

# AN UNDERWATER ACOUSTIC MODEL FIDELITY STUDY

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## INTRODUCTION

The U. S. Navy currently relies heavily upon tapes recorded at sea for training acoustic operators, particularly in the task of signature analysis. The use of such tapes is considered to introduce certain limitations or constraints. An alternative approach to the use of sea tapes for training is the development of computer-generated simulation models. However, models of high fidelity are expensive to develop and to implement in real time. Therefore, the question arises, could a lower level of model fidelity (one which is less expensive to develop and implement) be utilized effectively for certain portions of the training pipeline.

## APPROACH

The Naval Underwater Systems Center (NUSC) New London has developed a series of high-fidelity and a series of lower-fidelity models and would like to have the training potential of these models assessed. The Naval Training Equipment Center has agreed to make this assessment by conducting an experiment utilizing these models to train acoustic operators.

Prior to conducting an experiment using the NUSC models, the pilot study herein described was conducted. There were three goals of this study: (1) gain experience concerning the problems which could be encountered in attempting to conduct such a study, (2) assess the worth of certain experimental procedures and performance measures, (3) obtain a preliminary assessment of the results which might be expected when using stimulus materials developed from different levels of computer model fidelity as compared to materials recorded at sea.

## APPARATUS AND SUBJECTS

The device used was the 14B44 P-3C DIFAR Operator Trainer located at NAS Jacksonville, Florida. Subjects were acoustic Anti-Submarine Warfare Technician Basic (AW) personnel from the six (6) fleet squadrons located at NAS Jacksonville. Approximately 100 acoustic AW personnel were used as subjects. Because the training and experience of these AW personnel were quite varied, each subject was requested to complete a questionnaire concerning their experience, training and level of general ability. This questionnaire data was then

used in comparing the subject's pilot study performance data. Z scores were calculated from this data for the purpose of matching subjects. The factors used in computing Z scores were as follows:

1. Months of gram analysis experience.
2. Exam scores on Advanced Gram Analysis Courses.
3. Exam scores on Acoustic Wingslant Exam.

The Z score of a subject tells how far this particular subject is from the mean. In general, to compute the mean in the usual way is possible only when the scores being averaged have approximately the same worth. By converting the scores of each subject into Z scores, it is possible to obtain equal units of measurement despite the fact that the original units of measurement may have been different.

## STIMULUS MATERIALS

In conducting the experiment, the following eight targets were used:

1. U. S. Diesel Submarine
2. U. S. Nuclear Submarine
3. Soviet Type I Diesel Submarine
4. Soviet Type II/III Diesel Submarine
5. Soviet Type I Nuclear Submarine
6. Soviet Type II/III Nuclear Submarine
7. Naval Surface Ship
8. Merchant Surface Ship

Each target was presented in each of the following sets of stimulus material:

1. Operational tapes recorded at sea.
2. A high fidelity, very accurate simulation.
3. A low fidelity, degraded simulation.

The sea tapes of the above eight targets were obtained from the Patrol Wing Eleven Library of AN/AQH-4 tapes recorded at sea. Device 14B44 was used to generate the simulated target signatures of the same eight targets. This simulation was then degraded to provide the third major group of stimulus materials. These eight simulated target signatures contain the same clues on each of the sea tapes; however, each computer-generated signature was not made to match exactly any sea tape signature. All of the target signatures in the three sets of stimulus materials were analyzed and evaluated by four judges. These judges were experienced analysts assigned to the Analysis Section of Patrol Wing Eleven. This section is assigned the task of analyzing in detail all of the AQH-4 tapes recorded during squadron patrol flights. Criteria for evaluation and rating of the stimulus materials were the following:

1. Representativeness of the target signature.
2. Difficulty of Analysis and Classification.
3. Identification and description of target clues.
4. Actual classification of the target.
5. Determination of sea tape vs simulation.

The initial judging was done to provide a complete list of clues, to verify a representative sample of targets and clues, and to obtain a series of contacts varying in difficulty. This data was used as a standard against which to judge the pilot study subject's responses.

#### EXPERIMENTAL PROCEDURE

Each subject was presented each of the targets using the AN/AQA-7 Acoustic Data Processor. The displays consist of a paper chart recorder lofargram display and a CRT display. Each contact was 12 minutes in duration. Subjects were not permitted to use the audio normally available on the AN/AQA-7. All other controls normally available to the operator on the AN/AQA-7 were operable during the experiment. Each subject was provided the tools and materials normally used for analysis and classification of targets on the AN/AQA-7. In addition, each subject was provided a standard response form as shown in figure 1 for detailed analysis. This response form is usually not employed but considered necessary for the performance measurement in the experiment. The response form includes all the clues which are used to perform a detailed analysis and arrive at a final classification.

The time required to arrive at this final classification was also recorded. The target contacts were presented on the AN/AQA-7 in a random order. Subjects were debriefed concerning their analysis and classification after each target when necessary.

#### DESCRIPTION OF MODELS

Sea Tapes were located which contained contacts of each of the eight targets. High-fidelity ocean and target models were generated using Device 14B44. These models were developed to simulate the eight targets although no effort was made to exactly duplicate the sea tapes. The ocean model used in Device 14B44 includes the complete set of propagation loss profiles from the ASW Environmental Prediction Service (ASWEPS), which are generated using the Fast Asymptotic Coherent Transmission (FACT) model developed by the Office of Naval Research (reference 1).

The FACT Model is a Ray Acoustic Model which utilizes higher order theory for the solution in those areas in which the assumptions of ray acoustics are limiting. The geometric intensities computed by the classical expressions of ray acoustics are discarded at caustics where they predict infinite intensity. Rather, the field near the caustic is evaluated using the appropriate asymptotic expressions for the particular type of caustic. Caustic fields are extended into the shadow zone to the range of the cusp where the smooth caustic originated.

The total intensity at any one range point is computed by a "semi-coherent" addition of arrivals. For shallow sources and/or receivers the paths within an arrival order which differ only by a surface reflection at the source (and receiver) have predictable phases relative to one another. Phase differences between different families or arrival orders are less predictable. The "semi-coherent" summation refers to the coherent or phased summation of the first set of paths followed by the incoherent or power summation of the resulting sets. As the rate in the oscillations of a particular coherent summation increases, the range grid may become too coarse to adequately sample the oscillations. When this occurs the summation is performed with an effectively reduced coherence until, for very coarse grids, all paths are summed incoherently.

Axis-to-axis transmission is treated in the following way. The period of the axial ray is computed for the smooth profile corresponding to the linearly segmented profile. The ray with the same period when traced in the linearly segmented profile is found and the depths of its horizontal turning

NAME \_\_\_\_\_

AGE \_\_\_\_\_

Detailed Analysis and Classification

1. Shaft RPM \_\_\_\_\_ RPM \_\_\_\_\_ RPM \_\_\_\_\_ RPM \_\_\_\_\_  
 PSR \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_  
 PROPELLERS Predominance \_\_\_\_\_  
 BR \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_  
 No. Blades \_\_\_\_\_  
 No. Shafts \_\_\_\_\_

2.  Diesel  
 Turbine  
 PRIME  Other  
 MOVERS (Specify)  
 \_\_\_\_\_  
 \_\_\_\_\_

Diesel  
 2 cycle Engine RPM \_\_\_\_\_ RPM \_\_\_\_\_ RPM \_\_\_\_\_ RPM \_\_\_\_\_  
 CSR \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_  
 Predominance \_\_\_\_\_  
 4 cycle EFR \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_  
 No cylinders \_\_\_\_\_  
 No engines \_\_\_\_\_

Turbine  
 Shaft RPM \_\_\_\_\_ RPM \_\_\_\_\_ RPM \_\_\_\_\_ RPM \_\_\_\_\_  
 TSR \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_ Hz \_\_\_\_\_  
 Number turbines \_\_\_\_\_

3.  Direct Drive  Unknown  
 Electric  Geared Reduction Ratio \_\_\_\_\_:1  
 DRIVE SYSTEM  Geared Reduction  T/B ratio \_\_\_\_\_:1  
 Split Plant  T/S ratio \_\_\_\_\_:1

4. AUXILIARIES A1 Type \_\_\_\_\_ A2 Type \_\_\_\_\_ A3 Type \_\_\_\_\_  
 RPM \_\_\_\_\_ RPM \_\_\_\_\_ RPM \_\_\_\_\_  
 Fundamental \_\_\_\_\_ Fundamental \_\_\_\_\_ Fundamental \_\_\_\_\_

5. Clues used to classify ranked in order of importance

|                       |                       |                                 |                       |                       |                       |                       |                       |             |
|-----------------------|-----------------------|---------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-------------|
| 1st                   | 2nd                   |                                 | 1st                   | 2nd                   |                       | 1st                   | 2nd                   | Other Clues |
| <input type="radio"/> | <input type="radio"/> | Fundamental Spacing             | <input type="radio"/> | <input type="radio"/> | Doublets, triplets    | <input type="radio"/> | <input type="radio"/> | (specify)   |
| <input type="radio"/> | <input type="radio"/> | Predominance                    | <input type="radio"/> | <input type="radio"/> | Dynamics              |                       |                       | _____       |
| <input type="radio"/> | <input type="radio"/> | Bandwidth                       | <input type="radio"/> | <input type="radio"/> | Interference patterns |                       |                       | _____       |
| <input type="radio"/> | <input type="radio"/> | Stability                       | <input type="radio"/> | <input type="radio"/> | Auxiliaries           |                       |                       | _____       |
| <input type="radio"/> | <input type="radio"/> | Frequency spectrum distribution | <input type="radio"/> | <input type="radio"/> | Common ratios         |                       |                       | _____       |

6. Classification

| Diesel Submarines     |                       | Nuclear Submarines    |                       | Surface Craft         |                       |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 1st                   | 2nd                   | 1st                   | 2nd                   | 1st                   | 2nd                   |
| <input type="radio"/> |
| <input type="radio"/> |
| <input type="radio"/> |
| <input type="radio"/> |
| <input type="radio"/> |
|                       | U. S.                 |                       | U. S.                 |                       | Naval Surface         |
|                       | Soviet Type I         |                       | Soviet Type I         |                       | Merchant              |
|                       | Soviet Type II        |                       | Soviet Type II        |                       | Small Craft           |
|                       | Soviet Type III       |                       | Soviet Type III       |                       |                       |
|                       | British               |                       |                       |                       |                       |

1. This signature was produced from:  
 AQH-4 tapes \_\_\_\_\_ 14B44 simulation \_\_\_\_\_

2. Analyzing the target signature was:  
 Very Moderately Moderately Very  
 Easy Easy Difficult Difficult

3. The target signature is:  
 Not at All Slightly Fairly Very  
 Representative Rep. Rep. Representative

If you have any comments concerning this signature, use the back of this page.

Figure 1. STANDARD RESPONSE FORM

points are determined. If the source and receiver are between these depths, they are both moved to the nearer depth. The net effect of this move is to produce a cusped caustic at the range of the cusp which would occur for the axial-ray family in the equivalent smooth profile.

A phase-integral technique is used to reduce the intensity (on a frequency dependent basis) of the rays shallower than the ray-equivalent of the first normal mode. This simulates low-frequency cut-off effects on rays which cycle with vertical amplitudes, which are small in terms of wavelengths.

A shallow water model is included which may be exercised for water depths of less than 1000 feet, and frequency/bottom class combinations where rays striking the bottom at less than critical suffer no reflection loss. The resulting transmission loss curve is a smoothed approximation to the curve generated in the FACT model and requires considerably less computation time.

A half-channel model has also been included specifically for ASRAP purposes. For the particular source depths and frequencies used in ASRAP half-channel cases, the intensity is approximated by a curve of the form of

$$PL = A + 10 \log R$$

Where PL = Propagation Loss

A = function of source and receiver depth, frequency, and bottom depth

R = range

This curve approximates the normal direct result; however, it takes considerably less computer time.

The propagation loss profiles are input directly into computer memory via punched paper tape. A typical propagation loss profile set (reference 2) is shown in figure 2.

For each combination of shallow-deep, deep-shallow, shallow-shallow, and deep-deep source and receiver, the propagation losses at 50, 300, 850, and 1700 Hz are plotted. These curves are then used to determine, by interpolation, the total propagation loss for each simulated target spectral component. Each curve is approximated by 64 range points. Input data consist of source and receiver depths, velocity versus depth, bottom loss index and wave height.

Wilson's equation (reference 3) is used to compute the sound velocity profile in the

metric system as follows:

$$C = 1449.2 + 4.623T - .0546T^2 + 1.391(S - 35)$$

where C = sound velocity m/sec

T = temperature °C

S = salinity in parts per thousand

The spreading component value for spherical spreading is given by 20 Log R where R is the given range. For the special shallow water case, the 10 Log R loss term is used for cylindrical spreading.

The attenuation coefficient value is also dependent on ocean conditions and the frequency of sound. Bubble content of the ocean, atmospheric conditions, sea state, temperature, and sound velocity gradient all contribute to the attenuation coefficient in the real-world. The attenuation coefficient is given by Thorp's equation (reference 4) as follows:

$$a = \frac{.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2} \text{ db/Kyd}$$

where f = frequency KHz

The bottom losses in dB are computed by Fleet Numerical Weather Central, Monterey, California, as a function of angle of incidence, bottom roughness, and frequency and placed in look-up tables.

The total propagation loss (reference 5) is given by the following equation:

$$PL_T = PL_1 + PL_2 + PL_3 - CG$$

where PL<sub>1</sub> = Loss due to spreading and attenuation

PL<sub>2</sub> = Surface bounce loss

PL<sub>3</sub> = Bottom bounce loss

CG = Convergence Zone Gain

Classically, the average ambient noise spectrum levels between .1 and 25 KHz are given by Knudsen's curves (reference 6), as shown in figure 3. Knudsen's curves indicate a noise spectrum that is broadband in nature and has a roll off of -5 to -6 dB per octave with increasing frequency. Knudsen's curves are an accepted standard for the frequency range indicated above. The curves are adjusted in the simulation to provide appropriate shipping noise for different geographical operating regions.

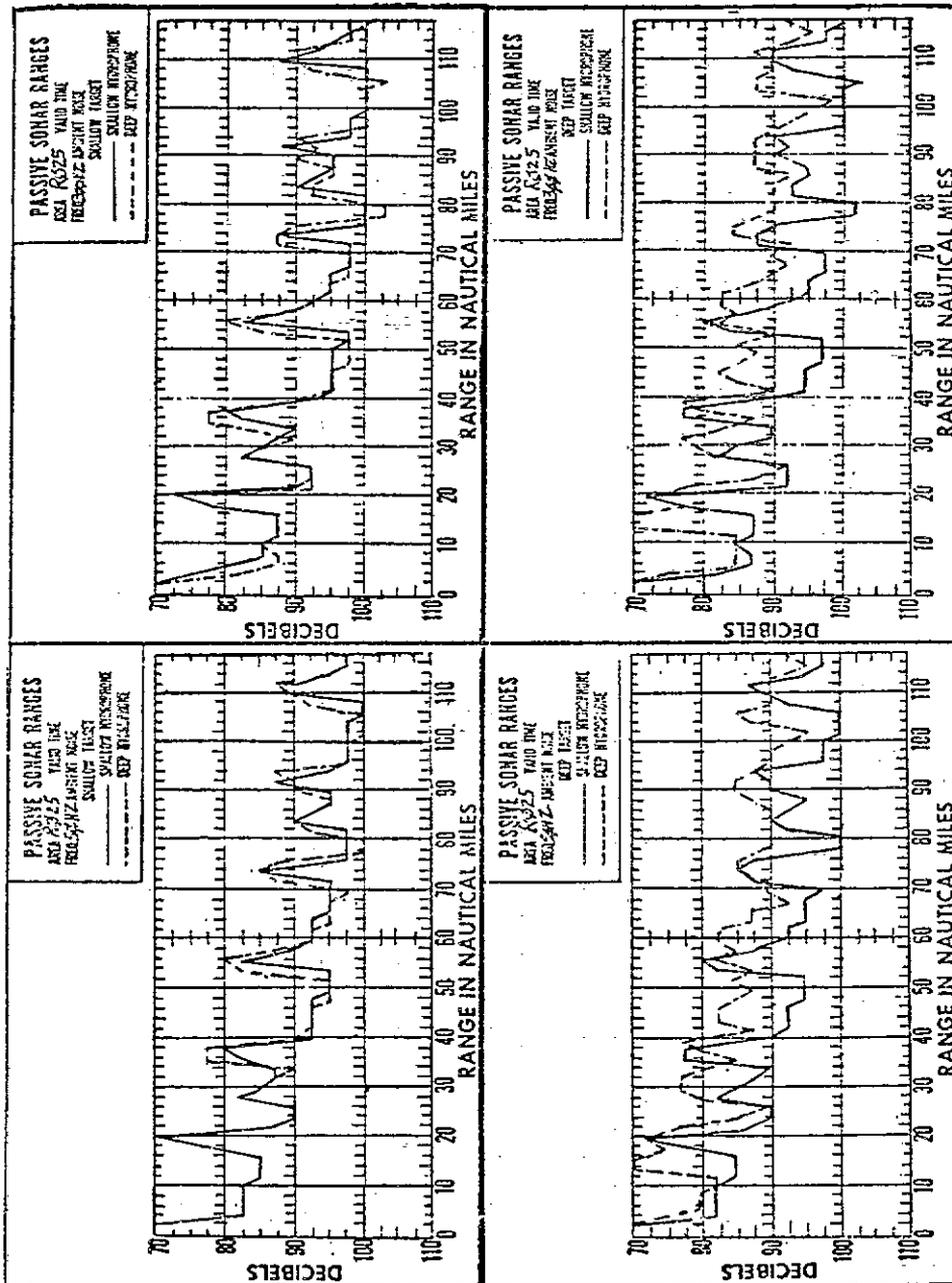


Figure 2. PROPAGATION LOSS PROFILES

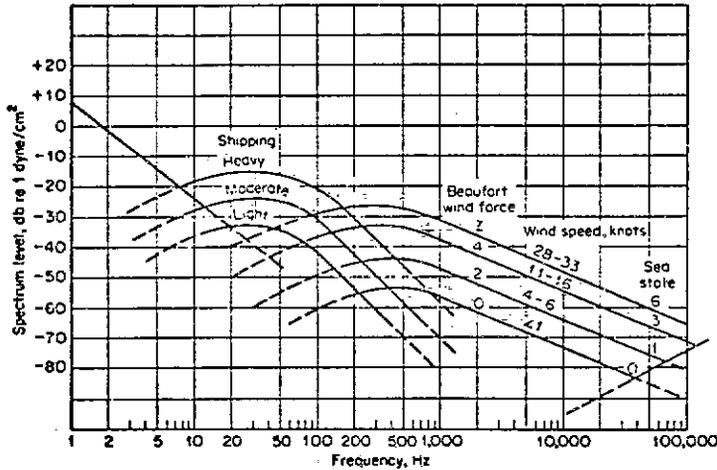


Figure 3. KNUDSEN'S CURVES

The target models include all of the target motion and acoustic characteristics. Motion and dynamic inputs are as follows:

- range
- bearing
- climb/dive rate
- depth
- turn rate
- acceleration
- speed
- power plant mods
- propeller mods
- stability
- engine RPM
- cavitation threshold.

The engine frequency is given by the following equations:

$$\text{Engine RPM} = \frac{\text{PPR}}{\text{SR}} \cdot [\text{Prop RPM}]$$

where PPR = power plant rate

SR = prop shaft rate

$$\text{Engine frequency} = \frac{1}{60} [\text{Engine RPM}]$$

$$\text{Propeller frequency} = \frac{1}{60} [\text{Prop RPM}]$$

$$\text{Mean prop RPM} = B V + 10B A t$$

where B = Blade pitch RPM/knot

V = velocity knots

A = acceleration knots/sec

t = time interval of integration sec.

The cavitation characteristics of a body can be defined by a parameter known as the cavitation index (reference 6) as follows:

$$K = \frac{P_o - P_v}{1/2 D V^2}$$

where  $P_o$  = Static pressure at propellers

$P_v$  = Vapor pressure of water

D = Density of water

V = Top velocity of propeller blades

The frequency-independent aspect effects (reference 7) are described by figure 4. The target input data specifies a source level for each signature component at a bow aspect. The received signal level is modified by the function shown in figure 4 according to the aspect of the source with respect to the sonobuoy.

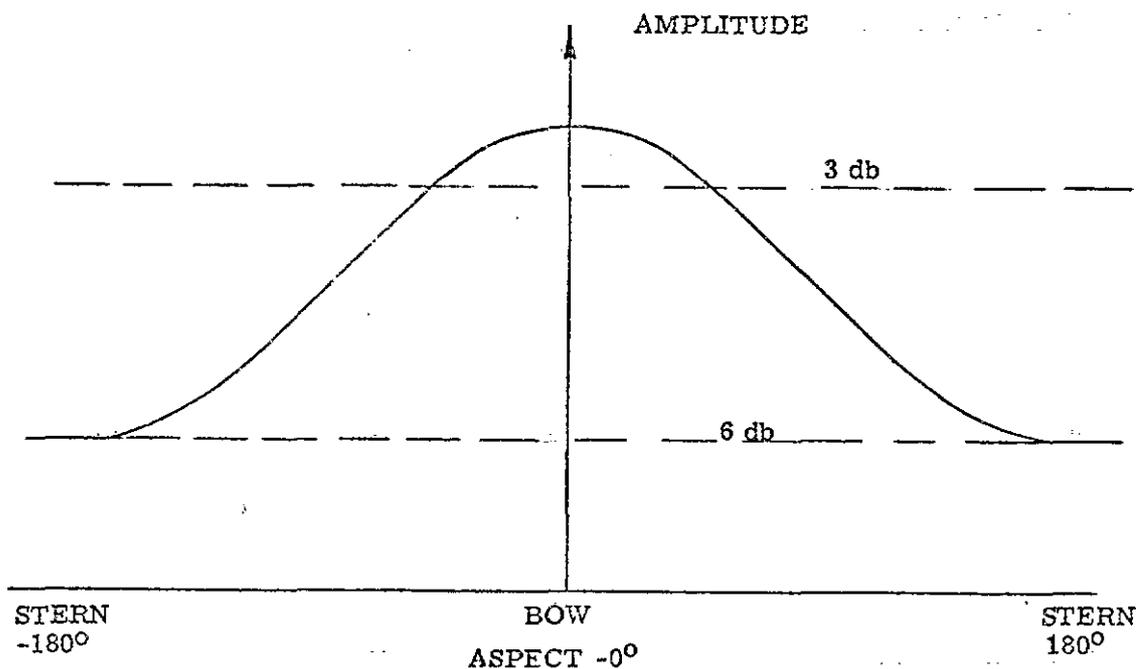


Figure 4. RECEIVED ENERGY VS ASPECT

The amplitude or intensity of the frequency lines that make up the target signature displayed on the AN/AQA-7 Signal Data Recorder are a function of the signal strength of the target radiated discrete frequencies and the composite noise as they are received by the sonobuoy. The standard equation is given as follows:

$$\text{SNR}(\text{dB}) = \text{SIG}(\text{dB}) - \text{NOISE}(\text{dB})$$

where SNR = signal to noise ratio at hydrophone

SIG = target signal strength at hydrophone

NOISE = composite noise strength at hydrophone

The noise is a sum of shipping, sea state, and biological noise input by the instructor.

The target signal strength at the hydrophone is given by the well-known sonar loss equation as follows:

$$\text{SIG}(\text{dB}) = \text{SL}(\text{dB}) - \text{PL}(\text{dB})$$

where SL = Source level of target

PL = Propagation loss in ocean

This equation (reference 4) is further expanded as follows:

$$\text{SIG}(\text{dB}) = \text{SL} - \text{ASPECT} + \text{CAV} - \text{PL}$$

where SL = Source level of target at the bow

ASPECT = Aspect dependent term as determined from figure 4

CAV = Cavitation calculated from previous cavitation equation

PL = Total propagation loss

The target models provide both narrowband and broadband sources of radiated noise. The narrowband sources in the model were derived from propulsion related machinery, including propellers, engines, reduction gears, generators, motors, and from auxiliary machinery such as generators, pumps, air

compressors and blowers. Physical factors such as the number of propellers, the number of propeller blades, reduction gear ratios, the number of engine cylinders, engine cycles and other known class characteristics are incorporated into the target model. Broadband sources are also combined into the model which reproduce the spectrum typical of the target class.

The fine structure of radiated tonals are included so as to show line strengths, width, and instabilities, as well as harmonic relationships. In the narrowband models for each target, line components include:

- a. Harmonic families associated with propulsion machinery; e.g., turbine lines for nuclear and steam engines, lines for engine and cylinder firing, and crankshaft lines for diesel and gasoline reciprocating engines.
- b. Harmonic families associated with gears such as turbine reduction and diesel reduction gears.
- c. Harmonic families associated with propeller shafts and blades. Singing propeller lines are included when observed on actual targets.
- d. Harmonic families associated with auxiliaries. Both speed dependent lines such as generators operating off main turbines and speed independent lines such as auxiliary pumps are included.

Line strengths for narrowband components are determined in accordance with published line strength data. Levels are specified as a function of speed and depth for speed dependent lines. Line widths are specified for all lines. Line stability models are provided for the unstable character of narrowband components. Line fading models are also provided.

Each target model is programmed with a dynamic model that will directly control the characteristics of both the broadband and narrowband target models. The dynamic model controls line frequency shifts and radiated noise level changes for changes in target and own ship heading or speed. The dynamic model functions include the following:

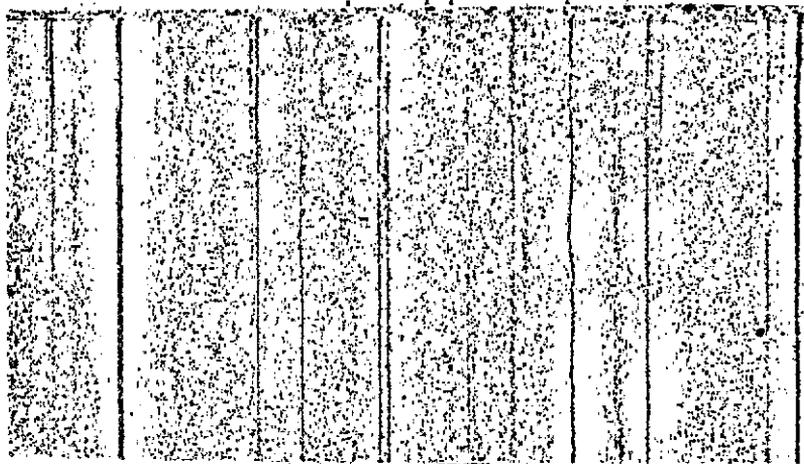
- a. During speed changes the broadband model levels are changed over the dynamic period from the initial to the final values.
- b. During target turns, the "bowing" of propulsion lines are provided during the dynamic period.

c. During target speed changes, the frequency shift of lines (narrowband) are modeled and include such effects as:

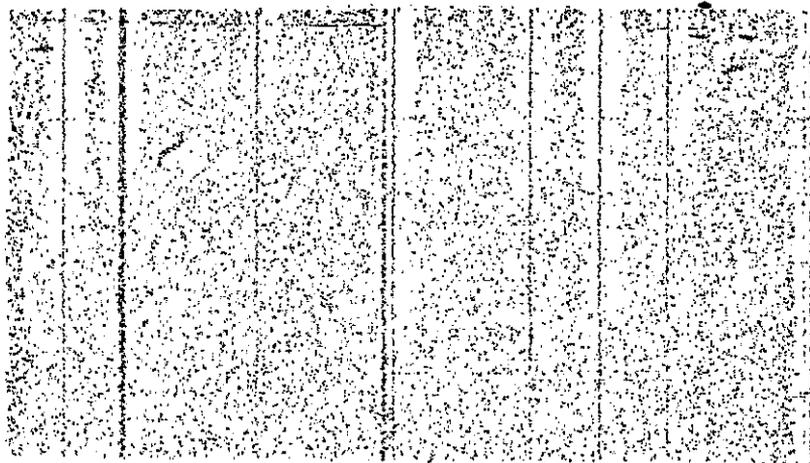
- (1) Changes in propulsion mode
- (2) Knee shifts of line frequencies
- (3) Abrupt shifts of line frequencies
- (4) Knee starts and stops.

After the high-fidelity models were developed, they were then simplified, to provide a degraded or less representative simulation for testing purposes in the study. The major objective in developing a degraded model was to simplify the classification task, to simplify the display and determine how this affected the subject's performance. It would be extremely difficult to measure or accurately assess the differences if both target and ocean models were degraded. There appears to be no way at present to determine which differences would be due to the target model degradation versus the ocean model degradation. Therefore, the decision was made to degrade the ocean model and leave the target models in the high-fidelity form. In particular, the signal-to-noise ratio was increased by decreasing the propagation loss attenuation. The attenuation was in effect increased to such a level as to position the target one yard from the sonobuoy. This would allow all of the discrete target-radiated frequencies to be displayed very plainly, thus simplifying the classification task. An example of the Lofargrams for the sea tapes, high-fidelity and low-fidelity models are shown in figure 5. The Lofargram consists of time on the vertical scale and frequency on the horizontal scale. The sea tape is an actual submarine signature recorded at sea by a sonobuoy and displayed on a Signal Data Recorder in a P-3C aircraft. The dark vertical lines are discrete target-radiated frequencies which are generated as part of the target-radiated noise. The salt and pepper background is broadband noise. The lightness of the gram on each side of the frequency lines is due to the Automatic Gain Control (AGC) of the airborne acoustic processor.

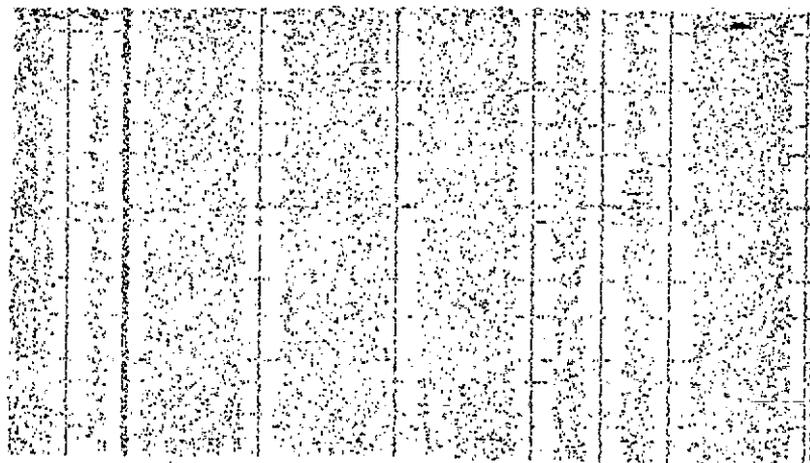
The high-fidelity simulation is similar to the sea tape. Most of the frequency lines are present to classify the target but no effort was made to exactly duplicate the sea tape. The identical discrete target-radiated noise lines are displayed in the low-fidelity simulation which are displayed in the high-fidelity simulation. However, since the signal-to-noise ratio is less, the lines have greater intensity or amplitude and appear darker or clearer on the Lofargram, especially with the AGC on each line. The



SEA TAPE



HIGH-FIDELITY SIMULATION



LOW-FIDELITY SIMULATION

Figure 5. COMPARISON OF STIMULUS MATERIALS

discrete target-radiated noise lines in the degraded model still have the same frequency, line width, and line stability, but the amplitudes are greater, making the lines appear darker. This was done to allow each subject to easily identify and measure each discrete frequency line, thus simplifying the classification task.

#### ANALYSIS OF DATA

The performance data for subjects was analyzed and compared. Analysis of this data provided the following information:

- a. Clues most frequently used for analyses of target contacts.
- b. The frequency bands most frequently used for target analysis.
- c. The time required to classify targets on sea tapes vs computer generated simulation.
- d. Accuracy of classification of targets on sea tapes vs computer generated simulation.
- e. Effect of experience, training, and schooling of subjects on ability to classify targets.

After initially looking at the data, we found that the low-fidelity simulation took the least amount of time to classify, the high-fidelity simulation next, and the sea tape required the longest time to classify. The simplified approach in the low-fidelity model of making the lines stronger and clearer apparently simplified the classification procedure considerably. This appears to be confirmed by the accuracy with which each subject classified the targets. The low-fidelity simulation was classified accurately most often, and next the high-fidelity simulation. The sea tape, representing the most complex signature, was accurately classified the least often. An

initial look at the data also showed that experience had no measurable effect on the ability of the subjects to accurately classify the target.

The pilot study described herein is considered to be successful in that all the major goals as previously outlined were accomplished and the results of this study are applicable to all acoustic training. Further analysis in this area will hopefully yield such information as operator performance versus model fidelity, the optimum fidelity model, and the most cost-effective model to be used for acoustic training.

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