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Development of Submarine Acoustic Information Management System

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Abstract

Agency for Defense Development (ADD) developed the Submarine Acoustic Information Management System (SAIMS Version 1.0) capable of interfacing some submarine sensors in operation and predicting detection environments for sonars. The major design concepts are as follows: 1) A proper acoustic model is examined and optimized to cover wide spectra of frequency ranges for both active and passive sonars. 2) Interfacing the submarine sensors to an electric navigation chart, the system attempts to maximize the applicability of the information produced. 3) The state-of-the-art database in large area is built and managed on the system. 4) An algorithm, which is able to estimate a full sound speed profile from the limited oceanographic data, is developed and employed on the system. This paper briefly describes design concepts and algorithms embedded in the SAIMS. The applicability of the SAIMS was verified through three sea experiments in October 2003-February 2004.

Keywords: *Sonar Performance Prediction, Tactical Information Analysis, Sound Speed Profile, Acoustic Model, Directional Detection Environment*

I. Introduction

Moderate to midget submarines have a few kinds of sonars mounted on their hulls and some performance prediction systems to get information crucial to their tactics or operations. Future big submarines, however, are expected to have sonar systems of more sophisticated and higher performance (for example, towed array sonar), leading to the need of performance prediction systems of more synthetic and efficient. The Korean navy has been operating some prediction systems for that purpose[1-3] but most of them are focused on just one type of sonar (i.e., frequency coverage is very narrow), limiting their application to other sonars or platforms. Among the information, which submarines can utilize in their operations, there are detection environments for targets, counter detection ones against enemies, and optimum depth to hide themselves from hostile forces.

ADD has developed the SAIMS capable of interfacing some submarine sensors in operation and predicting sonar performances for two years beginning March 2002. The SAIMS consists of 6 modules, each of them being connected systematically to conduct missions. The missions include: 1) real-time processing and displaying data from submarine sensors such as global positioning system (GPS), inertial navigation system (INS), conductivity-temperature-depth (CTD) and sonar console, 2) environmental data processing and inputs preparing for performance prediction, 3) performance predictions from passive to active sonars and from low to high frequencies, 4) sonar parameters management with the data base of noise and target features, 5) one-to-one friend-foe ASW (Anti-submarine Warfare) reconstruction, 6) tides and tidal currents prediction at the specified point and time.

This paper briefly describes design concepts, algorithms

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embedded, and architectures of the SAIMS. The results from the sea tests with a submarine and a surface ship are delivered as well.

II. The SAIMS Specifications

2.1. Design Concepts

Designing the SAIMS, we adopted the following concepts.

We considered many candidate models and chose one, the Gavssian beam method[5], to cover wide frequency ranges from 30Hz to 100kHz. The model is able to give major information in a minute keeping its accuracy within a tolerable error bound. We gave a little modification to the model itself and optimized the input parameters to make it be operational on the SAIMS. The model operates in two modes: one is to give depth-range fields for a selected section and the other for whole directions.

We designed an interfacing protocol through which the SAIMS get submarine information for real-time processing. The protocol consists of connecting cables and operation software. Because the information from the submarine sensors are also very crucial to other purposes, the protocol is kept running independent of the SAIMS, thus excludes any case when it fails to gather data due to interfacing problems between the two systems. Sonar performance predictions combined with the sensor data guarantee more reliability and applicability in real situations.

All historical data available were pre-processed and merged together to function as input data for the acoustic model or others. Sonar performance predictions need data such as sound speed (or temperature), attenuation coefficients, and density with depth in water and sediment. Getting tides and tidal currents at defined point and time requires pre-determined harmonic constants. Water depths of high resolution should be pre-processed for sonar performance predictions and tactics analysis in three dimensions. The SAIMS has about 1.6GB of pre-processed data distributed over 3,600x3,000 square nautical miles.

We designed and realized a system based on electric navigation chart, anticipating its efficiency and synergy to displaying the SAIMS results. The chart is commonly available on the four modules dedicated to processing of real-time information, environment data, ASW results and tides/tidal currents. The SAIMS has digital cells of more than 300 charts around Korean peninsula.

Moderate to midget submarines have only CTD sensor for oceanographic data with which the SAIMS has to produce sonar performance prediction. To get the data over the water column, they have to dive to certain depth to which they can do most. This action gives a chance for the foes to detect or even to classify submarines, being one of the worst cases submarine commanders do not want to face with. In addition, the maximum depth conventional submarines can reach is limited to a few hundreds meters, while sound speeds (or temperatures) still varies at the depth greater than the maximum. CTD data alone are not enough for acoustic models to run and we need a full sound speed profile over the whole water column which may range thousands meters. We designed and realized an algorithm to give full sound speeds using the CTD and historical data. The algorithm has dual modes: one is to estimate speed profile using CTD data retrieved for a few days and the other is to do that using CTD data when 'diving' event has been done.

The SAIMS was realized to have high levels of graphic user interface so that most jobs, from preparing input data to capturing output pictures, can be done in a minute. The system has software to help ease installation and embedded manual to refer at operation.

2.2. Architectures

The hardware configuration of the SAIMS can be divided into five components (Fig.1).

(a) Electric navigation chart

We employed the rules S-57/52 of International Hydrographic Office (IHO) in constructing and displaying the digital data cells. The SAIMS re-organize the necessary cells from the massive mother data. The new chart is called as 'System Electric

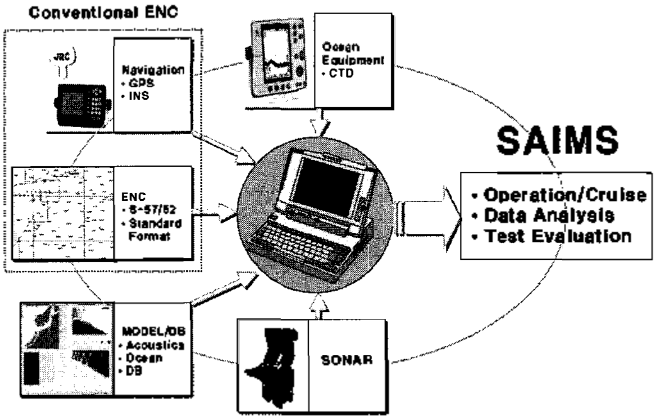

Figure 1. Hardware configuration of the SAIMS.

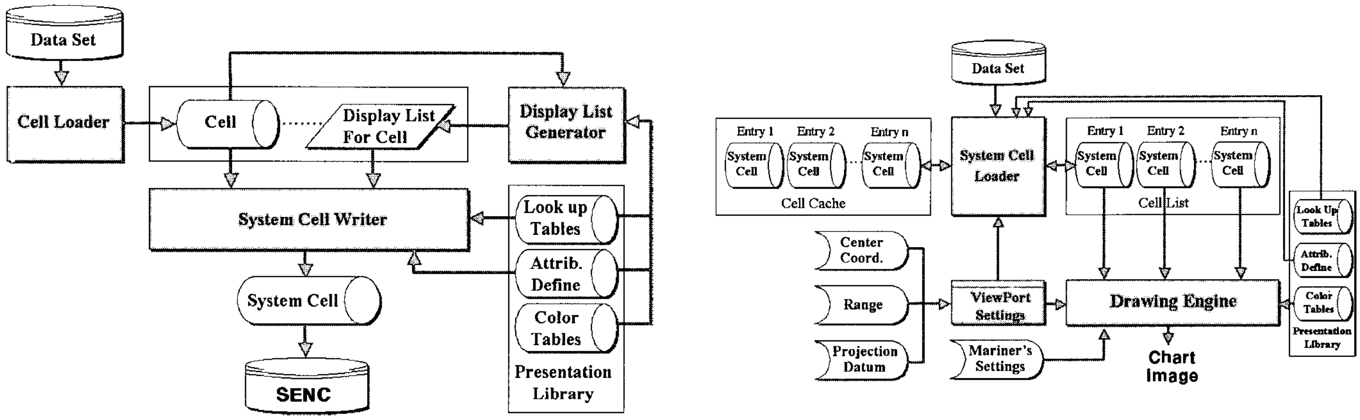

Figure 2. Procedures for converting into SENC format and for producing chart images.

Navigation Chart (SENC), differing from the original one. This chart leads to an optimized format and then too much shorter processing time. Displaying chart information into images, view port and mariner's setting (center coordinates, range, projection datum etc.) are additionally required. We added useful functions such as text/polygon editing, submarine track handling and user-defined targets managing, which are absolutely expected to give synergic effects to the tactical information from the SAIMS. Figure 2 shows the procedures for converting into SENC format and for producing chart images.

(b) Navigation equipment GPS/INS

Navigation information from GPS or INS is transmitted to the interfacing protocol with a rate of two data sets per second. For the safe retrieval of the data, the interface protocol operates independent of the SAIMS. The SAIMS just receives the data and displays them in digits or images on the SENC-based chart. The SAIMS can get even the data the protocol is saving now to conduct jobs user requests.

(c) Oceanographic equipment CTD

CTD is attached to submarines and measures temperature and conductivity with depth. Conductivity is converted into salinity using a simple expression. These data are also transmitted to the interfacing protocol from which the SAIMS get them to display in real-time or to estimate a full sound speed profile.

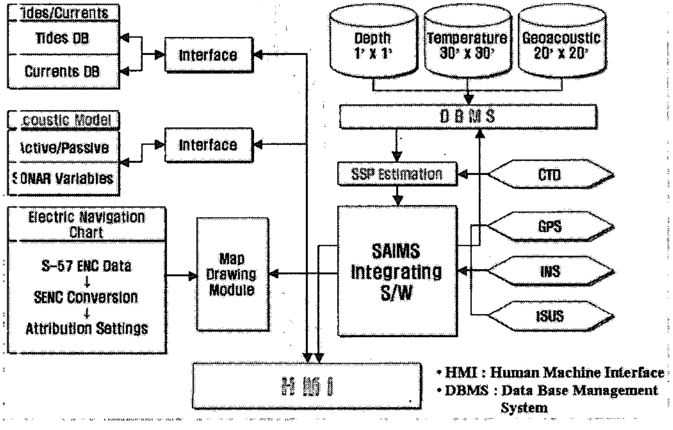

Figure 3. Connection among the models, databases and submarine sensors.

(d) Passive sonar

All sonars conduct target motion analysis (TMA) as they absolutely need to localization information to attack against the target. The SAIMS has another interfacing cable to get TMA information (instantaneous position, speed and bearing relative to own ship) from the sonar. Once getting the information, the SAIMS displays it on the chart in digit and symbol, which gives overall understandings to the sonar operators and the commander.

(e) Databases and models

These parts make themselves the heart of the SAIMS. The models are dedicated to computing acoustic fields, estimating sound speed profile, and predicting tides/tidal currents. Figure 3 is the block diagram showing the connection among the models, databases and submarine sensors in the SAIMS.

2.3. Functions

The SAIMS produce a lot of information useful for tactics or operations aid with 6 modules of which inputs or outputs are closely interconnected.

(a) Real-time information-processing module

- Display and manipulation of ENC
- Interface and display own ship information, CTD, target information
- Define parameters for sonar performance prediction
- Compute display acoustic fields for whole directions

Figure 4 gives an example of this module realized in the SAIMS.

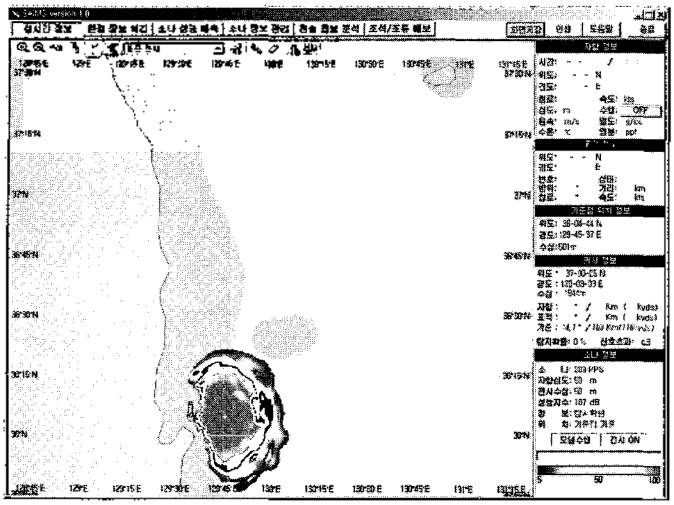

Figure 4. An example of the real-time information-processing module.

(b) Environment data processing module

- Display and manipulation of ENC
- Prepare inputs for the acoustic model in three modes : data base, CTD, user
- Data base management based on graphic user interface
- Define a section and get water depths along the section
- Estimate full sound speed profile over the whole water depth using CTD
- Estimate the optimum depth for submarines to hide against surface ships

Figure 5 shows some examples of this module realized in the SAIMS.

(c) Sonar performance prediction module

- Select or modify model inputs : environment, sonar, target, system etc.
- Predict sonar performance with depth and range : ray paths, propagation loss, detection probability, signal excess, detection range

Figure 6 gives an example of this module in the SAIMS.

(d) Sonar parameters management module

- Select a sonar type and edit parameters : active/passive, hull mount/towed array/sonobuoy etc.
- Select a target and edit parameters

(a) Anti-submarine Warfare (ASW) reconstruction module

- Display and manipulation of ENC
- Import necessary data sets: tracks/target detection logs
- Make decisions whether or not real detection was made
- Display the results on the ENC and summarize them into a file
- Define error bounds of range and bearing
- Process and display 3-dimensional bathymetry around the Korean peninsula

Figure 7 gives examples realized in the SAIMS.

(b) Tides and tidal currents prediction module

- Predict tides on the 22 locations around the Korean coasts

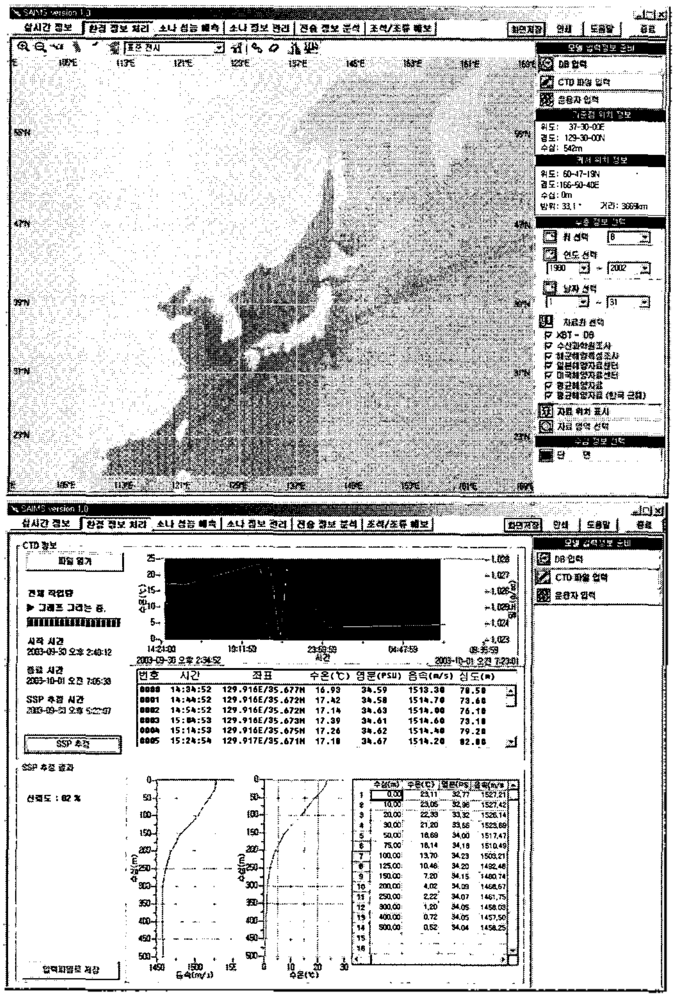

Figure 5. Some examples of the environment data processing module.

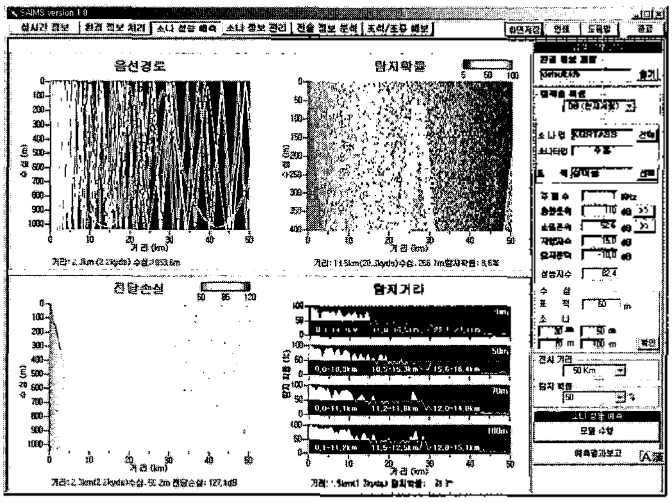

Figure 6. An example of the sonar performance prediction module.

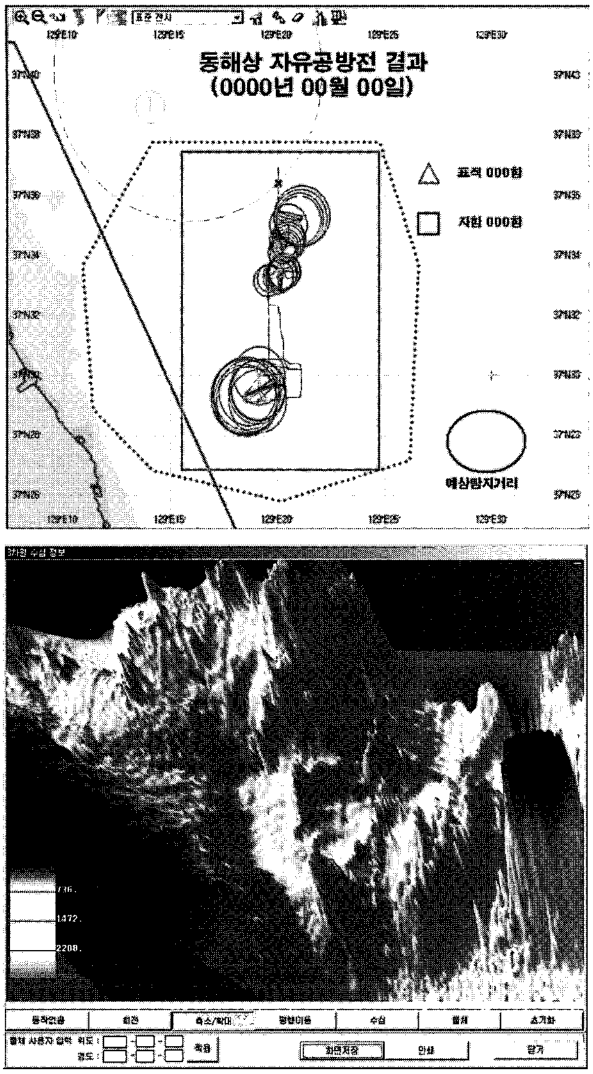

Figure 7. Examples of one-to-one ASW reconstruction and 3-dimensional bathymetry.

- Predict tides/tidal currents at any point and time defined by user

Tidal currents are based on the sea level heights gathered by atmospheric satellites and have a spatial resolution of 30'x30'. Hence, they give just overall patterns averaged over the water column in the region where user defined point belongs.

III. Sound Speed Estimation Algorithm

3.1. Estimation Procedure

Historical data may be decomposed into spatial eigenvectors and time coefficients, which stand for the space and time variations, respectively.[4] If we know proper eigenvectors and time coefficients at any specified position and time, we can estimate sound speed profile. Hence, finding these eigenvectors and coefficients is essential to the successful estimation. The following describes the estimation procedure.

(a) Prepare new time series data by interpolating the data corresponding to 15-th day of every two months.

(b) To enhance the dynamic range, the seasonal variations are subtracted from the data set.

(a) Construct data base of spatial eigenvectors by using empirical orthogonal function (EOF) analysis.

(b) Extract the exact eigenvectors corresponding to the submarine locations from the GPS/INS.

(c) Estimate time coefficients by referring to CTD information and by using the singular value decomposition analysis on the eigenvectors.

(d) Compute the variation components by summing spatial eigenvectors and time coefficients, and then add seasonal variations to get estimated sound speed.

3.2. Computation of Time Coefficients

In order to estimate the sound speed at the specified position, we have to find time coefficients from CTD and submarine tracks. We start with a matrix equation.

$$AX = b, \tag{1}$$

where A is eigenvector matrix corresponding to submarine locations, X is time coefficients matrix to be calculated, and b is CTD matrix whose seasonal variations are removed.

We can rewrite the matrix A by employing the covariance matrix S and decomposed matrices U, V.

$$A = USV^T. \tag{2}$$

We can express A by employing diagonal matrix C as

$$A = QCH^T, \quad C = U'S'V'^T. \tag{3}$$

From the Eqs.(2)-(3), we can get S, U and V as

$$S = U''^T S' V'', \quad U = QU'U'', \quad V = HV'V''. \tag{4}$$

If we express Eq.(1) with respect to U, V and S, we arrive at the following equation.

$$USV^{T}X = b. \tag{5}$$

We apply the singular value decomposition analysis over Eq.(5). The matrix S has singular values in diagonal positions. Among the singular values, there may be the ones not adequate for restoring b, which we replace them by 0 to reach a diagonal square matrix.

$$S = \begin{bmatrix} D & 0 \\ 0 & 0 \end{bmatrix}, \tag{6}$$

where D is a diagonal matrix.

We can deduce new expressions for matrices in Eq.(5) employing square matrices p1, q1 and null parts p2, and q2 as following.

$$V^{T}X = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix},\quad U^{T}b = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}, \tag{7}$$

The number of singular values for X is determined according to the rank of D.

3.3. Sound Speed Estimation

We finally get sound speed at any location and depth by summing the product of spatial eigenvector A and time coefficients X as following.

$$SS_F = SS_M + \sum_{i=1}^{N} A_F \bullet X_i, \tag{8}$$

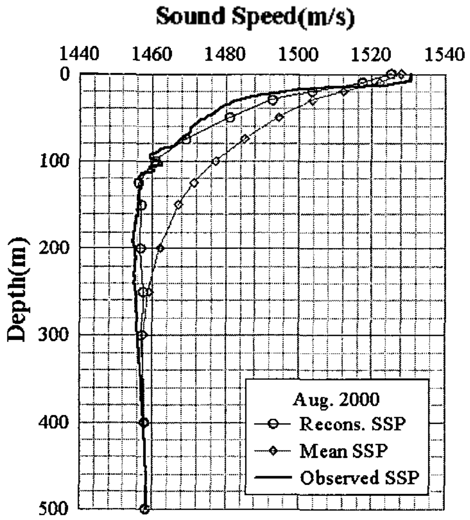

Figure 8. An example comparing the estimated sound speeds with the measured and mean values in the East Sea of Korea.

where SSF is the sound speed to be estimated, SSM is the monthly average, AF is eigenvector at the point, and Xi is time coefficients of each eigenvector. Sound speed at each depth over the water column follows the same analogy.

Figure 8 shows some examples comparing the estimated sound speeds to the measured and mean values in the East Sea of Korea. We can see that reconstructed (estimated) speeds are closer to the measured than historically averaged ones do.

IV. Acoustic Model Optimization

4.1. Application to Low Frequency

We designed the SAIMS so that it may be applied to multiple sonars of passive and active. Hence, it should adopt many acoustic models to cover wide frequency ranges. We checked out the possibility if only one model is enough to do the job.

In general, the Gavssian beam method[5], which is based on the ray theory, is known to be valid in high frequency. On the contrary, the models based on other schemes (for example normal

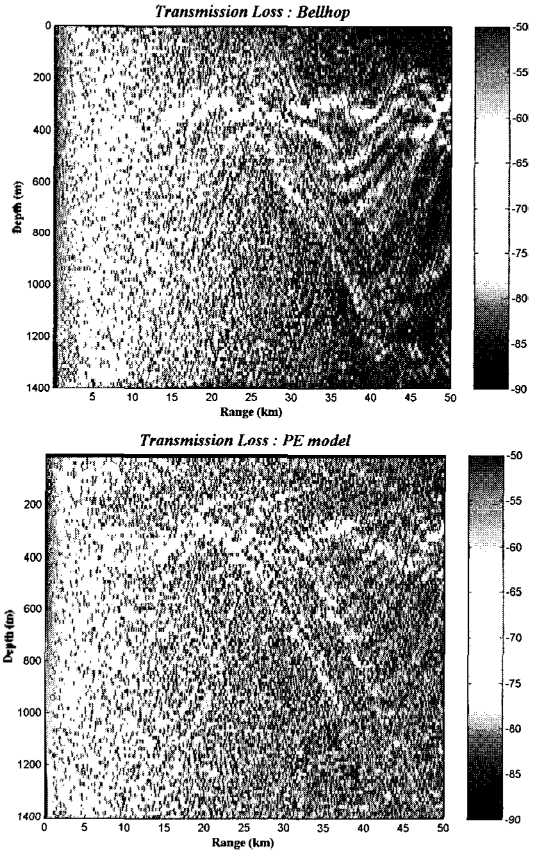

Figure 9. An example of propagation losses at 250Hz in the East Sea of Korea.

mode theory or parabolic equation) have strong merit in low frequency but critical limitation in high frequency mainly because computation time increases by geometrical series with frequency[6]. To apply the Gavssian beam method to low frequency, we should examine the conditions at which it is valid. We compared propagation losses from the Gavssian beam method and a parabolic equation based model (RAM) in deep and shallow environments. Figure 9 gives an example at 205 Hz in the East Sea of Korea. We can see that major features match very well in the two distributions.

4.2. Model Optimizations

The optimized grid numbers are 201 in range and 301 in depth, respectively. The maximum launch angle is variable within +/-70°. The most crucial factor affecting the accuracy of the results is total beam number, which should be inevitably varied with frequency. We applied the following criteria in determining the proper number.[4,6]

$$N_{beam} = \alpha + |\alpha - \beta| / A, \tag{9}$$

where α, β=ray angle in radian, the coefficient $A = (c/6fr)^{1/2}$, c=sound speed(m/sec), f=frequency(Hz) and r=maximum range(m).

Since the applied model adopts a kind of Gaussian beams along ray paths instead of traditional delta function, the accuracy could be affected by weighting function applied. In general, delta function caused unreasonable shadow and convergence zones. We considered three functions: Gaussian beam bundle (GBB), geometric beam (GEO), and simple Gaussian beam (SGB). After many simulations over the wide frequency ranges and comparisons with the RAM, we employed the GBB as a weight function along each ray path.

We also gave it a little modification to the model inputs. Once sound speed profiles are fed into the model, they are interpolated by conventional schemes. Conventional methods such as spline often lead to artificial spikes where temperature or sound speed varies sharply with depth. We introduced new method of interpolation, Akima spline [4], which is known to be valid even at the worst case when properties face high variations.

For the acoustic fields in all directions, we made the SAIMS conduct iterative computation for 22 sections. This configuration guarantees a minute of computation time in most cases. On a computer with CPU 1GHz and RAM 512 MB, one section (assuming depth 6,000m, range 50km and frequency 1kHz) requires about 2.75 seconds to get acoustic fields for four receiver depths, resulting in total time of 2.75x22 ≈ 55 seconds. An example of directional pattern of acoustic fields is shown in Figure 4.

V. Sea Tests

With a surface warship and a submarine, we conducted three sea tests to verify the applicability of the SAIMS. For the safety of the submarine, we had to do them in deep sea whose depth is more than 1,000m. Activating the active sonar, the surface ship cruised along the pre-defined tracks within the radius 3-45km. The submarine moved up and down vertically keeping the pre-defined courses and speeds. In the submarine, we collected all necessary data including sonar signal from the surface ship

Through the post-processing of test data, we could confirm the applicability of the sound speed estimation algorithm. The algorithm also worked quite well against historical CTD data from a submarine in shallow sea.

From the sea tests data, we also could see high fluctuation of received sound energy with depth. Figure 10 shows the depth variation of the submarine and energy spectra received at each depth. The energy spectra, where spherical spreading loss 20log(r) (r in m) is denoted by dotted curve, obviously show big

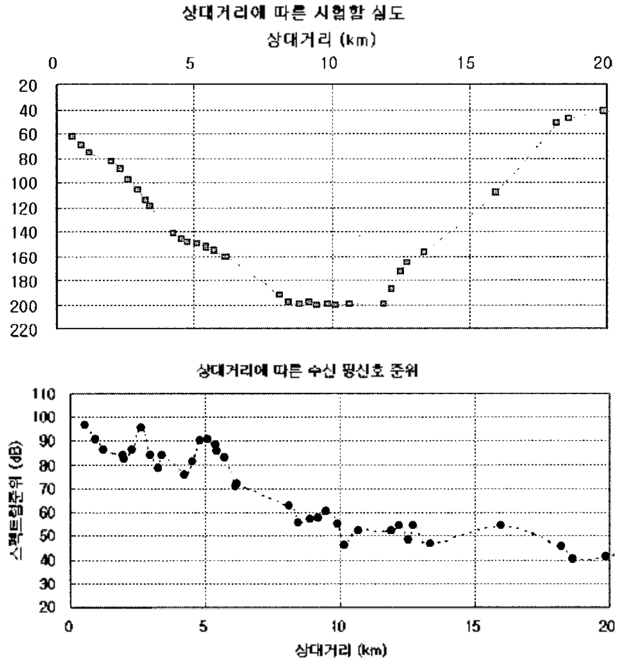

Figure 10. Depth variation and energy spectra received with each depth

jumps from the spreading loss curve, reaching up to almost 20 dB at range 5km. This phenomenon strongly suggests the existence of energy converging depths over the water column, and thus implies the fact that finding the optimum depth is critical to the tactics or operations of submarines.

We estimated detection ranges for the active sonar signal on the SAIMS by using environment and sonar data. The difference between the predicted and measured detection range was less than 15%.

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[Profile]

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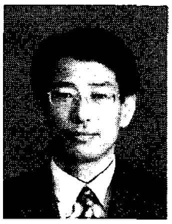

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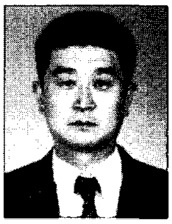

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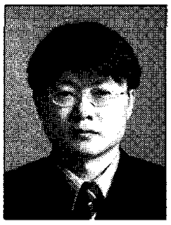

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