Using Adaptive Simulated Annealing to Estimate Ocean Bottom Acoustic Properties from Acoustic Data
SBIR Topic N99-217

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A. Executive Summary

The goal of the Phase I work for this SBIR award was the reduction in run times for both transmission loss and bottom scatter acoustic inversion codes. The reduction in run times was to be accomplished using a recently developed variant of the Simulated Annealing (SA) family of non-linear inversion algorithms. This variant on simulated annealing, called Adaptive Simulated Annealing[1] (ASA), can be significantly faster than conventional forms of simulated annealing because the ASA algorithm, as the name implies, is adaptive during run time. Gradients in the solution surface for each parameter are evaluated during runtime and the algorithm can recursively scale the cooling schedule during runtime for each parameter. In addition, the program can adopt an exponential type of cooling rate similar to Simulated Quenching (SQ) for the appropriate gradient in the solution surface for a given parameter.

The replacement of the Fast Annealing (FA) algorithm by the Adaptive Simulated Annealing (ASA) algorithm in PSI's transmission loss inversion code has resulted in run times between 12 and 16 times shorter. This reduction in run times has been accompanied by equivalent or improved fit between the predicted and measured transmission loss data compared to the results using the FA algorithm as measured by a chi-square metric[2]. These reductions allow for inversion of broadband transmission loss data in roughly 8 minutes[3] for the cases tested. The actual run time will depend on the number of frequencies and the complexity of the transmission loss environment. The transmission loss inversion code used for this work is based upon the Navy standard propagation loss model ASTRAL. ASTRAL is commonly used in Fleet applications where run time is balanced against accuracy. In addition, ASTRAL can be run for multiple frequencies with little increase in run time.

The reduction in run times noted here are for a variety of bottom slopes, up-slope, down-slope, and cross-slope, but are from a single experiment off the west coast of the United States. As has been noted in the open literature[4], non-linear inversion algorithms such as simulated annealing can require significant tuning to produce results that are acceptable in terms of both computational effort and robustness. While the transmission loss inversion results for this particular environment appear quite significant, it is imperative that a much broader study of the robustness of the ASA algorithm for this application be conducted in the Phase II program. The SBIR solicitation listed the following as plausible tasking for a Phase II award.

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[1] Ingber, L., "Very fast simulated re-annealing," *Mathematical Computer Modeling*, **12**, 967-973 (1989).

[2] Reduced chi-square is defined to be the sum of the square of the differences between the model and the data divided by the number of data points minus the number of parameters being inverted.

[3] The inversion code, written in Fortran, was executed on a Pentium II 450 MHz PC running Windows 95. All run time comparisons in this report will be based upon run times from this PC.

[4] Schmidt, H. and A. Baggeroer, "Physics-Imposed Resolution and Robustness Issues in Seismo-Acoustic Parameter Inversion," *Full Field Inversion Methods in Ocean and Seismo-Acoustics*, 85-90 (1995).

Phase II: Further development of selected algorithms will be performed, using real sea data for regions of known propagation conditions. Algorithms will be evaluated based on their ability to mitigate the problems associated with shallow water sonar.[5]

With the very promising results for the transmission loss inversion from the Phase I work, a logical extension of the work into a Phase II award is the evaluation of the robustness of the transmission loss inversion code with the ASA algorithm in a wide variety of environments, suitable to make a judgment on the algorithm's robustness for use throughout the world's oceans.

B. Phase I Findings

The goal of the Phase I work was to speed up existing transmission loss (TL) and bottom scatter (BS) inversion codes to make their use in tactical systems more viable. To accomplish this speed up, the implementation of the Adaptive Simulated Annealing (ASA) algorithm within both TL and BS inversion codes was proposed for the Phase I Base Program. The ASA algorithm, in comparison with most other forms of Simulated Annealing (SA), is adaptive during run time. Gradients in the solution surface for each parameter are evaluated during runtime and the algorithm can recursively scale the cooling schedule during runtime for each parameter. In addition, the program can adopt an exponential type of cooling rate similar to Simulated Quenching (SQ) for the appropriate gradient in the solution surface for a given parameter. Unlike the Fast Annealing (FA) method, the ASA method can be shown statistically to sample the best or global minimum for the system of interest during one cooling cycle (Ingber, 1989). The anticipated improvements in run times were between 5 and 20 times when comparing the ASA algorithm with the FA algorithm previously implemented in the acoustic inversion codes.

As a reference, the tasks that formed the Phase I Base Program were as follows.

- Base Program Subtask 1 - Implementation of the Adaptive Simulated Annealing (ASA) Algorithm with the TL and Bottom Reverberation Models
- Base Program Subtask 2 - Validation of the ASA Algorithm in the TL and Bottom Reverberation Models
- Base Program Subtask 3 - Documentation of the Implementation and Validation of the ASA Algorithm

A Phase I Option Program was also proposed in the Phase I proposal. The focus of the Phase I Option is the implementation of the TL and BS inversion codes on a dual-processor Windows NT/2000 machine. The implementation of the inversion codes on dual-processor COTS hardware is expected to yield additional reduction in run times. The tasks proposed for the Phase I Option are as follows.

- Option Program Subtask 1 - Implementation of the Multiple Processor Capability for the Inversion Algorithms

[5] Excerpt from the Navy SBIR solicitation 99-2, topic N99-217.

- Option Program Subtask 2 - Validation of the Multiple Processor Capability for the Inversion Algorithms
- Option Program Subtask 3 - Documentation of the Implementation and Validation of the Multiple Processor Capability

The proposed Phase II tasks will be discussed later in this summary report.

Base Program Subtask 1 - Implementation of the Adaptive Simulated Annealing (ASA) Algorithm with the TL and Bottom Reverberation Models

The start of the work on subtask 1 was delayed due to difficulties in scheduling a kick-off meeting with the technical points of contact at the Office of Naval Research and previously scheduled personal leave by both key investigators on this task. Work on this subtask began in late January and necessitated the first progress report being delayed from its initial delivery date of 31 December 1999 until 29 February 2000.

As previously stated, subtask 1 consisted of the integration of the ASA algorithm into both the TL and BS inversion codes. The first step in this process was the validation of the stand-alone ASA code against the benchmark test case. Following this validation, the process of integrating the ASA algorithm into the TL inversion code began. The TL inversion code is written entirely in Fortran 77 while the ASA algorithm is written in C. This mixed-language compilation was done using Compaq's Visual Fortran and Microsoft's C/C++. These packages share a common interface, the Microsoft Developer Studio, and makes mixed-language programming much simpler.

Version 20.2 of the ASA code was used in this subtask and was acquired from Lester Ingber's web site. The TL inversion used ASTRAL version 4.2 as the propagation model. Newer versions of the ASTRAL model are available and are proposed for integration into the TL inversion code as part of the Phase II tasking. The choice of ASTRAL as the propagation model was made because it is both a Navy standard propagation model, used in many performance prediction codes and tactical decision aids (TDAs), and offers much faster computational execution compared to Navy standard PE.[6]

Base Program Subtask 2 - Validation of the ASA Algorithm in the TL and Bottom Reverberation Models

Validation of the ASA algorithm was a two-stage process for both the TL and BS inversion codes. For the TL inversion code, the ASA algorithm implementation was first tested on synthetic data sets to tests the algorithm's ability to determine a set of LFBL parameters from transmission loss data generated by the ASTRAL propagation loss model. Second, the ASA algorithm implementation was tested on a limited set of measured transmission loss data to tests the algorithm's ability to determine a set of LFBL parameters from real sea data. These

[6] Navy standard PE 5.0 includes both the SSPE (Split-Step Parabolic Equation) and RAM (Range-dependent Acoustic Model).

comparisons are necessary to "tune" the inversion for the job of inverting acoustic transmission loss data. A similar process was followed for the bottom scatter (BS) inversion code. First the ASA algorithm implementation of the BS inversion code was tested on a synthetic data set to test the algorithm's ability to determine the seven bottom scatter parameters from broadband bottom scatter generated by the SCARAB bottom scatter model. Second, the ASA algorithm implementation was tested on a limited set of measured broadband bottom scatter data sets to test the algorithm's ability to determine the bottom scatter parameters for measured data. The results of both the TL and BS inversion codes validation against both synthetic and measured data are included in the following sections of this report.

Validation of ASA Algorithm in TL Inversion Against Synthetic Data

Validation against synthetic transmission loss data has some limited use in validating the proper operation of an inversion algorithm. Tests against synthetic TL data, TL data generated using a specific propagation loss model and then inverted using the same propagation loss model, can show that the inversion algorithm can converge in a case where there is no noise in the data. While this is certainly an unrealistic scenario, it is a necessary step in the testing of any inversion algorithm to validate its operation.

The results of three synthetic test cases will presented in this report to show the convergence of the ASA algorithm against synthetic data. The cases in order of their presentation in this report are a flat-bottom case, an up-slope case, and a down-slope case. For each case, TL data was generated using the ASTRAL model for 50 Hz to 3150 Hz in octave band steps. The TL inversion code with the ASA algorithm and the TL inversion code with the FA algorithm were each run on all of the synthetic test cases for comparison.

The flat-bottom case is shown in Figure 1 with the x-axis showing the reduced chi-square value characterizing the difference between the data and the inversion and the y-axis showing the number of generated cases for the ASA algorithm run. The number of generated cases is the number of times the ASTRAL model is called by the ASA algorithm during the algorithm's search of the solution surface.

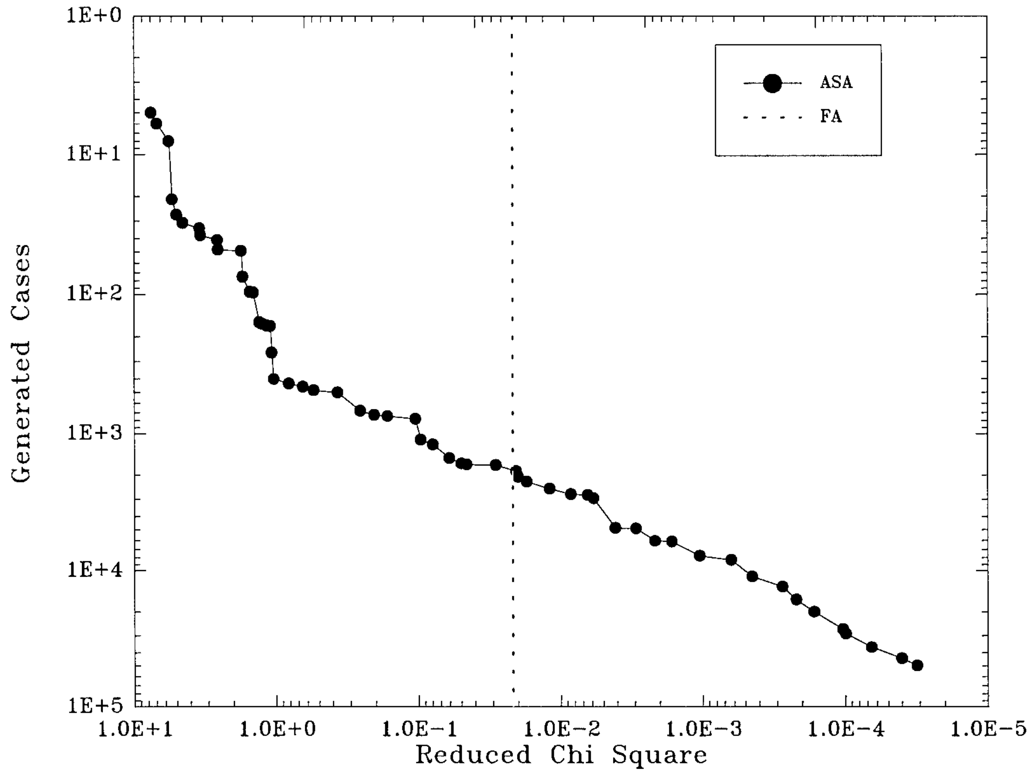

Figure 1: Comparison of ASA algorithm with FA algorithm for flat bottom synthetic transmission loss data set. Results from the ASA algorithm (denoted by the solid line with solid black circles) and the FA algorithm (denoted by the dashed line) are shown.

The flat-bottom synthetic test case shows the ASA algorithm continuing to converge towards the synthetic data with an increasing number of generated cases. This convergence will continue as the number of generated cases continues to increase until computational round-off errors become an issue to the inversion. The FA algorithm results come from an inversion of defined length and thus cannot be compared directly against the ASA algorithm results. However, the FA algorithm results for this case show what is commonly known about non-linear inversion algorithms. If allowed to run enough generated cases, most variants of simulated annealing will converge to a synthetic test case. The difference among the variants of simulated annealing is the rate at which they converge. This convergence rate between the ASA algorithm and the FA algorithm will be discussed in the next section showing inversion of measured transmission loss data.

The second synthetic test case was an up-slope bottom with the results shown in Figure 2. In this case, the ASA algorithm again shows convergence with an increasing number of generated cases. However, the FA algorithm results produce a reduced chi-square value comparable to the ASA algorithm results at the largest number of generated runs. As these methods search the solution surface is a quasi-random manner, the results from this particular case showing the FA algorithm producing results comparable to the ASA algorithm only indicates that the FA algorithm happened to sample near a minimum in the solution surface. Another run of the FA algorithm may produce a significantly different fit as measured by the reduced chi-square value.

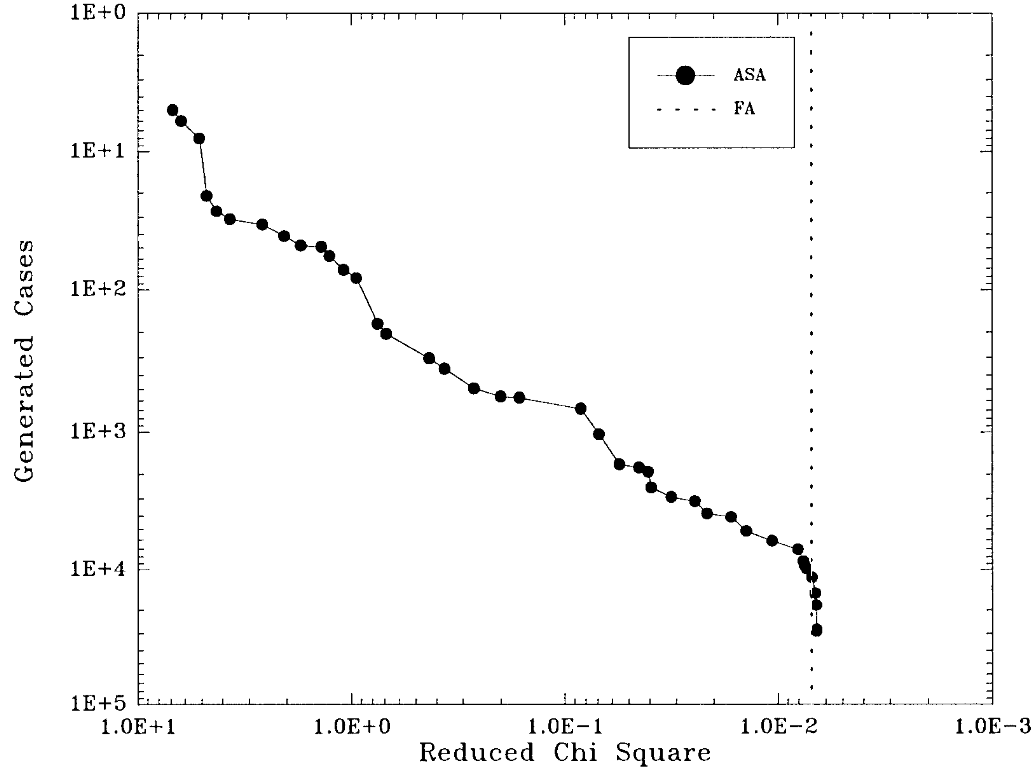

Figure 2: Comparison of ASA algorithm with FA algorithm for up-slope bottom synthetic transmission loss data set. Results from the ASA algorithm (denoted by the solid line with solid black circles) and the FA algorithm (denoted by the dashed line) are shown.

The third synthetic test case was for a down-slope environment and is shown in Figure 3. As in the flat-bottom test case, the ASA algorithm when allowed to run to a large number of generated cases produces a result with a small, reduced chi-square value. In this case the FA algorithm produces a result that is worse than the result from the ASA algorithm.

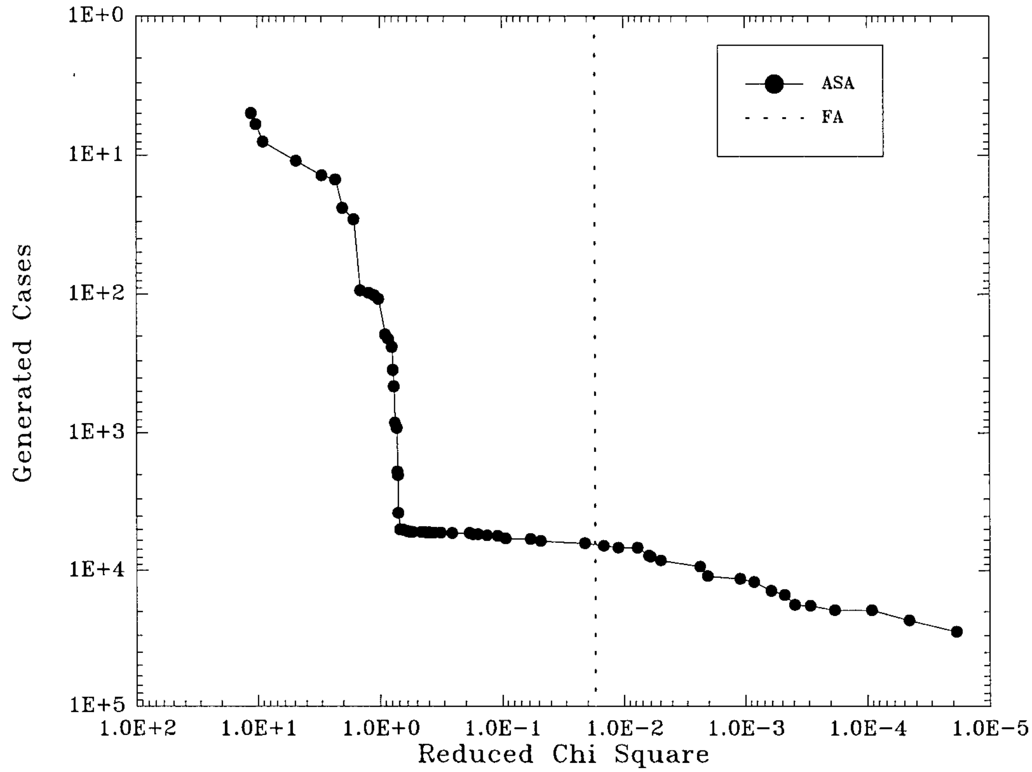

Figure 3: Comparison of ASA algorithm with FA algorithm for down-slope bottom synthetic transmission loss data set. Results from the ASA algorithm (denoted by the solid line with solid black circles) and the FA algorithm (denoted by the dashed line) are shown.

The results of these tests on synthetic transmission loss data show that the ASA algorithm is able to converge towards the synthetic data up to the maximum number of generated cases run. As previously noted, the ASA algorithm is designed to guarantee convergence towards the global minimum if allowed to run enough generated cases of the model. These tests simply show that the implementation of the ASA algorithm in the ASTRAL based TL inversion code is operating correctly. The next step in the evaluation of the ASA algorithm is testing the algorithm on measured transmission loss. Measured data often presents a considerably more challenging problem for an inversion algorithm because scatter in the data that can produce a much more complex solution surface than that found when inverting synthetic data.

Inversion of Measured Transmission Loss Data with TL Inversion using ASA Algorithm

The ASA algorithm implementation in the TL inversion code was tested on transmission loss data taken by PSI in 1995 using Mk-61 SUS and SSQ-57 attenuated sonobuoys.[7] The transmission loss measurements conducted as part of this experiment ran up-slope, down-slope,

[7] Neumann, P., C. Holland, and G. Muncill, "Environmental Characterization Using EER: Vizcaino Slope and Quinault Canyon Experiment Summary Report", PSI Report, February 1998.

and cross-slope but do not contain much variability in the water column properties. These data were chosen because the TL inversion code with the FA algorithm had been applied to the data and the results, including inverted LFBL parameters and chi-square metrics, were documented in the report referenced above.

The TL inversion uses the 10-parameter version of the LFBL database to describe the geoacoustic properties of the ocean bottom. The geoacoustic parameters that were inverted using the ASA algorithm are the following.

1. Sound speed ratio at the sediment-water interface
2. Bulk sediment density
3. Sound speed gradient in the sediment
4. Attenuation within the sediment
5. Attenuation gradient within the sediment[8]
6. Basement reflectivity
7. Frequency exponent for the attenuation

The resulting fits are compared with the Navy Standard databases: LFBL from 50-1000 Hz and MGS above 1000 Hz. Rather than try to fit a new MGS curve, the TL inversion code uses the LFBL model up to 5000 Hz. For each run, environmental data such as bathymetry and sound speed profiles in the water column were inferred from available databases and measurements during the experiment that consisted of AXBT sampling of the sound speed profiles.

Inversion of Transmission Loss Data from the Vizcaino Slope Site

The Vizcaino Slope site, as shown in Figure 4, is located just south of the Mendocino fracture zone off the coast of California. A more detailed map of the Vizcaino Slope experiment site is shown in Figure 5. The numbers on the map indicate the transmission loss track line number. The tracks vary between upslope and down-slope from receivers at the center of the leg (Vizcaino tracks 1 and 2) and upslope and down-slope from the receivers at the ends of the leg (Vizcaino tracks 3 and 4). Track 5 represents measurements along the continental slope at nearly constant bathymetry.

[8] Beta, a parameter for curvature of the sound speed profile, is a secondary parameter that is adjusted in discontinuous steps as a function of the sound speed gradient.

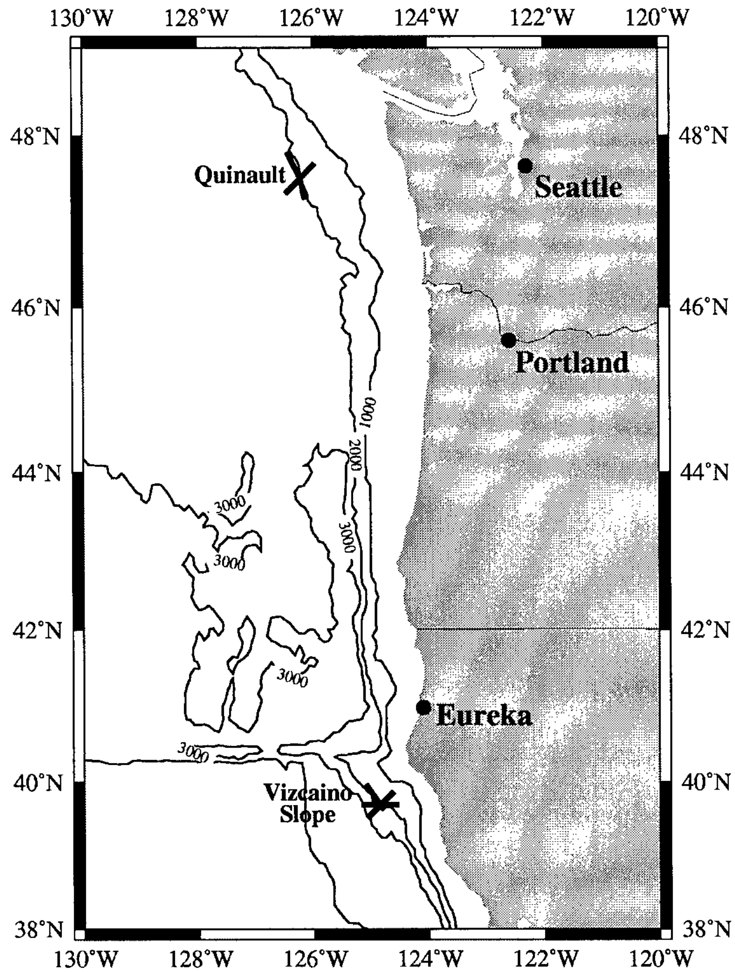

Figure 4: Map of sites (Vizcaino Slope and Quinault Canyon) from EER experiments conducted by PSI in July 1995.

Comparisons between the two inversion approaches, ASA and FA algorithms, and the measured data are shown first for the Vizcaino Slope tracks in the following order: track 1 (up-slope), track 2 (down-slope), track 3 (up-slope to sonobuoys at end of leg), track 4 (down-slope to sonobuoys at end of leg), and track 5 (cross-slope). Results from the Quinault Canyon site located off the coast of Washington State are presented later in this section.

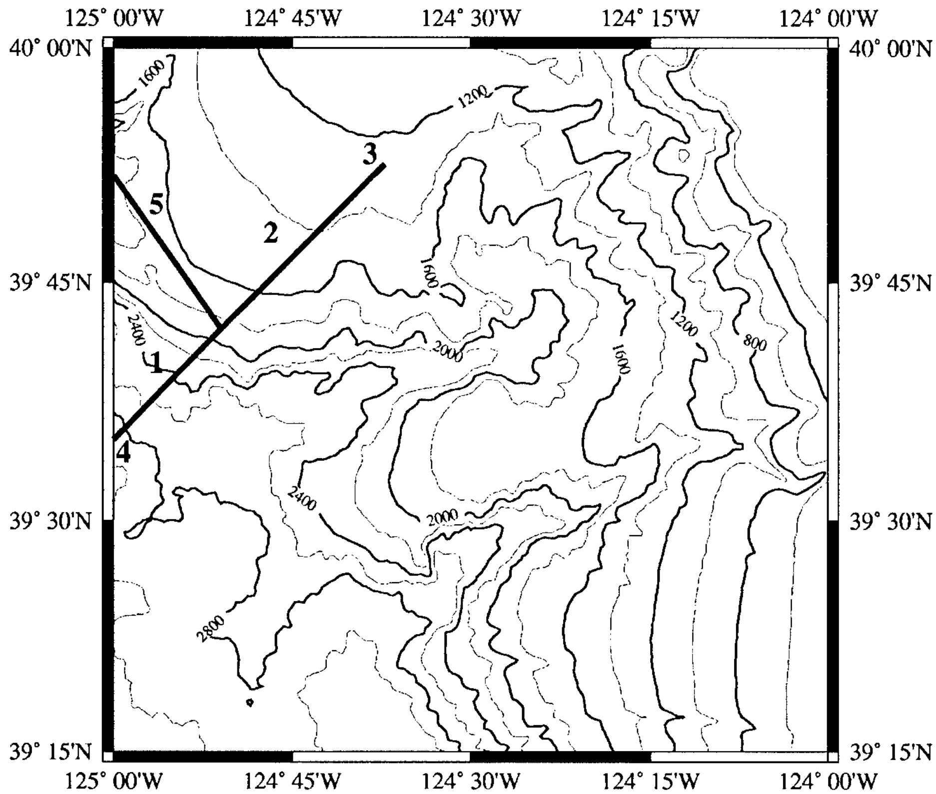

Figure 5: Detailed map of the Vizcaino Slope experiment site showing the transmission loss track lines overlaid on bathymetric contours (depth shown in meters).

The comparison between the measured transmission loss data and the inverted transmission loss predictions for Vizcaino Slope track 1 is shown in Figure 6. For comparison, the predictions made using the Navy standard bottom loss databases (LFBL and MGS) are also shown (denoted by the solid black line). The predictions using LFBL are relatively close to the data at lower frequencies (50 and 100 Hz) and are consistently under predict the transmission loss in the middle frequencies (200, 400, and 800 Hz). The predictions using the MGS database consistently over predict the transmission loss compared to the measured data at the higher frequencies (1600 and 3150 Hz). The inversion fits using the ASA algorithm (denoted by a dashed blue line for 1784 generated cases and by a dashed red line for 85040 generated cases) and using the FA algorithm (denoted by a dashed black line) are also shown in Figure 6. The importance of this plot is that the inversion fit for the shorter ASA run[9], representing between 2 and 7% of the computational time compared to the other two inversion fits, is nearly indistinguishable from the

[9] The shorter ASA run consisting of 1784 generated cases represent roughly 8 minutes of computational time on a Pentium II 450 MHz PC running Windows 95. All comparisons between inversion run times are based upon run times on this particular PC.

other inversion fits. The most significant difference between these three inversion runs is the computational effort needed for each.

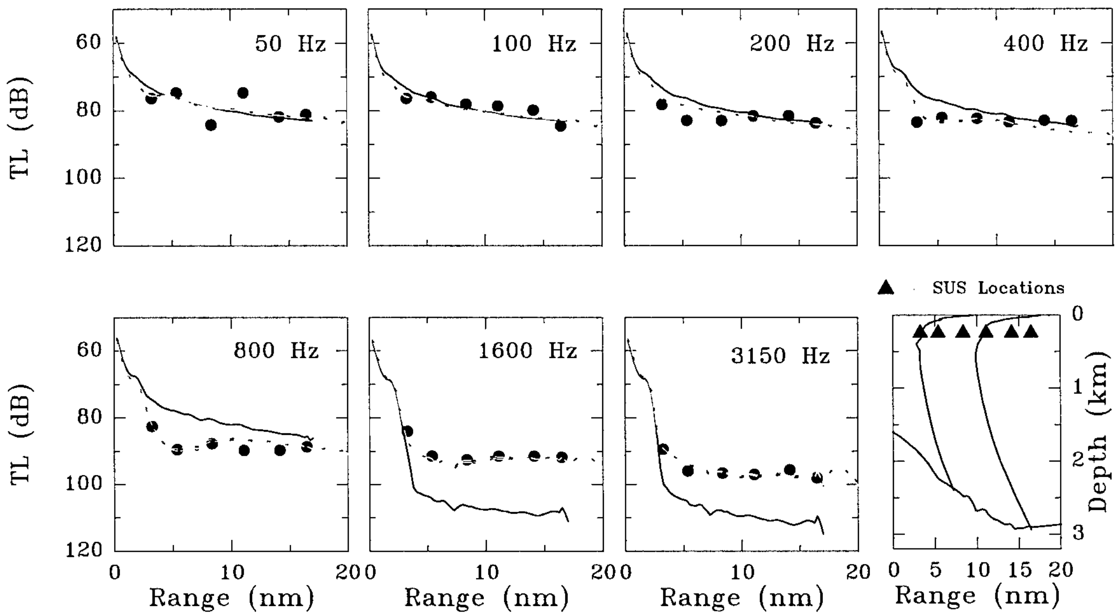

Figure 6: Vizcaino upslope (track 1) transmission loss data (solid black circles) plotted with prediction using Navy standard database (solid black line), inversion fit using ASA algorithm after 85040 cases generated (dashed red line), inversion fit using ASA algorithm after 1784 cases generated (dashed blue line), and inversion fit using FA algorithm (dashed black line).

The performance of the ASA algorithm as a function of the number of generated cases, for the transmission loss data shown in Figure 6, is shown in Figure 7. The convergence of the ASA algorithm, denoted by the solid black line with black circles in Figure 7, improves considerably, as measured by the chi-square metric, as the number of generated cases increases to nearly 2000. After 2000 cases, the chi-square metric continues to decrease with an increasing number of generated cases but at a much lower rate than for the first 2000 generated cases. For tactical purposes, the continued reduction in the chi-square metric past the first 2000 generated cases produce an almost indiscernible improvement in the transmission loss prediction with a considerable increase in the computation required. In addition, the inversion fit achieved using the ASA algorithm after the first 2000 generated cases produces a chi-square value nearly identical to that generated from the FA algorithm in roughly 7% of the time.

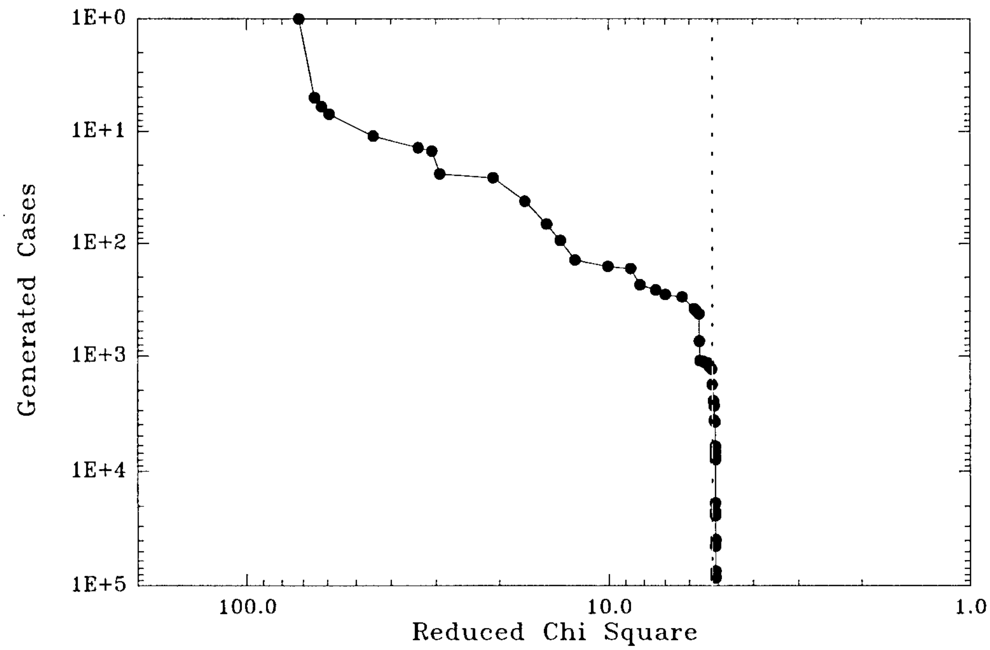

Figure 7: Convergence of ASA algorithm (solid line with black circles) for Vizcaino Slope track 1 (Figure 6) as a function of the number of generated cases. The dashed line for comparison shows the best fit from the FA algorithm.

The comparisons between the measured transmission loss data and the inverted transmission loss predictions for Vizcaino Slope tracks 2, 3, 4, and 5 are presented using the same graph format as shown in Figure 6 and Figure 7. The results for Vizcaino Slope track 2 are shown in Figure 8 in the same format as shown in Figure 6 for Vizcaino Slope track 1. The convergence of the ASA algorithm for Vizcaino Slope track 2 transmission loss data is shown in Figure 9. Similar to the results shown in Figure 7, the ASA algorithm rapidly converges to a prediction of the transmission loss data comparable to that from the FA algorithm after roughly 1000 generated cases. Allowing the ASA algorithm to run for 8 minutes (2000 generated cases) produces a prediction better than that predicted using the FA algorithm in a considerably shorter time.

The results for Vizcaino Slope track 3 are shown in Figure 10 and Figure 11. Unlike the results for Vizcaino Slope tracks 1 and 2, the predicted transmission loss using the ASA and FA algorithms show noticeable difference at many of the frequencies. The results from the ASA and FA algorithms are nearly identical in terms of the chi-square value for each. While the details in the transmission loss predictions from the ASA and FA algorithms are noticeably different, especially at the higher frequencies, in terms of a measure of goodness-of-fit they are nearly identical. The convergence of the ASA algorithm for Vizcaino Slope track 3 is shown in Figure 11. The ASA algorithm converges rapidly, in terms of the chi-square value, for the first 1000 generated cases. Allowing the ASA algorithm out to 100,000 generated cases produces an insignificant improvement in the chi-square value.

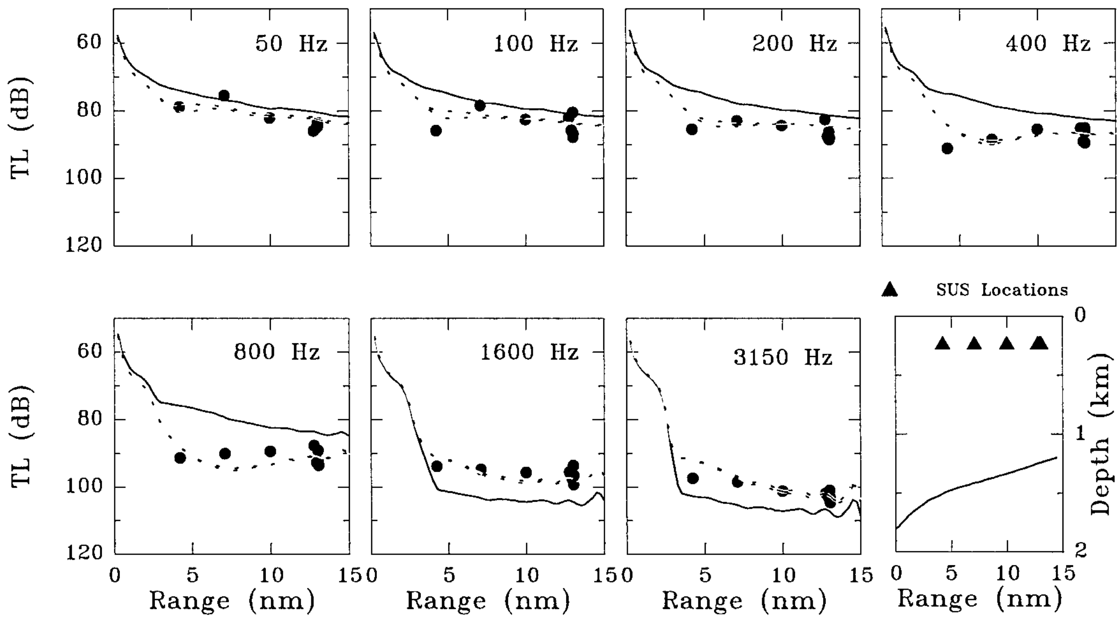

Figure 8: **Vizcaino down-slope (track 2) transmission loss data (solid black circles) plotted with prediction using Navy standard database (solid black line), inversion fit using ASA algorithm after roughly 2000 cases generated (dashed blue line), and inversion fit using FA algorithm (dashed black line).**

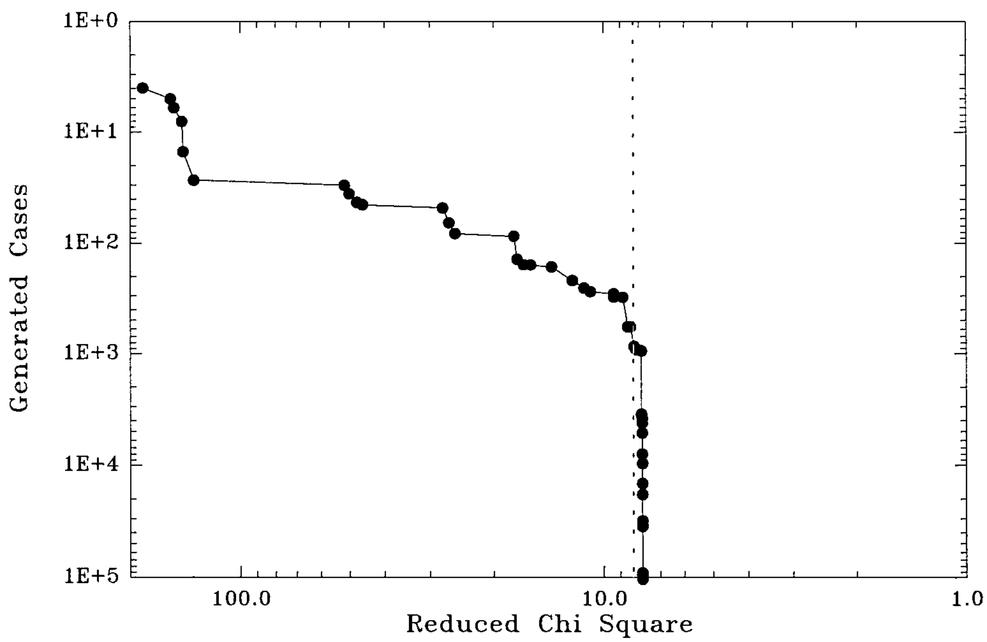

Figure 9: **Convergence of ASA algorithm (solid line with black circles) for Vizcaino Slope track 2 (Figure 8) as a function of the number of generated cases. The dashed line for comparison shows the best fit from the FA algorithm.**

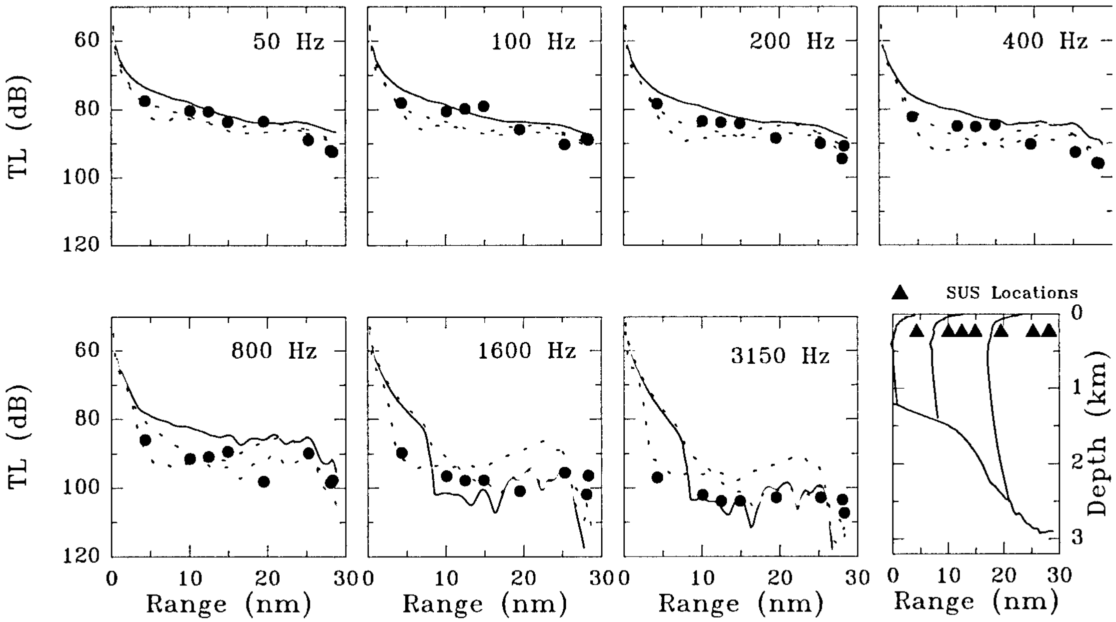

Figure 10: Vizcaino upslope (track 3) transmission loss data (solid black circles) plotted with prediction using Navy standard database (solid black line), inversion fit using ASA algorithm after roughly 2000 cases generated (dashed blue line), and inversion fit using FA algorithm (dashed black line).

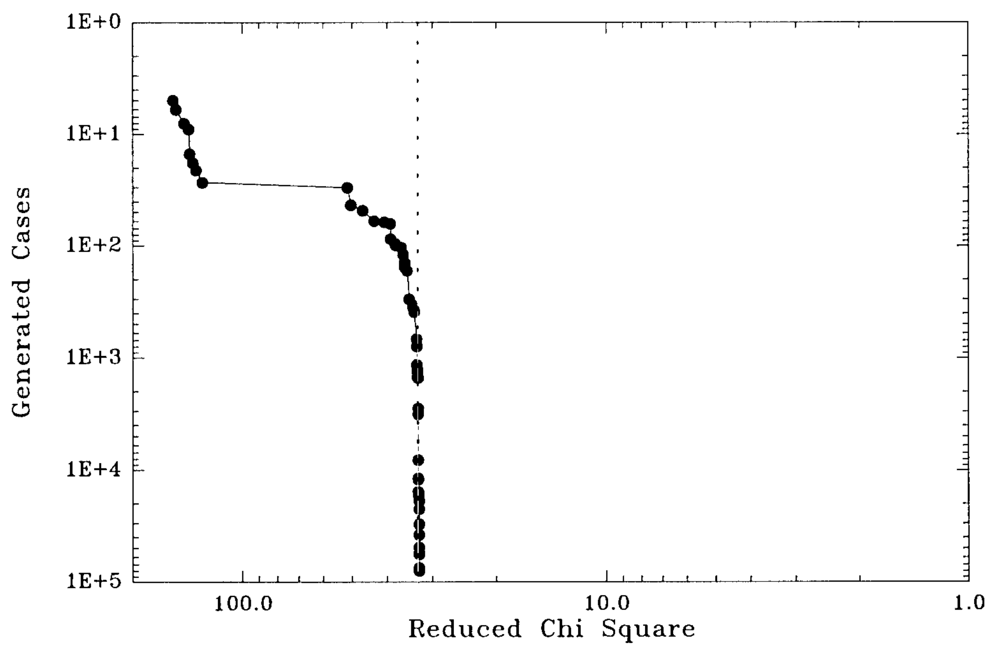

Figure 11: Convergence of ASA algorithm (solid line with black circles) for Vizcaino Slope track 3 (Figure 10) as a function of the number of generated cases. The dashed line for comparison shows the best fit from the FA algorithm.

Inversion of the transmission loss data from Vizcaino Slope track 4 and track 5 produce similar results to those previously discussed in this section. The results for Vizcaino Slope track 4 are shown in Figure 12 and Figure 13. Track 4 is a down-slope transmission loss data set similar to track 2 but covering ranges up to 30 nautical miles. The results for Vizcaino Slope track 5 are shown in Figure 14 and Figure 15. Track 5 is a cross-slope transmission loss data set. Similar to the inversion results from Vizcaino Slope track 3, the transmission loss predictions by the ASA and FA algorithms differ at higher frequencies. However, in terms of the chi-square value that measures the goodness-of-fit, the results from the ASA and FA algorithms are nearly identical. The most significant difference between the two algorithms is the computational time required to produce a prediction with a similar chi-square value.

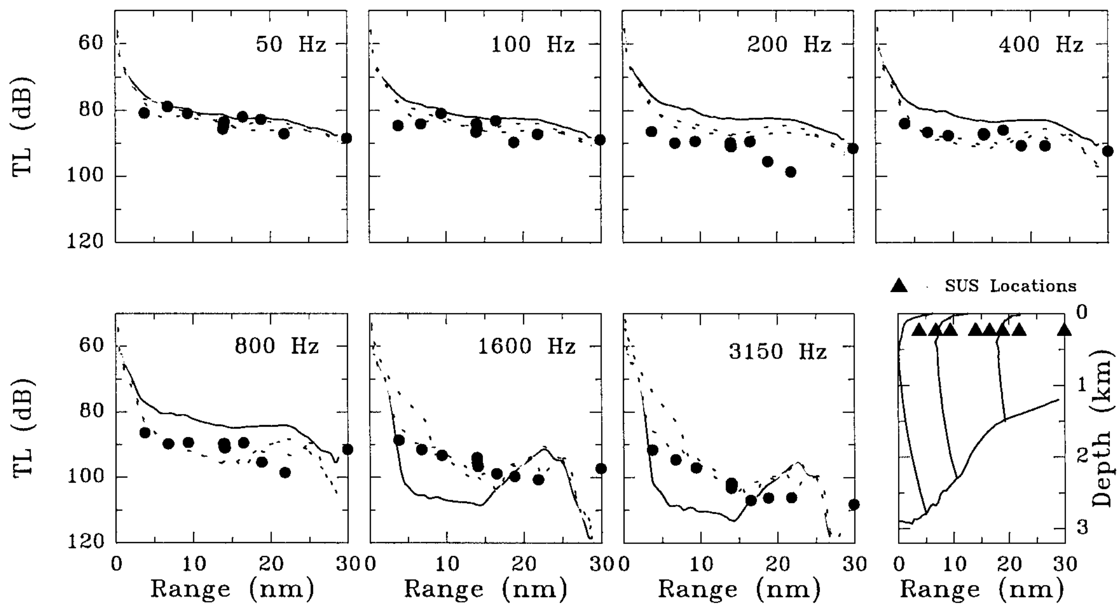

Figure 12: Vizcaino down-slope (track 4) transmission loss data (solid black circles) plotted with prediction using Navy standard database (solid black line), inversion fit using ASA algorithm after roughly 2000 cases generated (dashed blue line), and inversion fit using FA algorithm (dashed black line).

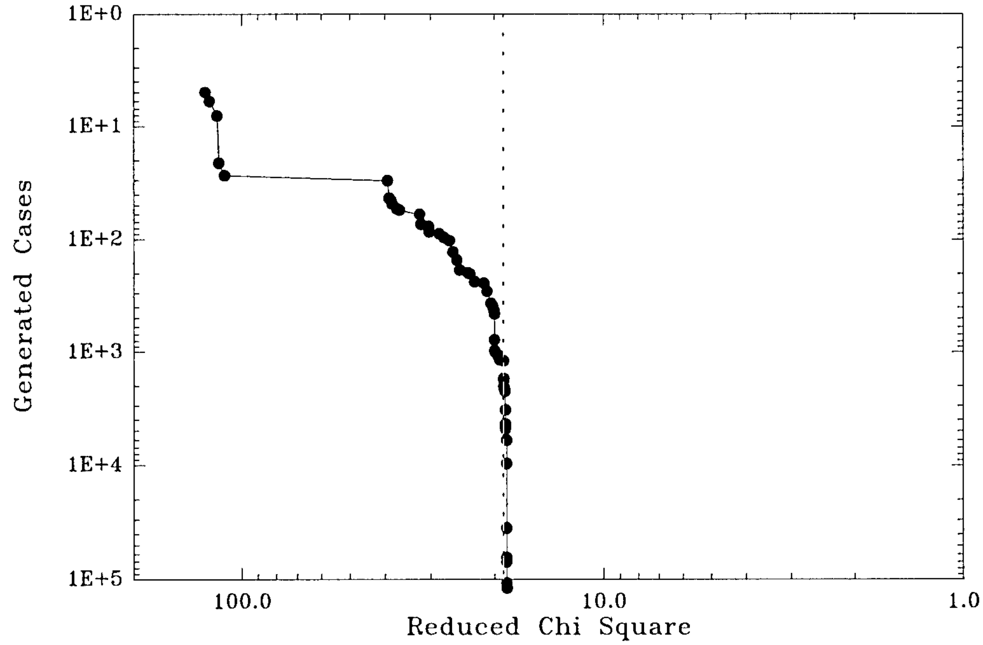

Figure 13: Convergence of ASA algorithm (solid line with black circles) for Vizcaino Slope track 4 (Figure 12) as a function of the number of generated cases. The dashed line for comparison shows the best fit from the FA algorithm.

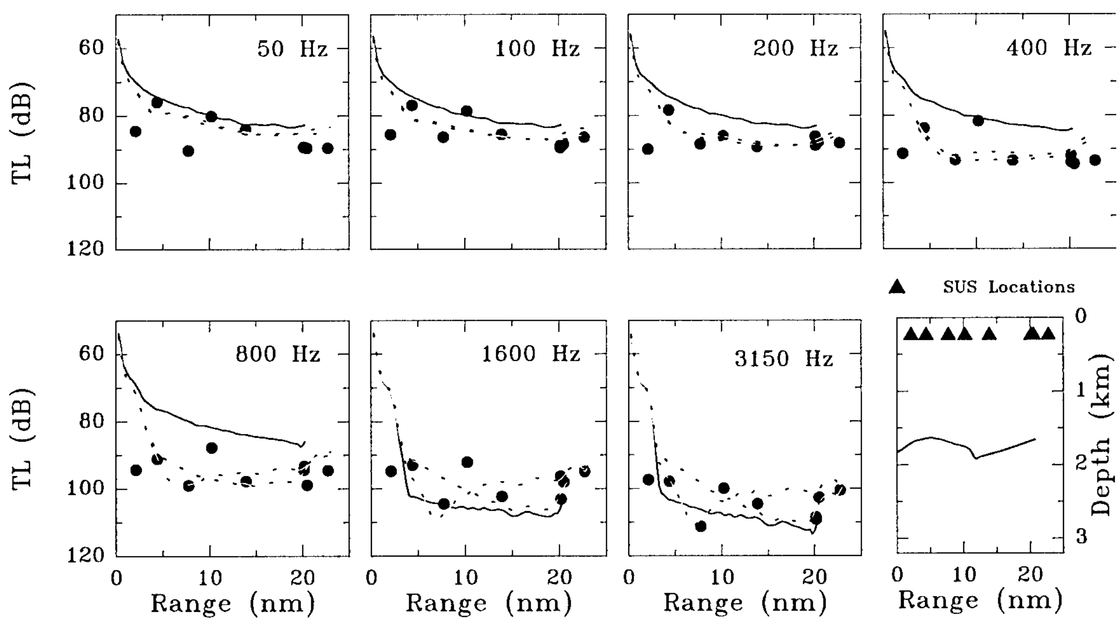

Figure 14: Vizcaino cross-slope (track 5) transmission loss data (solid black circles) plotted with prediction using Navy standard database (solid black line), inversion fit using ASA algorithm after roughly 2000 cases generated (dashed blue line), and inversion fit using FA algorithm (dashed black line).

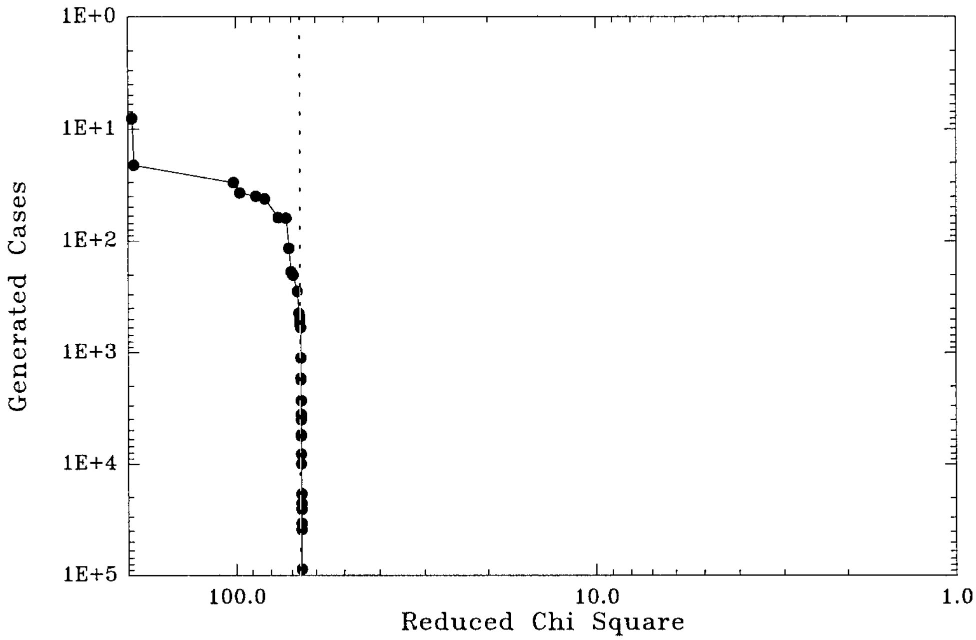

Figure 15: Convergence of ASA algorithm (solid line with black circles) for Vizcaino Slope track 5 (Figure 14) as a function of the number of generated cases. The dashed line for comparison shows the best fit from the FA algorithm.

Inversion of Transmission Loss Data from the Quinault Canyon Site

The Quinault Canyon site, as shown in Figure 4, is located off the Washington State coast. A more detailed map of the Quinault Canyon experiment site is shown in Figure 16. The numbers of the map indicate the transmission loss track line number. Both tracks at the Quinault Canyon site are cross-slope with an approximately flat bottom. For this reason and to increase the amount of transmission loss data available for the inversion algorithm, the data from both transmission loss tracks (tracks 1 and 2) at the Quinault Canyon site were combined and inverted to produce a single estimate of the LFBL properties of the ocean bottom at the site.

Results for the transmission loss data taken at the Quinault Canyon site will be included in this section of the report showing the inversion to data comparisons as shown in Figure 6 and the convergence of the ASA algorithm compared to the best fit of the FA algorithm as shown in Figure 7.

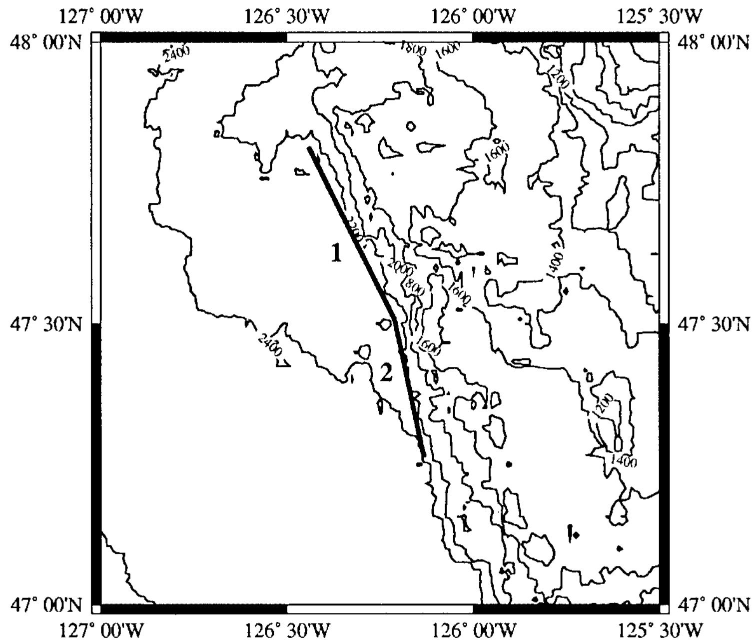

Figure 16: Detailed map of the Quinault Canyon experiment site showing the transmission loss track lines overlaid on bathymetric contours (depth shown in meters).

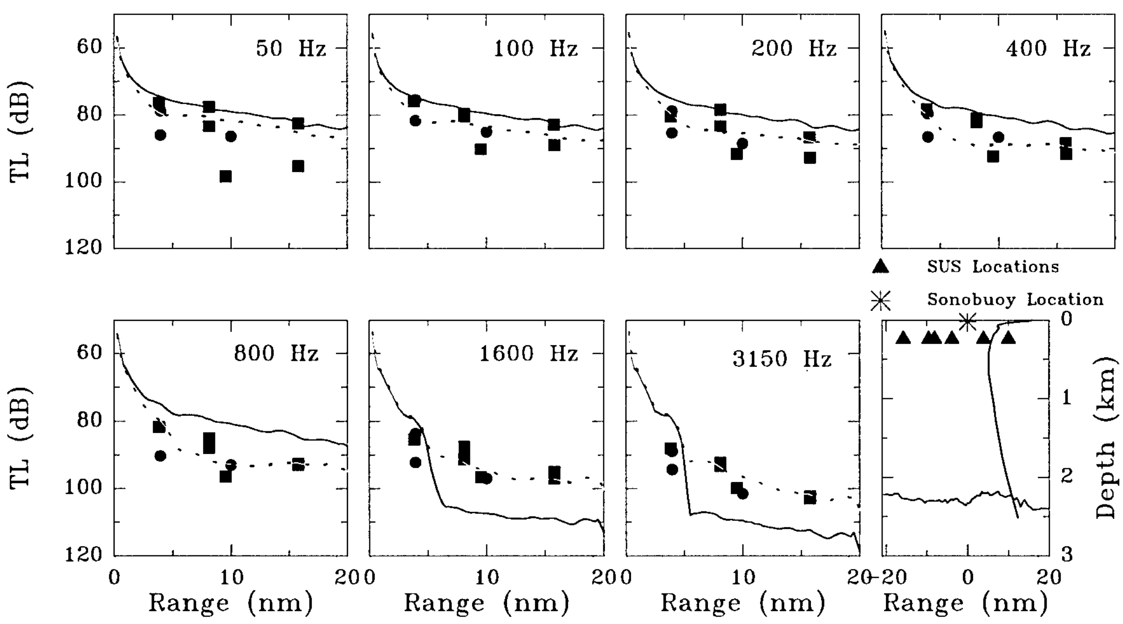

Figure 17: Quinault Canyon transmission loss data (solid black circles and squares) plotted with prediction using Navy standard database (solid black line), inversion fit using ASA algorithm after roughly 2000 cases generated (dashed blue line), and inversion fit using FA algorithm (dashed black line).

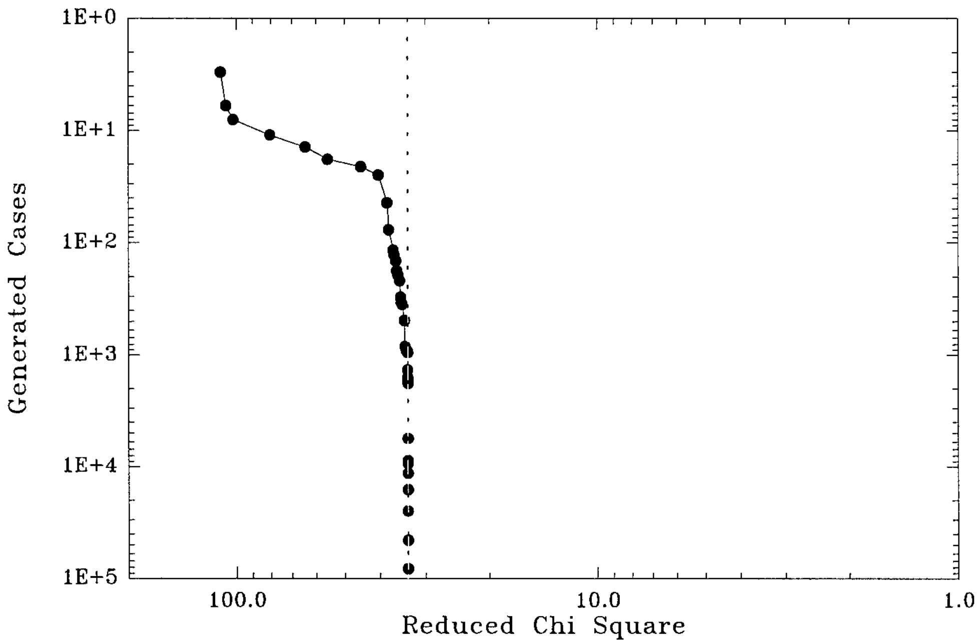

Figure 18: Convergence of ASA algorithm (solid line with black circles) for Quinault Canyon (Figure 14) as a function of the number of generated cases. The dashed line for comparison shows the best fit from the FA algorithm.

Summary of Inversion Results using ASA Algorithm on Transmission Loss Data

The most important difference between the inversion results using the ASA algorithm and the FA algorithm is primarily the computational time. As noted in the previous sections of this report, the ASA algorithm is capable of converging more rapidly and reliably than the FA algorithm. Results for each of the transmission loss data sets used in the testing of the ASA algorithm are summarized in Table 1.

The run times listed for the ASA algorithm are for a single cooling cycle and produce the results shown in the previous sections of this report. The advantage of the ASA algorithm, when compared to the FA algorithm, is the ASA algorithm's ability to reliably converge towards the global minimum in a single cooling cycle. The run times listed for the FA algorithm are for four runs of the prior version of the inversion software. Each of these runs is composed of five cooling loops and thus the run times listed are for 20 cooling loops each with different starting seed values. This may appear to be an unfair comparison of the two inversion algorithms. However, it was necessary to run the FA algorithm through at least four run of the inversion software to reliably produce a fit comparable to that generated by a single cooling cycle of the ASA algorithm. It is essentially a comparison of the computational effort needed to produce a comparable fit to the data using each of the inversion algorithms.

Table 1: Comparison of run times[10] for ASA and FA algorithm for TL data sets.

TL Data Set	ASA Algorithm Run Time	FA Algorithm Run Time
Vizcaino Slope Track 1	9 minutes	105 minutes
Vizcaino Slope Track 2	8 minutes	106 minutes
Vizcaino Slope Track 3	10 minutes	160 minutes
Vizcaino Slope Track 4	11 minutes	162 minutes
Vizcaino Slope Track 5	6 minutes	92 minutes
Quinault Canyon	9 minutes	120 minutes

The resulting LFBL parameters from both inversion algorithms are shown in Table 2 and Table 3 for the ASA and FA algorithm respectively. Even a cursory examination of the LFBL parameters in these two tables reveals some significant differences in the values of some parameters. The relevant comparison that should be made between the two inversion approaches, beyond the computational speed, is that LFBL parameters sets that produce comparable chi-square values are equally valid descriptions of the geoacoustic properties of the bottom. Given the errors in the measured data, the bathymetry, the sound speed profiles, and the propagation loss model used, there can be a non-trivial number of LFBL parameter sets that produce equally valid descriptions of the geoacoustic properties of the bottom. The salient question is how can one most efficiently search and find an LFBL parameter set that produces a fit of sufficient quality to meet the requirement at hand.

Table 2: Inverted LFBL parameters using ASA algorithm.

Parameter	Quinault Tracks 1&2	Vizcaino Track 1	Vizcaino Track 2	Vizcaino Track 3	Vizcaino Track 4	Vizcaino Track 5
Ratio	1.001	1.002	0.999	0.996	0.994	0.978
Bulk Density (gm/cm^3)	1.61	1.39	1.33	1.87	1.94	1.34
Sound Speed Gradient (sec^{-1})	4.30	1.87	4.76	1.61	0.753	4.62
Attenuation (dB/m/kHz)	0.1142	0.0001	0.1130	0.0156	0.0280	0.0677
Attenuation Gradient ($dB/m^2/kHz$)	0.00095	0.00150	0.00730	0.01170	0.00005	0.00177
Beta	-0.97	0.86	-0.97	0.86	0.01	-0.97

[10] Run times are expressed in minutes with all runs on a Pentium II 450 MHz PC running Windows 95 Revision B.

Parameter	Quinault Tracks 1&2	Vizcaino Track 1	Vizcaino Track 2	Vizcaino Track 3	Vizcaino Track 4	Vizcaino Track 5
Basement Reflectivity	0.26	0.06	0.57	0.52	0.29	0.06
Frequency Exponent	1.00	1.47	1.00	1.02	1.01	1.01

Table 3: Inverted LFBL parameters using FA algorithm.

Parameter	Quinault Tracks 1&2	Vizcaino Track 1	Vizcaino Track 2	Vizcaino Track 3	Vizcaino Track 4	Vizcaino Track 5
Ratio	1.001	1.004	1.000	0.994	0.997	0.978
Bulk Density (gm/cm^3)	1.61	1.35	1.33	2.38	1.72	1.34
Sound Speed Gradient (sec^{-1})	3.70	1.75	2.35	0.70	0.50	1.40
Attenuation (dB/m/kHz)	0.0915	0.0110	0.0730	0.0380	0.0185	0.0375
Attenuation Gradient ($dB/m^2/kHz$)	0.00065	0.00060	0.00010	0.00010	0.00010	0.00095
Beta	-0.970	0.860	-0.970	0.010	0.010	-0.500
Basement Reflectivity	0.035	0.15	0.10	0.15	0.35	0.15
Frequency Exponent	1.01	1.29	1.00	1.01	1.07	1.10

Validation of ASA Algorithm in BS Inversion Against Synthetic Data

The implementation of the ASA algorithm with the SCARAB bottom scatter model was tested against a single synthetic test case. The test case was a simple environment with an isovelocity sound speed profile and using a LFBL description of the bottom similar to that found in the Mediterranean Sea. The seven bottom scatter parameters were set to values at the middle of their allowable range. Both the ASA version of the BS inversion code and the FA version of the BS inversion code were run against this test case to have a basis for comparison. Results for this synthetic test case are shown in Figure 19.

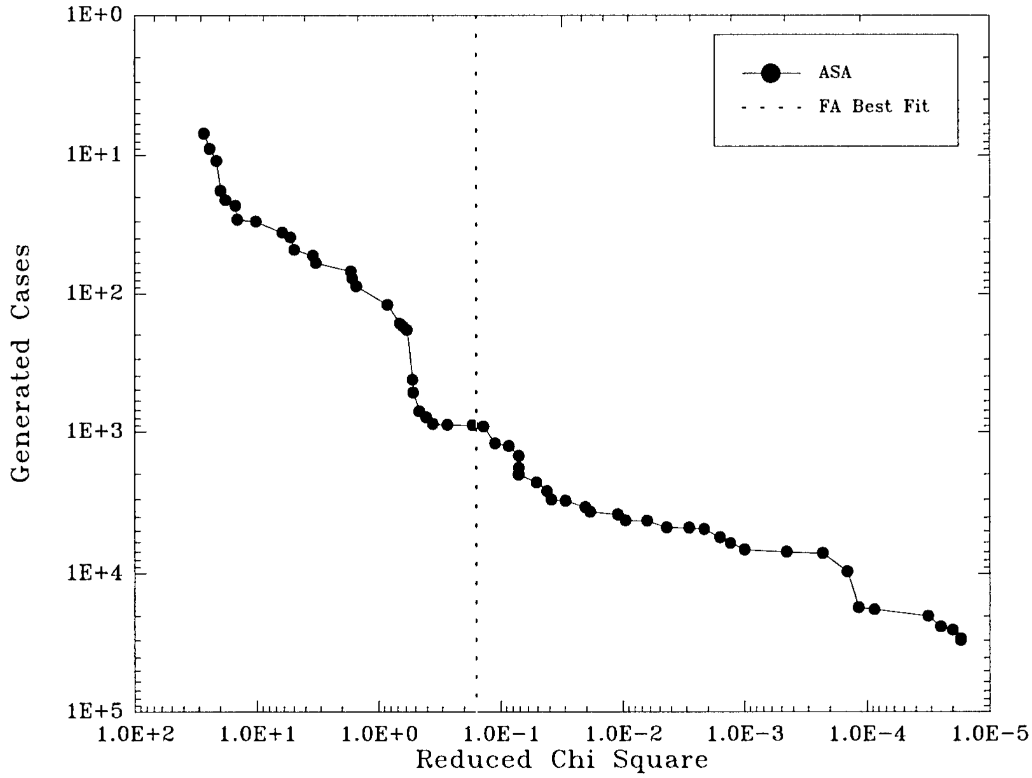

Figure 19: Comparison of ASA algorithm with FA algorithm for flat bottom synthetic bottom scatter data set. Results from the ASA algorithm (denoted by the solid line with solid black circles) and the FA algorithm (denoted by the dashed line) are shown.

The results shown in Figure 19 show that the ASA algorithm produces a result better than that of the FA algorithm for roughly 1000 generated cases and higher. The ASA algorithm also continues to converge as the number of generated cases is increased. For comparison, the results shown for the FA algorithm required 1 hour, 46 minutes, and 56 seconds on a Pentium II 450 MHz PC. The result for the ASA algorithm for 1000 generated cases, which produces a result comparable to that of the FA algorithm, took 8 minutes and 36 seconds on the same PC. The speed up when comparing results between the ASA and FA algorithm is a factor of 12.4. This speed up is comparable to the results observed for the TL inversion. In addition, when the ASA algorithm is allowed longer run times, i.e., more than roughly 9 minutes for this case, the inversion is able to produce increasingly better fits to the synthetic bottom scatter data set. Indeed, the chi-square value produced by the FA algorithm at the end of its nearly 2 hour run is three orders of magnitude larger than that produced by the ASA algorithm at the end of the same run time.

Inversion of Measured Bottom Reverberation Data with BS Inversion using ASA Algorithm

The ASA implementation of the BS inversion code was then tested against measured bottom scatter. The bottom scatter data was broadband bottom scatter data taken by NAVOCEANO in the eastern Mediterranean Sea. The data was taken using Mk-61 SUS and SSQ-57 sonobuoys deployed from a P-3 aircraft. Three data sets denoted by their run identification number were used for testing. As part of the tasking from PMW-185, PSI has more than 70 bottom scatter data sets from the eastern Mediterranean Sea that would be used as part of the proposed Phase II base program. The results for each data set are presented in graphs showing the reduced chi-square value as a function of the number of generated cases for the ASA algorithm. The results from the FA algorithm are also presented for comparison.

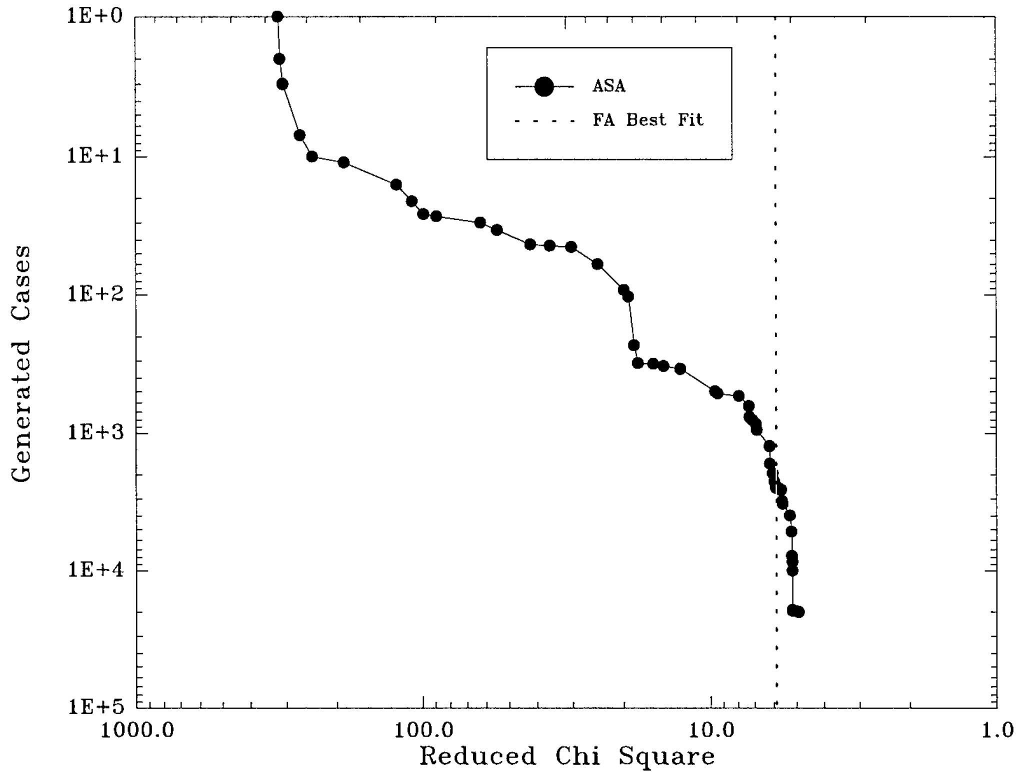

Figure 20: Comparison of ASA algorithm with FA algorithm for the M45 bottom scatter data set. Results from the ASA algorithm (denoted by the solid line with solid black circles) and the FA algorithm (denoted by the dashed line) are shown.

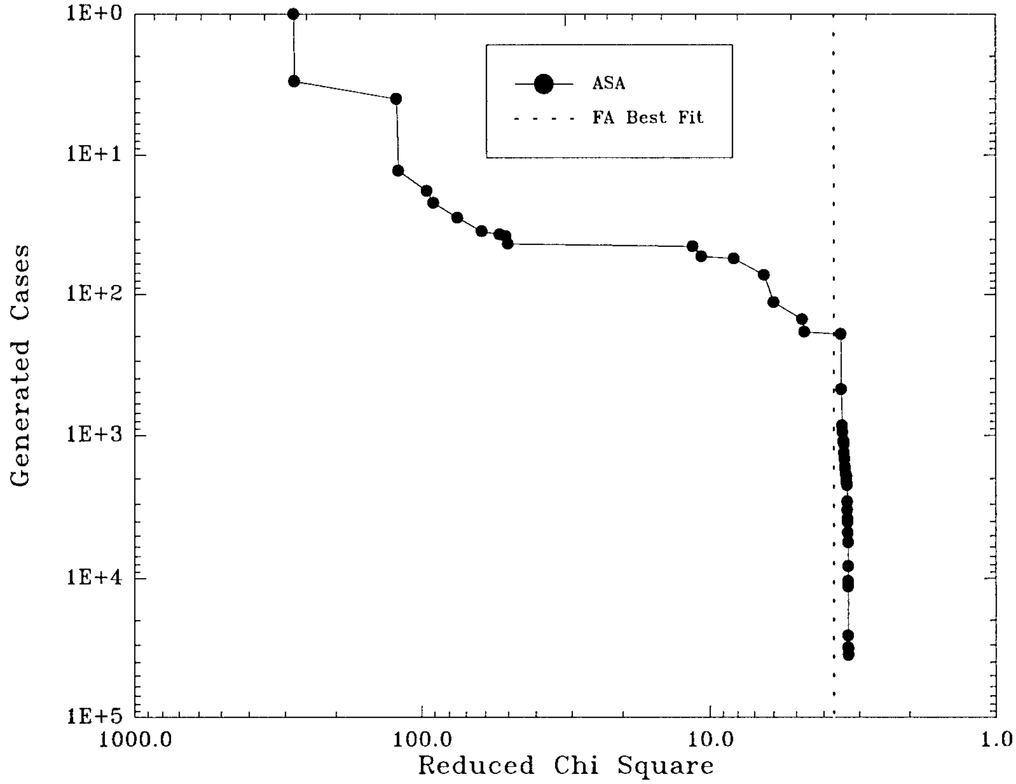

Figure 21: Comparison of ASA algorithm with FA algorithm for the M59 bottom scatter data set. Results from the ASA algorithm (denoted by the solid line with solid black circles) and the FA algorithm (denoted by the dashed line) are shown.

The results for data sets M45, M59, and M37 are shown in Figure 20, Figure 21, and Figure 22 respectively. For each data set, the ASA algorithm shows an ability to converge to a fit better than that of the FA algorithm in 2500 generated cases or less. For data sets M59 and M37 the ASA algorithm was able to produce a better fit than that from the FA algorithm in less than 1000 generated cases. It should be noted that the "tuning" for the ASA algorithm for these inversion runs was identical to that used for the TL inversion results using the ASA algorithm previously documented in this report. The ASA based BS inversion results also the show an asymptotic behavior as the reduced chi-square value appears to be converging asymptotically toward a final value. For this particular tuning, the convergence rate of the ASA algorithm was more variable than that observed for the ASA based TL inversion. This may indicate that another "tuning" for the BS inversion code would produce more consistent convergence rates but may also indicate more inherent variability in the convergence rates for the BS inversion compared to the TL inversion.

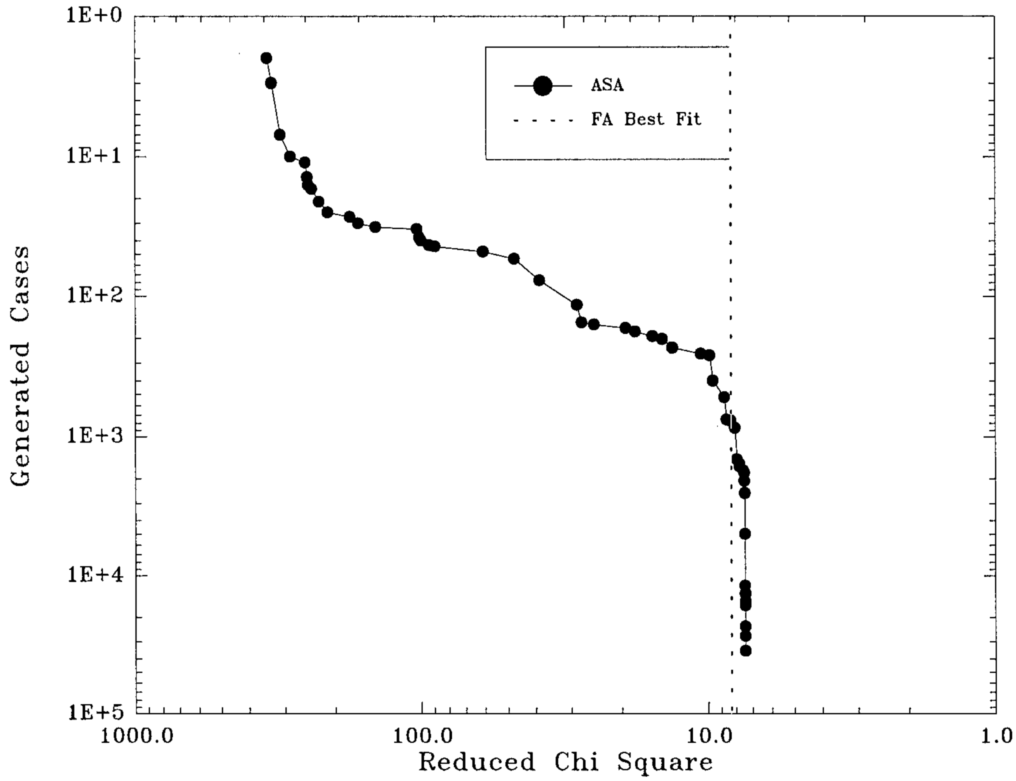

Figure 22: Comparison of ASA algorithm with FA algorithm for the M37 bottom scatter data set. Results from the ASA algorithm (denoted by the solid line with solid black circles) and the FA algorithm (denoted by the dashed line) are shown.

Table 4 provides a comparison of the run times for the three bottom scatter data sets for both the ASA and FA algorithms. The ASA algorithm run times are for the number of generated cases necessary to produce a reduced chi-square value better than that produced by the FA algorithm. The ratio of run times varies between 6.8 for data set M45 and 48 for data set M59. The ASA algorithm was able to produce an estimate of the bottom scatter parameters better than from the FA algorithm for data sets M59 and M37 in 193 and 767 generated cases respectively compared to 2501 generated cases for data set M45. This difference in the rate of convergence for the ASA algorithm causes the significant difference in the run time ratios. However, this difference in the rate of convergence for the ASA algorithm for the BS data sets is also a cause of concern since an automated inversion must be instructed or determine for itself when the inversion algorithm has converged sufficiently. As part of the Phase II base program subtask 1, additional work on studying the robustness of the ASA algorithm based TL and BS codes is proposed that will resolve such issues. More details on this proposed work is provided in Section C of this report titled "Phase II Tasks (Estimate of Technical Feasibility)."

Table 4: Comparison of run times for ASA and FA algorithm for BS data sets.

BS Data Set	ASA Algorithm Run Time	FA Algorithm Run Time
M45	36 minutes	246 minutes
M59	3.6 minutes	174 minutes
M37	13.5 minutes	157 minutes

The inverted bottom scatter parameters from both the ASA and FA algorithms for each of the three test cases are shown in Table 5. Similar to the TL inversion results shown in Table 2 and Table 3, there is considerable variability in the resulting parameters although the quality of the fit measured by the reduced chi-square value are comparable. As was noted in the TL inversion results of this report, the most significant differentiator between the two inversion algorithms, beyond the quality of fit compared to the measured data that each produces, is the computational effort that each requires. On this point, the ASA algorithm is significantly more efficient compared to the FA algorithm and produces estimates of the seven bottom scatter parameters that are equally valid as judged by the reduced chi-square value.

Table 5: Inverted bottom scatter parameters using ASA and FA algorithm.

	M45		M59		M37	
Parameter	ASA	FA	ASA	FA	ASA	FA
W-S Interface Strength	0.00020	0.0006	0.00339	0.0005	0.00155	0.00135
W-S Interface Exponent	2.400	3.8990	2.417	3.35	3.899	3.769
Volume Strength	3.5E-04	2.0E-04	1.5E-02	1.0E-04	4.7E-07	1E-04
Volume Exponent	1.999	1.973	1.999	1.727	1.999	1.792
Volume Aspect Ratio	3.904	2.78	24.273	3.03	25.086	3.23
S-B Interface Strength	0.99980	0.91505	0.99748	0.45955	0.99927	0.24135
S-B Interface Exponent	3.840	3.833	3.617	3.828	3.734	3.82

Base Program Subtask 3 - Documentation of the Implementation and Validation of the ASA Algorithm

Documentation for both the TL and BS inversion codes has been provided to Nancy Harned (POC at ONR) and Ken Dial (ONR) in both hard copy and on CDR. The CDR includes the source code, executables for a Windows PC, synthetic cases, and measured data cases. Also included on the CDR are copies of the progress reports, Phase I summary report, and Phase II preliminary plan.

Summary of Phase I Findings

In the limited number of test cases against both synthetic and measured transmission loss data, the ASA algorithm has shown an ability to provide estimates of LFBL parameters that are as good or better[11] than those from the FA algorithm with a significant reduction in run times. Run

[11] The comparison of goodness of fit is done using the chi-square metric.

times for the ASA algorithm compared to the FA algorithm for the same cases were between 12 and 16 times faster. Run times of roughly 8 minutes were observed for the measured data test cases although the run times for other cases will vary depending upon the complexity of the acoustic environment since run times for the inversion are very dependent upon the speed of the transmission loss model.

The TL inversion code used for this Phase I SBIR included the ASTRAL propagation loss model for several reasons. First, ASTRAL is a Navy standard propagation loss model that has been thoroughly evaluated as part of the OAML[12] approval process and receives regular upgrades and fixes. Second, due to the software architecture of ASTRAL, multiple frequency runs of ASTRAL can be done with little additional run times compared to single frequency runs of ASTRAL. For a multiple frequency inversion as done in this TL inversion, the computational savings from this feature are considerable. The implementation of another propagation loss model, such as PE 5.0 or GRAB, could be accomplished by only changing the code interface between the ASA inversion algorithm portion of the code and the propagation loss model portion of the code.

The inversion of measured bottom scatter data using the ASA algorithm showed a considerable reduction in run times compared to the results using the FA algorithm. Run times were decreased by a factor of between 6.8 and 48 for the three data sets inverted. As was noted in the summary of the bottom scatter data inversion, the variability in the convergence rates of the ASA algorithm for the bottom scatter data sets warrants additional exploration to explore other "tunings" of the ASA algorithm to more efficiently converge on the bottom scatter parameters.

The results presented in this summary report clearly do not provide universal proof of the robustness of the ASA algorithm for use in TL and BS inversion in all the world's oceans. It does however show that for the particular experiment data sets, the ASA algorithm can provide estimates of the LFBL and bottom scatter parameters that are as good or better than those from the FA algorithm with a considerable reduction in run times.

C. Phase II Tasks (Estimate of Technical Feasibility)

Given the positive nature of the results from the implementation of the ASA algorithm in the TL inversion code and conversations with the technical point of contact for this Phase I SBIR, there is a clear course of work that can be taken in the future. This course includes the Phase I Option proposed in the Phase I proposal and Phase II efforts described here and in the draft Phase II Preliminary Plan.[13] A brief review of the Phase I Option plan will be given and then details on the proposed Phase II tasking will be provided.

It is also important to note that PMW-185, under the Acoustic Research and Development Plan for FY 01 and 02, has expressed a strong interest in pursuing a Joint Funding Program for this Phase II tasking. As the budget for this work will not be finalized until just prior to the beginning

[12] OAML is the Oceanographic and Atmospheric Master Library maintained by the Navy to provide standardized models and databases for Fleet and research use.

[13] The draft Phase II preliminary plan is being submitted in conjunction with this draft technical summary report. A final version of each will be submitted by 31 May 2000.

of FY 01, Kim Koehler, Assistant APM Data Application of PMW-185, has indicated that funding for FY 01 comparable to that received in FY 00, which was $170K, is to be expected. The immediate interest in FY 01 from PMW-185 is participation in the ITW (Inversion Technique Workshop) and completion of the SCARAB model for evaluation by representatives[14] of the SABLE program at NAVOCEANO. Details on the SCARAB model were provided in the Phase I proposal. Details on the Inversion Technique Workshop will be provided under a separate section as part of the Phase II work.

Phase I Option

The Phase I Option Program will facilitate the Phase II goal of evaluation of the ASA algorithm by implementing both the TL and BS inversion codes using the ASA algorithm developed under the Base Program of the Phase I on a multiple processor Windows NT/Windows 2000 platform. The advantages of multiple processor hardware can be used to further increase the speed of the algorithms. The Option Program will also validate this multiple processor implementation using synthetic data. The Phase I Option Program is also divided into three subtasks paralleling the subtasks of the Phase I Base Program.

- Option Program Subtask 1 - Implementation of the Multiple Processor Capability for the Inversion Algorithms
- Option Program Subtask 2 - Validation of the Multiple Processor Capability for the Inversion Algorithms
- Option Program Subtask 3 - Documentation of the Implementation and Validation of the Multiple Processor Capability

The cost of the dual-processor Windows 2000 machine is being paid under tasking from PMW-185 for the development of the SCARAB model. We expect to purchase the hardware in June 2000 and will be looking at a machine with dual Pentium III 866 MHz processors with at least 512 MB of system memory. Current cost for the system is expected to be roughly $7,000. The change from the current Pentium II 450 MHz system to the proposed dual Pentium III 866 MHz system is expected to yield another 50% reduction in run times simply from the increase in processor speed before the implementation of any parallel processing speed-ups.

Phase II Base Program

The Phase II Base Program will explore the robustness of the ASA algorithm based inversions of both transmission loss (TL) and bottom scatter (BS) data. An evaluation of the inversion algorithms ability to invert measured acoustic data from the widest possible variety of acoustic environments will answer the following questions.

[14] Gene Brown is the NAVOCEANO principal investigator for the SABLE program and will be evaluating the SCARAB model for possible inclusion in his work in FY 01 and beyond.

- Are there any significant differences in convergence rates between quantifiably different environments (water column properties, bathymetric slope, geoacoustic bottom properties)?
- Can a statistically based determination be made of the trade-off between inversion run times and robustness of inverted parameters be made? Is this trade-off also a function of the environment and if so, what are the key environmental factors that affect this trade-off?

A related issue is how to provide a description of the uncertainty in each of the inverted parameters produced by an acoustic inversion. In a simplistic view, this can be though of as a standard deviation for each inverted parameter. In reality, given the complex topography of the solution space a standard deviation representation may be extremely misleading. The fundamental goal of characterizing the uncertainty in each inverted parameter is summarized in the following question.

- How can the uncertainty in each inverted parameter be expressed to accurately the dependence on that parameter and the cross-dependencies with other parameters? What representation would be most useful to future propagation models that can treat uncertainty in description of the acoustic environment?

Another set of important questions must be answered to understand the tactical use of acoustic inversions as defined in the report. In particular, tactical measurements of transmission loss require a bi-static or multi-static geometry.

- What acoustic data can be collected as part of in-stride multi-static Fleet operations and what acoustic data can only be collected as part of dedicated data collection operations?
- Data collected by one set of combatants and inverted for an updated set of LFBL or bottom scatter parameters should be made available to all combatants in the area. What limitations are there in applying inverted results to other frequencies and sonar types?
- Can this acoustic inversion technique be applied to learning more about the sound velocity profile along a track? Where could the current inversion technique be applied to acoustic and non-acoustic data to provide an estimate of a tactically important environmental parameter?

The Phase II Base Program proposes a three-stage approach to the work. The first stage, subtask 1, consists of exercising the TL and BS inversion code with the ASA algorithm over a broad range of acoustic environments to determine the robustness of the inversion algorithm as a function of the environment. The second stage, subtask 2, consists of formulating and implementing a method to characterize the uncertainty in each of the inverted acoustic parameters and the cross-dependencies between the acoustic parameters. The third stage, subtasks 3, consists of transforming the results from subtask 1 into a practical method for application of inversion techniques into a tactical system. Details for each subtask of the base program are provided in the following sections.

Phase II Base Program – Subtask 1

The goal of subtask 1 is to exercise the TL and BS inversion code with the ASA algorithm on a broad enough set of acoustic data from a wide variety of acoustical environments to determine the following.

- Are there any significant differences in convergence rates between quantifiably different environments (water column properties, bathymetric slope, geoacoustic bottom properties)?
- Can a statistically based determination be made of the trade-off between inversion run times and robustness of inverted parameters be made? Is this trade-off also a function of the environment and if so, what are the key environmental factors that affect this trade-off?

Because the inversion technique used is automated, large amounts of data can be inverted in batch runs without requiring user intervention. With this ability, some effort will be required to setup the input files for each data set and format the measured acoustic data in the proper format. However, once that is complete a variety of options are available to examine the convergence of the TL and BS inversion. The goal of the study is to understand the trade-offs that can be made between the robustness of the inversion and the required computational time. Understanding this relationship and the effect of the acoustic environment on it would give the system developer not only an ability to both provide an estimate of the geoacoustic properties of the ocean bottom in the time required but also an estimate of the robustness of the inversion.

The TL inversion code used in the subtask will use the most recent OAML approved version of the ASTRAL propagation loss model.[15] The BS inversion code will use the most recent version of the SCARAB model available.[16]

Products from Phase II Base Program Subtask 1

The product from this subtask will be a report documenting the inversion results from all the TL and BS data sets. The report will look for dependencies in the rate of convergence based upon the acoustic environment. Various tunings of the ASA algorithm will also be explored and documented in the report. The fundamental questions that this report will strive to answer are the questions in the bulleted items written in previous section.

Timetable for Phase II Base Program Subtask 1

Phase II Base Program Subtask 1 will start at the beginning of the Phase II period of performance and take 12 months to complete. All work will be done by PSI personnel based at the McLean, Virginia offices of PSI.

[15] ASTRAL Version 5.0 is currently in the OAML queue and may be approved this year. ASTRAL-G is currently under development but an approximate date for OAML approval is not known at this time.

[16] SCARAB Version 2.0 that will use RAM as the propagation model

Phase II Base Program – Subtask 2

The goal of subtask 2 is to determine and implement a method to characterize the uncertainty in the inverted LFBL parameters. As noted in the results of the Phase I work, the LFBL parameters shown in Table 2 and Table 3 each produce equally valid predictions of the transmission loss compared against the measured data. When the inverted LFBL parameters[17] are applied to a different frequency range, for example, it is important to be able to characterize the uncertainty in each parameter and the cross-dependencies between the parameters. Only with this knowledge will one be able to assign a confidence interval to the transmission loss predictions at different frequencies.

This subtask aims to produce a means of characterizing uncertainty in geoacoustic bottom parameters than can be used in current and future Fleet propagation loss models and tactical decision aids. In the most simplistic case, each inverted LFBL parameter would also have a standard deviation value to characterize the variance in the parameter. More complex examples include inverted LFBL parameters whose probability density function has more than one peak each with an associated standard deviation. An issue that must also be considered is the likely potential that inverted LFBL parameters are inherently correlated with other LFBL parameter(s) and that varying one parameter must result in changes in other LFBL parameters.

It should be clear that the exact details of this proposed subtask are yet to be determined. However, PSI is in a unique position with our relationship with De Wayne White[18], the developer of the ASTRAL propagation loss model, and with Dave King[19] of NRL-SSC to interact with the model developers and help frame this next step for propagation loss models. The variability in the littoral environments and the uncertainty in both database and inverted parameters require that propagation loss model produce more than just a single TL curve. Considerably more value can be realized by providing transmission loss with a confidence interval at each range.

Products from Phase II Base Program Subtask 2

The product from this subtask will be a software segment that along with the TL and BS inversion algorithms using the ASA algorithm characterize the uncertainty/variance in the inverted parameters in a form that is compatible with either current or future propagation loss model and tactical decision aids. This software will be integrated with the TL and BS inversion codes in such a way that its operation is transparent to the user.

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[17] Bottom scatter parameters instead of LFBL parameters can also be used in this line of reasoning.

[18] De Wayne White is currently a PSI employee and his expertise with the ASTRAL model can be used to determine what characterization of LFBL parameter uncertainty can be incorporated into current and future versions of ASTRAL.

[19] Dave King and Stanley Chin-Bing, both of NRL-SSC, are the technical advisors to the Acoustic Research and Development program at PMW-185. Dave King routinely evaluates propagation loss models for the OAML-SRB and has considerable expertise in both ASTRAL and Navy Standard PE.

Timetable for Phase II Base Program Subtask 2

The initial work on this subtask is to begin a dialog with the model developers and determine what are the existing and future capabilities for handling parameter variance/uncertainty in Fleet models. This initial effort during the first year of the Phase II work is a small effort but is necessary to insure that the products from this subtask are compatible with Fleet models. The effort during the second year will be the production and testing of the software to produce a characterization of the parameter uncertainty from both TL and BS inversions.

Phase II Base Program – Subtask 3

The goal of subtask 3 is to determine how to tactically implement the TL and BS inversion codes developed under the Phase I Base Program and validated under the Phase II Base Program subtask 1. Perhaps the most important question that must be answered as part of this subtask is the following.

- What acoustic data can be collected as part of in-stride multi-static Fleet operations and what acoustic data can only be collected as part of dedicated data collection operations?

This question goes beyond the time-tested techniques of measuring transmission loss from an aircraft using a pod of sonobuoys and SUS sources and looks toward collaborative operations among all participants. For example, EER sources in a sonobuoy field can be used as a bistatic source for surface ships sonars and towed arrays. In a similar method, helicopter-dipping sonars can be used as a bistatic source for surface ships sonars and towed arrays as well as aircraft and helicopter deployed sonobuoy. The challenge is in determining what acoustic data can be collected in-stride as part of normal operations and what acoustic data can only be acquired as part of dedicated operations.

The work proposed under this subtask is clearly related to and complimentary of other work being conducted both at ONR and within other Navy organizations. Coordination with and avoiding duplication of effort will be required to make this subtask successful in its goals.

Products from Phase II Base Program Subtask 3

The product from this subtask will be effected by and dependent on the work being done at ONR and other Navy organizations. The product should be a report detailing the findings of the study. The report will delineate the capabilities of in-stride acoustic measurements for the various platforms and combinations of platforms. The report will also describe those acoustic measurements that require dedicated operations and the benefit those dedicated measurements provide.

Timetable for Phase II Base Program Subtask 3

With coordination and cooperation with other projects key to the success of this subtask, the initial work in the first year of the Phase II award would be to determine the current work in the field and determine the scope of work suitable for this subtask. The first year of this effort, like that in the Phase II Base Program subtask 2 is a small effort but necessary to avoid duplication of efforts. The bulk of the work on this subtask will be conducted in the second year of the Phase II award.

Phase II Option Program

Two subtasks are proposed under the Phase II Option Program. Option subtask 1 proposes to develop a methodology for combining both historical and inverted LFBL parameter into a single coherent environmental database for use in tactical deployments. Option subtask 2 proposes to use the ASA algorithm to determine the sound velocity profile structure as a function of range using measured acoustic data. A summary of each option subtask including the products and timetable for each is included in the following sections.

Phase II Option Program – Subtask 1

For the concept of "network-centric" warfare to become a realizable, the following question must be answered.

- Data collected by one set of combatants and inverted for an updated set of LFBL or bottom scatter parameters should be made available to all combatants in the area. What limitations are there in applying inverted results to other frequencies and sonar types?

Related to this question is the problem of creating a unified view of the battle space environment from measured acoustic data. Creation of an updated battle space environment requires an ability to mesh or replace historical data with newly generated data inverted from acoustic measurements. This is not a trivial task by any measure as past work on creating updated bathymetric charts using historical and measured data has shown. Limiting the scope of the interest for this subtask to the geoacoustic properties of the bottom[20] presents a more tractable problem.

Phase II Option Program – Subtask 2

A potential option task was identified in discussions with the Ken Dial during a meeting at ONR to discuss the Phase I results and potential Phase II work. The idea proposed was to investigate the potential for determining the sound velocity profile of the water column along a transmission loss track using measured acoustic data and the ASA algorithm. Following the concept of both TL and BS inversion of acoustic data, using a propagation loss model than can synthesize an arrival structure and a parameterized description of the sound velocity profile[21] as a function of range, the inversion algorithm would minimize the difference between the measured data and model predictions by varying the sound velocity profile as a function of range. As noted in the

[20] The geoacoustic properties of the bottom would be represented in terms of LFBL in one of the three current formats (10-parameter LFBL, 15-parameter LFBL, and N-layer LFBL).

[21] A description of the sound velocity profile that only uses several points, e.g. inflection points in the sound speed profile, would reduce the number of free parameters that would need to be inverted.

introduction to the Phase II tasking, there are potentially other applications of this inversion technique to both acoustic and non-acoustic data that could also be explored under this subtask.

Inversion Technique Workshop (ITW) Directed by PMW-185 in FY 01

An outgrowth of the results from this Phase I SBIR work has been the interest from PMW-185 in evaluating the ASA algorithm against other versions of simulated annealing (SA) and more broadly against other inversion algorithms. The means for such an evaluation will be an Inversion Technique Workshop (ITW) to occur in FY 01. Current planning is for the release of the test cases in the November/December 2000 time frame with the workshop to be held approximately six months later in May 2001.

The evaluation criteria for the ITW differ somewhat from the criteria used in this SBIR work. The interest in the SBIR work has been on providing a robust, fast inversion for tactical implementation. The issue of finding the "global minimum" in the solution space has not been addressed since the computational requirements of finding the "global minimum" cannot be balanced with time limitations for tactical use. A primary judging criteria for the ITW is the ability of the inversion algorithm to find the "global minimum" for the test cases provided.

Consequently, each participant in the ITW will be provided the model used to generate the synthetic data cases as well as the input data file for the model with the parameters to be inverted for removed. This arrangement will focus the evaluation of the workshop results solely on the inversion algorithm and not on the participants' choice of models. A secondary evaluation criteria that will be used is the ability of the participant to invert for unknown parameters using less sophisticated propagation loss models[22] and/or inversion algorithms that are not guaranteed statistically to find a "global minimum."

The plans for FY 01 and FY 02 that include the Inversion Technique Workshop fall under GAIT (Geoacoustic Inversion Techniques). Exit criteria for GAIT version 1.0 is delivery of an OAML approved, DII COE compliant GAIT Version 1.0 to the SPAWAR Horizontal Integration (HI) effort in FY 02 for integration into Fleet Tactical Decision Aids via GCCS-M 5.X.[23] The role that Adaptive Simulated Annealing will play in GAIT Version 1.0 will depend on the findings from the Inversion Technique Workshop in FY 01.

The tasking proposed for FY 01 for PMW-185 provides an immediate opportunity to transition the Phase I work into a 6.4 funded program with commercialization potential in an identified transition to a Fleet application.

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[22] The propagation loss model that is being proposed for the generation of the synthetic test cases is the COUPLE model. Time permitting, PSI proposes to invert the test cases using the latest version of the ASTRAL model, where applicable, to explore the results using a less sophisticated propagation loss model.

[23] Kim Koehler is circulating a draft execution plan, dated 21 April 2000, for Acoustic Research and Development at PMW-185, for feedback and inputs. The wording in this report for the exit criteria for GAIT Version 1.0 is taken from that draft execution plan.

D. Phase III Commercialization Opportunities

The potential commercialization of the work conducted under this Phase I and proposed Phase II award cover a range of Fleet applications. The ability to rapidly and robustly invert transmission loss data for LFBL parameters has application in any bi-static or multi-static use of Fleet assets. As an example of the utility of this technique, two examples of potential Phase III commercialization are discussed.

Inversion of TL Data Collected By a Sonobuoy Field

The deployment of a sonobuoy field presents an opportunity to obtain TL measurements in a variety of azimuths over the area where the sonobuoy field is deployed. The use of either SUS or EER sources with the field of receiver allows for a rapid sampling of the environment. Software for TL inversion based upon the ASA algorithm can be hosted on inexpensive COTS equipment on an aircraft or helicopter to provide near real-time updates to the LFBL properties of an area of interest. For the cases tested in the Phase I award, run time between 6 and 11 minutes can be expected on a COTS machine costing less than $1,000. Current laptop technology would allow these run times to be further reduced. In addition, a Phase III transition of this technology would occur in roughly 24 month allowing for continued increases in microprocessor speed for both desktop and portable computers.

To show our familiarity with this topic, some unique advantages and disadvantages of acoustic data collection using sonobuoys are presented. An example of a sonobuoy pattern designed for environmental acoustic data collection is shown in Figure 23 from the Vizcaino Slope site as shown in the map in Figure 4.

The sonobuoy pattern is arranged in manner optimum for acoustic data collection and not for detection and prosecution of a target. A sonobuoy pattern design primarily for detection and prosecution of a target will more than likely produce acoustic data of poorer quality than from a sonobuoy pattern designed primarily for acoustic data collection. In addition, a number of padded sonobuoys[24] are used in this sonobuoy pattern to extend the dynamic range of the measurements and these buoys are not commonly available to the Fleet. The use of padded sonobuoys is necessary to mitigate the problem of overloading[25] a sonobuoy when the acoustic signal the sonobuoy is measuring exceeds the acoustic dynamic range of the sonobuoy. While these comments may tend to cast some doubt of the use of a sonobuoy field to measure acoustic data in conjunction with the task of target detection and prosecution, there are a number of advantages in using a sonobuoy field when compared to other platforms.

[24] Padded sonobuoys are attenuated from the conventional sonobuoys used by the Fleet by a prescribed amount (20, 40, 45, 60, 70, and 80 dB are common although others have been used).

[25] Overloading, often referred to as clipping, occurs when the acoustic energy at the sonobuoy exceeds the capability of the sonobuoy to process and transmit that acoustic waveform back to the aircraft or helicopter. In practice, the SSQ-57 and SSQ-77 sonobuoys have a dynamic range of roughly 35 dB that significantly limits their use when paired with active sources.

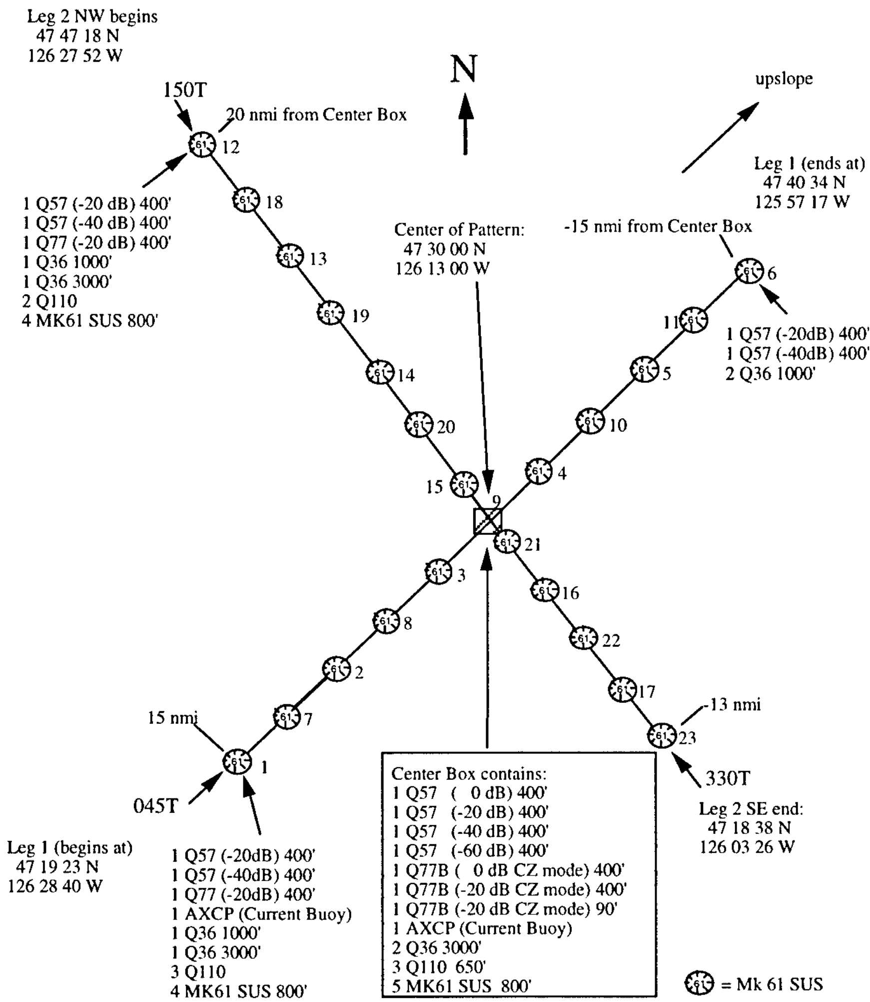

Figure 23: Sonobuoy pattern from experiment conducted in July 1995 at the Vizcaino Slope site shown in Figure 4 and Figure 5.

A primary advantage of a sonobuoy field over most other Fleet platforms is the ability to cover a large geographic area in a relatively short time. Because the aircraft or helicopter can monitor an entire sonobuoy field once deployed, a much larger area can be examined when compared to a single surface ship with or without a towed array. A second advantage is that the sources used with a sonobuoy field are commonly broadband sources.[26] The Phase I results were for broadband TL data covering the frequency range of 50 to 3150 Hz. Providing TL data covering a wide frequency range allows the inversion to better estimate the LFBL parameters as certain

[26] Both the Mk-61 SUS and SSQ-110 source are broadband sources commonly used in air ASW operations.

frequency ranges are more sensitive to certain LFBL parameters.[27] The advantages of a sonobuoy field, large geographic coverage, relatively low cost, and availability of broadband sources, make sonobuoy fields a promising candidate for deployment of a system for on site, tactical environmental measurement and characterization.

The past challenges of fielding such a system on an aircraft or helicopter have been mitigated by the recent availability of COTS hardware capable of digitizing 16, 32, or more channels of acoustic data, processing the data for transmission loss, and performing the inversion for an LFBL description of the ocean bottom. The ability to host this type of system in a carry-on/carry-off arrangement is currently available using COTS hardware and at the conclusion of the proposed Phase II work should be available in a smaller, cheaper, and more capable box.

Inversion of TL Data Collected By a Surface Ship From a Bi-static Source

The use of a hull mounted sonar or towed array as a bi-static receiver for a source represents another potential application of this inversion approach. The sources may be SUS, EER sources, helicopter-dipping sonars, or any other source available. As with the sonobuoy field, the receiver is essentially a fixed point over the time period of interest, nominally no more than 30 minutes. A key difference between these approaches is that using a sonobuoy field alone allows for the deploying platform to control the geometry and timing of events. Using a surface ship as a bi-static receiver requires coordination and cooperation between the various assets used.

Summary of Phase III Commercialization Opportunities

While these two approaches, which are just a subset of the many possible source/receiver combinations, requires different processing to arrive at transmission loss as a function of frequency and range, the inversion code required to handle the resulting TL inversion is identical. The cost for any of these approaches would be dictated by the effort required to acquire and process the acoustic data into transmission loss data once the inversion software developed under the Phase I work and tested and implemented under the proposed Phase II work is complete.

[27] High frequency acoustic energy may only penetrate several meters into the ocean bottom sediment sampling only the properties (sound speed and density) of the sediment at the water-sediment interface.

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The Phase I work goal was the reduction in run times for both transmission loss and bottom scatter acoustic inversion codes. The reduction in run times was accomplished using a recently developed variant of the Simulated Annealing (SA) family of non-linear inversion algorithms called Adaptive Simulated Annealing (ASA), which can be significantly faster than conventional forms of simulated annealing. The replacement of the Fast Annealing (FA) algorithm by the ASA algorithm in PSI's TL inversion code has resulted in run times between 12 and 16 times shorter accompanied by an improved fit between the predicted and measured transmission loss data.

15. SUBJECT TERMS

Simulated annealing, non-linear inversion, transmission loss, Adaptive Simulated Annealing (ASA), bottom scatter, LFBL, automated inversion, optimization

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