand. Fig. 14 gives the comparison of the sensitivity of acoustic sensors in water and in sediment. This is the case of pure ambient noise without any tones. In the figure, the noise levels are relative values. The noise levels in water and in sediment show that generally the levels are lower in sediments, the difference being somewhat variable with frequency bands. That is, in frequency ranges 500-1500Hz, the difference is relatively stable with its average of 3-4dB, while it increases in overall in 100-500Hz and 1500-1500Hz. As can be seen in the figure, the difference becomes small and eventually

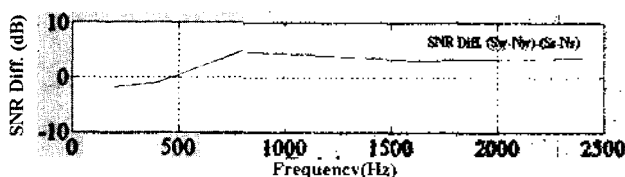


(a) Ambient noise levels in water and in sediment.

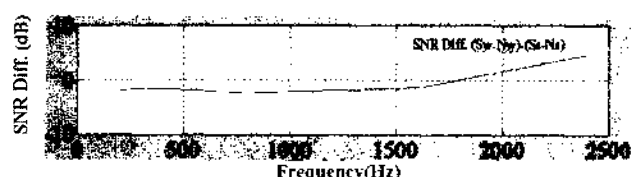


(b) Level difference.

Fig. 14. Comparison of sensitivity of acoustic sensors in water and in sediment. The levels are relative values.



(a) Range 1160m



(b) Range 2250m

Fig. 15. SNR differences between the sensors in water and in sediment.

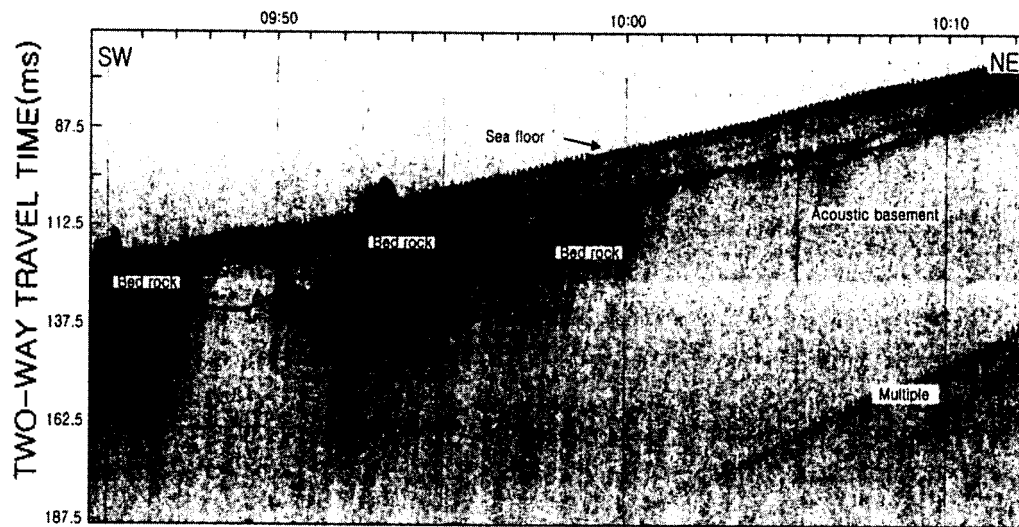


Fig. 16. An example of bottoms having complicated structures with range.

zero with the frequency decreased in ranges 0-500Hz, which implies that the acoustic energy of low frequency dissipates slowly with sediment depth and thus it can affect deeper than that of high frequency. More quantitative results may be obtained with a sound source transmitting CW tones. Fig. 15 shows the SNR differences between the sensors in water and in sediment. The levels in the figures are relative values. The CW signals have five frequencies of 0.2, 0.4, 0.8, 1.6, and 2.4kHz. At source-receiver range 1160m (Fig. 15a), the SNR differences between in water and in sediment give a little negative values at 0.2 and 0.4kHz whereas positive values at higher frequencies. The negative values mean that the SNRs of the sensor in sediment are higher than those in water. Hence, at lower frequencies of 0.2 and 0.4kHz, the sensors in sediment may give better SNRs than those in water. At source-receiver range 2250m (Fig. 15b), however, the differences are negative from 0.2 to 1.6kHz, saying that the sensors in sediment would give better SNRs. That is, the SNR differences between in water and in sediment shows large fluctuations with source-receiver range. The cause of these fluctuations may be attributed to the differences of sediment types and structures along the source-towing paths. The bottom structure gathered around the experiment site (Fig. 16), which clearly shows very complicated structures with ranges, is supporting this viewpoint. It is very impressive that sand is covering very rough rocks and thus

making the surface of the bottom smooth.

The descriptions above are limited to the case of sand sediment and the sediment itself is highly variable with depth and range. For the operation of sonars in shallow waters, further studies are required as follows:

- Sensitivity and SNR patterns in sediments of various types and structures.
- Visco-elastic effects of bottom and their application to acoustic models.
- Equipment design and its application to measuring geoacoustic properties.
- Possibility of employing geophones in detecting signals through bottoms.

V. Summary

This study considers the environmental factors affecting propagation loss and sonar performance in the East Coast Sea of Korea. The factors considered are: (a) water mass variations, eddies, fronts, and internal waves as oceanic factors affecting propagation loss, (b) stationary and non-stationary ambient noises affecting the *FOM*, (c) geoacoustic properties affecting propagation loss and sensitivity degradation when acoustic sensors are laid under sediments.

As one of the oceanic phenomena, water mass distributions can be changed dramatically in a few weeks in the

East Coast Sea of Korea. Simple calculation with the case when the NKCW (North Korean Cold Water) develops shows that the propagation loss may reach in the worst up to 10dB over range 5km. Another factor, an eddy has typical dimensions of 100-200km in diameter and 150-200m in thickness. Employing a typical eddy and assuming frequency 100Hz, its effects on propagation loss appears to make lower the normal formation of convergence zones with which sonars are possible to detect long-range targets. The vertical movement of convergence zones may result in 10dB difference in received signals in a given depth. Thermal fronts also appear to be critical restrictions to operating sonars in shallow waters. Assuming frequency 200Hz, thermal fronts can cause 10dB difference in propagation loss between with and without them over range 20km. Internal waves in shallow waters are expected to affect on the performance of fixed sonars. An observation made in one site in the East Coast Sea of Korea reveals that the internal waves may appear in near-inertial period and their spectra may exist in periods 2-17min. A simulation employing simple internal wave packets gives that they break convergence zones causing the performance degradation of *FOM* as much as 4dB at frequency 1kHz. An acoustic experiment, using fixed source and receiver at the same site, reveals that the received signals fluctuate tremendously with time reaching up to 6.5dB in the frequencies of 1kHz or less. To examine the details of internal waves effects on sound propagation, further studies should follow on their spatial characteristics, generation-dissipation mechanisms, and three-dimensional modeling in which major dynamics are considered.

Ambient noises give negative effects directly on the sonar performance. Measurements at some sites in the East Coast Sea of Korea suggest that the noise levels greatly fluctuate with time, for example noon and early morning, mainly due to ship traffics. The average difference in a day may reach 10dB at frequency 200Hz. Another experiment using an array of hydrophones gives that spectrum levels of ambient noises are highly directional, their difference being as large as 10dB with vertical or horizontal angle. This fact is strongly implying that we should obtain *in-situ* information of noise levels to estimate reasonable sonar performance. As one of non-stationary

noise sources, an eel may give serious problems to sonar operation on or under sea bottoms. An observed eel noise in a pier of water depth 14m appears to have duration time of about 0.4 seconds and frequency ranges of 0.2-2.8kHz. The presence of an eel may increase ambient noise levels to average 2.16dB at the frequencies concerned, being large enough to degrade detection performance of the sonars on or below seafloors.

Although bottom properties are most important parameters in determining sound propagation in shallow waters, they are often strongly variable with sediment depth and horizontal range, and even lack of knowledge. The main issues of geological factors regarding propagation loss are bottom bathymetry/structure, sediment types, and geoacoustic modeling. Many observations in shallow waters are suggesting that the losses are highly dependent on bottom properties in horizontal direction causing fluctuations of tens of dB over tens of km. Another issues, which should be considered before acoustic sensors are laid under bottoms, are their sensitivity and SNR variations compared to the case in water. An experiment using hydrophones in the water and sediment gives that sensitivity drops of 3-4dB are expected for the hydrophones in sediments at the frequencies of 0.5-1.5kHz. The SNR difference between in water and in sediment, however, shows large fluctuations rather than stable patterns with source-receiver ranges. For the sonar operations in shallow waters, further studies should be directed on the issues regarding bottom effects such as (a) sensitivity and SNR patterns in various types of bottom, (b) visco-elastic effects, (c) equipment design to measure geoacoustic parameters.

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[Profile]

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