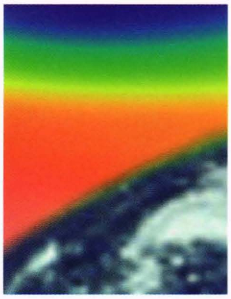

A Simulated Ocean Environment for a Maritime Simulation Demonstration

Fred C. Newman, Michael R. Carnes, Gregory N. Valenzuela, John G. Hughes, and Edward Khedouri

A simulated ocean environment was developed and implemented to support the September 1993 Maritime Simulation Demonstration sponsored by the Advanced Research Projects Agency. The demonstration was based on a scenario for a hypothetical naval operation using low-frequency acoustic detection technology in the Sea of Japan. Objectives were to provide a realistic ocean environment and to demonstrate the ability of Navy operationally based real-time products to support complex simulations. An assessment of the Sea of Japan revealed that February environmental conditions yielded the best acoustic detection ranges and hence greater opportunity for player interaction. This result underscores the importance of environmental considerations in both the planning and execution of a simulation. The environmental description was then developed from a dynamic model of the Sea of Japan as well as available climatological and bathymetric databases. The same ocean environment was provided to all simulation participants to achieve consistency and realism, although calculations of acoustic system performance still varied because the participants used different acoustic models.

INTRODUCTION

Late in 1992, the Advanced Research Projects Agency (ARPA) conceived a plan for a simultaneous demonstration of several maritime simulation technologies. The Maritime Simulation Demonstration, conducted 13–17 September 1993, combined those technologies to simulate a hypothetical naval operation during February in the Sea of Japan. The demonstration was performed as a distributed, interactive simulation in which separately located computer systems, simulating naval platforms and command centers, communicated with each other via high-speed data transmission links. Many of the simulated systems required a physical description of the Sea of Japan ocean environment. To simulate a physical ocean environment that would realistically affect the conduct of the naval operation, a three-dimensional sound-speed field was developed by the Naval Research Laboratory using a dynamic ocean model. Additional environmental parameters were obtained from standard Navy databases.[1]

The principal components of the demonstration were (1) the Acoustic Warfare Integration Laboratory, a wargaming network of computer workstations simulating ships, submarines, aircraft, and command centers, developed by SAIC (Science Applications International Corp.); (2) the acoustic time series simulator, a highly sophisticated assemblage of computer software and hardware that uses descriptions of sea surface conditions, surface shipping, and target acoustic characteristics to simulate the total acoustic signal received by each sensor, developed by Alliant Techsystems; (3) the Acoustic Warfare Decision Support System, a tactical data fusion and planning system, developed by AT&T Bell Laboratories; (4) the Submarine Combat Information Laboratory at the Applied Physics Laboratory, a mock-up of a submarine control room participating as a friendly attack submarine; and (5) a simulated unmanned underwater vehicle for detection and location of explosive mines in shallow water, developed by the Draper Laboratory. Figure 1 illus-trates most of the data links among the several systems. More comprehensive descriptions of the Maritime Simulation Demonstration are given in Refs. 2 and 3.

The central focus of the demonstration was to simulate the use of a low-frequency active underwater acoustic system to detect echoes from potentially threatening submarines as well as the use of passive acoustic receiving arrays to detect sounds made by these targets as they moved about the Sea of Japan. The active acoustic system employs a transmitting acoustic source, suspended from a ship, some of whose energy is reflected from the target and detected by an underwater acoustic receiver. If the receiver is (nearly) colocated with the source, the system is called monostatic. If the receiver's location is significantly different from that of the source, the system is called bistatic. This demonstration used a single transmitting source with both monostatic and bistatic receivers.

THE ENVIRONMENTAL SCENARIO

Several factors in the ocean environment determine the spatial distribution of acoustic energy propagating away from a source or a reflecting target. The most

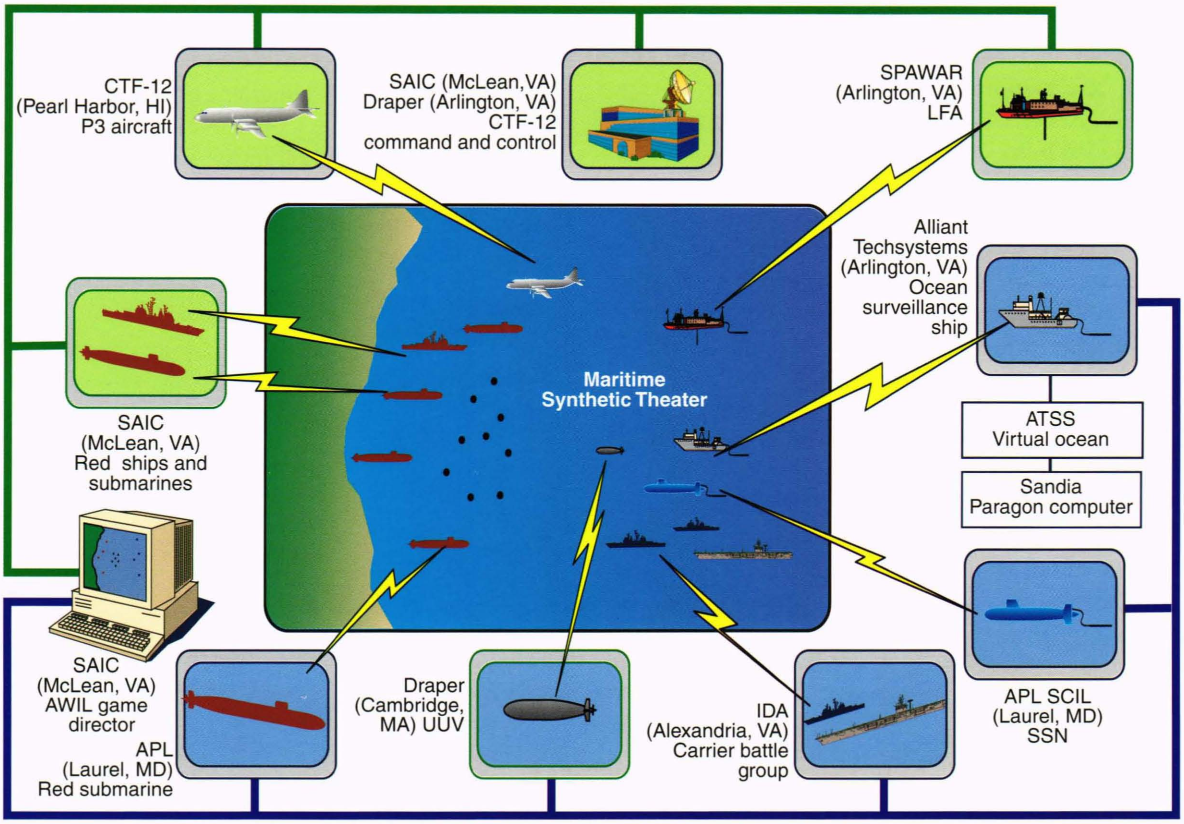

Figure 1. Schematic representation of the Maritime Simulation Demonstration showing linkages on the Defense Simulation Internet among systems in the Acoustic Warfare Integration Laboratory (AWIL) and other simulated systems (CTF = Commander Task Force, SPAWAR = Space and Naval Warfare Systems Command, LFA = low-frequency acoustic, ATSS = acoustic time series simulator, SCIL = Submarine Combat Information Laboratory, SSN = nuclear-powered attack submarine, IDA = Institute for Defense Analysis, UUV = unmanned underwater vehicle).

influential factors are the spatial variation of the speed of sound throughout the ocean volume, the ocean bottom topography, and the nature of the ocean bottom material. Spatial variation of the speed of sound can cause highly nonuniform distribution of acoustic energy due to refractive effects. The dynamic model representing the spatial variation of the sound-speed field in the simulation is discussed in the following section. Bottom topographic features such as continental slopes, seamounts, islands, and ridges can act as large acoustic reflectors and scatterers. The nature of the bottom material determines the way in which acoustic energy is refracted, scattered, and absorbed. Scattering from biota within the volume of the ocean, as well as from the ocean surface made rough by surface waves, can also significantly affect the distribution of acoustic energy.

The simulated naval operation was conducted in the southwestern basin of the Sea of Japan (red box in Fig. 2). Bathymetric data were obtained from the Navy's Digital Bathymetric Data Base, DBDB-5, which provides depth values for the world's ocean bottom on a 5 × 5 minute grid. Simulated platforms were free to move about along arbitrary tracks irrespective of grid point locations. The boundaries and bottom of the basin tend to act as reflectors of the sound from the acoustic source, thereby producing unwanted acoustic reverberation that can reduce or even eliminate the ability of the system to detect echoes from enemy submarines. Reverberation was therefore an important effect included in modeling the propagation of acoustic energy in order to assess whether the low-frequency acoustic system could detect enemy submarines at particular locations of interest as they moved about the area. Reverberation can also be caused by acoustic scatterers such as certain species of fish and zooplankton within the volume of the ocean. This effect is known as volume reverberation.

The bottom of the basin consists of a rather thick layer of sediment. Typically, the ocean bottom acts as a rough scattering surface and, when acoustically imaged by the low-frequency acoustic source, causes some acoustic energy to be diffusely scattered in all directions. The intensity and angular distribution of the scattered energy depend on the physical properties of the bottom material. Some of the acoustically imaged energy is scattered back to the monostatic and bistatic receivers. This backscattered energy is another form of bottom reverberation. Upon consideration of the characteristics of the bottom sediment layer in the southwest Sea of Japan, the bottom backscattering strength was estimated to be -35 dB/m^2 (personal communication, R. Dicus, SAIC, 1993).

Surface reverberation is caused by the scattering of sound from the underside of the wave-roughened ocean surface. The recommended values for mean wind speed and mean waveheight were 5 to 6 m/s and 0.5 m, respectively (personal communication, M. Head, Naval Oceanographic Office, 1993). These values were held constant over the entire geographic area and throughout the simulation.

On the continental shelf, west of the basin and very near the coast, a 4 × 4 minute area (red dot within box in Fig. 2) was chosen within which locations were selected to represent underwater explosive mines. Here, bathymetric values were interpolated from DBDB-5 to a 0.1-minute grid. The mine locations corresponded to designated points within this high-resolution grid. During the demonstration, the simulated unmanned underwater vehicle traversed this grid in its search for mines.

DEVELOPMENT OF THE SOUND-SPEED FIELD

To determine the most favorable ocean sound-speed conditions to meet the simulation objectives, acoustic propagation conditions for both summer and winter were assessed. Sound-speed profiles were computed from historically observed profiles of temperature and salinity retrieved from the Master Oceanographic Observation Data Set (MOODS), which is maintained and regularly updated by the Naval Oceanographic Office. The latest version of MOODS is also maintained by the Environment Group within APL's Submarine Technology Department. Summer profiles, shown in Fig. 3a, exhibited a very warm, high-sound-speed surface layer, which causes energy from a near-surface source to be strongly refracted downward.

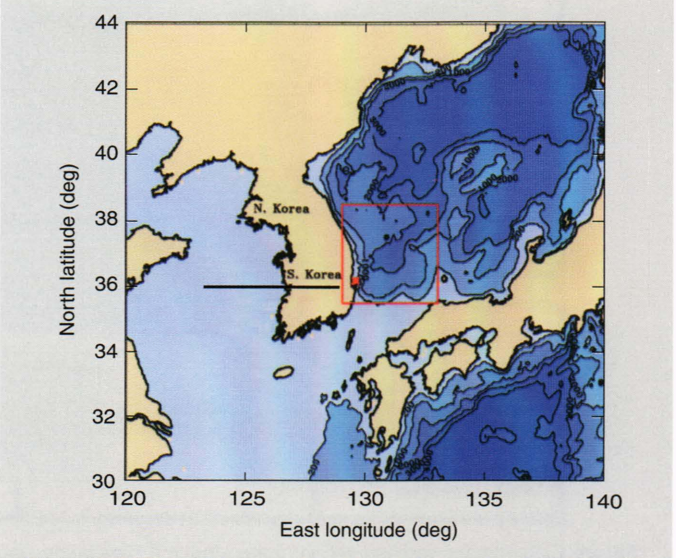

Figure 2. Bathymetric map of the Sea of Japan showing the area (red box) in which the simulated naval operation was conducted and the location of the simulated underwater mine field (dot within the box). Depths are given in meters. The area represented is 900 × 952 nmi.

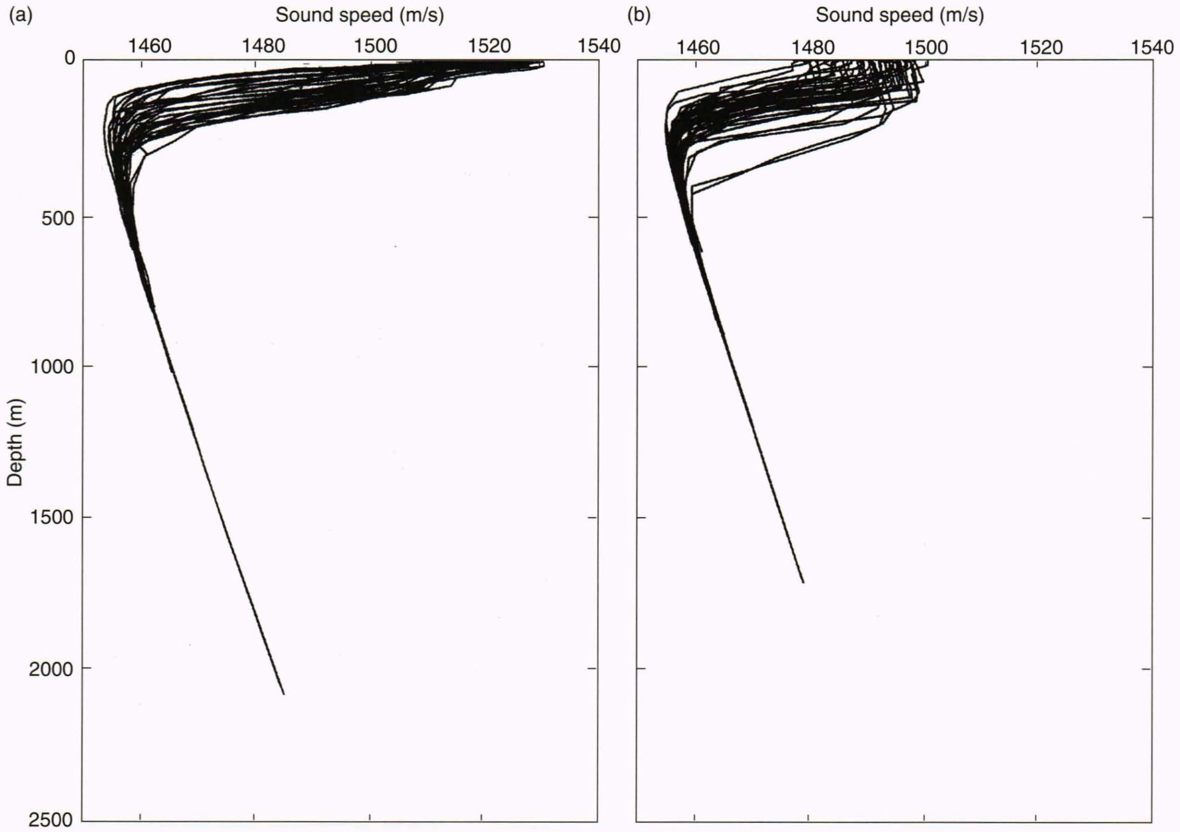

Figure 3. Sound-speed profiles in the southwestern basin of the Sea of Japan (35.5–38.5°N, 129.0–133.0°E) calculated from historically observed temperature and salinity profiles: (a) September profiles, (b) February profiles.

The acoustic propagation models to be used in the simulation all predicted that the resulting bottom reverberation would cause somewhat limited performance of the low-frequency acoustic system. Winter profiles, shown in Fig. 3b, exhibited the same general shape, but with more moderate sound speeds in the surface layer, less downward refraction of acoustic energy, and consequently less bottom reverberation. Winter, specifically February, was therefore chosen for the simulation because bottom reverberation was minimal, thus allowing the best low-frequency acoustic detection of enemy submarines.

The sound-speed fields for the Sea of Japan were simulated using a combination of two numerical models and two ocean climatologies. The primary model was the Navy Layered Ocean Model based on a version originally written by Hurlburt and Thompson.[4] The domain of the particular model used here extends from 121 to 130°E and from 15 to 48°N, encompassing the North Pacific subtropical gyre, the Kuroshio and Oyashio currents, and the Sea of Japan. The Sea of Japan is connected to the Pacific Ocean in this model through the shallow Korea and Tsugaru straits. The horizontal resolution is approximately 0.125° in latitude and 0.167° in longitude. This nonlinear, primitive equation model has two active layers in the vertical structure, a free surface, and realistic bottom topography in the lower layer. The model has been spun up from rest over several decades, forced by climatological winds. Since 1981, it has been forced by daily wind stresses derived from an atmospheric model at the European Centre for Medium-Range Weather Forecasts.

The model's surface height field was modified to match available information on the ocean's synoptic state for a particular day using a technique called rubber sheeting.[5,6] With this method, the positions of fronts and eddies are moved, using spatially correlated displacements, to match the positions observed in satellite IR imagery. Typically, these observations take the form of lines traced along the thermal front boundaries of the ocean's surface, which are prepared by personnel at the Naval Oceanographic Office's Warfighting Support Center.[7,8] The lower-layer pressure anomalies in the model are predicted from the modified surface height field using statistical relationships derived from model fields obtained from multiyear runs.[9] Instead of substituting the modified fields and then continuing the model run, the modified fields are assimilated slowly into the running model using a technique called nudging.[10,11]

The model fields resolve the horizontal structure of the ocean adequately, but the two layers do not satisfactorily represent the vertical structure required for ocean acoustic prediction. Also, the modeled variables include potential density but not temperature, salinity, or sound speed. Previous studies have demonstrated the predictability of temperature and salinity profiles from sea surface height (or dynamic height at the surface) and surface temperature.[12,13] For the present application, a database for the upper 1000 m of the ocean was constructed using a similar technique for the Sea of Japan from edited profiles of temperature and salinity extracted from the National Oceanographic Data Center archives. By using this database, three-dimensional grids of temperature and salinity in the upper 1000 m of the ocean can be constructed from the surface height grid of the hydrodynamic layered model.

The resulting fields of temperature and salinity contain only the climatological near-surface vertical structure (surface mixed layer and seasonal thermocline). Upper-ocean modifications to these fields due to local wind stress are incorporated using the Thermodynamic Ocean Prediction System,[14–16] an upper-ocean mixed-layer model. In a final step, the temperature and salinity fields are extended to the bottom by smoothly splicing the modeled profiles in the upper 1000 m to climatological profiles below 1000 m extracted from the Navy's Generalized Digital Environmental Model.[17]

The process just described was applied to satellite IR imagery from 2 and 8 February 1993 to produce highly realistic (high-fidelity) sound-speed fields representing ocean conditions 1 week apart. Contour plots of sound speed at the surface for these dates are shown in Figs. 4a and 4b, respectively. Their principal feature is a meandering ocean front extending from Korea to the northeast. The frontal meanders are grossly similar on both dates but differ noticeably in detail. These differences are typical of frontal evolution over a 1-week period in the Sea of Japan. The front extends down into the volume of the Sea of Japan to about 400 m. Profiles from the 2 February sound-speed field are shown in Fig. 5 and can be seen to closely resemble the observed MOODS profiles shown in Fig. 3b.

The Maritime Simulation Demonstration included both an advance planning phase and a tactical planning phase prior to the actual naval operation. The former represented the development of general strategy, which typically occurs several weeks in advance. The latter, which occurs only days in advance, requires the latest and most complete environmental information available. For this demonstration, the sound-speed field of 2 February was used for advance planning, and the same sound-speed field, partially updated with profiles representing 8 February conditions, was used for tactical planning. To simulate the real-time incoming ocean profile data (e.g., profiles obtained from surveillance aircraft deployed in anticipation of impending

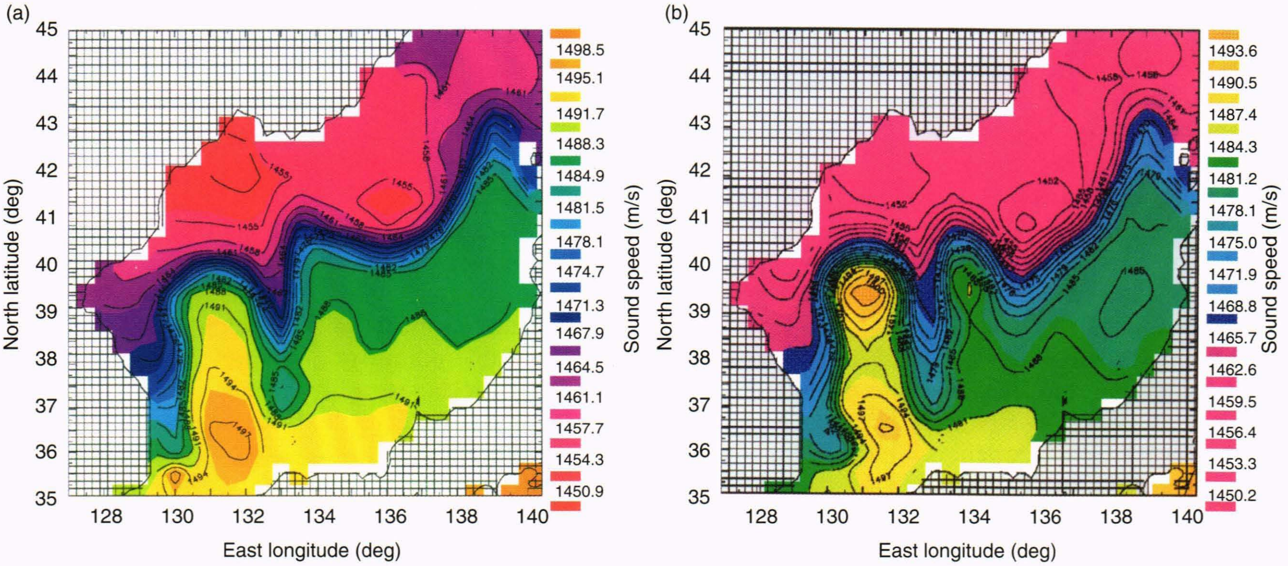

Figure 4. Color contour plots of the modeled surface sound-speed field for the Sea of Japan. Areas occupied by the black grids represent land: (a) 2 February 1993, (b) 8 February 1993.

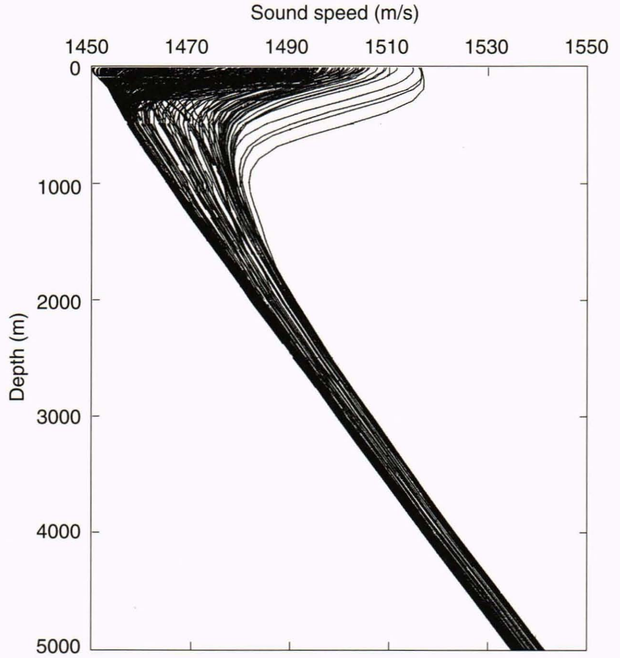

Figure 5. A sampling of sound-speed profiles from the modeled three-dimensional sound-speed field in the Sea of Japan on 2 February 1993.

operations), selected profiles from the 8 February field were used to update the 2 February field. The update process was executed using the Modular Data Assimilation System (MODAS) developed at the Naval Research Laboratory.[18,19] MODAS provides a modular approach to the development of a three-dimensional gridded sound-speed field in support of underwater acoustic system performance predictions. It assimilates randomly located *in situ*, satellite, and climatological data, as well as a "first guess" three-dimensional gridded field (the 2 February field in this case) to generate a smoothed, gridded output field.

The updated February sound-speed field was then used to perform acoustic model calculations to predict low-frequency acoustic system effectiveness under current conditions in order to plan the naval operation to follow. In the demonstration, the updated 2 February sound-speed field was the last field about which the participants had information. The 8 February sound-speed field was used to represent the actual ocean in which the naval operation was conducted. Thus, the operation was conducted in an ocean environment about which the participants had only incomplete information. This was done deliberately to enhance the realism or fidelity of simulating the latest (incomplete) environmental information available to a real naval operation.

ACOUSTIC MODEL RESULTS

Three different acoustic models were used simultaneously. The acoustic time series simulator used a normal mode model called Kraken,[20,21] the Acoustic Warfare Integration Laboratory used the Advanced Underwater Acoustic Modeling Project (AUAMP) model,[22] and the Acoustic Warfare Decision Support System used the parabolic equation (PE) model.[23] In each case, the acoustic model used was best suited for the particular requirements of the respective system. Since different acoustic models can produce differing propagation outcomes given identical environmental inputs, results were compared to determine whether inconsistent acoustic descriptions of the same environment might occur. Inconsistencies could result in one participant (representing a submarine, for example) calculating that his platform is not detectable at his location during a particular moment of the simulation, while another participant (representing a receiver array ship, for example) calculates that the former's platform is easily detectable.

Several test cases showed PE and Kraken to give nearly identical results from the same environment. Therefore, PE was considered to represent both models, and the comparison was performed only between PE and AUAMP.

The quantity (in dB) used for this model comparison is called signal excess (SE), the amount by which the target echo intensity exceeds a threshold level (DT) required for detection. It is computed from an expression known as the sonar equation:

$$\mathrm{SE} = \mathrm{SL} - \mathrm{TL}_1 - \mathrm{TL}_2 + \mathrm{TS} - \mathrm{RV} - \mathrm{AN} - \mathrm{DT}\,,$$

where

SL = acoustic source level (dB),

TL_1 = transmission loss (dB) from source to target,

TL_2 = transmission loss (dB) from target to receiver,

TS = target strength (dB) of the target submarine,

RV = intensity (dB) of acoustic reverberation,

AN = intensity (dB) of ambient noise from shipping and sea surface noise, and

DT = acoustic detection threshold (dB).

The values for SL and DT are constant and were chosen to represent the particular acoustic system characteristics being simulated. The value for TS was chosen as constant for purposes of this evaluation, but during the simulation TS depended on the aspect presented by the submarine hull to the incident acoustic energy as well as the orientation of the hull with respect to the direction in which energy is reflected to the receiving array. The value of AN for any given beam of the receiving array depended on the anisotropy of the ambient noise field at the location of the array. The values of TL_1 and TL_2 were calculated using a propagation loss model, and RV was calculated using a reverberation model. A reverberation model calculates the total received acoustic intensity as a function of time due to reflections from bottom features such as seamounts, ridges, islands, and continental margins. The SE value was calculated for target ranges from 0 to 200 nmi from the center of the monostatic and bistatic system locations. Because the shape of the sound-speed profile varies with the range (distance) of the target from the acoustic system and because the details of this profile shape variation can change with the direction along which target range increases, SE was calculated along radials separated by 5° and covering the full 360°. Calculations were performed for target depths of 60 and 150 ft for both the 2 February and 8 February sound-speed fields. Results for the bistatic calculations were very similar in character to the monostatic results and are therefore not included here.

The SE results shown in Figs. 6 and 7 for PE and AUAMP, respectively, exhibit concentric, irregular, annular regions of higher SE separated by regions in which SE is lower or even negative. Negative SE values represent regions where the specified target strength is not detectable. In both figures, the receiving array is oriented north–south, resulting in somewhat reduced SE north and south of the array. Significantly, when comparing SE area plots, a change of color by only one interval may indicate an SE increase (decrease) from the high (low) end of one color interval to the low (high) end of the next higher (lower) color interval. The appearance of some feature in one SE plot may therefore differ dramatically from the corresponding

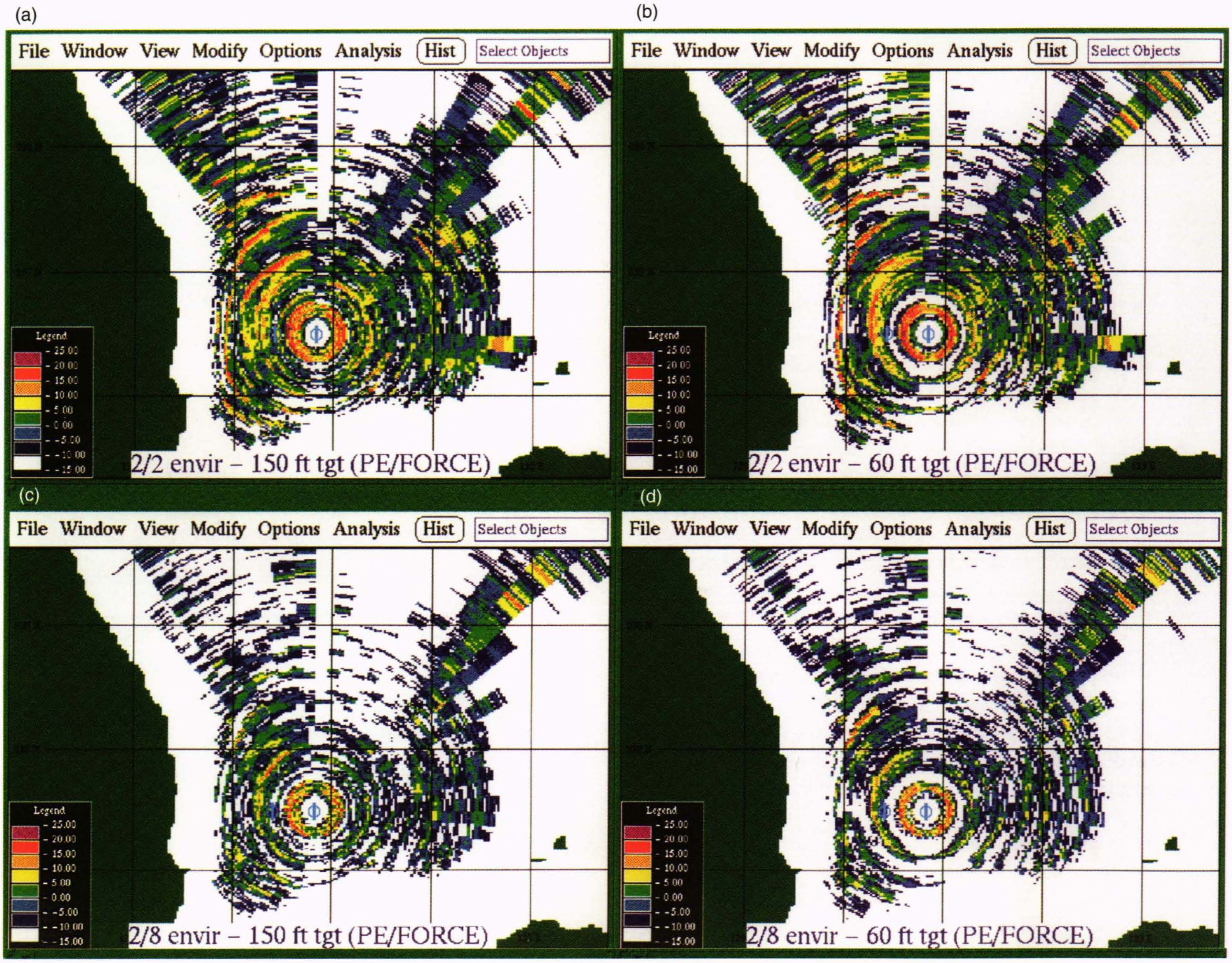

Figure 6. Signal excess plots computed using the parabolic equation (PE) propagation loss model: (a) 2 February, target at 150-ft depth; (b) 2 February, target at 60-ft depth; (c) 8 February, target at 150-ft depth; (d) 8 February, target at 60-ft depth.

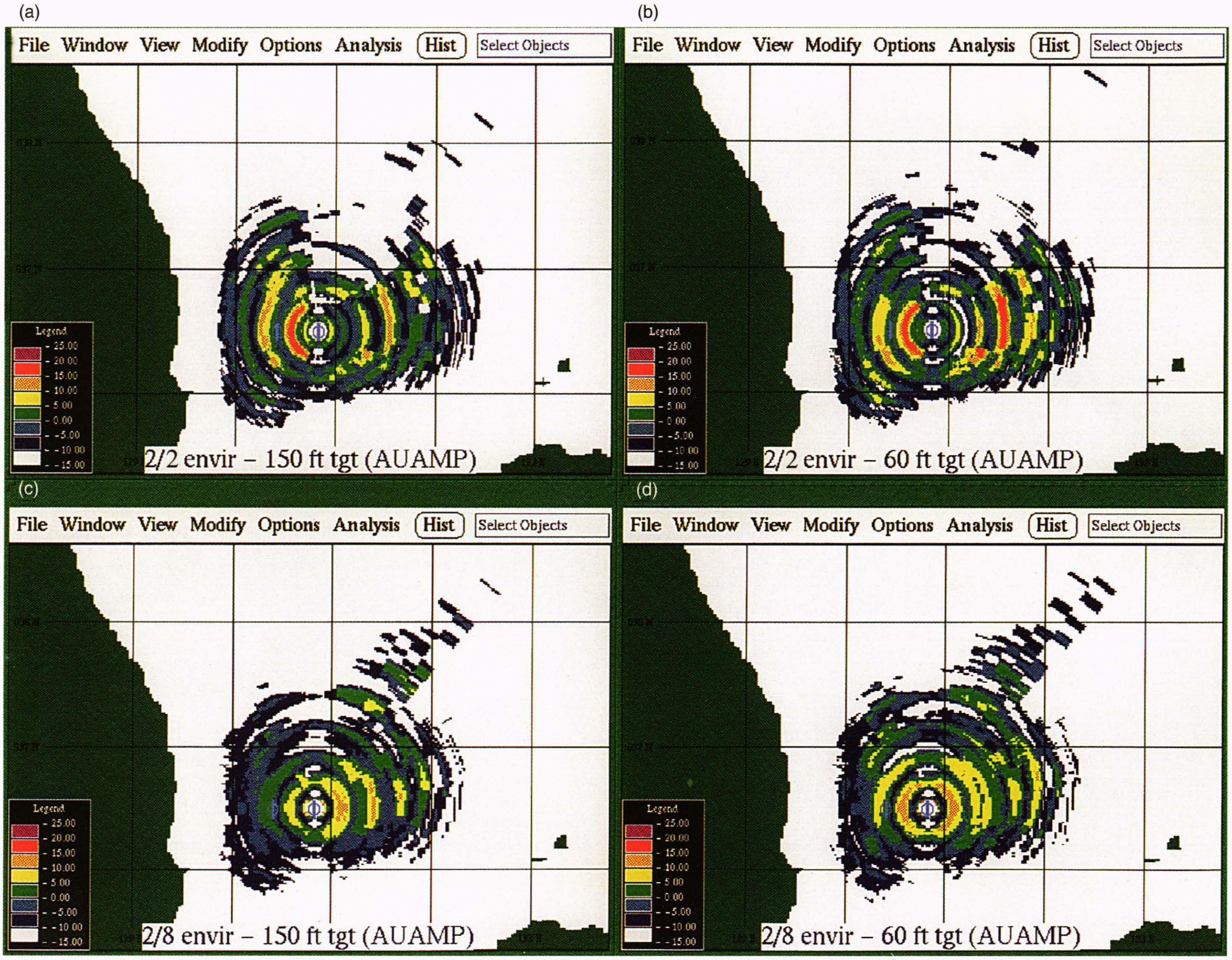

Figure 7. Signal excess plots computed using the Advanced Underwater Acoustic Modeling Project (AUAMP) model: (a) 2 February, target at 150-ft depth; (b) 2 February, target at 60-ft depth; (c) 8 February, target at 150-ft depth; (d) 8 February, target at 60-ft depth.

feature in another plot, despite a rather insignificant difference in the SE value for that feature.

Because the AUAMP transmission loss varies more smoothly with range than PE transmission loss, the results for PE (Fig. 6) appear more granular than those for AUAMP (Fig. 7). Also, the details of high SE regions differ slightly between the PE and AUAMP results. For example, the width of the high SE regions is generally slightly greater in the AUAMP results, whereas the PE results include numerous small regions where SE is greater than in the AUAMP results. Both models agree that the total amount of high SE area is reduced somewhat for the 8 February environment. The AUAMP model predicts that the total high SE area is greater for the 60-ft target depth than for the 150-ft target depth, but PE results exhibit very little difference for the two. The AUAMP and PE results were sufficiently similar that the interplay of targets and other platforms was not disrupted by discrepancies in target detectability among the various systems represented. The purpose of this simulation was only to provide a feasibility demonstration, however, and more technically demanding simulations might require a greater degree of correspondence among participating models with respect to their response to the physical environment.

SUMMARY

An ARPA-sponsored Maritime Simulation Demonstration was conducted in September 1993 to simulate a hypothetical U.S. naval operation in the Sea of Japan. A team of scientists—representing participants in the simulation—conceived, developed, and implemented a highly realistic time-evolving ocean environment within which Navy acoustic systems operated.

Values of the parameters constituting the environment were obtained from current standard Navy databases and from a Naval Research Laboratory model encompassing the subtropical Pacific Ocean and the Sea of Japan. Candidate ocean environments were used in each of the participating acoustic models, and results were compared in order to select an environment producing minimal performance inconsistencies among the various participating acoustic systems. The ocean environment was then distributed to all participants well in advance of the actual simulation to allow all possible preliminary acoustic model calculations to be completed. This procedure minimized the calculation load during the simulation, allowing the time scale of the simulation to be as nearly "real-time" as possible.

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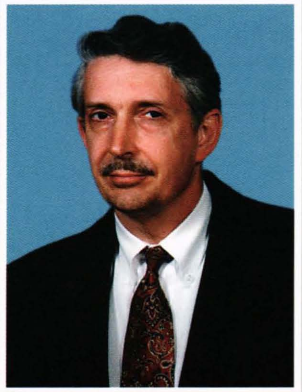

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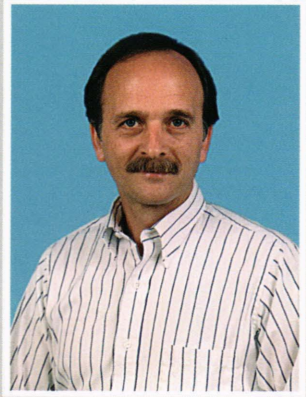

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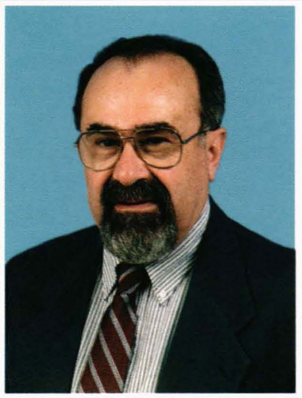

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