RECENT ADVANCES IN OCEAN MODELING TECHNIQUES FOR SONAR TRAINERS — FBM SOT

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INTRODUCTION

Realistic simulation of the received signals from ships and submarines is the primary objective of the Fleet Ballistic Missile Sonar Operational Trainer (FBM SOT) built by Honeywell's Training and Control System Center. The sonar suites on board the FBM submarines provide reliable information conveying a target's movement and identity. Acoustic properties of the ocean significantly affect the visual and aural representations of a ship's signal. The ocean medium's variability can be used advantageously in locating and tracking a ship as well as to cause confusion resulting in tactical errors. Recognizing and utilizing various sound propagating characteristics of the oceans is an essential training goal.

REQUIREMENTS OF THE OCEAN MODEL

The SOT is comprised of an instructor control center, a mini-computer complex, nontactical hardware and tactical hardware. The nontactical training hardware provides shaped signals utilizing real-time program computations controlled by an instructor's inputs. Tactical hardware is stimulated by these signals subsequent to their being inverse beamformed. The SOT classroom is a duplication of the sonar suite of FBM submarines, permitting extremely realistic training on bearing time recorders, cathode-ray tube (CRT), spectrum analyzers, lofargram recorders, and audio headsets.

The ocean acoustic model must behave realistically in a wide frequency range and exhibit ocean acoustic characteristics typically exploited by the sonar arrays and their sophisticated signal processors. Therefore, sound transmission in surface ducts, convergence zones, deep sound channels, and shadow zones must be simulated. The acoustic model is also required to furnish the data to simulate interference patterns which can be used to determine a ship's closest point of approach (CPA). Figure 1 illustrates the spectrum history of a ship as it passed the CPA as shown on a test spectrum analyzer.

Data obtainable from ray theory models is in the most convenient form for trainer modeling. Several acoustic computer program models such as Ray-Normal Mode Theory (RAYMODE), Navy Interim Surface Ship Model (NISSM), or Continuous Gradient Ray Tracing System (CONGRATS V) provide ray information including path travel time, angle of arrival and phase angles, as well as propagation loss. Path loss information is used to attenuate signals as a function of frequency, to represent accurate detectability. Path arrival angles convey location information; multipaths can reflect the condition of detecting a target on more than one beam. Interference patterns are sensitive to the time delays between arriving paths, their phases and their relative amplitudes.

The contracting agency, the Naval Underwater Systems Center, selected a modified version of the CONGRATS V program,[1] developed by Dr. Henry Weinberg, to supply the primary acoustic path data. The modified program computed eigenray data valid in the frequency domain of the sonars and in the environmental domain of the FBM submarines. The summation of the eigenrays between a source and a receiver produces the phenomena of convergence zone, surface ducts, deep sound channels, and shadow zones. The presence of these phenomena is dependent on the sound velocity profile, the bottom type, sea state, source to receiver range, source depth, receiver depth, and the signal frequency. Given specific values for these parameters, CONGRATS V generates scores of paths in nonreal time on a UNIVAC 1108 computer. Table 1 illustrates the numerical form of data output by the CONGRATS V program at a range for a specific source and receiver depth combination at 250 Hertz. The sound velocity profile is given in Figure 2. Figure 3 is a diagram of the rays emanating from the source.

To achieve real-time requirements of updating at a one-second rate while retaining CONGRATS V accuracy, data is precomputed and stored on disk for recall during training. Data bases for up to 12 sound velocity profiles each with two bottom types and sea states are available to the instructor. A logical record of information is stored for each receiver/source range and depth pair combination of a data base grid point. The record contains propagation losses at each of 30 1/3 octave frequencies for one or two paths. Also included are values for a path's geometric features: arrival angles, travel times, and discrete phases. The geometric features are assumed to be frequency independent.

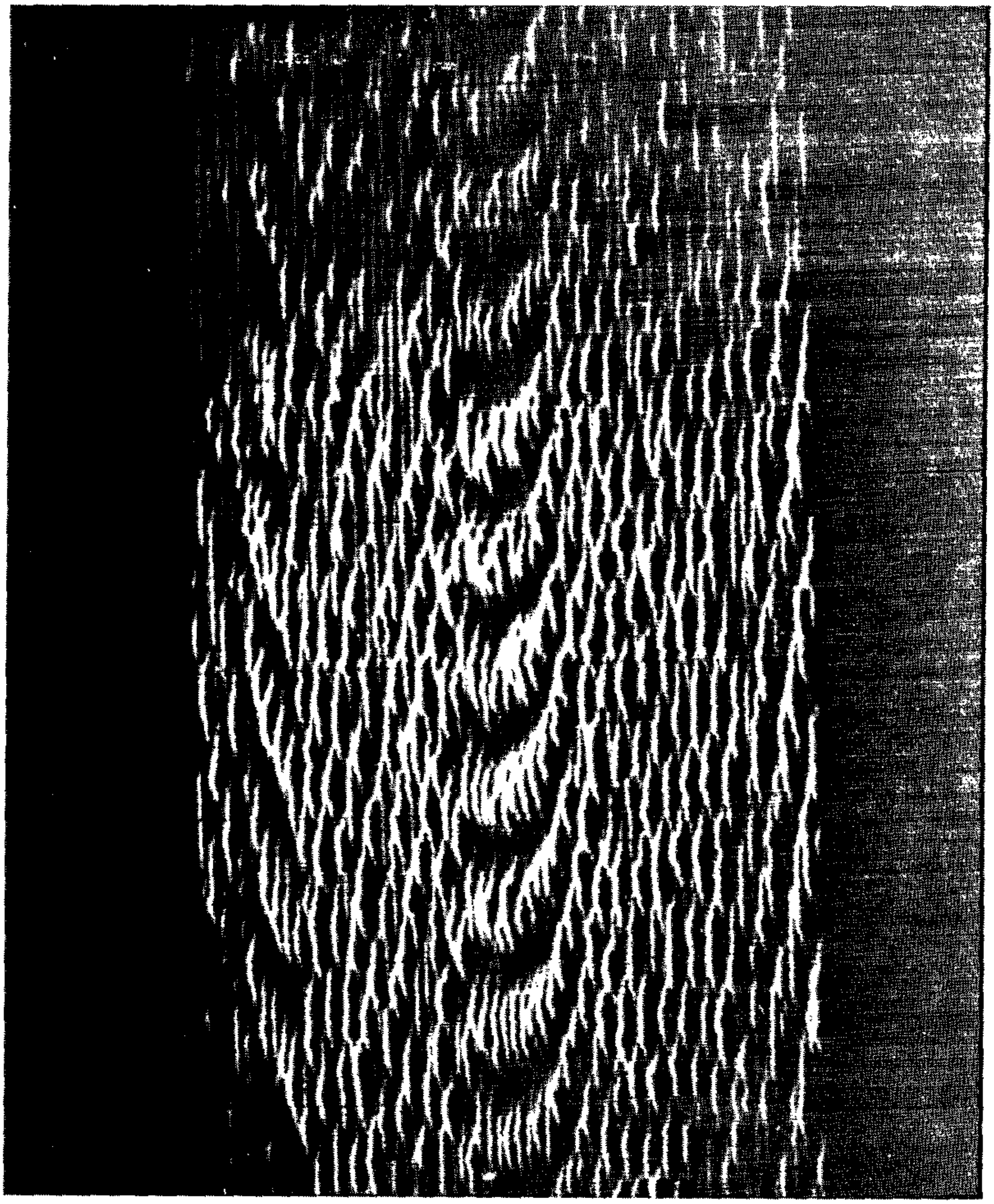

Figure 1. CPA Interference Pattern

Table 1. CONGRATS V Eigenray Data

Range (Kyd)	Frequency (Hz)	Time (Sec)	Source Angle (Deg)	Target Angle (Deg)	Loss (db)	Phase (Deg)
46.00	250.00	27.579512	12.704108	-12.829039	111.158517	15.6673
46.00	250.00	27.577041	11.873343	-12.007204	93.170468	2.3768
46.00	250.00	27.728279	.818916	- 1.978295	109.050736	-148.4483
46.00	250.00	27.606488	12.719545	12.844322	109.986238	-159.1082
46.00	250.00	27.602059	11.589337	11.726534	92.831084	-180.0000
46.00	250.00	27.733551	.818916	1.978295	105.116444	-278.1175
46.00	250.00	27.624273	-12.729931	-12.854603	109.103580	-159.7823
46.00	250.00	27.618164	-11.386219	-11.525900	92.665692	-180.0000
46.00	250.00	27.735632	- .818916	- 1.978295	102.323842	-307.2848
46.00	250.00	28.293893	16.903569	-16.996447	104.929779	-180.0000
46.00	250.00	27.743140	2.510893	- 3.089612	97.178627	-245.2994
46.00	250.00	27.743140	2.510893	- 3.089612	92.342027	-385.3410
46.00	250.00	27.651324	-12.770833	12.895096	136.050659	-349.6331
46.00	250.00	27.642172	-11.073878	11.717554	92.392936	-360.0000
46.00	250.00	27.740905	- .818916	1.978295	100.638495	-477.9066
46.00	250.00	28.329292	17.100242	17.191993	104.988511	-360.0000
46.00	250.00	27.751066	2.736899	3.275880	103.827311	-414.0223
46.00	250.00	28.352898	-17.228818	-17.319844	105.030611	-360.0000
46.00	250.00	28.388828	-17.415368	17.505364	105.094591	-540.0000
46.00	250.00	27.745878	- .538281	- 1.879576	134.131605	-793.0954
46.00	250.00	27.745926	.345626	- 1.833750	125.575147	-803.7864
46.00	250.00	27.750934	- .270971	1.821167	134.450928	-965.7295

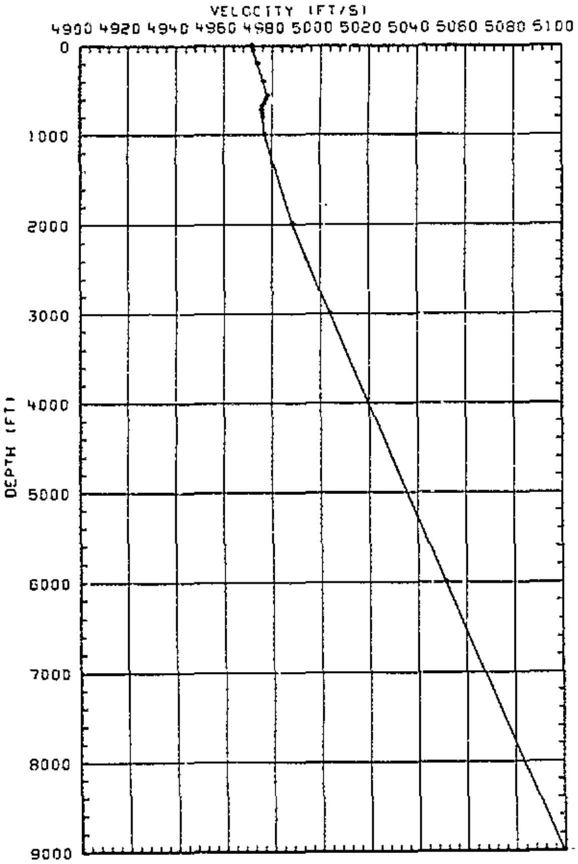

Figure 2. Sound Velocity Profile

The trainer ocean acoustic model problem was to retain the important acoustic features modeled by the CONGRATS V program while simulating only two acoustic paths for real-time training scenarios. Since many CONGRATS V generated eigenrays exist between the source and receiver, the determination of the optimal two-path data is critical.

DEVELOPMENT OF A TRAINER ACOUSTIC RAY MODEL

Initially, the trainer design proposed to match the coherent summation of all the CONGRATS V eigenrays generated between the source and receiver. Government specifications would be met if the coherent sum of the two data base paths at each of the 30 1/3 octave frequencies equalled the CONGRATS V sum as calculated from:

$$N = 020\log_{10} \left| \sum_j (10^{-0.05N_j})(e^{i(2\pi f t_j + \emptyset_j)}) \right|$$

where,

- N = summed propagation loss of all eigenrays between a source and receiver
- N_j = propagation loss for the jth eigenray (dB)
- f = frequency (Hz)
- t_j = travel time for the jth eigenray (seconds)
- $\emptyset_j$ = phase angle of the jth eigenray (radians)

This constraint was believed necessary in order to preserve the well-known Lloyd's mirror coherence effect that the CONGRATS V data could reproduce. The distance between grid storage points cirtically depended on this requirement and consequently the size and cost of producing a data base.

The proposed trainer design divided the CONGRATS V eigenrays into two groups: those arriving at the receiver from the upward direction and those arriving from the downward direction. One of the strongest rays from each group was selected for data base storage of its geometric features.[2] The propagation losses of the fastest traveling path were computed at each frequency based on the absolute and relative strengths of the two selected rays. To meet specification requirements, the computation of the path loss associated with the slower ray employed an inverse coherent summation algorithm at each frequency. The computation utilized the coherent summed propagation loss of all the CONGRATS V eigenrays, the fast path's loss, and the times and phases of the two selected paths. Thereby, the satisfaction of specification requirements were ensured. However, data generated from this approach failed to stimulate the SOT system satisfactorily. The division of rays according to direction was too restrictive for all environmental conditions. Large variations in the coherent levels associated with each ray at adjacent frequencies and ranges produced unrealistically discontinuous aural and visual effects. The normally stable amplitude of individual rays had to be retained (at the expense of not exactly matching the CONGRATS V coherent levels) in order to realistically stimulate the inverse beamformers with signals generated in real time. The tactical beamformers could then receive signals which exhibit realistic frequency and time characteristics.

Recognition of these shortcomings led to a reanalysis of the system needs and the data generated by CONTRATS V. Subsequently a new method was designed to generate an effective two path-training data base. The algorithm is compatible with most ray theory models.

THE TWO-PATH ALGORITHM

The two-path selection criteria endeavors to reflect the geometric features of the dominating CONGRATS V eigenrays. The dominating eigenrays do, of course, change as a target enters different transmission regions, such as surface ducts or shadow zones. Because the SOT data base is limited

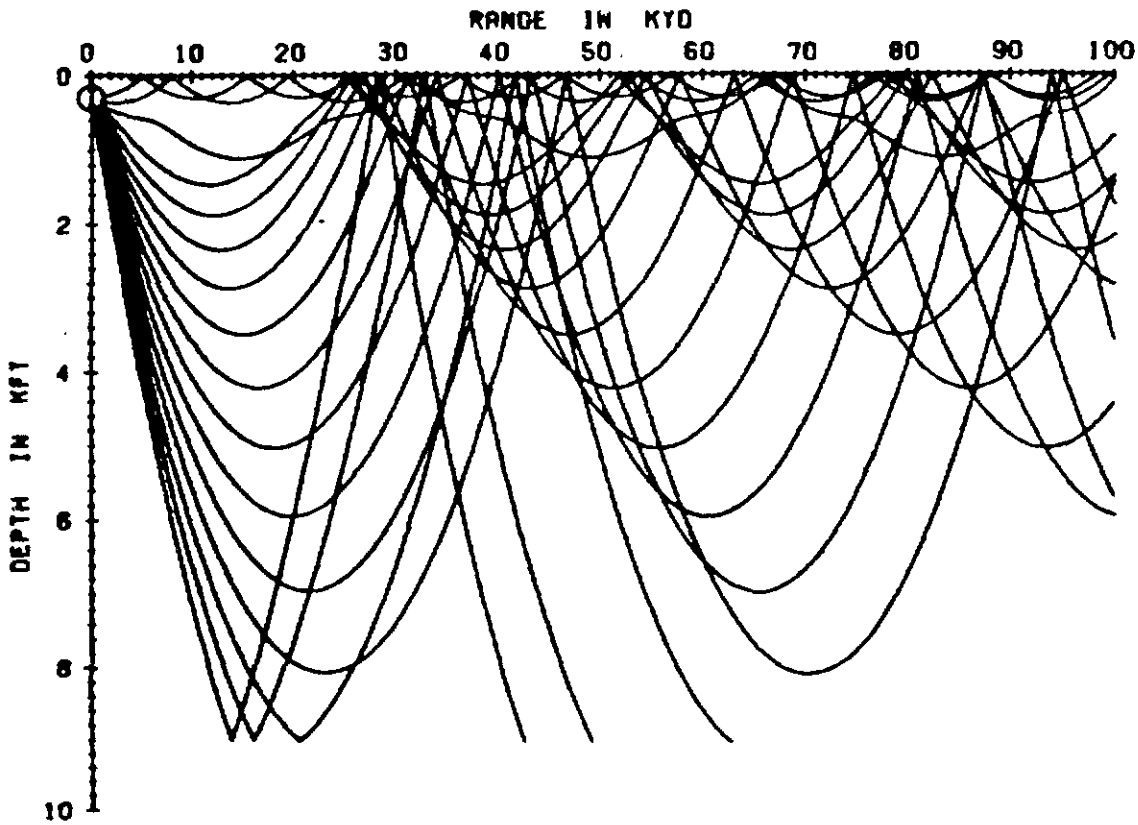

Figure 3. CONGRATS V Ray Diagram

to two-path information selected at distinct points in the ocean, occasional discontinuities in the data may cause abrupt transitions. A real-time lag smoothing process alleviated these abrupt shifts between depth and range storage points.

Before describing the mechanics of the data base algorithm, some knowledge of the CONGRATS V eigenray data is required. Certain mathematical conditions cause the CONGRATS V program to produce imaginary rays which are identical to each other in angles and time as illustrated in Table 1. Preferably, the geometries of the two selected rays should be different and indicative of two strong modes of signal transfer between a source and receiver. For example, there may be strong direct paths, several strong surface bounce paths and some weak bottom bounce paths. Since the algorithm is limited to selecting two rays, the best selection for training purposes would be a direct path and one of the surface bounce paths. For the SOT data base, CONGRATS V generated up to 65 eigenrays between a source and receiver. Typically, as the range or depths vary, the eigenrays geometry varies continuously and smoothly. Therefore, the geometries of the two stored rays can be directly taken from two CONGRATS V eigenrays. Constraints imposed on integration and interpolation technques, employed by the CONGRATS V program to reduce execution time, cause an eigenray's amplitude to fluctuate slightly. Artifical switching of selected eigenrays caused by such fluctuations is avoided by saving and comparing the previous range's selections to the present selections.

Each CONGRATS V generated eigenray's amplitude is power summed into one of two groups, yielding the two propagation losses associated with the stored paths at each frequency. Power summation results in smoother path loss curves than coherent summation, while yielding more accurate detection levels than obtainable from a single eigenray. The two-path selection algorithm completely defines the geometries of each path. Those rays closest in absolute angle to one of the selected paths get summed together with that path. The total noncoherent energy of the eigenrays are thereby retained at each frequency. The path losses associated with each ray are computed as follows:

$$N1 = -10 \log \sum_{i=1}^{n} (P_i)^2$$

$$N1 = -10 \log \sum_{j=1}^{m} (P_j)^2$$

where,

P_i = Amplitude (in micro Pascals) of i th eigenray whose angle is nearest to the selected ray, i_1, wherethere are n such eigenrays.

P_j = Amplitude (in micro Pascals) of j th eigenray whose angle is nearest to the selected ray, j_1, *where there are m* such eigenrays.

N1 = Computed Path 1 propagation loss at a frequency for data base storage.

N2 = Computed Path 2 propagation loss at a frequency for data base storage.

The selection procedure is accomplished at a predetermined frequency of 250 Hz. Following is a description of the two-path geometry selection logic. The paths whose geometries are chosen are herein identified as i_1 and j_1.

I. Data Base Production Initialization

A. Path 1 geometry:

Select the strongest ray (i.e., with greatest magnitude based on rms amplitude) to be i_1. Store its angles, time, and phase to the nearest 180 degrees (SOT hardware constraint).

B. Path 2 geometry:

Select the strongest ray which is at least 3 degrees separated from i_1 in absolute angle value and within 10 dB of its strength. If such a ray doesn't exist, select the second strongest path as j_1.

C. Propagation losses:

1. At each frequency power sum all paths i, whose angles are closest in absolute angle value to selected path i_1. Store those values of N1.

2. Likewise, power sum all paths j and store those values of N2.

II. Subsequent Data Points

A. Path 1 geometry choices in increasing priority order:

1. Select the present strongest ray to be i_1.

2. If the following conditions prevail, select the previously chosen i_1.

a. The previously selected path i_1 has a strength within 3 dB of the strongest path.

b. The previous path is substantially different from *the present strongest;* i.e., the previously selected path's angles differ by more than 1.25 degrees from the present strongest path.

B. Path 2 geometry choices in increasing order of priority:

1. Select the second strongest ray to be path j_1.

2. Select a ray which is within 10 dB of the strongest ray and is separated from it by at least 3 degrees in absolute angle value to be j_1.

3. If the previously chosen i_1 is to be stored, select the strongest ray which is within 10 dB of it and separated at least 3 degrees in absolute angle value to be j_1.

4. If the following conditions prevail, select the previously chosen path j_1.

a. The previously selected path j_1 has a strength within 3 dB of the highest priority present choice for path j_1.

b. The present highest priority choice for path j_1 and the previously chosen path j_1 differ substantially; i.e., their angles differ by at least 1.25 degrees.

C. Propagation losses:

1. At each frequency, power sum all paths i. Store those values of NI.

2. Likewise, power sum all paths j. Store those values of N2.

III. Single-Path Data

Data base logical records for ranges in excess of 70 kiloyards contain only one-path information since the sonar equipment is not as sensitive to multipath effects at distant ranges. The strongest path's angles, time and phase are stored. The stored propagation losses are the total CONGRATS V eigenray power sums at each of the 30 frequencies.

DATA BASE PERFORMANCE

Data bases for the various specified sound velocity profiles, sea states, and bottom types are currently being generated on the UNIVAC 1108 computer. One data base has been tested within the system. Favorable responses concerning its convergence zone and surface layer behavior have been received from the instructor-user community. Interference patterns are successfully produced on CRT spectrum analyzers and gram chart recorders. A picture of a target at CPA with an interference pattern is presented in Figure 1.

CONCLUSION

The effectiveness of using fixed ocean acoustic multipath data bases for advanced sonar training will emerge as the students train on the recently delivered trainers. The algorithm presented in this paper can easily be extended to select a greater number of paths for future, more sophisticated trainers. It is compatible with several propagation models and yields comparable ocean characteristics while functioning in real time.

REFERENCES

1. Weinberg, H., Generic Sonar Model, NUSC Technical Document 5971, January 1979

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