NOAA Technical Memorandum NMFS

MAY 1998

ACTIVE TOWED-ARRAY ACOUSTIC SYSTEM DESIGN STUDY FOR YELLOWFIN TUNA IN THE EASTERN TROPICAL PACIFIC FISHERY AREA

C. David Rees

NOAA-TM-NMFS-SWFSC-251

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

NOAA Technical Memorandum NMFS

The National Oceanic and Atmospheric Administration (NOAA), organized in 1970, has evolved into an agency which establishes national policies and manages and conserves our oceanic, coastal, and atmospheric resources. An organizational element within NOAA, the Office of Fisheries is responsible for fisheries policy and the direction of the National Marine Fisheries Service (NMFS).

In addition to its formal publications, the NMFS uses the NOAA Technical Memorandum series to issue informal scientific and technical publications when complete formal review and editorial processing are not appropriate or feasible. Documents within this series, however, reflect sound professional work and may be referenced in the formal scientific and technical literature.

This paper was prepared by C. David Rees under contract No. 43ABNF61572 from the National Marine Fisheries Service, Southwest Fisheries Science Center, 8604 La Jolla Shores Dr., La Jolla, CA 92037-1508. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or the National Marine Fisheries Service. Charles Oliver of the Southwest Fisheries Science Center served as Contract Officer's Technical Representative for this contract.

Explanatory Note

This report is one in a series on the potential for technology applications to enhance efficiency in commercial fisheries, reduce the catch of non-targeted species, and provide new tools for fishery assessments in support of the NMFS strategic goals to build sustainable fisheries and recover protected species. A report synthesizing the results of this series of studies is planned. We hope the distribution of this report will facilitate further discussion and research into the application's potential usefulness, but should not be construed as an endorsement of the application by NMFS.

Pursuant to changes in the Marine Mammal Protection Act in 1988, the NMFS' SWFSC began another series of ETP-related studies in 1990, focused on developing and evaluating methods of capturing yellowfin tuna which do not involve dolphins. This series of studies has been conducted within the SWFSC's Dolphin-Safe Research Program. Studies on the potential use of airborne lidar (LIght Detection And Ranging) systems began in 1991, and studies on low-frequency acoustic systems to detect fish schools at ranges much greater than currently possible were initiated during 1995. In addition to their use as an alternative to fishing on dolphins, these systems have potential to increase the efficiency of the fishing operations by locating fish schools not detectable by customary visual means, and as a fishery-independent tool to conduct population assessments on pelagic fish. They also have potential to adversely impact marine animals.

The Dolphin-Safe Research Program is investigating, through a series of contracts and grants, five airborne lidars: 1) the NMFS-developed "Osprey" lidar (Oliver et al. 1994), 2) the Kaman Aerospace Corporation's FISHEYE imaging lidar (Oliver and Edwards 1996), 3) the NOAA Environmental Technology Laboratory's Experimental Oceanographic Fisheries Lidar (Churnside et al. 1998), 4) the Arete Associates 3D Streak-Tube Imaging Lidar, and 5) the Detection Limited's lidar . An initial study on the potential effects of airborne lidars on marine mammals will be completed during 1998 (Zorn et al. 1998).

The Dolphin-Safe Research Program has completed, through a series of contracts and grants, acoustic system studies on 1) the acoustic target strength of large yellowfin tuna schools (Nero 1996), 2) acoustic detection parameters and potential in the eastern tropical Pacific Ocean (Rees 1996), 3) **the design of** two **towed acoustic systems (Rees 1998**, Denny et al. 1998) and, 4) the potential effects of low-frequency sound on marine mammals (Ketten 1998). Studies are in progress to measure swimbladder volumes from large yellowfin tuna and to determine experimentally the effects of blast and acoustic trauma on marine mammals.

Chuck Oliver
Dolphin-Safe Research Program
Southwest Fisheries Science Center
P.O. Box 271
La Jolla, California 92037

Dolphin-Safe Research Program Detection Technology Reports

Churnside, J.H., J.J. Wilson, and C.W. Oliver. 1998. Evaluation of the capability of the experimental oceanographic fisheries lidar (FLOE) for tuna detection in the eastern tropical Pacific. Environmental Technology Laboratory, Boulder, CO.

Denny, G.F., K.E. deVilleroy, and P.K. Simpson. 1998. Long-range tuna school detection sonar system design specification. Grant (NA77FD0044) report. Scientific Fishery Systems, Inc., Anchorage, AK., 38 p.

Ketten, D. 1998. Marine mammal auditory systems: a summary of audiometric and anatomical data and its implications for underwater acoustic impacts. Contract (40JBNF600312) report. Harvard Medical School, Boston, MA., 97 p.

Nero, R. W. 1996. Model estimates of acoustic scattering from schools of large yellowfin tuna. Contract (40ABNF510351) report NRL/MR/774-95-7708. Naval Research Lab. Stennis Space Center, MS. 21p

Oliver, C., W. Armstrong, and J. Young 1994. "Development of an airborne LIDAR system to detect tunas in the eastern tropical Pacific purse-seine fishery" NOAA-TM-NMFS-SWFSC-204. 65 p.

Oliver, C.W. and Edwards, E.F. 1996. Dolphin-Safe Research Program Progress Report II (1992-1996). Southwest Fisheries Science Center Admin. Rpt. LJ-96-13. 91p.

Rees, C. D. 1996. Modeling of acoustic detection of yellowfin tuna in the eastern tropical Pacific fishery area. Contract (40ABNF510351) report. NCCOSC Code 541, San Diego, CA. 83p plus appendices.

Rees, C. D. 1998. Active towed-array acoustic system design study for yellowfin tuna in the eastern tropical Pacific fishery area. Contract (43ABNF61572) report. NCCOSC Code 541, San Diego, CA. 58p plus appendices

Zorn, H.M., J.H. Churnside, and C.W. Oliver. 1998 (in review). Laser safety thresholds for cetaceans and pinnipeds. Environmental Technology Laboratory, Boulder, CO.

NOAA Technical Memorandum NMFS

This TM series is used for documentation and timely communication of preliminary results, interim reports, or special purpose information. The TMs have not received complete formal review, editorial control, or detailed editing.

MAY 1998

ACTIVE TOWED-ARRAY ACOUSTIC SYSTEM DESIGN STUDY FOR YELLOWFIN TUNA IN THE EASTERN TROPICAL PACIFIC FISHERY AREA

Prepared by
C. David Rees

Naval Command, Control and Ocean Surveillance Center
Research, Development, Test, and Evaluation Division
Acoustic Branch (Code D881)
San Diego, CA 92152-6435

This study was funded by NOAA's Dolphin-Safe Program
(Southwest Fisheries Science Center, La Jolla, CA 92038)

NOAA-TM-NMFS-SWFSC-251

U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary
National Oceanic and Atmospheric Administration
D. James Baker, Under Secretary for Oceans and Atmosphere
National Marine Fisheries Service
Rolland A. Schmitten, Assistant Administrator for Fisheries

Table of Contents

Executive Summary ..... **i**
I. Review of Acoustic Requirements **1**
Overview 1
Definitions of Terms 1
Acoustic Propagation in the study area 2
Overview of how detection requirements impact system design 3
Discussion of Probabilities of Detection in the Study area 3
Discussion of Acoustic Energy at various ranges 3
II. General parameters of Active Acoustic Detection Systems **8**
Source Strength 8
Target Strength 8
Collimation 8
Noise 9
Beamforming 10
Tracking Requirements 10
III. Detection Characteristics Parameters for study area **11**
Ranges 11
Minimumn fish school sizes 11
Waveforms 11
Optimal operating frequencies 15
Discussion of choice of optimization parameters 16
Probability of detection requirements 16
Detection Feasability and processing model 17
Area Coverage 18
Environmental model case 24
Parameters 25
Number of elements 26
Time resolution for edge detector (binning size) 26
Tow distance 26
Noise Resistance 27
IV. Hardware Requirements **28**
Sound sources 28
Level and power requirements 29
Cycle time requirements 29
Frequency requirements 30
Directionality (collimation) requirements 31
Discussion of ship mounting 32
Optimal source depths 33

Sample source 41
Towed Array 41
Strength Member 42
Hydrophones 42
Electrical cabling 43
Protection and waterproofing 44
Minimum and maximum towing speeds 44
Other sensors 45
Array Deployment / Towing / Retrieval 45
Space Requirements 45
Proposed deployment technique 45
Maneuvering limitations while towing 46
Proposed retrieval technique 47
Location of apparatus 47
Emergency separation and retrieval 47
Safety Issues 48
V. Software Requirements 49
Brief signal processing overview 49
Standard beamformers 49
Noise discrimination 50
Processing requirements, Phase coherence 51
Real-time interface 51
Beamformer 52
Display interface 53
Software design 53
VI. Testing Procedures 54
VII. Costs 56
Estimates by system 56
VIII. Operations 57
Detection Mode 57
Tracking Mode 57
Minimization of Acoustic Impacts 58
Maximization of Detection 58
Tuna boat noise profiling 58

Appendix A (Acoustic intensity at ranges and depths) ..... 59 - 158
Appendix B (Pulse waveforms at various ranges) ..... 159 - 223
Appendix C (Modelled thinned long line array detections) ..... 224 - 394
Appendix D (Processor detection output by depth, range, and SSP) ..... 395 - 517

Executive Summary

This study modeled specific system configurations for an active towed-array acoustic detection and tracking system for yellowfin tuna in the Eastern Tropical Pacific (ETP) fishery area. The goals of the study were to determine the feasibility of using such a system as an aid to tuna fishery boats, enabling a tuna boat to detect and close on a school of yellowfin tuna without direct visual contact and without using such secondary indicators as a school of dolphin or floating surface debris ("log fishing"), and to analyze different possible acoustic system configurations to determine a practical design in terms of cost, system efficiency, and impact on boat operations. Furthermore, the acoustic yellowfin tuna system should, under good acoustic propagation conditions in the water, be able to operate at ranges significantly beyond what is possible today, under conditions where tuna fishing is currently impractical (such as nighttime), and ideally be able to discriminate the desired target--yellowfin tuna--from other marine species. Such an acoustic detection system would also have practical application in terms of estimating tuna populations and distributions to aid in fisheries management to prevent over fishing and the taking of secondary species, such as dolphin.

The Eastern Tropical Pacific extends from approximately 25 degrees north latitude to 15 degrees south latitude, and from the Americas coast out to 140 degrees West longitude. This study concentrated on the northern portion of the ETP (no significant differences are expected in the southern part) and used a previously derived set of characteristic environmental conditions to represent the area. These characteristic conditions were derived by identifying the smallest set of conditions such that the large majority of any conditions in the area would be sufficiently close to at least one characteristic condition. Tuna school acoustic properties were based on previously modeled results for a variety of school sizes, fish sizes, and fish spacing.

In an active system, a predetermined acoustic signal is broadcast from a "source", reflects off the target of interest (yellowfin tuna school), and is received at a receiver array (a set of hydrophones with known relative positions). If the received signal is strong enough, analysis of the signal receive times at the receiver array locates the target reflector at a specific range and bearing. Given enough knowledge of the target reflection characteristics and propagation conditions, detailed frequency analysis of the signal can also determine the type or class of target--for example, identifying the fish species. Given the characteristic environmental conditions, a large number of parameters determine the result, including the source strength (the intensity of the source), target strength (how the target reflects the signal), source collimation (the source beam pattern), the total system noise (environmental noise, electronic noise, processing noise, etc.), tracking requirements, and target stability

This study modeled acoustic detection system configurations with the source either fixed to or towed close to the tuna boat, and with the receive array in a "towed array" configuration: the array towed at the end of a cable deployed from the boat. The main advantage of this configuration is that the receive array is removed from the noisy tow ship, by far the main source of noise obscuring the reflected signal; in addition, long baseline arrays are possible. The study modeled the complete end-to-end performance of many different combinations of system parameters: propagation of the

signal to the target fish school (including ducting, or sound-channel-focusing, effects), the reflection from the fish school, propagation back to the towed array, receiving the signal at the individual hydrophones in the array in the noise field at the array, and the signal processing of the received signals to obtain detection, and if detected, range and bearing to the target.

Because there appears to be inadequate knowledge as to whether the ocean propagation channel maintains phase stability over the small aperture of a convention half-wavelength-spaced array for the very long ranges considered (out to 40 km) in the 5-10 kHz frequency band identified as optimal for propagation, acoustic signal processor modeling was done using a thinned long array approach. In this configuration the towed array hydrophones are spaced not at half-wavelengths, but sparsely over much longer distances, and detection is made by comparing signal arrivals at the array elements (a time-domain edge processor, because it detects the "edge" or increase in acoustic power corresponding to a signal arrival). If phase stability does hold, a half-wavelength array would probably have superior performance and thus better results than those modeled. A desirable early step in developing a tuna towed array system would be to carry out some simple tests on phase stability at these frequencies and ranges in good ETP propagation conditions.

Modeled results for a simple configuration consisting of 12 hydrophones spaced at 20 meters and towed 500 meters behind the boat, with a source strength of 200 dB, and using the simple edge signal processor to determine detection and, if detected, range and bearing estimate, produced surprisingly good results using a conventional beamformer. The conventional beamformer uses the known system configuration and water-column properties to provide constraints on received signals, identifying the reflection arrival bearing from the relative arrival times on individual elements and the range from the total elapse time from signal broadcast to towed-array reception. Nonconventional processors that rely on predicted results can further increase system detection and tracking performance, but this seems unnecessary in view of the conventional processor prediction.

The number of false alarms, or system identifications of a target not a yellowfin tuna school as a desired target, is very difficult to estimate and can only be reliably determined through experiments. Propagation effects at these extended ranges can produce dramatically altered waveforms at the receiver array, as demonstrated in the study, implying that species identification through the frequency structure of the reflected pulse would be difficult. Nonetheless, neutral-network based processing has handled similar applications in target identification, and would be a good candidate in an advanced fisheries acoustic detection system for target species identification. Under the good characteristic ETP propagation conditions, the modeled system showed good to excellent detection and localization properties out to ranges just beyond 20 km. Such good propagation conditions make up the majority of the ETP area characteristic conditions during the winter and summer seasons studied (fall and spring seasons were not studied but are expected to have similar overall properties).

Modeled system results were studied in terms of correct detection, range and bearing estimate accuracy, arrival linearity, and peak power and average power received on the array. A global study over all conditions and configurations studied using a weighted scoring system identified an optimal source depth around 20 meters. Optimal receive-array depths showed more variation and could be

tuned to actual conditions if environmental measurements were made from the boat, but an overall receive array operating depth around 80 meters produces good overall results. This study concentrated on results out to 20 km with, as just noted, good operating results under most expected conditions. These consistently good results with a 200 dB source fall off in the modeled system at about 22 km, but under favorable environmental conditions and quiet seas scattered detections are expected out to 30-40 km range.

Total development costs for an operating acoustic towed-array yellowfin tuna detection and tracking system are estimated to be in the $600K to $1.1M range, depending on the degree of customized development necessary for some system components. The revolution in modern electronics has dramatically reduced the cost of many subcomponent systems and this trend is expected to continue. Acoustic signal processing load was estimated for the configurations modeled and found to be well within the capabilities of available signal processing hardware hosted by a standard desktop computer. A number of possible deployment, operating, and retrieval techniques were put forward in the study, including possible techniques for marine life acoustic damage abatement and methods for minimizing impact on ship operations. Some constraints on ship operations are required for successful system operation and are given in the study. If the acoustic detection system operates with the predicted efficiency, increased fish catch and more efficient operations would more than compensate for slower cruise speeds and directional constraints. System display and operation can be designed for successful operation with an average tuna boat crew with the same level of expertise required to operate other modern on-board equipment.

To summarize, good overall detection, localization and tracking was shown by the relatively simple active acoustic towed-array system configuration modeled out to ranges of just beyond 20 km for a majority of the historically expected ETP environmental conditions. Under good acoustic propagation conditions, some scattered detections are expected out to 30-40 kilometers. These results were obtained with a modeled high-intensity 200 dB source. While species identification would be difficult due to propagation effects at range, neural networks show promise of being able to successfully determine school properties, although actual testing would be required. There is no technical reason a towed-array system could not be incorporated and operated on current tuna boats. The acoustic tuna system would be able to operate under conditions not possible with current techniques (nighttime, fog, low visibility) and would not rely on secondary identifiers, such as dolphin schools or surface debris. Recommended further investigations would focus on phase-stability tests, tuna boat noise profiling, acoustic scattering signatures from actual tuna schools, potential biological damage to marine life, and proof-of-concept tests.

I. Review of Acoustic Requirements

Overview

This study is an attempt to arrive at a reasonable design configuration for an acoustic detection system to be used by either a research vessel or a tuna fishing boat to detect and track schools of yellowfin tuna in the Eastern Tropical Pacific Tuna Fishery Area (ETP). It builds on a previous feasibility study of the ETP area for such a system, Modelling of Acoustic Detection of Yellowfin Tuna in the Eastern Tropical Pacific Fishery Area (Rees 1996), as shown in Figure 1.

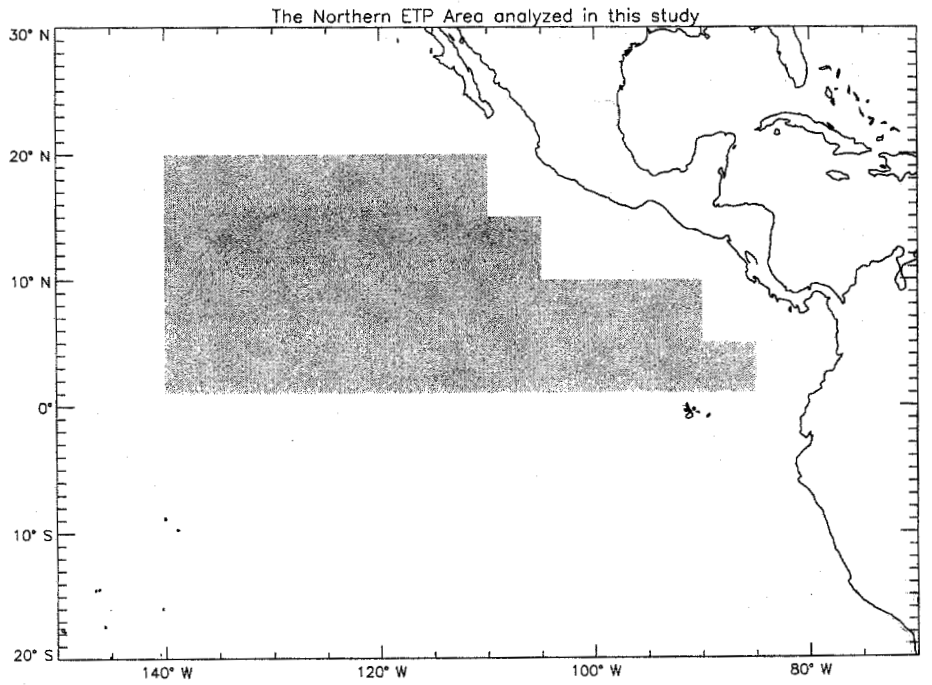


Figure 1. Area analyzed.

The study was performed at NCCOSC RDTE DIV (NRad), the Navy research laboratory in Command, Control and Ocean Surveillance located in San Diego, CA, mailing address NCCOSC RDTE DIV D881, San Diego, CA 92152-6435. The acoustic performance modelling was done by Dr. C. David Rees, NRaD. The study was financed by the Dolphin-Safe Program (Mr. Chuck Oliver, COTR) at the Southwest Fisheries Science Center, mailing address Southwest Fisheries Science Center, La Jolla, CA 92038.

Definitions of Terms

All values given in decibels (dB) in this report are calculated in acoustic intensity and should be read as: dB re 1 pW/m^2.

Acoustic Propagation in the study area

Acoustic propagation is summarized in the earlier report. The essential characteristics are a sound speed profile with a minimum at a depth on the order of 1000 meters, and with occasional surface duct (an area of trapped acoustic propagation, like speaking down a hallway) depending on the time of year and oceanographic conditions. Only the top 100 meters or so are of interest in terms of detecting tuna. The study area was analyzed to find representative sound speed profiles that provide a good basis set for describing propagation in the area. Adequate coverage was found for four basis sets for four generic propagation conditions in the area. The basis sets were derived by a procedure of basis distance maximization.

Because only a small part of the top of the water column is of interest in propagation, detailed analysis of bottom conditions and bathymetry is not necessary. Instead a range-independent model was adopted, with a generic set of bottom conditions designed to match overall characteristics of the area.

These spanning basis sets of environmental parameters (SSPs, bottom conditions, absorption, etc) were derived in the earlier study. Figure 2 shows the conditions.

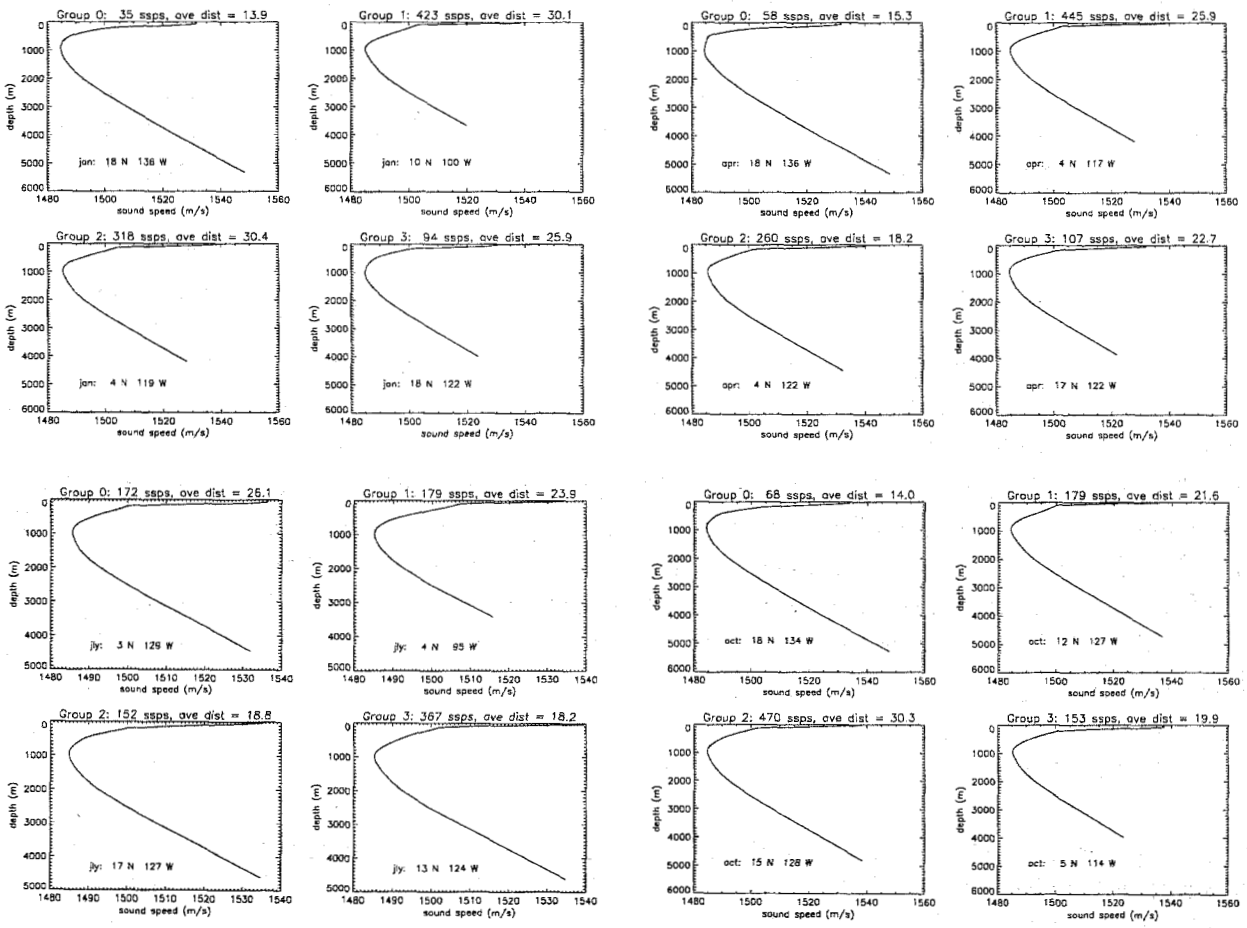


Figure 2.

Overview of how detection requirements impact system design

System design is done to optimize the chance of detection of an arbitrary school of tuna in the study region. This optimization is performed by calculating realizations of acoustic signals given prescribed source characteristics, pulse characteristics, and receiver (array) characteristics. The study then chooses the configuration that yields the highest (most likely) detection characteristics, subject to the constraints that may be imposed by marine mammal safety, system costs, and other real-world factors required to design a practical, achievable detection system as opposed to an idealized system.

In addition it is necessary to track (produce range and bearing estimates) for a tuna school for long enough periods of time to close on the school or to verify its coordinates and behavior. This imposes additional stability constraints.

The previous feasibility study determined that probabilities of detection in the surface layers for ranges out to 40 km were optimized by using an active system (a system where a source broadcasts an acoustic signal, which is reflected from the school) and a towed array (a series of hydrophones towed behind the vessel at a specified receiver depth and element spacing).

Discussion of Probabilities of Detection in the Study area

Studied systems showed good detection characteristics for reasonable source levels out to ranges of 20 km for levels of effective system noise in the range of 10 dB, with scattered detection characteristics out to a range of 40 km (10-50%). Detailed time-of-flight studies were only carried out in the 20 km range.

The arrays were modeled by using NRaD D881's Gaussian Beam propagation model to model arrival times at all combinations of parameters in the top 100 meters of the water column for frequencies in the target band, with actual modeled frequencies lying in the 6-10 kHz band. These results are then combined into a random-access database. Results are extracted from the database for sets of specific conditions and used to derive expected results at various array locations when subjected to a processing algorithm either using a simple time-of-flight direction and range determination, or a matched filter approach which matches the observed set of arrivals at the array to that expected from the model.

Discussion of Acoustic Energy at various ranges

To aid in assessing the possible impact on marine species, the following tables 1-8 give the expected average RMS sound intensities for given source levels at specified ranges from the source. The values given in the tables are the average sound intensity (decibels) in the top 100 meters of water at the given range for a 200 dB source at depths from 10 to 100 neters in 10-meter increments. Values for different source intensities SL can be found by adding (SL-200) to the reported values. Non-average, detailed values for all range-depth combinations less than 100 meters are given in the Appendices. In addition, Figures 3 and 4 show the distribution of acoustic energy through the full water column out to 10 km for a 200 dB source at 20 m depth with a horizontally-focussed 80-degree full width beam for each of the 8 characteristic SSPs studied in detail (jan0-jan4, jly0-jly4).

NOR ETP Jan grp 0 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	135	135	134	134	136	131	136	133	131	134
2	130	130	128	129	130	126	125	128	124	128
3	128	127	127	126	123	125	123	122	119	125
4	124	120	124	123	121	121	115	120	121	118
5	123	124	122	120	119	119	117	115	116	116
6	122	120	121	118	115	117	115	109	115	115
7	118	119	119	116	110	116	109	105	111	112
8	119	117	117	115	117	112	97	68	113	112
9	114	115	116	116	112	112	39	0	111	110
10	119	119	116	113	111	111	0	0	96	110
11	119	117	115	114	109	107	0	0	44	91
12	118	117	114	115	110	100	98	100	99	99
13	114	116	116	114	108	102	105	105	104	107
14	115	117	114	112	109	104	103	105	102	103
15	115	114	112	113	108	101	101	103	100	103
16	111	112	112	110	108	101	103	106	104	103
17	115	112	111	111	109	99	101	100	103	100
18	109	113	110	111	103	103	105	104	103	102
19	111	111	106	109	106	101	99	105	97	103
20	111	111	110	105	107	105	101	102	103	100
21	108	111	108	108	106	102	101	98	102	101
22	111	110	110	105	103	100	100	101	101	98
23	111	105	105	109	105	104	100	101	97	100
24	108	108	110	106	102	100	100	101	101	99
25	109	110	104	107	105	101	101	99	100	101
26	106	106	104	105	102	100	100	94	97	101
27	107	108	105	105	104	96	100	96	100	101
28	105	107	104	103	102	100	98	99	98	99
29	106	106	107	104	102	99	100	99	95	99
30	103	107	103	104	100	97	97	99	101	98
31	104	106	103	101	101	96	96	100	99	98
32	102	102	98	104	99	95	98	99	94	98
33	103	104	100	100	94	94	98	97	94	96
34	103	103	103	103	99	94	96	96	98	98
35	101	98	99	99	99	98	94	94	95	98
36	100	102	99	99	96	94	92	96	97	95
37	104	102	100	97	97	92	96	92	94	94
38	99	97	101	97	96	91	93	92	93	92
39	102	100	96	97	93	95	92	92	92	91
40	98	97	97	100	95	95	96	93	92	92

Table 1.

NOR ETP Jan grp 1 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	126	125	127	130	127	130	128	128	129	127
2	123	119	120	119	121	121	122	123	123	121
3	118	120	116	116	116	114	110	117	116	115
4	119	114	114	113	114	101	108	113	108	114
5	115	112	107	110	109	88	89	103	105	111
6	115	111	95	101	102	65	72	90	96	100
7	115	102	86	87	88	86	77	70	75	90
8	113	102	105	104	103	105	104	99	96	97
9	116	109	107	106	109	106	107	106	106	106
10	115	106	106	107	103	105	104	106	104	107
11	115	104	107	102	103	104	105	106	104	101
12	112	104	103	104	105	106	105	106	101	104
13	111	108	106	103	103	107	106	98	103	105
14	109	107	105	104	105	102	102	106	106	107
15	111	105	105	104	106	106	105	105	104	107
16	103	104	104	103	106	107	105	102	104	106
17	107	103	105	104	104	101	104	106	106	102
18	103	101	101	103	104	102	101	101	102	104
19	106	102	103	101	104	102	104	105	100	101
20	106	104	104	101	103	102	101	103	105	98
21	104	105	104	102	99	103	99	105	99	104
22	104	104	103	100	102	100	100	101	101	102
23	106	102	104	101	102	103	102	101	103	98
24	104	99	100	98	101	98	99	103	99	100
25	104	102	101	103	101	101	97	97	101	98
26	104	101	101	98	101	103	102	99	98	100
27	103	99	98	100	100	100	98	97	100	98
28	103	99	98	95	98	100	101	99	100	99
29	103	99	101	99	100	98	99	98	97	96
30	99	98	98	94	98	98	96	99	99	95
31	99	99	100	96	97	94	98	92	95	93
32	98	97	99	96	99	96	95	96	96	97
33	99	97	98	96	96	96	98	95	96	96
34	97	94	93	100	97	98	95	93	96	94
35	99	95	96	91	97	95	94	97	95	94
36	97	96	94	94	97	95	92	95	94	94
37	95	96	91	88	98	92	94	94	94	95
38	96	93	90	91	91	94	91	92	91	94
39	94	92	88	85	89	90	91	95	92	92
40	93	90	87	88	86	93	94	92	95	88

Table 2.

NOR ETP Jan grp 2 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	131	135	133	133	132	134	128	129	133	130
2	126	128	126	124	124	125	125	124	124	125
3	123	124	122	121	123	118	120	114	119	120
4	122	123	117	118	114	117	116	114	113	118
5	121	120	116	116	116	116	116	73	70	116
6	122	117	112	100	116	97	110	0	0	100
7	116	117	76	39	113	33	91	0	0	39
8	120	108	0	0	113	0	18	0	0	0
9	116	116	75	88	103	84	83	81	75	52
10	117	116	108	108	108	109	106	104	106	104
11	117	116	110	106	110	108	105	104	106	107
12	116	111	107	108	107	107	107	101	107	105
13	117	113	107	104	105	107	107	104	105	105
14	113	109	105	107	107	106	104	106	107	107
15	111	111	106	105	100	103	104	106	105	106
16	115	109	108	102	106	104	106	106	106	106
17	112	106	101	106	105	106	102	104	101	104
18	112	110	106	107	105	104	104	105	105	102
19	109	110	105	105	102	103	105	106	104	106
20	109	109	105	101	104	103	102	106	107	106
21	110	108	102	107	107	103	103	106	104	102
22	108	106	104	105	104	105	105	104	104	103
23	106	104	102	104	100	103	104	100	106	103
24	107	106	102	100	101	103	101	99	101	99
25	109	104	102	103	96	102	100	101	103	104
26	108	105	103	101	102	100	104	102	101	100
27	106	103	99	100	98	102	102	98	100	102
28	105	102	99	100	99	99	98	101	97	101
29	107	102	100	101	98	103	102	100	99	101
30	104	101	98	100	100	102	100	98	98	98
31	103	98	101	98	99	99	101	102	98	100
32	105	102	100	97	100	101	100	99	99	94
33	106	97	100	99	92	98	100	97	98	97
34	102	102	97	99	99	97	95	96	96	94
35	101	96	99	95	97	96	94	96	96	97
36	103	98	97	97	99	97	94	96	100	95
37	102	100	98	97	98	98	95	97	97	97
38	100	98	97	97	96	96	97	95	97	97
39	98	99	99	97	94	96	96	97	96	91
40	104	98	100	97	96	95	96	93	94	96

Table 3.

NOR ETP Jan grp 3 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	133	134	133	131	132	132	130	128	135	133
2	128	124	129	123	126	127	127	125	120	123
3	124	125	121	120	121	120	122	120	119	122
4	123	124	117	119	118	119	118	111	118	118
5	123	119	119	116	116	115	115	116	110	92
6	124	119	117	112	111	115	87	104	96	20
7	123	118	113	79	77	105	13	54	34	0
8	119	117	108	3	1	57	0	0	0	0
9	118	116	105	107	109	109	105	108	106	106
10	118	114	106	108	105	108	110	109	107	109
11	116	114	109	107	107	107	108	105	106	107
12	116	114	106	106	106	104	106	105	107	104
13	115	113	108	108	108	106	102	104	107	106
14	115	117	107	106	104	104	104	101	106	106
15	114	110	106	107	107	102	107	105	106	107
16	115	111	102	104	106	110	106	108	106	104
17	112	110	104	106	106	104	105	105	108	105
18	112	111	107	106	106	106	104	104	106	103
19	112	112	104	103	104	103	104	104	106	104
20	112	112	106	104	107	103	105	106	105	104
21	112	108	107	103	102	104	105	105	105	104
22	107	107	102	103	99	104	102	102	101	105
23	110	108	105	101	103	104	104	103	105	102
24	109	106	101	104	102	99	102	103	102	102
25	109	109	104	101	101	101	101	104	102	103
26	107	107	102	98	103	99	102	102	99	100
27	109	106	102	101	95	100	97	101	102	101
28	105	104	99	101	101	100	99	101	103	99
29	106	104	100	101	100	101	101	100	100	101
30	107	104	101	99	100	97	98	100	99	100
31	104	102	101	99	99	99	104	97	100	99
32	103	105	100	101	95	99	95	97	98	97
33	106	102	96	100	96	95	96	100	98	98
34	101	102	97	94	98	98	99	98	98	97
35	102	101	94	98	100	99	94	95	99	96
36	104	102	100	99	99	98	98	95	96	96
37	100	103	97	95	92	97	96	95	93	92
38	102	98	94	95	98	97	97	97	92	97
39	102	95	101	95	94	98	95	96	97	95
40	103	97	95	96	98	96	92	96	97	94

Table 4.

NOR ETP Jly grp 0 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	137	136	135	135	136	130	133	135	129	133
2	130	129	131	126	130	127	129	127	126	126
3	125	121	124	123	124	124	122	122	119	122
4	124	126	122	122	121	120	120	119	120	118
5	121	122	123	116	120	119	118	116	118	116
6	124	120	119	120	115	116	117	116	115	102
7	124	121	117	116	113	114	114	113	112	50
8	121	119	115	115	114	112	112	113	87	0
9	121	119	115	115	112	112	111	111	13	0
10	121	118	114	113	110	110	108	107	108	104
11	119	116	117	111	111	108	103	109	103	107
12	118	117	111	113	112	108	105	107	107	105
13	118	113	113	113	108	103	106	105	107	104
14	115	116	113	114	109	105	107	105	107	101
15	115	113	111	112	106	101	105	106	105	105
16	115	112	114	111	108	105	104	105	106	100
17	114	112	113	110	107	103	101	104	105	105
18	114	114	110	109	109	104	105	99	105	103
19	109	114	113	111	106	102	102	102	103	103
20	110	112	110	109	105	106	106	103	103	103
21	111	108	109	108	106	103	102	99	103	103
22	112	111	108	109	105	104	103	100	99	103
23	109	109	110	107	104	98	104	103	102	98
24	111	107	107	105	104	105	103	101	98	102
25	108	108	107	107	104	103	103	101	101	99
26	108	106	105	103	106	102	101	102	102	101
27	108	106	105	102	102	104	103	98	101	100
28	106	106	106	105	99	98	98	101	101	101
29	108	105	102	102	99	98	99	97	100	100
30	107	106	101	103	103	98	100	101	98	96
31	103	104	104	100	104	96	100	98	100	98
32	104	105	101	103	100	101	101	97	99	95
33	103	105	100	101	101	98	102	99	98	99
34	106	96	99	99	100	100	98	97	100	98
35	107	105	101	95	100	98	97	96	99	99
36	100	100	98	98	98	97	96	98	94	96
37	101	103	100	102	98	96	96	95	97	97
38	103	105	100	95	97	97	96	95	93	98
39	100	100	102	97	98	98	97	97	93	95
40	100	101	100	97	99	97	93	96	91	94

Table 5.

NOR ETP Jly grp 1 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	134	131	129	131	131	130	130	130	129	131
2	127	122	126	120	118	122	121	123	122	123
3	126	118	119	115	118	114	119	119	104	110
4	123	121	117	96	87	74	95	117	72	98
5	123	115	116	31	11	0	27	93	19	64
6	120	118	110	0	0	0	0	25	0	9
7	119	118	73	33	36	56	11	0	0	0
8	117	112	110	109	107	110	111	109	109	108
9	118	112	108	110	108	108	111	107	107	108
10	113	112	108	109	108	104	107	109	110	109
11	115	110	109	109	110	107	105	107	107	105
12	112	111	111	104	107	108	105	109	108	103
13	112	109	109	106	108	105	105	109	106	108
14	110	109	107	104	108	109	110	107	105	106
15	109	109	108	107	108	109	108	106	107	105
16	108	108	107	109	105	105	104	107	106	108
17	105	113	108	106	104	107	105	105	105	107
18	108	108	108	106	108	105	106	106	108	107
19	106	109	103	106	103	105	105	106	107	107
20	109	109	107	108	107	103	102	104	104	106
21	105	104	102	104	106	106	100	106	105	106
22	107	104	104	106	104	103	101	101	103	103
23	105	107	105	100	106	105	103	105	103	103
24	104	105	101	105	104	102	104	104	102	104
25	105	104	102	102	102	100	105	105	102	103
26	104	106	104	103	101	99	100	102	102	102
27	105	101	105	103	104	101	102	99	104	100
28	101	104	102	102	102	98	101	100	100	101
29	100	100	101	101	104	103	97	103	96	100
30	102	99	102	102	100	98	101	101	101	100
31	101	101	103	102	97	101	99	100	98	99
32	103	104	102	102	98	99	100	100	101	100
33	101	101	97	102	103	100	98	99	100	97
34	99	100	96	98	98	98	97	100	97	100
35	99	97	97	98	99	98	96	99	99	101
36	91	98	96	96	101	97	97	93	96	99
37	94	96	94	96	94	99	95	96	97	97
38	96	95	90	91	92	96	97	96	97	98
39	93	98	89	92	89	96	93	95	95	91
40	95	97	91	91	91	98	94	94	94	93

Table 6.

NOR ETP Jly grp 2 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	125	123	128	127	124	128	128	126	127	130
2	123	124	120	124	123	121	121	122	119	122
3	119	116	119	120	118	112	117	118	119	118
4	118	113	112	114	112	112	113	112	112	115
5	112	111	109	111	108	105	109	108	110	108
6	110	105	103	108	103	106	106	101	105	105
7	108	99	99	103	100	95	96	98	100	100
8	106	89	93	97	91	91	91	91	95	93
9	105	83	83	90	80	79	82	82	87	85
10	105	99	102	98	99	99	96	98	98	98
11	103	102	101	100	104	103	101	101	99	97
12	105	103	101	100	105	100	102	103	99	104
13	101	101	100	102	101	100	100	102	103	100
14	100	100	101	102	97	101	100	104	101	101
15	101	99	99	103	102	102	99	101	100	101
16	101	98	97	96	99	98	100	101	102	99
17	100	100	101	98	100	99	98	98	100	95
18	100	97	100	99	98	102	99	97	101	99
19	99	100	101	99	100	99	98	99	100	101
20	100	98	99	96	102	97	100	97	99	97
21	98	97	103	101	97	100	100	95	100	99
22	96	98	98	99	98	98	99	94	101	99
23	93	100	101	101	100	96	99	100	95	99
24	96	98	97	97	98	98	95	96	99	98
25	98	95	98	97	94	97	97	97	99	93
26	97	96	94	95	93	96	95	96	98	94
27	96	95	95	96	95	96	95	95	95	94
28	96	97	94	97	95	94	97	96	98	96
29	95	96	94	95	95	95	96	96	96	92
30	94	95	95	94	93	91	95	97	95	96
31	95	97	96	93	90	94	92	94	94	94
32	96	95	93	93	92	92	95	92	93	92
33	95	92	92	93	91	93	93	92	90	92
34	94	93	90	92	92	91	93	91	90	91
35	95	91	94	93	90	92	92	92	92	91
36	92	92	92	92	91	93	92	92	93	94
37	90	94	89	91	92	93	90	93	92	86
38	91	94	90	91	89	90	90	90	90	90
39	92	90	90	92	89	92	91	90	92	91
40	88	90	89	91	89	90	89	85	89	90

Table 7.

NOR ETP Jly grp 3 6khz SL=200

R(km)	Source Depth 10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
1	135	135	134	134	136	131	136	133	131	134
2	130	130	128	129	130	126	125	128	124	128
3	128	127	127	126	123	125	123	122	119	125
4	124	120	124	123	121	121	115	120	121	118
5	123	124	122	120	119	119	117	115	116	116
6	122	120	121	118	115	117	115	109	115	115
7	118	119	119	116	110	116	109	105	111	112
8	119	117	117	115	117	112	97	68	113	112
9	114	115	116	116	112	112	39	0	111	110
10	119	119	116	113	111	111	0	0	96	110
11	119	117	115	114	109	107	0	0	44	91
12	118	117	114	115	110	100	98	100	99	99
13	114	116	116	114	108	102	105	105	104	107
14	115	117	114	112	109	104	103	105	102	103
15	115	114	112	113	108	101	101	103	100	103
16	111	112	112	110	108	101	103	106	104	103
17	115	112	111	111	109	99	101	100	103	100
18	109	113	110	111	103	103	105	104	103	102
19	111	111	106	109	106	101	99	105	97	103
20	111	111	110	105	107	105	101	102	103	100
21	108	111	108	108	106	102	101	98	102	101
22	111	110	110	105	103	100	100	101	101	98
23	111	105	105	109	105	104	100	101	97	100
24	108	108	110	106	102	100	100	101	101	99
25	109	110	104	107	105	101	101	99	100	101
26	106	106	104	105	102	100	100	94	97	101
27	107	108	105	105	104	96	100	96	100	101
28	105	107	104	103	102	100	98	99	98	99
29	106	106	107	104	102	99	100	99	95	99
30	103	107	103	104	100	97	97	99	101	98
31	104	106	103	101	101	96	96	100	99	98
32	102	102	98	104	99	95	98	99	94	98
33	103	104	100	100	94	94	98	97	94	96
34	103	103	103	103	99	94	96	96	98	98
35	101	98	99	99	99	98	94	94	95	98
36	100	102	99	99	96	94	92	96	97	95
37	104	102	100	97	97	92	96	92	94	94
38	99	97	101	97	96	91	93	92	93	92
39	102	100	96	97	93	95	92	92	92	91
40	98	97	97	100	95	95	96	93	92	92

Table 8.

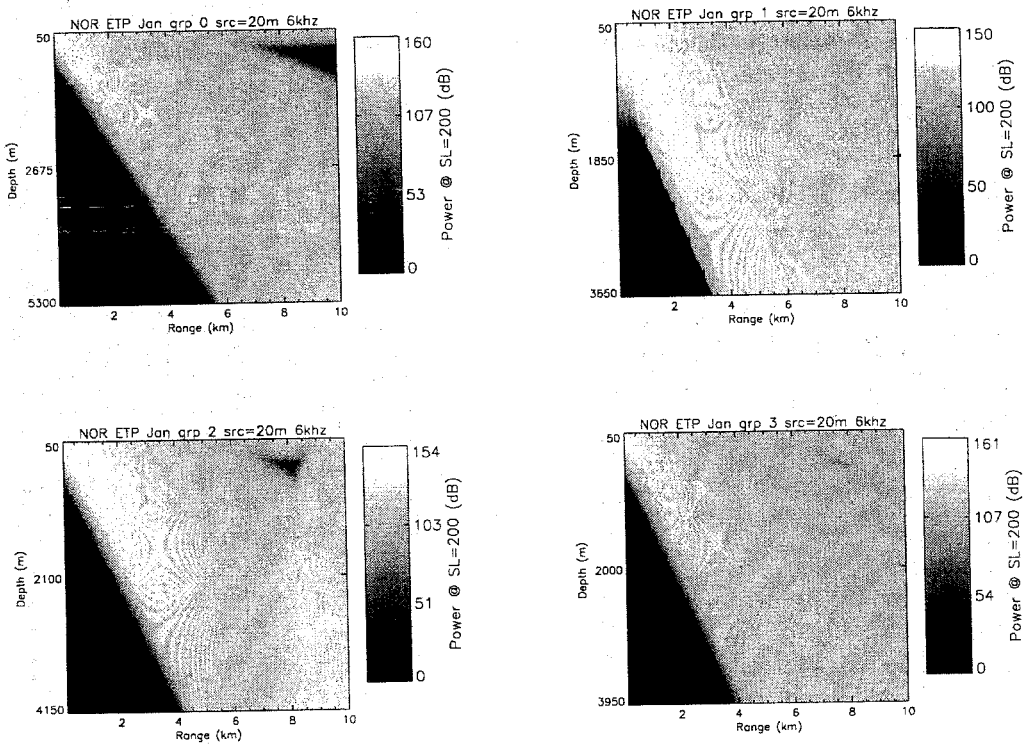


Figure 3.

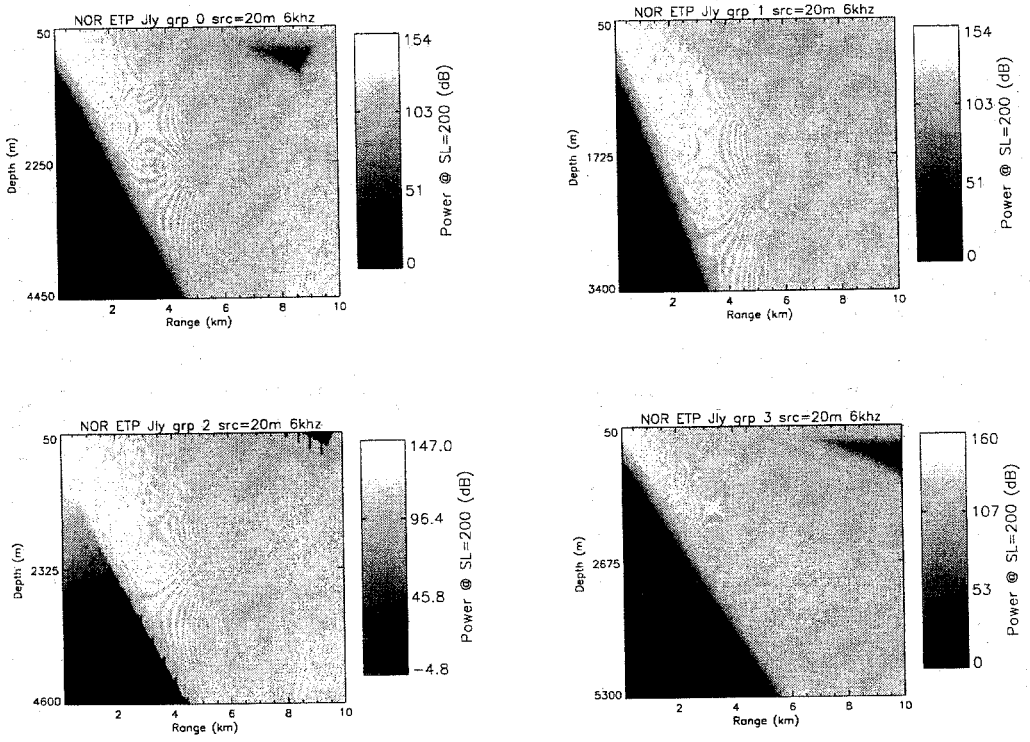


Figure 4.

The acoustic levels displayed in the tables and figures represent the RMS intensity of a continuous tone at the displayed frequency, 6 kHz. That is, they are the levels a calibrated acoustic power meter would display given a 200 dB source operating continuously under the conditions specified. The total acoustic energy delivered is in turn a function of how long the signal persists, or the pulselength. Longer pulse lengths obviously deliver more total energy.

Biological damage to a marine mammal or other marine life is a function not only of RMS intensity, but also of peak intensity, total duration, frequency, and waveform. A specific waveform will be altered in terms of its frequency distribution function by propagation through the ocean waveguide, as is demonstrated later in this report. In general it is only possible to assess potential biological damage in detail if the conditions are very highly specified, including the specific waveform and pulse length the organism is subjected to, the absolute sound level, and the specific species (including size and age) that is under consideration. Such a detailed analysis is beyond the scope of this document; however, the RMS intensities reported, jointly with a specified source duty cycle and pulse length, can provide a good average assessment when applied by someone appropriately qualified in assessing acoustic impacts on marine life.

II. General parameters of Active Acoustic Detection Systems

Source Strength

Source strength is the single most important factor in an active detection system. An analogy might be looking through a fog with a flashlight. The brighter the flashlight, the farther one can see. In addition it is assumed that the source can achieve some degree of collimation (directing acoustic energy in a specific direction). Source strengths of 150 to 200 dB were studied. Minimum collimations were hemispheric (2 pi steradians) to 60 degree halfwidth.

Target Strength of Yellowfin Tuna Schools

Target strengths were modeled by Dr. Redwood Nero, NRL (1996). Response at above 1 kHz frequencies in his study are essentially flat. Characteristic target strength results are shown in Figure 5.

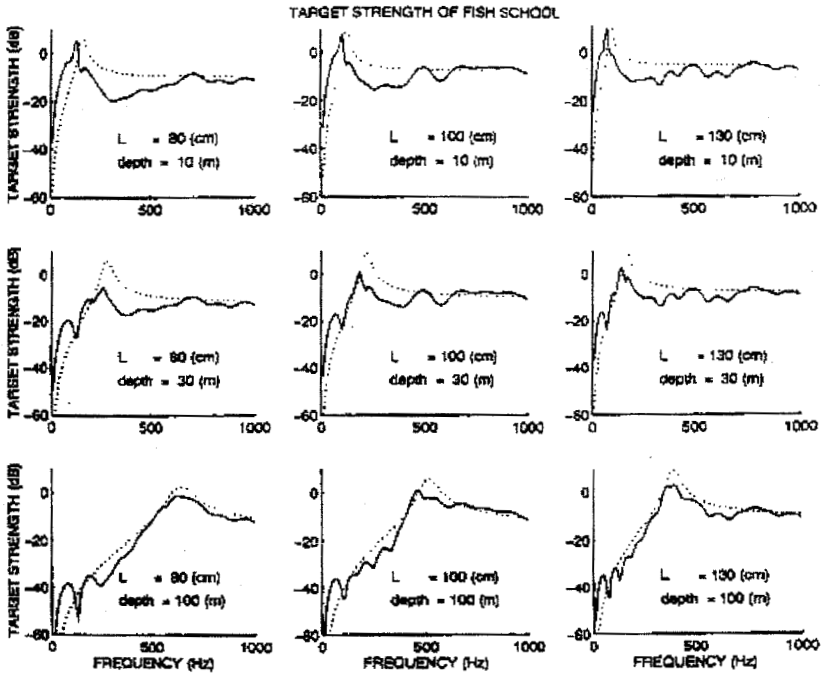


Figure 5.

Collimation

see source strength

Noise

In a time-of-flight detection system, the effective noise is the variation in the background level, not the background level itself, since detections consist of seeing excursions above the background level that match the source pulse characteristics.

Wind-generated background noise is at an absolute level on the order of 50-60 dB under conditions where one could operate a towed array with reasonable ease. Statistical variations are on the order of sqrt(N) or 7 dB. Statistical variations that match a given pulse width, etc., are much lower, on the order of a dB or less. Recall that these are effective levels.

Reverberations effects consist of a reflected pulse arriving from the surface or the bottom at a receiver, or (for the sake of convenience) the original broadcast pulse itself. Because these signals are much stronger than the reflected signal from a tuna school, no detection is possible during these times. These effects are modeled by calculating "blackout" times during the arrival of reverberation signals during which an affected array element yields no detection. There is also a guard band around the calculated reverberation to completely screen the direct signal.

System noise consists of variation in the hydrophone outputs and processing system. Such noise in modern systems is typically very small, on the order of a dB or less, although the processing may contribute to the system noise.

There are two classes of Signal-to-Noise Ratios (SNR): preprocessing (raw) and postprocessing (processed). Due to amplification gains in the processing (detecting only "signals" that correspond to expected reflections from tuna schools), very low raw SNRs can be detected, even at the level of -10, -20, or -30 dB (with the numbers closer to zero corresponding to simpler systems). Processed SNRs must be greater than one to be detected.

The difference between raw and processed SNRs comes from noise suppression. Noise suppression is achieved by using a matched filter; that is, a filter that only counts as a detection a set of received signals on the array that match the expected output from a reflection from a tuna school. Matched filters can be shown to be optimal; that is, there is no better filter for the purpose of detection and tracking. Defining a match can be the difficult part of building a matched filter. Neural network processing is a way of implementing a matched filter without necessarily knowing all the characteristics of the filter, and could be applicable in tuna detection. Neural network processing is not studied here, however, because there is insufficient information to practically assess such processing in this specific application, beyond noting that it is a promising match to the requirements.

The filter used in this study is essentially an edge detector - that is, it only cares about the leading edge of an arriving signal. This filter results in a number of simplifications in the signal processor and the study and is thus a practical system to implement in the system model. It's use does mean, however, that there is minimal information available about the characteristics of the reflector (school of fish). More information can be derived by analyzing the signal characteristics themselves (the actual received signal).

Beamforming

Beamforming is the process of combining the outputs of the array elements to derive an estimated direction of the arriving signal. The direction is specified relative to the array axis. In this study zero degrees corresponds to the array axis direction pointing to the rear of the array (away from the tow), and 180 degrees to the front of the array (towards the tow). These two conditions are called "endfire"; the condition of a signal arriving perpendicular to the array axis is called "broadside" and is the "best" (optimal) direction for detection. Beamforming is symettric about the array axis; that is, there is no way to tell right from left on the array. This ambiguity is resolved by the collimation of the source.

Tracking Requirements

Tracking requires accurate range and bearing estimates for a time period long compared to the time scale of the target's motion. In the modeled conditions, continuing detection probabilities greater than roughly 30% should yield acceptable tracking. Assuming a duty cycle time roughly on the order of one minute, then ten pulses would be delivered in ten minutes, a time period short enough that it seems likely the target fish school would experience only a small change in relative position. If ten points are scattered randomly throughout an area, with 30% (3) corresponding to an actual location, then the result will be (on average) seven randomly distributed points with three points tightly clustered. Clusters of two points from random overlap would occur too frequently to assign a high likelihood of that cluster corresponding to an actual target, whereas a three-point cluster would be significant. Thus the 30% detection probability rough estimate for continuous tracking.

In the studied configurations, then, tracking should not be a problem and should be acceptable in the modeled range.

III. Detection Characteristics Parameters for study area

Ranges

Ranges were studied from 3 to 20 km for an active system, resulting in round-trip ranges of from roughly 6 to 40 km. The system realizations were available at arbitrary values within this range.

Minimum fish school sizes

Only fish school sizes modeled by Nero (1996) were used, with the "small" fish size most frequently used. Nero adjusted his study to maintain a constant fish school volume, meaning more fish for small size. Due to the relatively flat response to acoustic signals at frequencies greater than 1 kHz, changes due to different Nero fish school size were minimal. Extrapolation to different fish school volumes is unknown.

Waveforms

The study utilized mainly an edge-detector configuration, meaning that only the leading edge of waveforms was truly significant in the processing. Different types of waveforms available include:

1. An impulsive source, which is a source that delivers all its power to the medium at a single instant. Explosives constitute impulsive sources. Impulsive sources were not modeled here.

2. A monofrequency source, (Figure 6) that turns on at a given time and frequency, and stays on at constant amplitude for a given duration time delta-t. The RMS plot for such an output is:

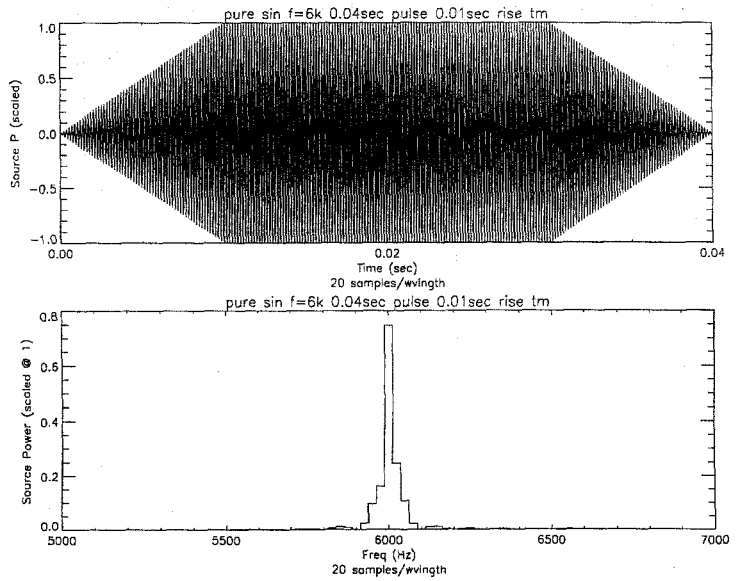


Figure 6.

3. A comb source, consisting of a combination of monofrequency sources but at different frequencies. The RMS plot is shown in Figure 7:

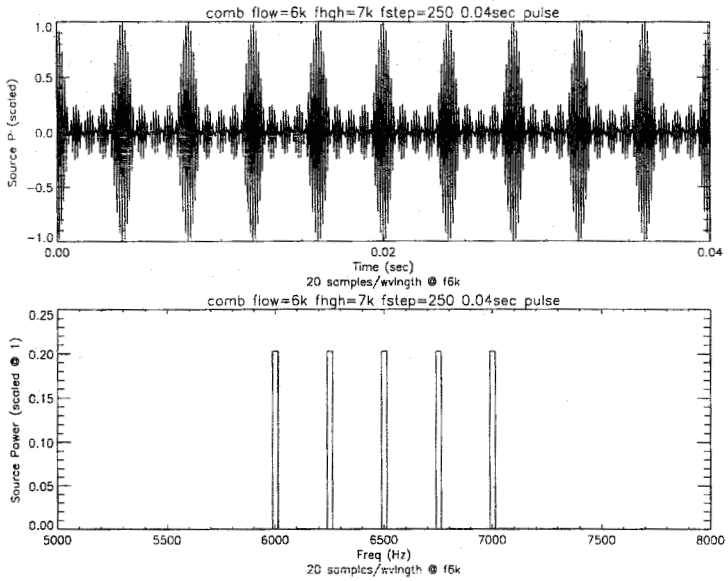


Figure 7.

4. A hyperbolic source, which has a frequency transform (power spectral density) consisting of an average linear behavior in frequency. The RMS plot is shown in Figure 8:

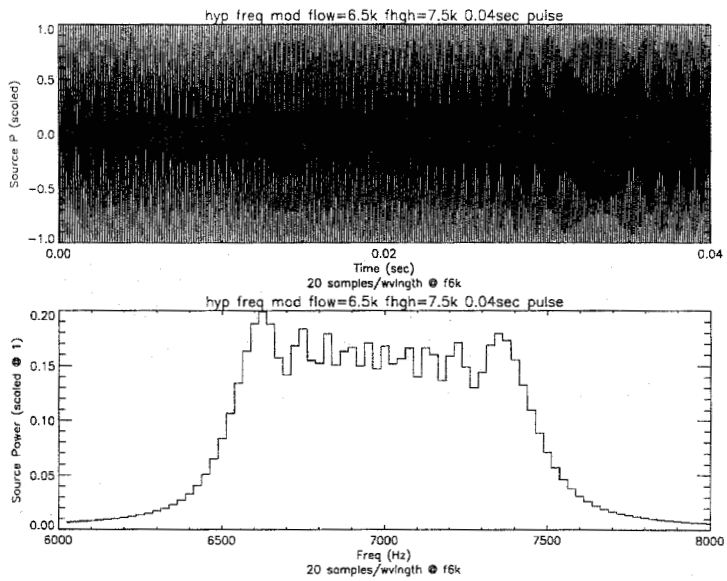


Figure 8.

5. A frequency chirp having linearly increasing instantaneous frequency with time (Figure 9.). The frequency chirp has a flat power spectral density function (equal power in all bins between the start and stop frequencies), and thus is a good probe of all frequencies in a given band. The RMS plot is:

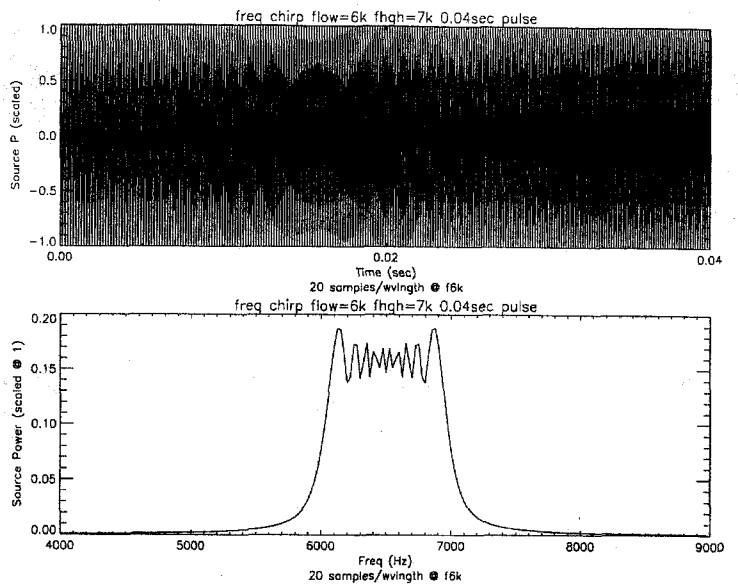


Figure 9.

To illustrate how propagating through the ocean waveguide distorts the time and frequency content of a broadcasted acoustic waveform, Figure 10 demonstrates the above chirp waveform's time and frequency characteristics for each separate arrival as the pulse propagates outward. The predicted waveform characteristics are shown for 2-kilometer increments from 4 to 20 kilometers distance, inclusive. There is a single arrival at each of 4 km range, 6 km, 8 km, and 10 km; three distinct arrivals at 12 km range; and two distinct arrivals at 14 km, 16 km, 18 km, and 20 km. These predicted waveforms are only a lowest-order calculation incorporating the multipath structure of the ocean waveguide, and complex time-varying effects such as doppler spreading from the moving ocean surface and scintillation from multiple scattering effects are not included.

It is obvious that quite severe distortions in time and frequency content can occur as an acoustic pulse propagates in the ocean. It is important to consider these distortions when using the detailed information content of the pulse to classify a target; the waveguide distortion effect may mask or alter the reflection characteristics of a fish school or other target. It can also be of importance to consider the waveguide modifications in the frequency power spectrum when considering acoustic impacts of the broadcast pulse at different frequencies.

Note that the frequency power spectrum of the original broadcast chirp pulse was flat - that is, it had equal power at all frequencies in the broadcast bandwidth. Note also that these predictions are one-way predictions only (before reflection and propagation back to the receiver). Scattering from the target and return propagation introduce even further distortions.

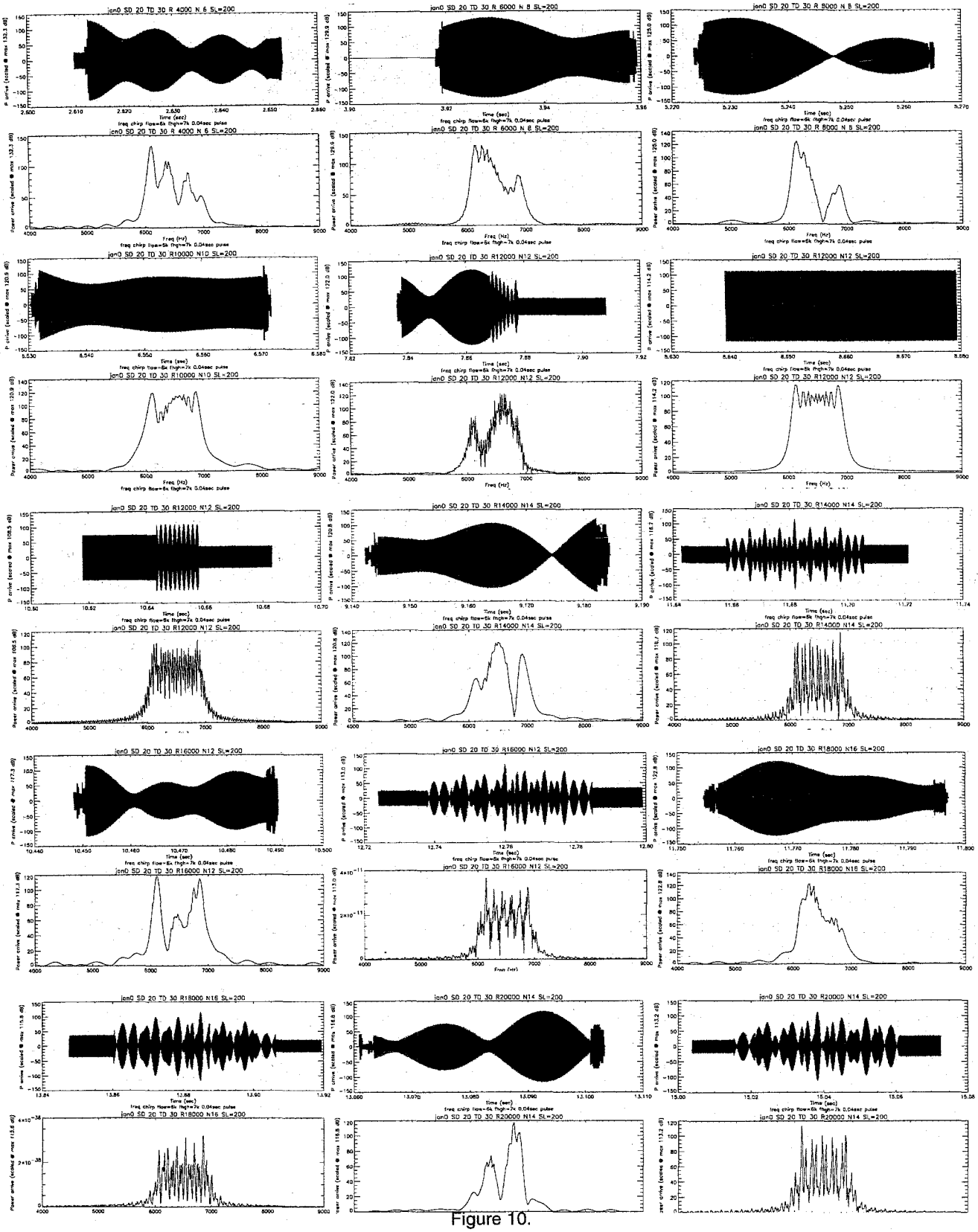

jan0 SD 20 TD 30 R 4000 N 6 SL=200
jan0 SD 20 TD 30 R 6000 N 8 SL=200
jan0 SD 20 TD 30 R 8000 N 8 SL=200
jan0 SD 20 TD 30 R10000 N10 SL=200
jan0 SD 20 TD 30 R12000 N12 SL=200
jan0 SD 20 TD 30 R14000 N14 SL=200
jan0 SD 20 TD 30 R16000 N12 SL=200
jan0 SD 20 TD 30 R18000 N16 SL=200
jan0 SD 20 TD 30 R20000 N14 SL=200
Time (sec)
Freq (Hz)
freq chirp flow=6k fhgh=7k 0.04sec pulse

Figure 10.

6. A broadband source, which broadcasts energy throughout a band of frequencies in relatively equal amounts during the time the source is operational. Such sources are not efficient for detection purposes, because the frequency characteristics of the probe pulse are essential for being able to perform a matched filter and thus noise reduction. Thus no modeling was done for a broadband source.

Optimal operating frequencies

Low-frequency operations would be useful for determining characteristics of the reflecting target from its frequency response. The modeled frequency response of a tuna school (Nero, 1996), however, is probably not a reliable guide to the actual frequency response due to variation in school volume, orientation, direction, speed, density, etc. It is possible that a neural-net type approach could "learn" to discriminate yellowfin tuna characteristics from other types of targets, however. The viability of such approaches could only be decided by actual operations of a system.

Low frequencies (below 1 kHz) were not modeled in this study.

Narrow-band operations (monofrequency sources) were studied at 6 and 8 kHz. Differences were minimal between the two frequencies. Operations would be acceptable at either frequency.

Comb-type waveforms basically constitute combinations of narrow-band type operations. They are useful if the information provided by scattering from a target or propagation conditions provide significantly different information on the nature of the target or the target estimated location at different frequencies. At the greater than five kHz frequencies studied here, and using a simple edge detector configuration in the processing software, there is minimal difference between propagation or source at frequencies studied, so there would be minimum usefulness of comb-type waveforms. Lower-frequency combs could be useful for differentiating target types after information is gathered on different target-type responses. A lower-power lower-frequency system might be used at close range for the purpose of determining the target type (tuna school, other fish type).

The spacing in the comb should be chosen to provide the maximum amount of information for the minimum processing - that is, for the minimum number of comb frequencies. If different responses were seen to frequencies differing by 50 Hz, then a 50 Hz spaced comb would be advisable. It seems likely that responses at small frequency differences would be minimal due to smearing effects, so a comb spacing (if used) on the order of 50 to 100 Hz would probably be advisable.

Sweep-type waveforms have the same restrictions as to usefulness as comb-type waveforms. In a sweep-type waveform, the centerline of the frequency power spectrum of the pulse follows a prescribed behavior; for example, a decreasing linear relation between frequency and power spectral density (hyperbolic), which has advantages for overcoming doppler changes in detection characteristics. Doppler changes are caused by frequency shifts due to relative motion of the source and target; for example, the shift of siren's or horn's frequency as it nears and then recedes. For an edge-type detector modeled here, doppler frequency shifts are irrelevant provided the guard band chosen on the gating frequency (if the incoming signal is being frequency transformed and processed by frequency bins) is large enough to include any doppler shift.

Broadband operations are an inefficient use of signal power for the purpose of detecting tuna schools, and are not recommended.

Discussion of choice of optimization parameters

Parameters for the acoustic detections system are optimized with respect to several aspects. The most important is whether the tuna school can be detected at all over the designated range from the source: a system that produces poor detection over the designated range is worthless. The next most important characteristic for the tuna application is the ability to track the tuna school: to produce estimated range and bearings to the school that are within acceptable errors for most of the designated range, and to produce sufficiently consistent range/bearing estimates that a target school could be tracked long enough to either follow its behavior or close on the school. The next most important characteristic after tracking is target discrimination: the ability to tell a school of yellowfin tuna from a school of some other type of fish, or from a whale, or other target. Little is known about using different response characteristics to discriminate different fish school targets, so it is difficult to estimate feasibility or design a technique without more data - such as would be provided by an operating system. Other important parameters include overall system cost, reliability, ease of use by nonacousticians, the sea conditions the system could operate under, feasibility of array deployment and retrieval, possible interference of the array system on conventional tuna boat operations, navigation and noise restrictions on the towing vessel during system deployment, operation, and retrieval, and other factors.

There are tradeoffs between many of these factors. For example, a working system could almost certainly be designed and implemented given unlimited funds; a research and implementation program to gather all data, build test systems, develop processing, and so on, might well be funded at a rate of several million dollars per year for five years or so. However, smaller systems with a good chance of success could be built with significantly less over less time. Similarly, there are tradeoffs between ease of use and system effectiveness in terms of detection and tracking.

Probability of detection requirements

The primary study looked at ranges out to 20 kilometers and angles from zero degrees (along the array axis, away from detection of tow) to 150 degrees. Depths were analyzed down to 100 meters. Any targets at greater than roughly 150 degrees are typically obscured by tow ship noise.

Detection was assessed by requiring the following minimum conditions on the array: a hit (successful edge discrimination) on a minimum percentage of the total elements in the array within a time Tsig, and successful reconstruction of at least one range and bearing estimate from the total set of all hits to arrive on the array. A successful estimate is any reconstruction that corresponds to a physically realizable range and bearing location, and that is consistent with the variances in the edge-detection results from the array. A sample set of predicted edge detections on a 12-element array is shown in Figure 11.

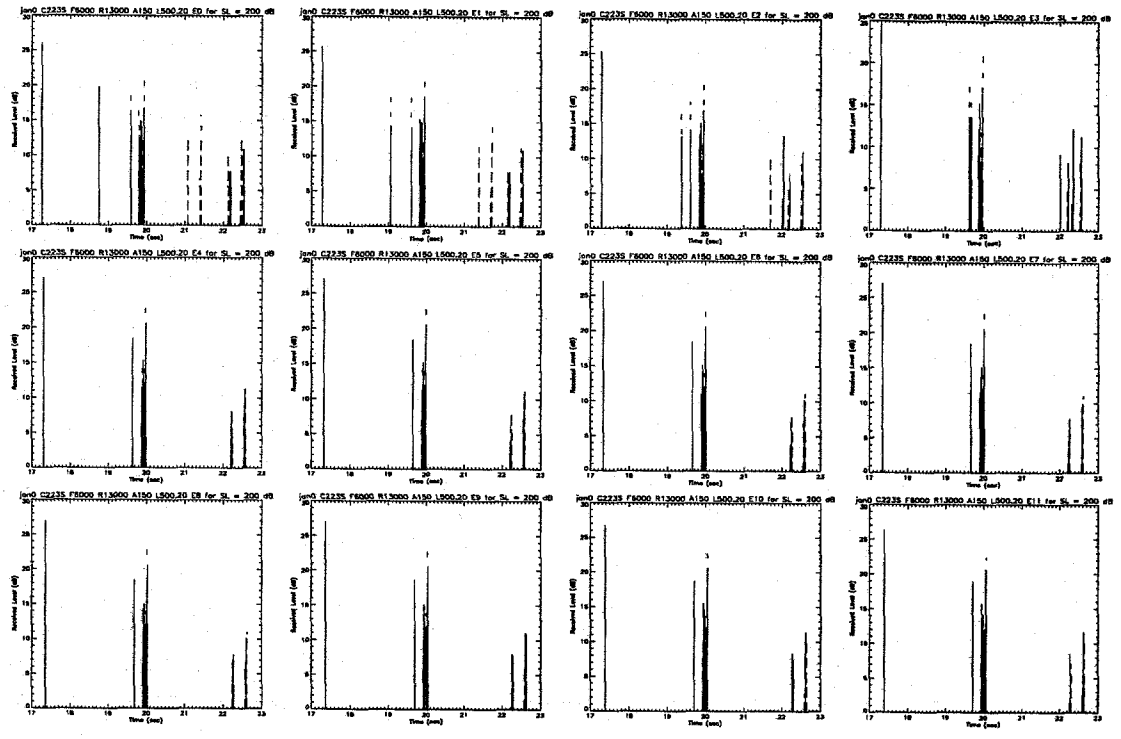


Figure 11.

The minimum fraction of array elements with a predicted edge detection was taken as 70% to ensure good utilization of the array.

Tsig was set by the time for an acoustic signal to travel across the array at longest orientation, with a guardband of half again this time.

Detection results for the 200-dB equivalent source were good throughout the 20 km study area. There are typically ranges and depths where either little acoustic energy propagates (called "shadow zones"), or where the arrival structure is sufficiently complex that no reliable location estimate can be produced. These ranges and depths are functions of the propagation conditions and will impact any array system, no matter how efficient. In general the study showed that coverage of the area was good, with only a few significant bands in range/bearing space where detection was poor.

Detection Feasability and processing model

The processing model is of a simple edge-detection system on each element, with occurance of a pattern of edge detections on the array that correspond to a physically realizable signal, given the source broadcast strength and type, and the target's reflection characteristics (target strength). The edge must be at the right frequency for sources that broadcast in a restricted frequency range. Additional constraints can be added, but for the purposes of assessment only, this model is adequate.

The processing model works as follows:

Each array element (hydrophone) communicates its output to the processor. The output is selected for the correct frequency, typically by using an active filter that passes only frequencies in the desired band. The filter may be present at the element: at-element filtering can reduce operating specifications and result in a less expensive system but constrains the system to operate at a preselected frequency band. The processor looks at the power on each element binned into time chunks to average over random variation and to incorporate the digital aspect of the processing. Typically a running-average type filter is applied to the output time bins for smoothing. When the power on an element rises above its background level by a specified amount, that is counted as a hit on that element at that time bin. The processor only needs to compare channels and hits within the Tsig time, reducing processor load to feasible levels. The processor keeps a list of the current hits on each element, and at each time step (the time bin size), compares the output of all channels to see if there are hits on at least Nmin of Nelem elements. Whenever this N of M condition is met, the processor attempts a reconstruction (range and bearing estimate) on the elements that constitute the hit set. If a successful estimate is found, the hit set and location estimation are put in a list of current estimates.

Typically many hit sets and estimates are generated for a single pulse insonification of the target school, due to multiple arrivals, fluctuations, and different combinations. The processor builds the estimation list over the expected time from the source type (typically on the order of the pulse length) and then compares, averages, or otherwise combines the estimation set to produce a final estimation of target location, or perhaps to decide that no consistent target location can be found. The algorithm used here is a simple "best choice" estimation: the processor chooses the "best" location estimate by looking for (first) the most elements used in the reconstruction and (second) the minimum estimated variance in the reconstruction parameters. Better algorithms are possible, but this is adequate for assessment.

This model has the advantage of being simple to implement, minimizing processor load and thus cost and ease of use, and of being able to tolerate large absolute levels of constant background noise (a necessity for operations in the vicinity of a noisy tuna boat). The edge-detector is also less susceptible to small variations in array alignment caused by currents, boat maneuvers, etc.

Area Coverage

The simple best-planewave processor model just described produced surprisingly good results over the studied range. Adequate beams for tracking and good detection characteristics were present in most or a large majority of cases.

Originally it had been felt that a preprocessed matched-filter processor might be necessary to obtain adequate system performance. However, since the simple planewave beamformer produced better than expected results and is considerably simpler to implement than the matched preprocessed model, the planewave beamformer is acceptable and recommended for this application.

Environmental model case

The results for the ETP area are actually for the four characteristic environment types and for the four seasons, using historically average sound speed profiles and generic acoustic absorption values. Due to time constraints, only the two most-distant seasons in terms of propagation characteristics, Winter and Summer (january and july average characteristic functions) were analyzed.

The corresponding geographic distribution in the Northern ETP of the characteristic environment types is shown in Figure 12. Results for the corresponding characteristic function are expected to apply, at least roughly, in these geographic areas. The areas are labeled according to the characteristic environment number (four characteristic environments were adequate to represent the area, using a maximized-basis-distance derivation of the characteristic environments) 0, 1, 2, or 3, and by the season of the year, jan, apr, jly, or oct. Thus one characteristic environment would be labeled by "jan0", and so on.

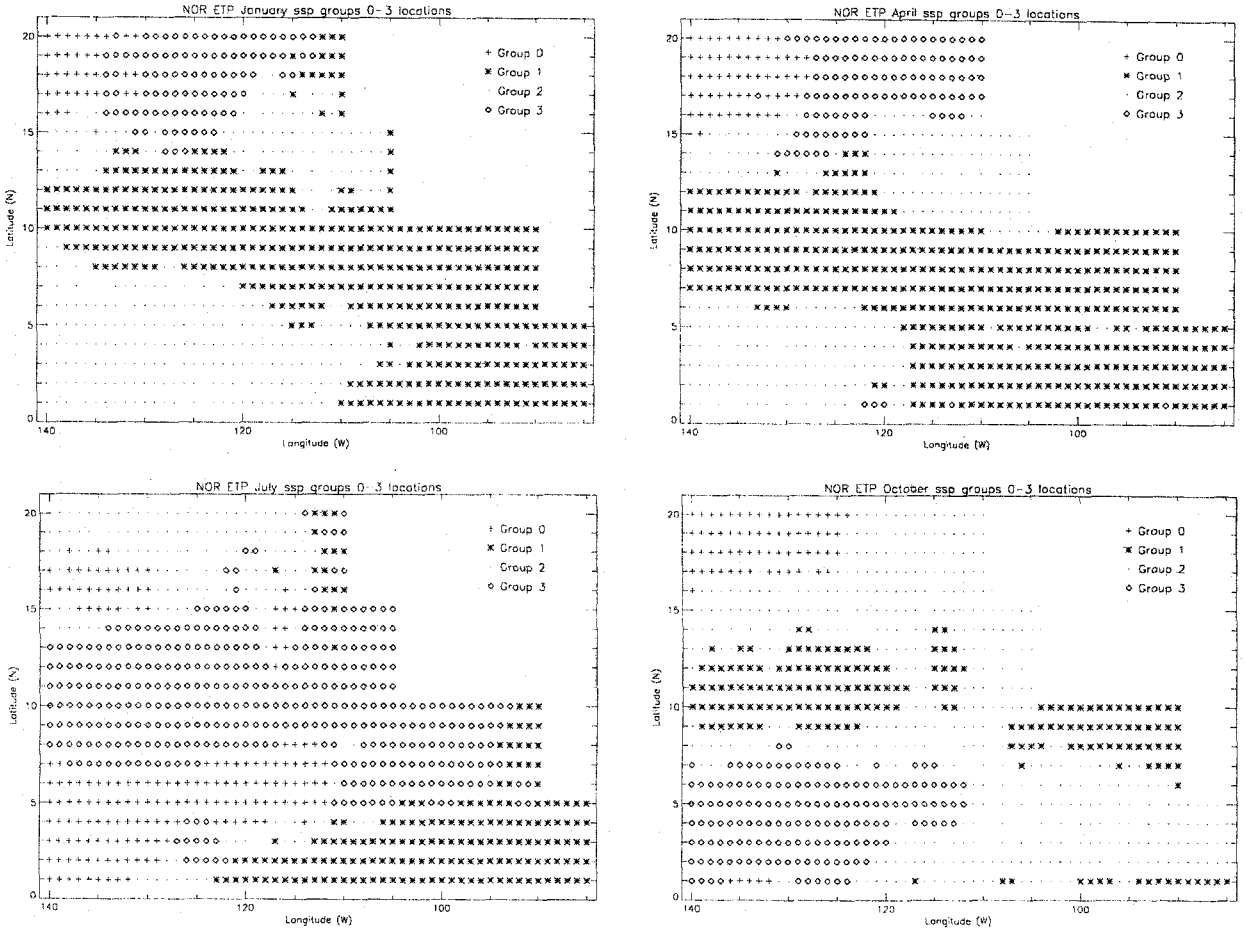


Figure 12.

Because these results are for characteristic environments over historically-averaged times, actual results may vary considerably in a particular instance. Significant changes from historical averages, such as strong El Nino conditions, may also produce varying results. Over a long period of time and a large number of locations in the ETP, however, the derived results are expected to represent an oper-

ating tuna detection system in the ETP.

Parameters

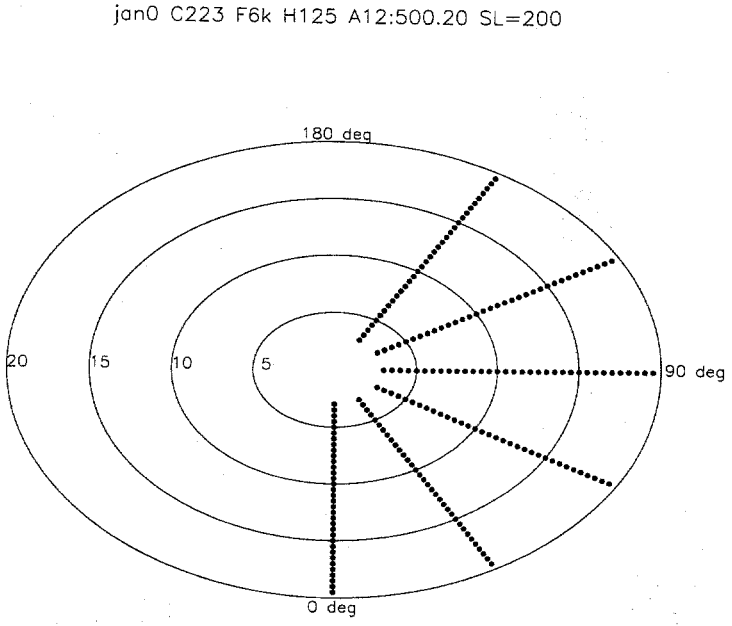
Typical results of the edge-detector model are shown in Figures 13-21 for a particular choice of system parameters. Detailed results for other combinations of system parameters are included in the appendices. Results are shown in terms of processor detection and predicted location accuracy, first arrival times on the array, peak power on the array, and average power on the array.

The processor detection and prediction accuracy is shown in a radial plot of the search space. If a detection was made (in the simulation) at the test location, it is indicated by a line from the test location (the actual location of the target) to the predicted location from the processor. Thus a perfect detection would be represented by a single point. Short lines indicate small errors, and long lines large errors. Errors increase with range. In the plots, it is seen that nearly all errors are towards the perpendicular direction; this is an artificial result of the reconstruction algorithms assumption of perfect hemispheric resolution and in reality the errors would be distributed around the test radials. Lack of a simulated detection (a school was present but not detected) are represented by large black dots.

First arrivals, peak acoustic power, and average power are displayed in the remaining plot for each radial as a function of range. Each radial line is labeled by its angle (see following paragraph) with the lower-right corner of the angle label abutting the labeled line. Again black dots represent no-detects. Linear first arrivals represent detections easier to reconstruct in a plane-wave beamformer, and higher powers represent better detection probabilities.

Figure 13 shows the test locations - that is, acoustic array results were calculated at the dotted locations. The test locations were at half-kilometer increments from 3 kilometers out to 20 kilometers along the 0, 30, 60, 90, 120, and 150 degree radials. The coordinate system is such that 0 degrees corresponds to the array axis away from the tow direction, 90 degrees is perpendicular to the tow direction, and 180 degrees is in the tow direction. Range circles are shown at 5, 10, 15, and 20 kilometers. There is no test run in the direction of the tow ship because tow ship noise overwhelms any signal in this direction. Because a straight array is right-left symmetric, only one hemisphere need be analyzed.

Figures 14-21 show results for this configuration for the eight characteristic environments studied: jan0, jan1, jan2, jan3, jly0, jly1, jly2, and jly3. The configuration number ("Cijk") gives the source, target, receiver configuration: i is source depth in tens of meters, likewise j for the target and k for the receiver (array). A "0" configuration number represents 100 meter depth. Thus C223 represent 20 m source depth, 20 m target school depth, and 30 m array depth. The central frequency of the pulse is given by the F-number ("Ff"), with f the center frequency. Processor effective sampling frequency of the edge detector is given in Hertz by the H-number ("Hh"). The array configuration is given by the A-number ("An:l.s"), where n is the number of elements, l is the tow distance (lag) to the receive section in meters, and s is the element spacing in meters. The source level is indicated by "SL".



Range, Angle Test Locations

Figure 13.

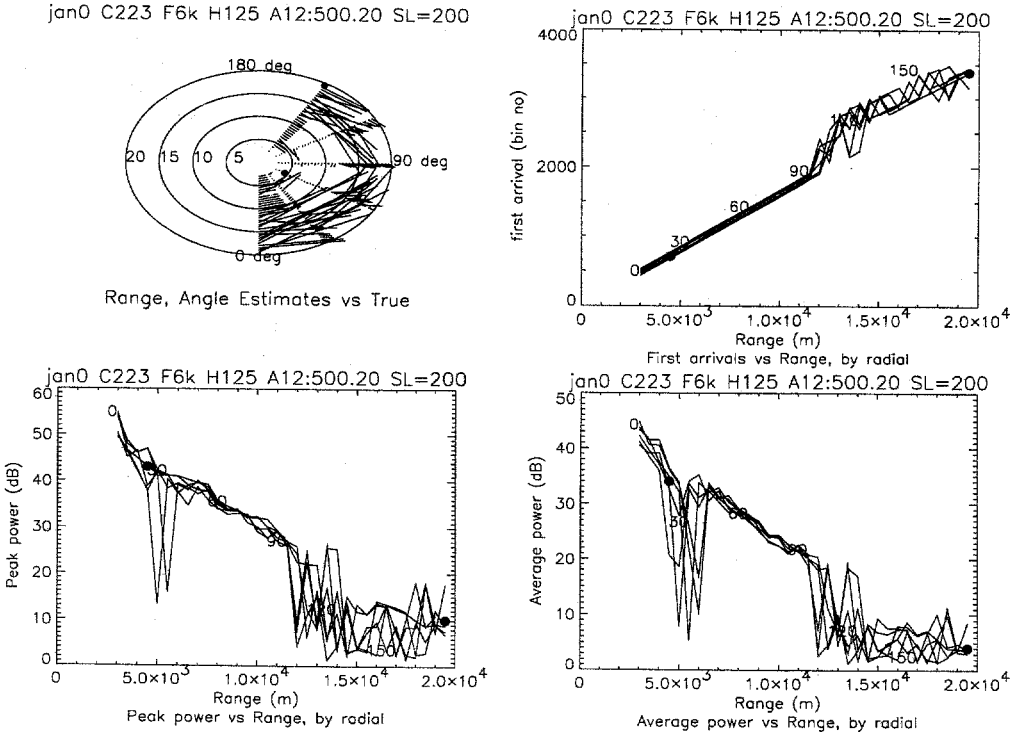


Figure 14.

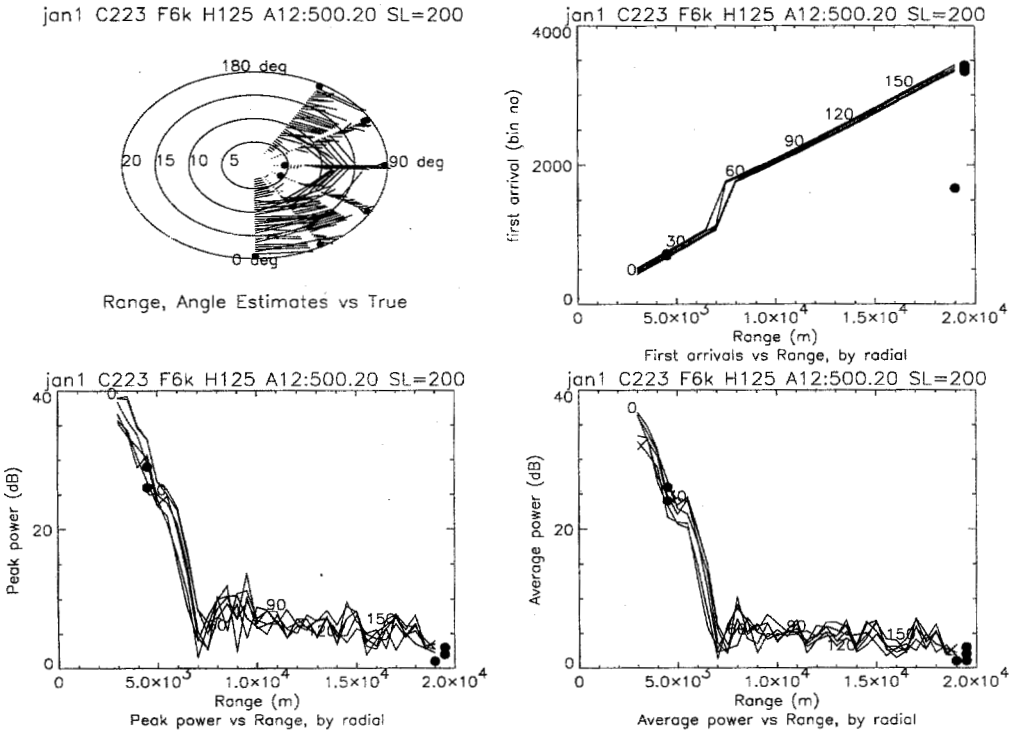


Figure 15.

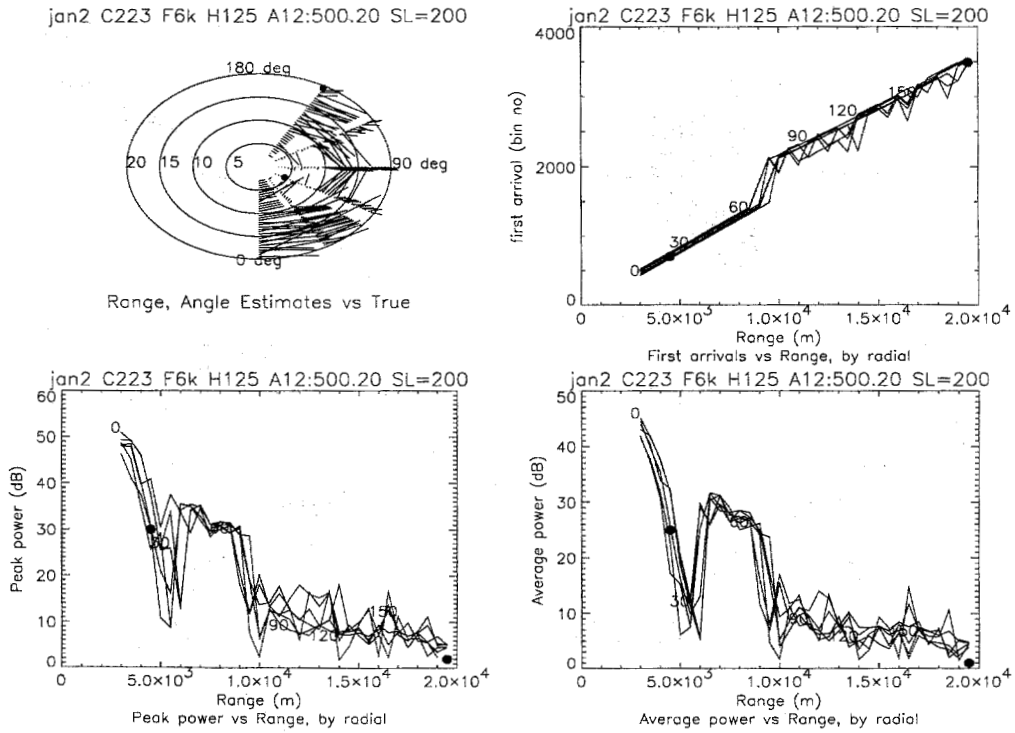


Figure 16.

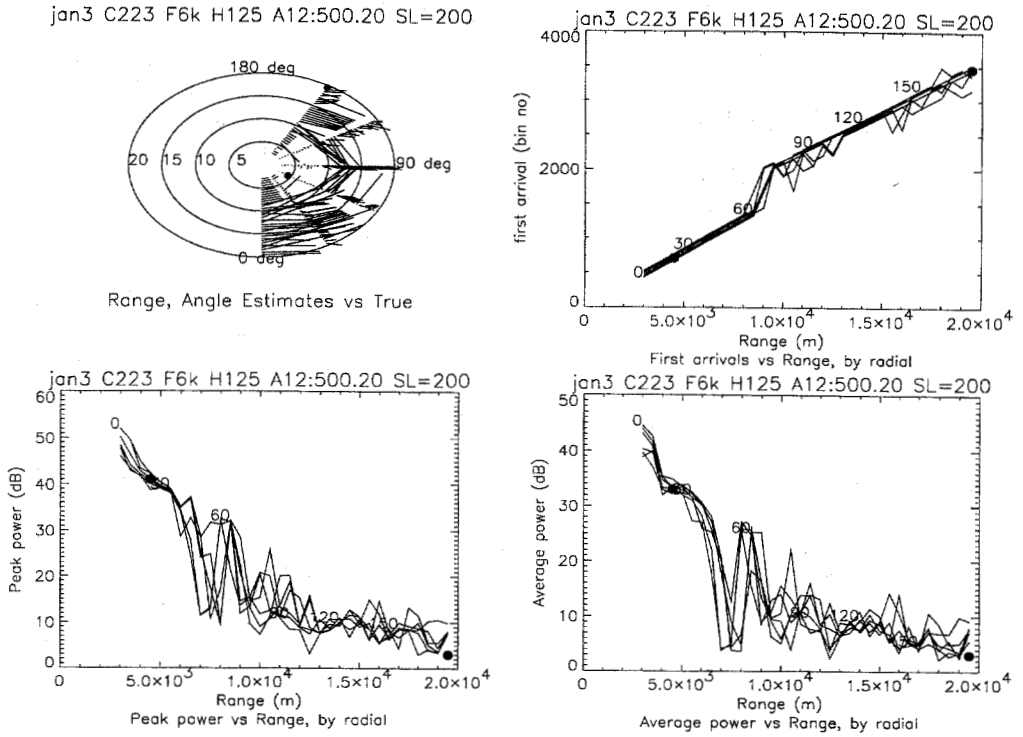


Figure 17.

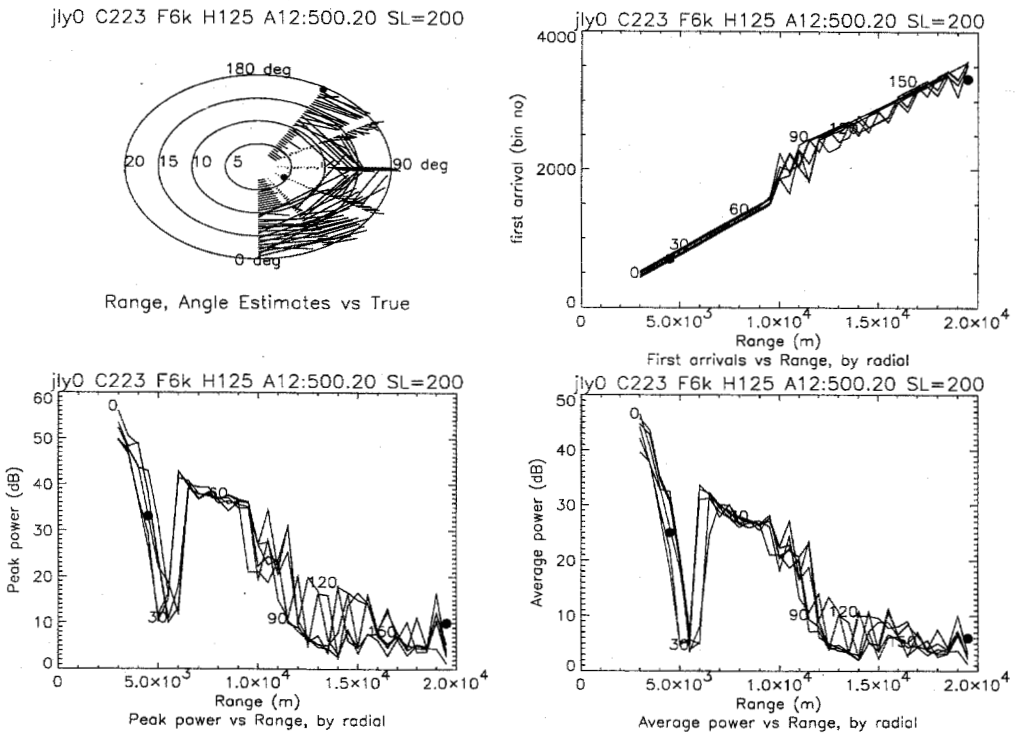


Figure 18.

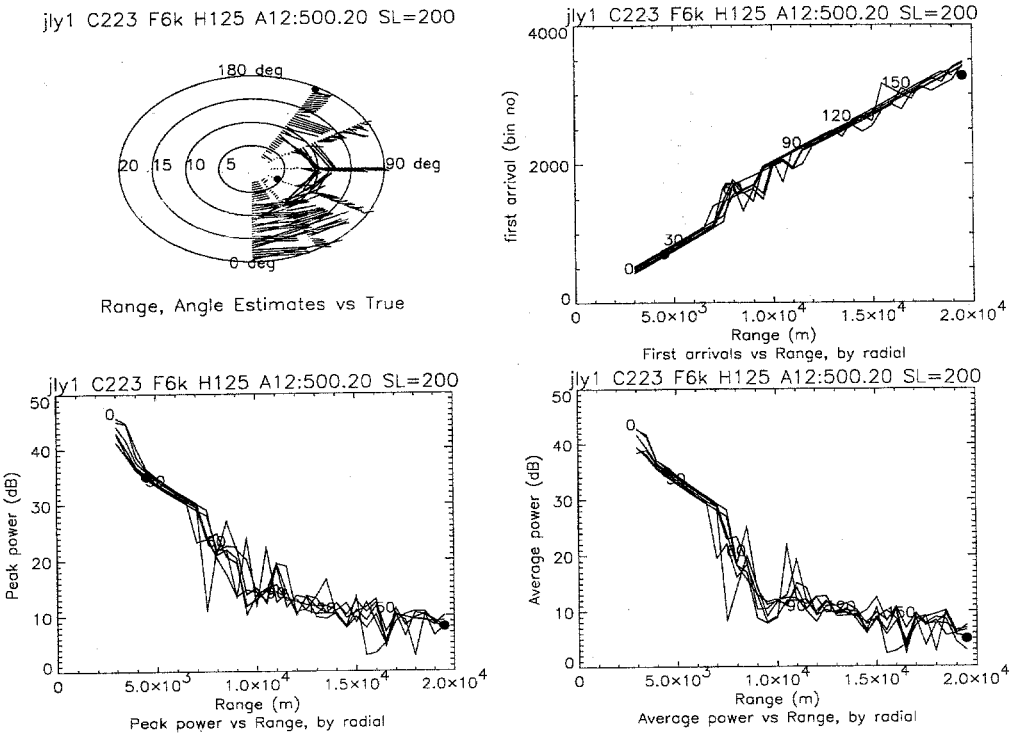


Figure 19.

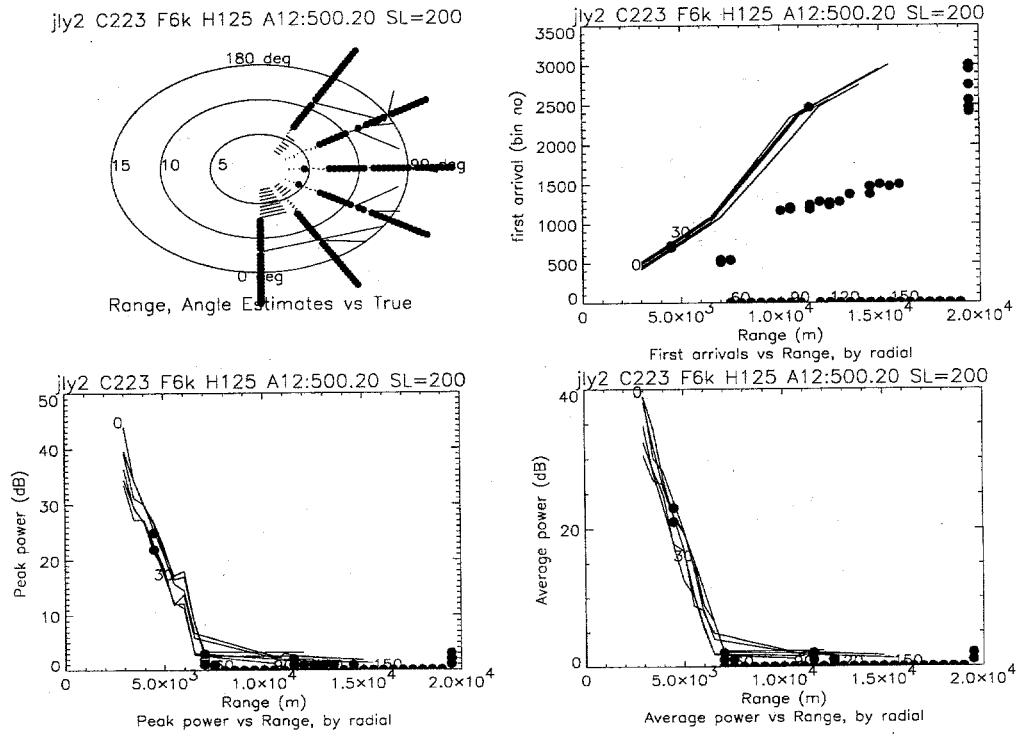


Figure 20.

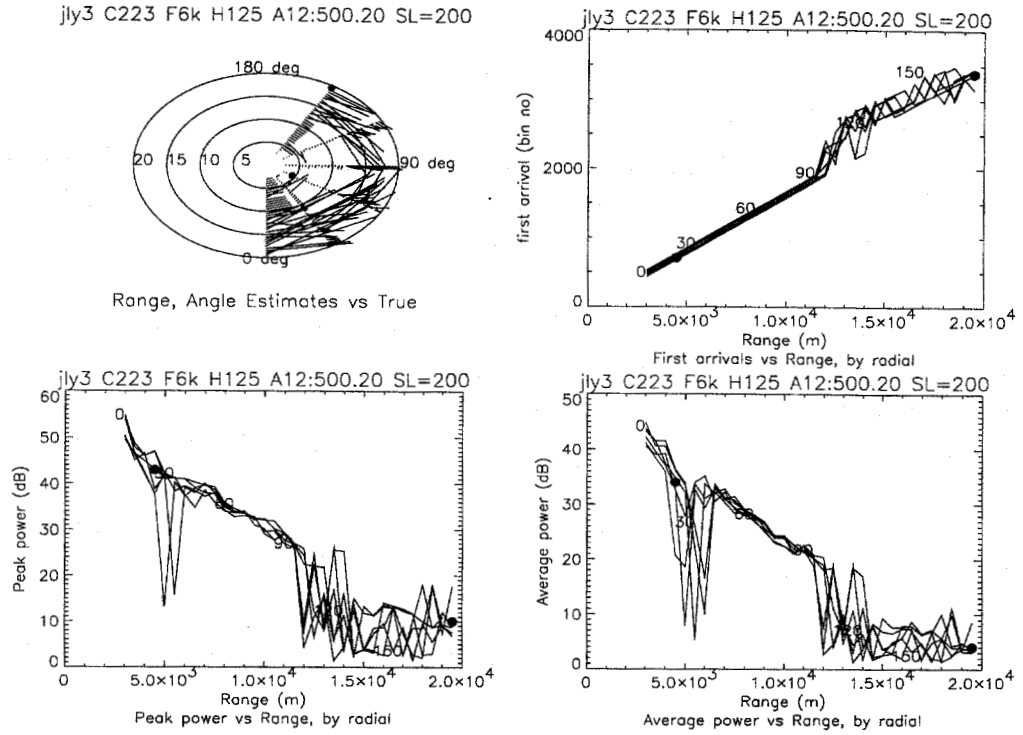

jly3 C223 F6k H125 A12:500.20 SL=200
180 deg
20 15 10 5
90 deg
0 deg
Range, Angle Estimates vs True
jly3 C223 F6k H125 A12:500.20 SL=200
first arrival (bin no)
Range (m)
First arrivals vs Range, by radial
jly3 C223 F6k H125 A12:500.20 SL=200
Peak power (dB)
Range (m)
Peak power vs Range, by radial
jly3 C223 F6k H125 A12:500.20 SL=200
Average power (dB)
Range (m)
Average power vs Range, by radial

Figure 21.

Number of elements

The processor had sufficient information with a simple 12-element array to handle adequate location and tracking, inside the 20 km maximum range intensively studied. Improved beamforming was, as expected, seen with a 20-element test array, but not overwhelmingly so.

The array gain, or gain from having more than one element available to process and compare, increases as log Nelem, where Nelem is the number of elements in the array, at least for planewave beamformers. For long distance operations, maximizing the number of elements thus increases detectability and improves tracking. However this also increases processor load and system complexity.

Inside the 20 km range, given adequate peak source strength in the broadcast direction, a simple 12-element array would be adequate.

For more distant ranges, a 20-element array or higher number of elements might be necessary to increase array gain.

In the study, most analysis was done with 12 elements to minimize processor time in this computationally-intensive work.

Time resolution for edge detector (binning size)

Time sampling resolutions as low as 100 Hz produce acceptable results in the inside 20-km range study. Significantly improved results are seen by a minor increase to 125 Hz sampling. The actual array sampling rate would be higher than the processor sampling rate to smooth random variations and provide a baseline. Typically, the actual element sampling rate would be four to ten times higher than the processor rate.

Provided higher sampling rates did not produce unacceptable processor loads, higher sampling rates would improve discrimination at near ranges and detectability at long ranges.

Processor resolution sizes better than .008 sec are acceptable for the edge detector.

Tow distance

No precise estimate of optimal tow distance can be made without a more detailed noise profile of the tow ship. However, in general the receive section should be towed as far as possible from the ship, or at least well outside the severe noise field.

Noise Resistance

Noise resistance is increased by the thinned long array due to independent noise fields at the sensors. The large aperture also helps increase noise resistance. Any additional measures that can be taken to improve noise resistance are highly advisable, including screening (filtering out) any known strong acoustic lines (narrowband frequencies) from the tow ship, minimizing flow turbulence around the hydrophone elements, isolating receiver elements from cable vibration or other mechanical sources of acoustic noise, discriminating against the vertical noise field, adaptive processing to form beams away from known noise sources, and so on. The acoustic receive elements should be highly stable in their characteristics and response so that the processor can discriminate known noise signals from system noise and received signals.

IV. Hardware Requirements

Sound sources

In the active sonar yellowfin tuna fish detection system studied here, the characteristics of the acoustic source are critical. The sound projector puts an acoustic pulse into the water, with the pulse designed to propagate well in the water sound speed structure, to minimize the distortions due to propagation in the lossy channel with variable boundary interaction, and to provide the maximum reflected energy from the target fish school. The more information that can be returned to the receiving system in terms of pulse structure and duration, and so on, the higher the likelihood of correct classification of the target in terms of fish species, bubble cloud, or other possible reflector. But before any classification can occur, the target must be detected, meaning that a sufficient amount of power with some defining characteristic(s), such as pulse length, frequency, or pulse shape, must arrive at the receiver to cross a preset detection threshhold. This received power must be statistically greater than the average noise in the channel after sorting characteristics are applied. Here sorting characteristics mean any feature of the received acoustic energy that can be used to distinguish the signal from the noise. For example, if the incoming energy is being processed by frequency, then only the noise energy in the relevant signal frequency band is important: if the noise is high at 5 kHz but low at 6 kHz, and the signal is at 6 kHz, then the high noise at the lower frequency is irrelevant.

The sound source must be reliable at the power output the source is driven at. NRaD experience with inexpensive sound sources at lower frequencies than the frequencies considered in this report indicate that inexpensive sources obtained commercially off-the-shelf sometimes have a tendency to fail if driven continuously at their rated maximum output, but perform reliably if driven continuously at 10 dB below the maximum rated output, or at lower continuous powers. The sound source to be used in this application, if operating at longer ranges, would be driven at a relatively low duty cycle (how frequently the source is active) to allow for propagation to distance and back. A low duty cycle should increase reliability and lifetime. Only actual experience with a source can reliably indicate its reliability.

The sound source consists of various components. The element that actually injects the sound into the water by oscillating at the required frequency is the transducer and is the most critical element. Transducers are typically designed to operate in a given frequency band because the magnitude of the oscillation required for a given power at a given frequency requires larger surface areas for efficient coupling of the source oscillation to water oscillation at lower frequencies, due essentially to the Releigh Law requiring at least a wavelength of aperture to maintain coherence across the surface when driving at a particular frequency. Transducers are typically piezoelectric in nature, consisting of a material that expands or contracts along the direction of an applied electric field bonded to a supporting structure and configured in such a way that efficient source-water coupling occurs. Frequently the piezoelectric material is configured to generate an expansion/contraction in the diameter of a cylindrical structure, thus providing the oscillating surface that couples to the water. The transducer must be in good contact with the water; the most efficient source is completely decoupled from the supporting platform (tuna boat), thereby minimizing energy transmitted into the supporting structure and lost in dissipative mechanisms.

Other components of the sound source consist of the electronics necessary to drive the transducer: (1) a waveform generator to generate the prescribed waveform to be reproduced by the oscillations of the source (which must of course be within the dynamic range of the transducer); (2) a power amplifier to amplify the waveform to the electrical voltage and current levels necessary to drive the piezoelectric material at the prescribed amplitude; and (3) any supporting timing, monitoring, or other electronics. To derive ranges from round-trip travel times of a reflected acoustic pulse, the initial power applied to the source to generate the waveform is linked to starting a clock to derive the detection times. Thus the source activation is linked to the processing electronics.

Level and power requirements

Most of this study was done with a supposed 200 decibel source, which is definitely stretching the state of the art in acoustic sources. Actual operational sources tend to be rated at peak outputs of around 185 dB. Results derived in the study as to operational configurations are typically linear in powers with a range of 15-20 dB, so results can be scaled linearly to lower power sources.

Transducer elements off-the-shelf in the 185 dB rated peak output range are available for around $5K-$15K. Elements rated at higher powers are more costly.

The system end-to-end simulation (simulation from waveform injection, through propagation to the target fish school, reflection from the school, propagation back to the receiver, and through the edge-detector algorithm) shows a critical break for detection at the 185 dB projector level at around 12 km for favorable propagation conditions. Whereas the 200 dB source has potentially good detection characteristics for yellowfin tuna fish schools out to ranges of 20 km plus given good noise minimization at the receive array and in the processing algorithms, the 185 dB source shows good characteristics out to this breakpoint for favorable propagation conditions. Operations in other conditions might further limit the range. For more detailed information, see the results of the end-to-end study.

Waveform generators and power amplifiers are readily available off the shelf to handle these applications. Costs should be on the order of less than $10K for these components.

Note that there is a tradeoff between the power the source puts in the water and any limits necessary to protect marine life in the vicinity of the source. There is more discussion of this issue in the section of discussion of acoustic energy at various ranges.

Cycle time requirements

The cycle time (how often the source is active) is set by the propagation characteristics. After a pulse is generated, one must wait a sufficient amount of time for the pulse to make the round trip to the target and back from the longest expected range - if pulses are generated at a shorter time interval, then returns from separate pulses interfere and it becomes impossible to disentangle the separate returns. The cycle time must also be long enough to allow any reverberation (reflections from bathymetric features, such as seamounts and the bottom) to die out. In addition, there has to be a guard band built

into the cycle time to ensure nonoverlap of sound pulses.

At the longer ranges considered in this study, reverberation effects are not considered to be the limiting factor. Propagation times determine the cycle time.

After the safety lapse time built in to protect against pulse-to-pulse interference, reverberation, and the guard band are accounted for, it is desirable to have the most frequent cycle rate possible, because this maximizes the amount of acoustic energy in the water over time, and thus maximizes the probability of detection.

For ranges out to 5 km, a 5 second cycle time would provide an adequate safeguard. Other range cycle time safeguard intervals are: out to 10 km, 8 second cycle time; out to 15 km, 15 second cycle time; out to 20 km, 18-20 second cycle time.

The duty cycle, because of the long cycle times, is expected to be low. Too long a pulse length unnecessarily raises the cycle time and the processing burden, while too short a pulse length may not put adequate energy in the water and thus reduce probability of detection. For processing systems that look in detail at the frequency/time/other characteristics of the reflected pulse, there is no point in having a pulse length longer than the stability interval of the medium and the reflecting target. In the case of a fish school, the stability interval would be determined by the fish school, such as changes in depth, direction, bunching, or starting new behaviors, such as prey pursuit, feeding, or other activities. While detailed behavior of yellowfin tuna schools is unknown in terms of the school parameters (change of direction, bunching, etc), it is difficult to imagine that these school parameters would stay constant over a time interval longer than a few seconds. Pulse lengths longer than one second would thus seem to be of limited use.

Reliability of the source is a key issue, since the entire detection system depends on reliable source operation. Low duty cycles should increase source reliability, but driving the source at the high intensities envisioned here is known from experience to have the potential of seriously lowering source reliability. Experience with actual sources is essential to gathering more information.

To be cost effective, the source should have a mean time between failures significantly greater than the cruise time (several months), and sufficiently long enough such that the economic return of the system is significantly greater than costs. For example, if an acoustic detection system resulted in a 50% increase in fish catch for the same cruise time, then the amortized costs of the system over a year compared to the economic benefit over a year (50% of total catch) imply that the system must be operational for a fraction of the time such that benefits exceed costs. A very rough estimate based on this criteria puts the required mean time between failures to be greater than roughly one year.

Frequency requirements

This study focussed on the frequency band of 6 to 10 kHz due to the results of the previous study, "Modelling of acoustic detection of yellowfin tuna in the ETP" (Rees, 1996). Similar results to those derived in this study are expected throughout the 1 kHz to 10 kHz regime.

Classification of the target would rely on frequency analysis of the frequency components of the returned pulse (which is equivalent to saying analyzing the time structure of the returned pulse). To discriminate a yellowfin tuna school from another type of fish school is a challenging undertaking, relying on knowledge of fish school behavior, swim bladder characteristics, and any other determining factors. Complicating classification relying on the characteristics of the target (as described by the target strength (TS) as a function of frequency, school size, orientation, clustering, etc.) is the fact that the ocean sound channel itself results in frequency distortion of the propagated pulses over the ranges considered here. Some typical examples are provided in the discussion of powers versus ranges with the modeled time propagation at various ranges for favorable propagation conditions. These are one-way predictions and only include the multipath effects of propagation, not additional distortion from noise effects, surface scintillation, second-order scattering, and other secondary propagation effects. In short, these predictions include only the lowest-order, most basic propagation effects. It is readily apparent that significant distortions of the broadcast pulse structure are the rule in long-range propagation.

If the propagation structure is well-enough known, then these ocean channel distortion effects can be removed through a matched-filter processing approach taking into account the propagation structure. Significant gains can be realized through this technique, but mismatch with the actual environment can result in degradation of the signal instead of gain.

Exploiting the full characteristics of the reflecting target, as described in the study by Nero (Model Estimates of Acoustic Scattering from Schools of Large Yellowfin Tuna, 1996) implies a bandwidth on the order of a kiloHertz for the source pulse.

On the other hand, if it was decided that frequency information or time-structure information in a broadcast pulse was of little value in classification of yellowfin tuna schools (due, for example, to channel distortion effects), then little bandwidth would be required in the source and the source could be constrained to a small frequency band around the optimal propagation frequency.

Actual experimental results with an operational system would be required to make the determination as to the effectiveness of pulse information in yellowfin tuna (or other fish species) classification. Note that gathering such experimental information implies that the initial system would have the one kHz bandwidth.

Directionality (collimation) requirements

This study assumed that the source had at least hemispheric directionality in order to resolve the right-left ambiguity present in the array processing and thus improve operating characteristics. Using a more tightly collimated beam reduces the total power required, although the peak power output across the beam must still be on the order of the power requirements specified. That is, a collimated source would need 185-200 dB output in the study configuration averaged across the half-power beamwidth of the source.

The left-right ambiguity can also be resolved through boat navigation and thus a directional source is not essential to operation of the system.

Directional sources consist, for examle, of a plate driven to oscillate as opposed to a cylinder driven to oscillate. A directional source could be attached to the ship hull with greater ease than a non-directional source. Directional sources could be scanned around the ship to provide forward or backward look information, although in the simplest configuration the directional source would have a beam perpendicular to the ship's direction of travel and scanning the surrounding area would be effected simply by the boat's motion through the water.

A vibrating plate is a less efficient coupling of energy from the source to the water than a vibrating cylinder or sphere due to edge effects. A half-cylinder source poses problems of stress imbalance in the source structure. High-power transducers thus tend to be nondirectional, although there is no intrinsic reason that a transducer cannot be designed in a directional configuration.

Experience and modeling have shown that considerable gain can be achieved by focussing the transducer's radiated energy in the horizontal direction. A cylindrical transducer naturally has this characteristic with a horizontal beamwidth on the order of 90 degrees centered on the horizontal due to its physical shape. Strong focussing in both vertical angle and range can be achieved by using a multiple element source with several vertical elements phase-coupled. Such sources have obvious advantages but would be to complex and difficult to handle for a tuna fisheries application.

The recommended source would have hemispheric directionality (left-right), but this is not essential for system operations.

Discussion of ship mounting

Most efficient coupling of a nondirectional source to water is achieved if the source is completely decoupled from the supporting platform (tuna boat). This would imply a separate tow from the boat of a source, separate, that is, from the receive array tow. This would seem to be the optimal configuration: one tow line for the receive array, and a separate tow line for the source.

Tuna fisheries captains recommend against any tow from a tuna boat other than from the rear. Leading a tow line off the port side was also recommended against. These requirements add risk to separate source and array tows because they would enter the water relatively close together, thus implying a risk of entanglement of the tow lines, which would be a serious problem. If two separate tow lines did become entanged, most likely the only solution would be to stop operations and attempt to manually retrieve the source and array using skiffs in the water. Both source and receive array could be damaged. There is some chance that either or both would have to be cut away and abandoned. Obviously this is a situation to avoid.

Lines could be kept separate by towing off different sides of the boat, towing one line off a horizontal boom to keep it well separated from the other, and towing the source and receive array at widely separated depths and distances so that the tow lines would have different water entry points and

depths. Abrupt boat maneuvers while source and array are deployed could still tangle the lines, however; one possible preventative measure could be to enable an alarm triggered by abrupt boat maneuvers when the source and array are deployed. The alarm would sound and warn of danger of entangling tow lines.

Other possible configurations for the source include physically affixing the source(s) to the hull of the vessel, which would require drydocking the boat to affix, maintain, and/or repair the source; or suspending the source from a physical substrate attached to the boat which would enter the water and maintain the source position, with the source attached to the physical guide structure by a (preferably short) tow line. This second option would be, in essence, a sort of underwater crane that would reach down 10-20 meters beneath the water surface before towing the source - or perhaps be physically attached to the source. A crude image of this can be envisioned by recalling the common "water dipper novelty birds", with a glass "bird head" repeatedly dipping beneath the water off of a pivot attached its base. The structure that enters the water would be streamlined for water flow.

The advantage of the affixed-to-hull configuration is that the source is in a known location, immovable, and thus has no danger whatsoever of entanglement with the array tow. Disadvantages include the necessary drydocking, decreased source efficiency, and the possibility of damage to the source during dockings, etc. The advantage of the dipper configuration is that there is essentially no possibility of entanglement, the source is well positioned, and can be easily deployed and retrieved for service, protection, and so on. The disadvantage of the dipper configuration is that the dipper would have to be developed and appropriately designed by marine/mechanical engineers, would have to be affixed firmly to the deck so there is no chance of loss (bolting?), and could conceivably take up considerable deck space - which might not be readily available.

The recommended configuration is the widely-separated double tow, although if an effective dipper device could be developed and implemented at relatively low cost, and if adequate deck space is available, the dipper would be preferable because it would eliminate the risk of entanglement.

Optimal source depths

An extensive study was made of the optimal source depth (depth at which the acoustic source should be operated). The optimal depth depends on the propagation conditions and the noise conditions and is also coupled to the receive-array depth. That is, both source depth and receive array depth must be simultaneously maximized for probability of detection.

The results of the end-to-end simulation were used to study all combinations of source depth, receive-array depth, target yellowfin tuna school depth, a set of representative ranges, and the four characteristic sound speed profiles for each of winter and summer. The actual ranges of these parameters studied were as follows: (1) source depths: from 20 to 100 meters in steps of 10 meters; (2) receiver depths: from 20 to 100 meters in steps of 10 meters; (3) tuna school depths: from 20 to 100 meters in steps of 10 meters; (4) ranges of 4 km, 7 km, 10 km, 14 km, and 18 km; (5) the jan0, jan1, jan2, jan3, jly0, jly1, jly2, and jly3 characteristic sound speed profiles.

The end-to-end simulation consisted of injection of the acoustic pulse into the water, propagation to the target school, scattering from the target school, propagation back to the receive array, and processing through the edge-detect algorithm to see if a detection occurred, where the predicted location was compared to the actual location, and other parameters of merit.

All predictions were done for 90 degree targets; that is, targets that were perpendicular to the receive array (and thus the course of the boat). This is the optimal look direction for the array.

Results were derived for four key quantities: (1) the peak power seen on the array if detected; (2) the average power seen on the array if detected; (3) the range error if detected; and (4) and angle error if detected. The peak power on the array is directly related to the overall probability of detection in a single pulse. The average power on the array is related to the probability of detection over a number of pulses or a long time interval. The range error is the fractional error in range of the predicted location compared to the actual location; for example, if the predicted range was 4 km and the actual range was 5 km, then the range error would be (5 km - 4 km)/(5 km), or 0.2 (20%). The angle error is the absolute difference between the predicted angle and actual angle; for example, if the predicted angle was 93 degrees and the actual angle was 90 degrees, the angle error is 3 degrees.

As just noted, predictions were generated for all combinations of the source depth, receiver depth, and other parameters. These results are available in the appendices in two forms: graphical tables, and gray-scale plots. In the graphical tables, the four key quantities are displayed by actual value in tables of receiver depth versus source depth, with one table for each combination of the remaining parameters (target depth, range, and characteristic SSP). In the gray-scale plots, the values are represented graphically with darker grays corresponding to higher values (zero is white), so that the eye can easily pick out the "best" value. Thus in the basic gray scale plots, black areas are best for the peak power and average power plots, while white areas are best for the range and angle error plots.

These are far too many combinations to consider (although they could easily be programmed into a processing system to produce optimal source and receiver depths given local water properties from the tow ship), and so the individual predictions are combined further into average results represented by "scored plots". These plots are termed scored plots because the averages are taken to yield standard "scores" so that the average results can be compared in a meaningful manner, much like college SAT tests. Scores are chosen so that a "best" value represents the highest score (255) and the "worst" value represents the lowest score (0). The scored plots are also available in graphical tables and gray-scale plots, but because they are scored, in these gray scale plots, blacker areas always represent the "best" alternative.

Scores were set as follows: (1) for peak and average powers, a score of 0 represented 0, a score of 255 represented 20 dB or more (with a 200 dB source); (2) for range error, a score of 0 represented an error of 0.5 or more, a score of 255 represented an error of 0; (3) for angle error, a score of 0 represented an error 10 degrees or more, a score of 255 represented an error of 0. A result of 255 in a scored plot would thus mean that all the results that were averaged to make up the scored plot were "best values".

Several possible choices can be made for representing no detections (where the fish school was not

detected by the processor), depending on how much negative weight one wishes to assign to lack of detection. The lightest penalty for no detection would be to assign a score of zero, but this underweights no detections because it is more important to have a detection at all than to have highly accurate predicted locations, etc. In the scoring system adopted here, no detections were weighted as negative scores of half the maximum possible score, giving a no-detection a medium negative weight. Again this is similar to the way a college SAT is scored to eliminate the positive score that would be obtained by making random guesses.

Averages were done over (1) all ranges, other parameters fixed; (2) all fish school depths, other parameters fixed; (3) all target depths and ranges, only characteristic SSP fixed; and (4) all quantities. To optimize for any range, consult plots (1); to optimize for any fish school target depth, consult plots (2); and so on.

A word on the notation of the scored plot titles. For a compact notation for the relevant quantities being averaged (or not) out of the many posibilities present, target depths, ranges, and SSPs are represented by indices corresponding to the values actually used. Target depth indices are prefixed by "TD", range indices by "R", and SSP indices by "SSP". The final "A90" denotes that the simulation was at 90 degree bearing. The correspondence between indices and values is given in the following table:

index	Target Depth	Range	SSP
0	20 m	4 km	jan0
1	30	7	jan1
2	40	10	jan2
3	50	14	jan3
4	60	18	jly0
5	70		jly1
6	80		jly2
7	90		jly3
8	100		

Detailed results can be seen by consulting the appendices. Summarized here are the broadly averaged results: (A) results averaged over all ranges and target depths, and (B) results averaged over all conditions. The figures correspond to the (A) and (B) averaging as follows: fig 22, (A) for jan0; fig 23, (A) for jan1; fig 24, (A) for jan2; fig 25, (A) for jan3; fig 26, (A) for jly0; fig 27, (A) for jly1; fig 28, (A) for jly2; fig 29, (A) for jly3. Figure 30 shows (B) averaging, results averaged over all conditions, including the environment type in the study area.

Optimized source depths: For average (A): (1) jan0 profile, 20 m; (2) jan1 profile, 30 m; (3) jan2 profile, 20 m; (4) jan3 profile, 20m; (5) jly0 profile, 20 m; (6) jly1 profile, 20 m (80 m also acceptable); (7) jly2 profile, 40 m; (8) jly3 profile, 20 m. For average (B) (averaged over all conditions): 20 meters.

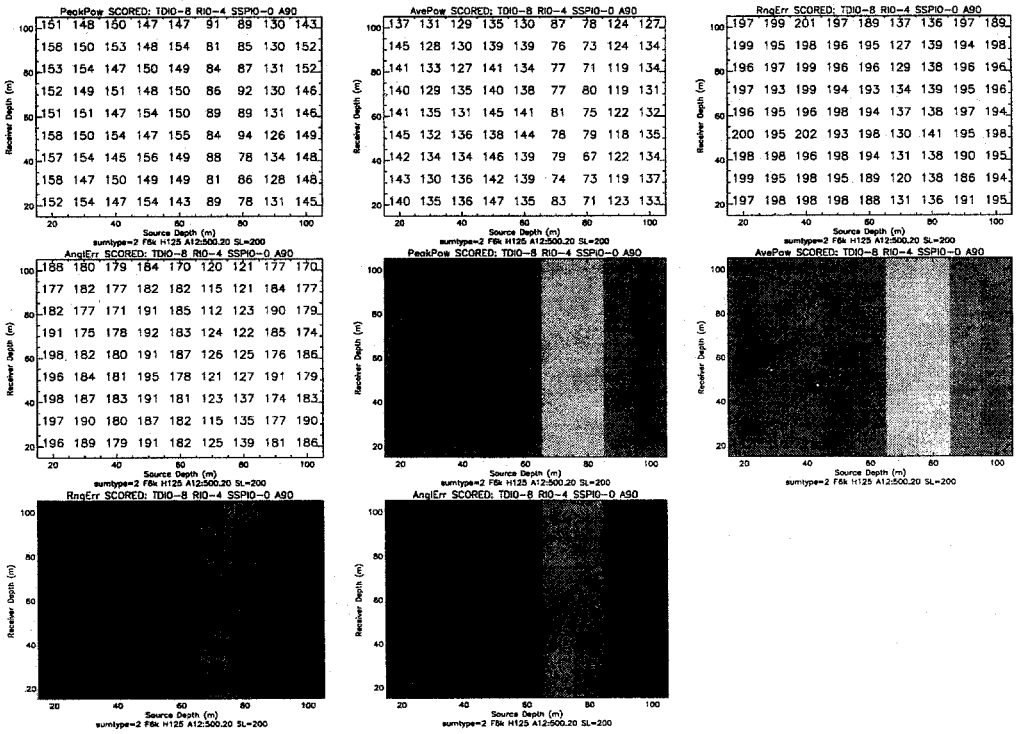


Figure 22.

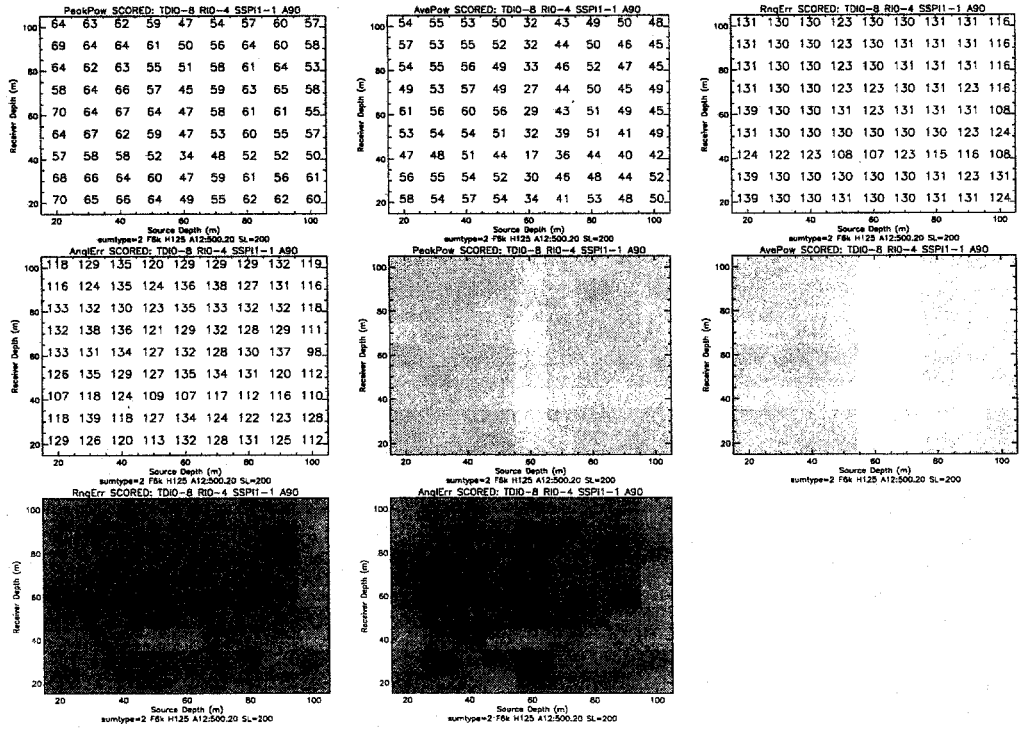


Figure 23.

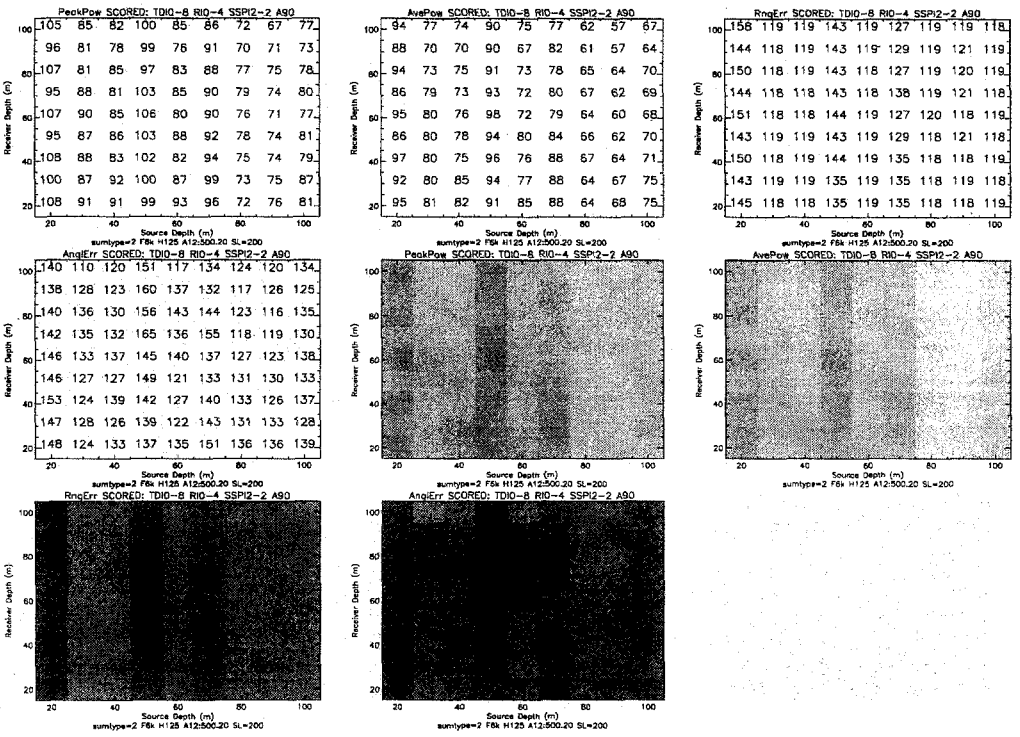


Figure 24.

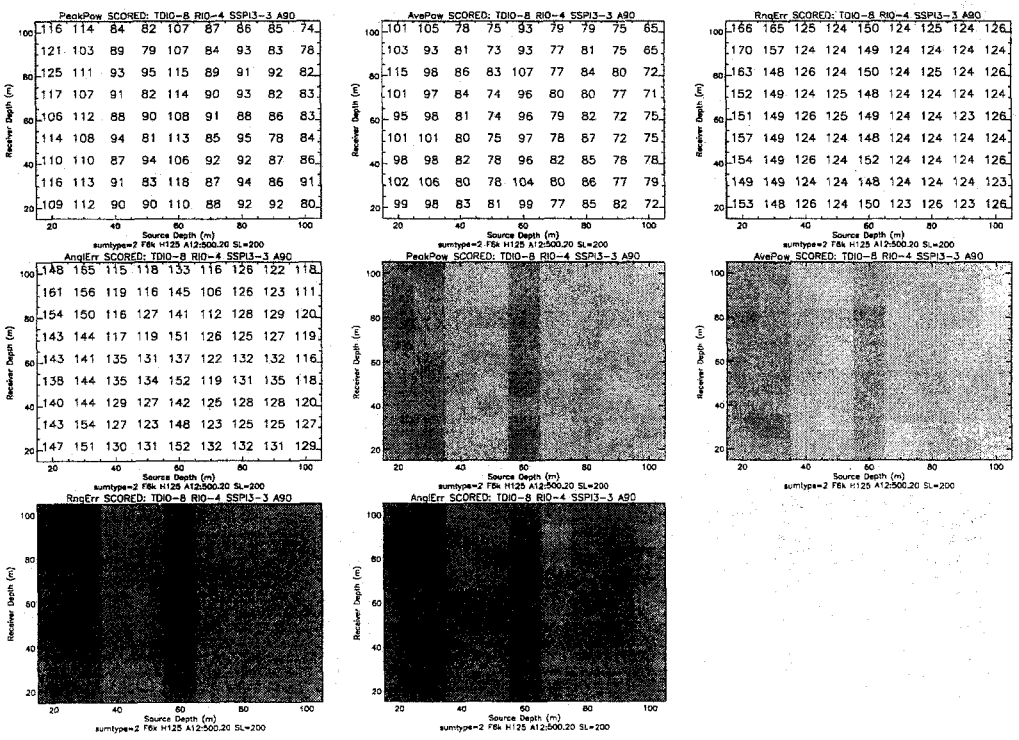


Figure 25.

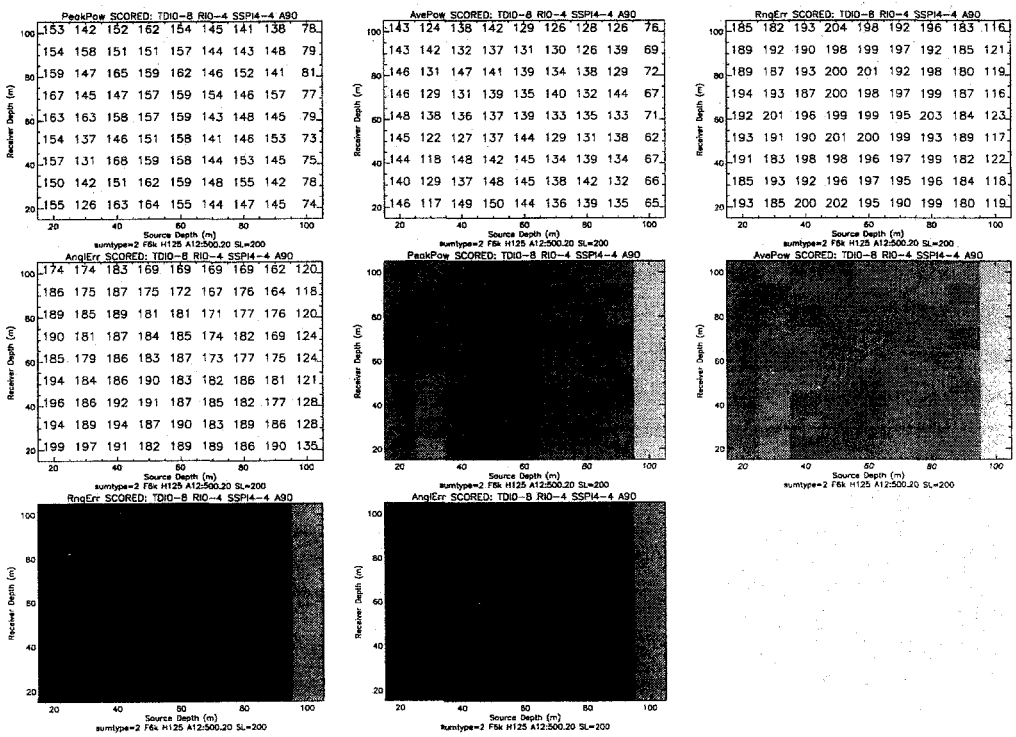


Figure 26.

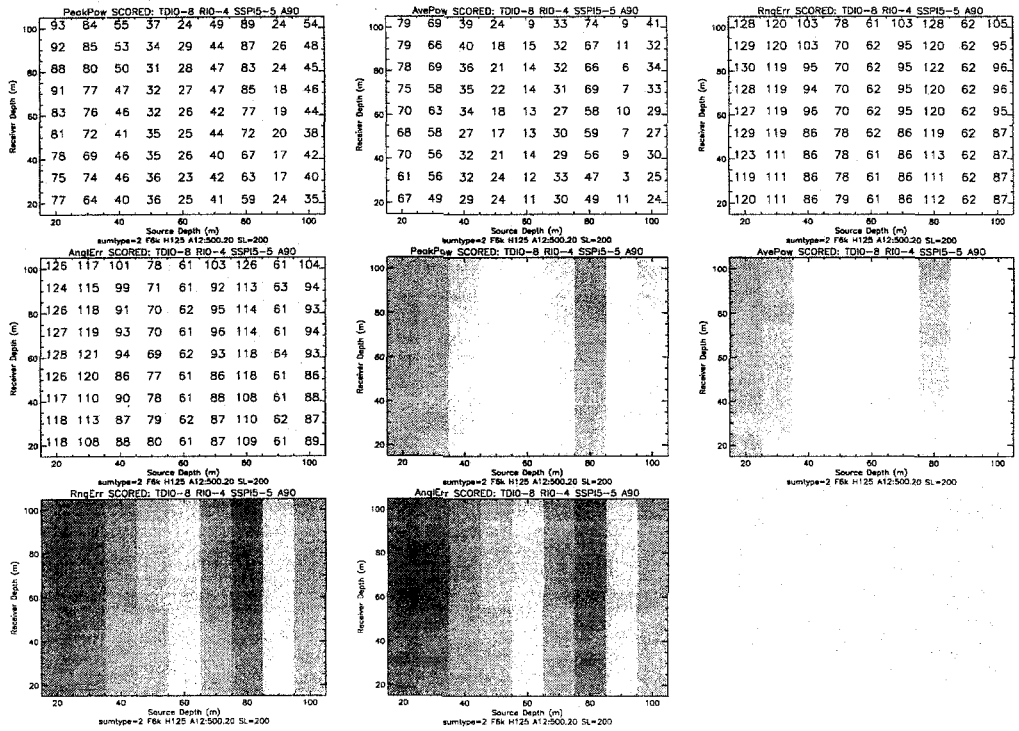


Figure 27.

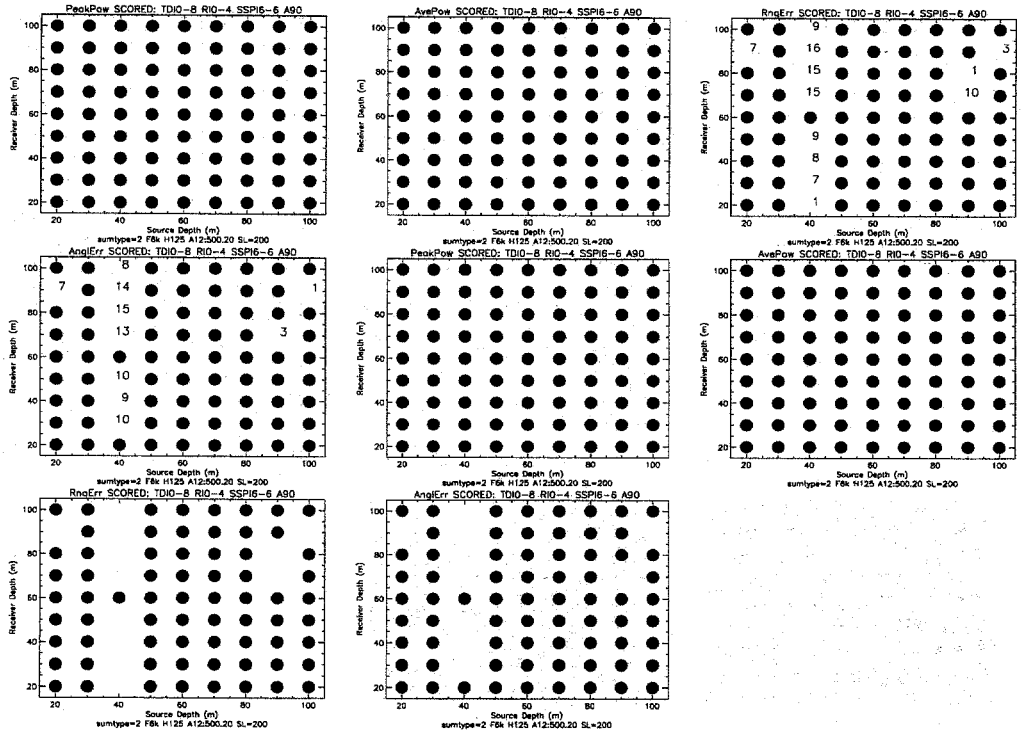


Figure 28.

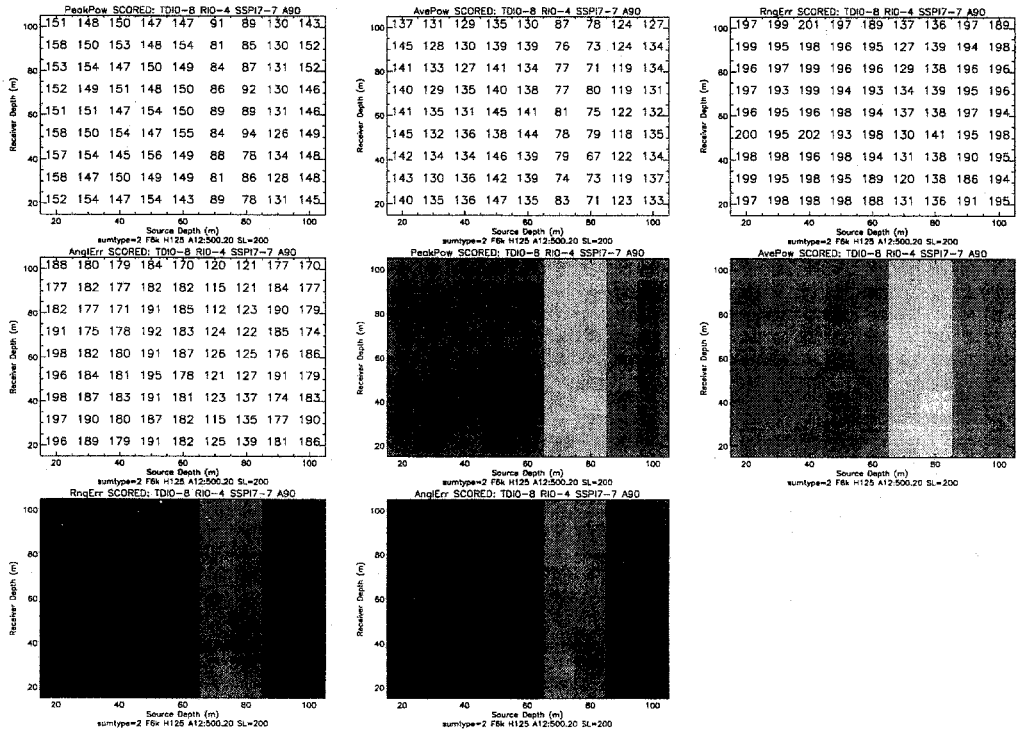


Figure 29.

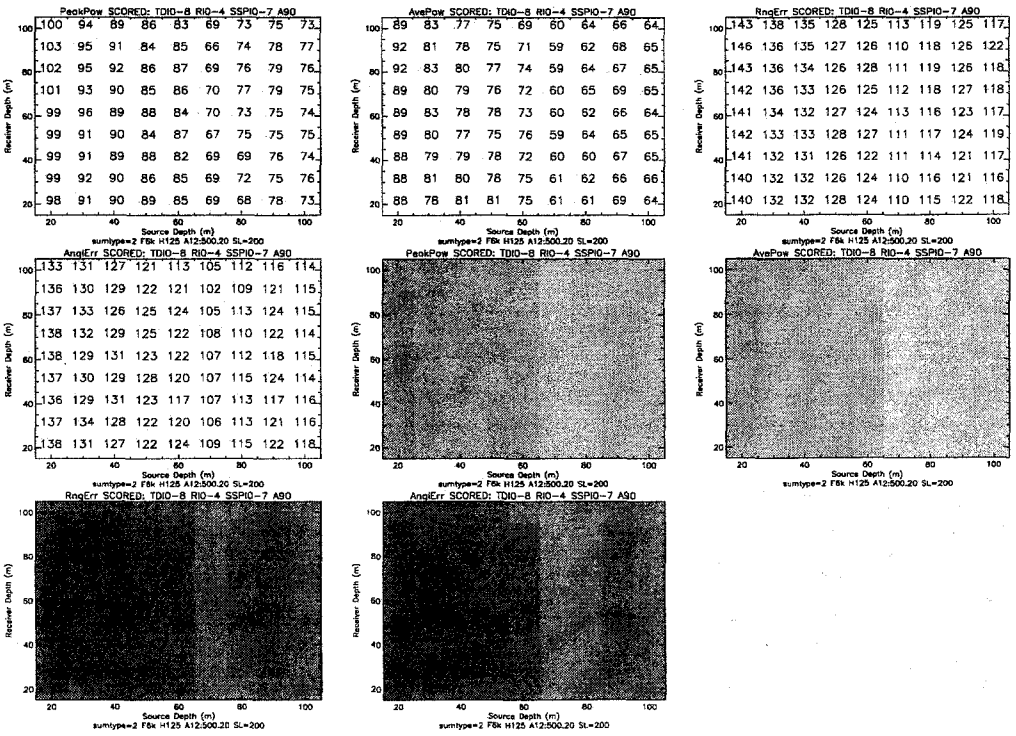

PeakPow SCORED: TDIO-8 RIO-4 SSPIO-7 A90
AvePow SCORED: TDIO-8 RIO-4 SSPIO-7 A90
RngErr SCORED: TDIO-8 RIO-4 SSPIO-7 A90
AngiErr SCORED: TDIO-8 RIO-4 SSPIO-7 A90
PeakPow SCORED: TDIO-8 RIO-4 SSPIO-7 A90
AvePow SCORED: TDIO-8 RIO-4 SSPIO-7 A90
RngErr SCORED: TDIO-8 RIO-4 SSPIO-7 A90
AngiErr SCORED: TDIO-8 RIO-4 SSPIO-7 A90
Receiver Depth (m)
Source Depth (m)
sumtype=2 F8k H125 A12:500.20 SL=200

Figure 30.

Sample source

All electronics are estimated to fit in a single rack. Cost of electronics is estimated at around $10K. The transducer is estimated at $10K up to $50K or more for a specifically designed source. Labor and development costs are estimated at 1/2 to 1 man year with supporting technicians, or approximately $100K to $200K. Testing and calibration costs are estimated at $50K. Costs for development of a dipper device are not estimated. Integration costs are not estimated, but may run as high as 1/2 of development costs.

Source would be deployed at 20-30 meters depth on a short tow line as widely separated from the array tow cable as possible. Cycle time would range from 3 seconds for close-range operation to 20 seconds for distant operation. Pulse length less than 1 second. Frequency bandwidth of at least 1 kHz preferably in the range 6 to 10 kHz, but possibly in the range 1 to 10 kHz. Mean time between failures for continuous duty operation at these parameters preferably greater than approximately one year.

Towed Array

The towed array is the receiver section of the tuna acoustic detection system. It is towed some distance behind the tow ship (tuna boat) chiefly to physically move the receiver away from the noise field generated by the tow ship - which for the case of a tuna boat is very noisy - and also to isolate the receiver from vibrations and mechanical interference from the tow ship. Using a towed array also enables the receiver to have a much larger aperture than that possible if the array were physically affixed to the ship. An increased aperture size is necessary for long wavelengths, and in the case of the thinned long array considered as a bottom-line operational system for tuna detection if phase stability does not hold over long ranges at frequencies greater than several kHz, is necessary to improve noise filtering and array response.

The array consists of a physical tow cable, a vibration isolator to decouple from the tow ship, the receive array section, array electronics, and optionally another vibration isolator, and a tow stabilizer. If the array uses phase stability to do conventional beamforming, then the receive array section could be compact, with a hydrophone spacing of 75 cm when cut for 1 kHz reception, and only 10 cm when cut for 7 kHz. Thus for a 20-element array, the total length of the receive section would be only about 15 meters, and the array receive section could be designed in essence to incorporate the final stabilization element.

The final stabilizing element can be a simple drogue designed to keep the array tow line taut or a towfish designed to maintain array depth as long as tow speed is within acceptable limits. Being able to maintain the array at a constant, desired depth is advantageous to take advantage of the optimal tow depth for signal reception.

The receive array section consists of a number of hydrophones arranged in a straight line and spaced to adequately sample the frequencies the array is designed for. The Nyquist requirement mandates that the signal must be spatially sampled at least twice as frequently as the shortest wavelength to be detected by the array, because otherwise a degeneracy exists between frequencies on the array and it

becomes impossible to resolve the degenerate frequencies. Thus the spacing criteria for hydrophones in the receive section is chosen for phase-stable receivers as lambda/2, with lambda the shortest wavelength to be detected.

Thinned long arrays, which process in the time domain and are not subject to the constraints of phase stability, do not have the lambda/2 requirement. Instead the element spacing in such arrays is chosen for noise reduction and to match the sampling frequency.

Strength Member

The tow cable to the array must support the stress of the tow against water resistance, and also carry telemetry and power cables to the array. The ideal tow cable is nearly neutrally buoyant and has laminar flow along the cable, reducing cable strum (the vibration of the cable due to vorticity in the flow pattern past the cable), cable stress, and noise contamination on the hydrophone section. Tow cables typically have some small negative buoyancy to aid submerged towing.

The material of choice for the strength member in the tow cable is Kevlar due to its superior strength and light weight. Integrated with the Kevlar strength member are the power lines (sheathed copper wires) and the telemetry lines (either sheather copper wires for electrical data transmission or optical fibers for optical transmission).

The tow cable should be able to support up to a 1-km tow at the maximum tow speed. Although discussions indicate that current tuna boats operate at cruise speeds of 12 knots or greater, stability of the tow cable and array in the water, in addition to reduction of flow noise past the array, puts limits on the maximum tow speed. No precise projection of what the maximum effective tow speed would be has been done, but tow speeds in excess of approximately 10 knots could cause problems for the array.

Hydrophones

The hydrophones are the actual sensors that measure the water pressure at their location, and thus detect the incoming signal if possible. Various commercial hydrophone designs and equipment are available that meet the needs of a towed array. The hydrophone must be sensitive to the frequencies to be detected (in this case, 1 to 10 kHz), preferably have a linear response throughout the operational frequency regime, and have sufficient dynamic range in order to detect the relatively small signal while under tow and pressure at tow depth. The constant pressure at the hydrophone due to tow and depth are uninteresting from the standpoint of signal detection; one is only interested in the relative dynamic response of the hydrophone.

Various types of hydrophones exist; typically the basic sensor mechanism involves measuring either the voltage generated when a material or physical construction is subject to stress or the change in capacitance as small displacements occur in a spacing between capacitative surfaces (the displacements being caused by the changes in external pressure). Recently experimental optical hydrophones have been successfully tested; these hydrophones rely on changes in optical path length due to com-

pression or expansion of an optical fiber coil. Optical hydrophones are not yet advanced enough to be used in this application.

The very small signal generated by the small displacements from an incident acoustic wave in the hydrophone capacitance must be carefully amplified to preserve the response of the physical sensor. A preamplifier associated with the hydrophone has this job and must be carefully matched with the voltage response of the hydrophone, as well as being insensitive to any offsets caused by operation at depth. Commercially available electrical hydrophones come with the complete hydrophone including preamplifier section, providing a proscribed voltage range output, and may be purchased in calibrated form so that the separate hydrophones constituting the receive section are compatible.

The end-to-end simulation indicated that as few as 12 hydrophones would be acceptable for the thinned long array concept. Approximately 20 hydrophones would be appropriate for a phase-stable conventional array (sampling at approximately 10 points per frequency, cut for two frequencies - a low and high frequency - in the frequency band). Increasing the number of hydrophones from 12 in the thinned long array would provide several dB further noise reduction.

Having hydrophones programmable for multiple gain settings is useful to adapt to local operating conditions and would be advisable in the array.

There is little point in having the hydrophones sensitive to arrivals at vertical angles greater than 45 degrees relative to the horizontal; essentially all incoming acoustic energy at these angles is noise and not signal. It has been suggested, therefore, that configuring or having hydrophones with directional characteristics that focus on the horizontal plane to plus/minus 45 degrees would yield large noise reductions and thus increased sensitivity and range. Such vertical directionality could be implemented by either screening the hydrophones from the vertical direction by noise baffles (such as foam) or by using planar hydrophone sensor elements. This would only be effective if the receive section of the array can be maintained in a known orientation; signal-to-noise would actually be negatively affected if the receive section of the array were in an unexpected orientation and directional hydrophones were used. Towed array designs tend not to use directional hydrophones due to the difficulty of maintaining a known orientation of the receive section during tow.

Estimated cost of commercially available hydrophones with acceptable characteristics is $5K to $7K per hydrophone.

Electrical cabling

Optical communication links have superior noise immunity but tend to degrade with time and are more difficult to repair if broken. For the tuna detection application, straight sheathed copper twisted-wire cabling should be adequate.

Data rates on the telemetry links depend on how much processing is done at the array. If most DSP processing is done locally to the array, data rates to the tow ship can be relatively low. For the case of 20 channels with 4x sampling at 5 kHz, this implies a roughly 400 kb data rate of raw data to the tow

ship. Cabling would be required to handle this rate over distances up to about 1 km. This should not be a problem.

Protection and waterproofing

All components must be sheathed and waterproof to maximum tow depth, which in this study is taken to be relatively shallow (within 100 m depth). Waterproofing for sections containing electronic components is provided by a hosewall, inert in seawater. Pressure compensation for operations at depth is provided by either a liquid (oil) fill or a solid fill. The liquid fill is generally considered more desireable because of its vibration damping characteristics and superior pressure adaptability.

Materials for the hosewall typically consist of polyvinyl chloride (PVC) or polyeurethane (PU) or related materials - basically one can imagine large tygon tubing. Neoprene with interwoven supporting material has also been used. Strength members are provided by interwoven steel wire, kevlar cord, dacron, or other material. A transparent material is useful for liquid pressure-compensation fill to ensure that all bubbles have been removed.

Standard marine connectors can be used to join sections of the array.

Minimum and maximum towing speeds

The ship must maintain some forward headway or else the tow cables will go slack and possibly become entangled. In addition a minimum tow speed is required to maintain array stability and linearity in the water during tow. There is also a maximum acceptable tow speed, since high speeds may excite large amounts of strum on the cable and towed array, resulting in unacceptable noise levels. Also high stress levels from very high tow speeds could damage array connections or cause other problems.

Discussions with tuna boat captains indicate that tuna boats typically maintain cruise speeds over 12 knots. This would be high for a towed array in operational mode, but would be acceptable in nonoperational mode. If the tuna acoustic detection system is successfull, it significantly extends the search radius of the tuna boat out to 20 km or greater and down to depths of 100 meters, vastly increasing the volume of water that can be searched in the equivalent time. In fact, the deep water cannot be searched by any method at this time. Thus slightly reduced towing speeds would be more than compensated for the greatly increased water volume that can be searched by the system at any given time. Also the acoustic system is equally effective when searching at night, thus doubling the time a tuna fish school could be searched for.

Projected operational tow speeds would range from 2 to 10 knots. Higher speeds could be maintained in a nonoperational mode, that is, when it is desired to quickly transit to another area. It would not be necessary to reel in the array provided transit speeds were not extreme.

Other sensors

In addition to the hydrophones used to detect acoustic signals, other sensors may be deployed in the array. Such other sensors include temperature sensors, pressure sensors for operating depth, and heading sensors. Temperature sensors can be useful for thermocline information, depth sensors for determining the operating depth of the array and possibly adjusting, and heading sensors to ensure that the array is properly aligned. Because these sensors are sampled at a very low rate compared to the hydrophones, they impose minimal extra requirements on the telemetry and/or processing. Such sensors can be placed arbitrarily in the array, provided they do not interfere with hydrophone operation.

It would also be useful to carry equipment for measuring temperature as a function of depth to locate the thermocline, or better yet, to measure the full sound speed profile in near-surface waters via a CTD-type sensor. A CTD measurement system would be essential if a matched-filter processing system were used to compensate for the environment. Such systems are readily available from commercial suppliers for on the order of $5K to $10K.

Array Deployment / Towing / Retrieval

The array would be deployed from a spool off the rear of the boat. The spool could be anchored to the deck at the rear of the boat, movable so that it could be stored in an out-of-the-way location when not in use, or anchored midship or near the cabin with the array and tow cable taken through guides to the rear of the ship. A standard hydraulic or electric winch-like spool is satisfactory, preferably with a guide to ensure that the array and tow cable spool on and off smoothly and without kinks. No special storage techniques or activities are required; the tow cable and array are simply spooled on and off the drum and left on the drum for storage when not in use. Hydraulic or electrical power would be readily available from the boat.

Space Requirements

Space requirements for the array spooler are minimal. The size of the drum depends on the length of cable to be stored on the spool and the size of the cable. As an example, consider a 1-inch diameter cable and a three-foot-wide drum with an inner diameter of 18 inches. The outer diameter of the drum required to store one kilometer of cable would be only 54 inches (minimum) or 5 feet with safety allowance. Thus the footpad of this spool would be approximately 3 feet by 3 feet, with a height of approximately 5 feet.

The formula relating the length of cable (L), the spool width (W), spool inner radius (Ri), cable radius (Rc), and number of layers (Nl) that can be wrapped on the spool is

$$L = \pi W [Ri/Rc + Nl(Nl+1)].$$

Proposed deployment technique

Permanently anchoring a spool at the rear of the boat would seem inadvisable due to interference with

the netting pile. If the spool is not directly at the rear of the boat, then the array and cable will have to be taken through guides to the rear of the boat. A small boom off the side of the boat is one possibility. Enough cable would be unspooled from the drum to manually walk the cable to the rear of the boat, leading it through the guide(s). The rear of the tow cable/array would be allowed to enter the water and kept free of the boat by the boat maintaining constant headway at moderate speed. After the cable is in the water, the length of cable to place the array at operating distance from the boat is unspooled from the drum by running the drum through the prescribed number of revolutions. While unspooling, the boat should maintain a constant heading at moderate speed to avoid any danger of tangling or snaring the cable.

Total deployment time is estimated at approximately 10 minutes.

The array will be operational immediately after deployment.

Maneuvering limitations while towing

While the array is deployed the boat should maintain a constant heading for as long as possible. The chief purpose of this towing strategy is to maintain the array in good alignment (standard beamforming assumes that the array is linear; deviations from a linear array degrade performance), to avoid exciting oscillations or causing other instabilities in the array cable, and to allow the accumulation of data in a stable configuration (a single orientation) so that statistics can be accumulated over longer time periods, aiding in array processing and noise suppression through averaging.

Excessive tow speeds can excite cable oscillations or increase the flow noise around the receive array to unacceptable levels. A constant tow speed should be maintained in order to keep the array under a constant tension and therefore stable. Some forward headway needs to be maintained to prevent the array and tow cable from sagging in the water and possibly kinking, looping, or otherwise becoming entangled. Tow speeds of 2 to 10 knots are advisable.

Sudden turns and maneuvers should be avoided to prevent tangling the array or tow cable or putting severe stresses on them. While in a tow configuration, the boat should never cross its own path, or abruptly come to any heading more than approximately 60 degrees from the current tow heading. Changes from one heading to another heading are best made gradually over an extended distance so that the curvature of the array while maneuvering stays low. Results of the acoustic detection system during heading changes are generally not useful.

If their are other skiffs or boats in the water during an array tow, they should avoid the rear of the boat and the area where the tow cable enters the water. Speedboats or other boats should also avoid operating in the vicinity of the receive section of the array, as noise from their engines and passage will severly contaminate any signal arriving on the array and make effective use of the array impossible. It is advisable to at least attempt to generate as little noise as possible through boat operations while the array is operational.

Any boat towing a line, anchor, net, or anything through the water at any depth below the immediate

surface should avoid the entire general area of the tow cable and array because of the danger of the extraneous line entangling the array or cable and causing severe damage.

In summary, the general goals for effective array operation during an array tow are to maintain constant heading and speed for as long as practical, and to avoid an abrupt maneuvers. Any boat or operation that risks snaring or entangling the towed cable and array should stay clear.

Proposed retrieval technique

While the tow ship maintains constant heading and moderate speed, the tow cable is spooled back onto the storage drum. The amount of tow cable in the water should be kept track of so that retrieval of the mechanical components and receive section of the array are not damaged on retrieval. Retrieval of the actual hydrophone section and associated electronics should be done more carefully to avoid damaging them.

The array would have to be retrieved before a tuna net could be deployed from the boat due to likely entanglement. Estimated retrieval time for the array is approximately 10 minutes.

One possibility to speed operations if closing on a tuna school would be to rewind part of the tow cable when close to the school. This would put the array more into the noise field of the tow ship, but the decreased distance to the fish school would compensate. Actual operations might disclose other shortcuts or tricks to speed array retrieval.

Location of apparatus

Permanent anchoring of the array spool at the rear of the ship seems inadvisable due to interference with the netting pile and net/boat operations in the area. The two remaining possibilities are a movable spooler that could be locked down at the back of the boat for operations and wheeled forward for storage when not in use, and a spooler permanently locked down in the midship area or cabin area that would deploy through a guide to the rear of the ship. Although a movable spooler would make deployment in and out of the water easy due to the location adjacent to the water, it seems impractical to expect the crew to shuttle a possibly bulky spooler about a significant amount, and might be an invitation to a serious error such as failure to lock down adequately. It thus seems that the most practical option would to locate the spooler amidship and use a guide at the rear of the boat. A small boom to the side might work well.

Emergency separation and retrieval

In an emergency it may be necessary to quickly detach the array and free it from the ship. While the array can certainly be cut away, this would most likely result in loss of the entire towed array (of course, a small price to pay if an emergency situation merits it). It is thus advisable to have a quick-release mechanism incorporated that would permit possible retrieval of the array at a later time. For example, when the array is deployed to operating distance there can be a quick release with a section

with a buoy or other flotation attached, so that the array could be retrieved via the buoy later if the quick release is used. Alternatively the spool itself can incorporate flotation if the spooler is located such that the spool can be dumped overboard easily and without interfering with rigging, etc.

Safety Issues

It is known that high-intensity in-water acoustic sources can constitute a human health risk. There have been serious injuries to Navy divers operating too closely to low-frequency high-power acoustic sources. Ship's crew should be appropriately cautioned and divers should not be in the water when the source is operational. There should be safety features such that the source could not be activated until it was verified that waters immediately around the boat were clear of divers, swimmers, or people in the water.

V. Software Requirements

Brief signal processing overview

The signal processing is the software that takes the raw received pressure levels from the hydrophones in the array and "interprets" it in order to extract any signal from a transmitted pulse reflected from a target tuna fish school, and produce an estimation of the school's bearing and distance from the ship. The signal processing may also attempt classification of the returned signal by looking at various characteristics of the signal; that is, attempt to decide whether the reflection is from a yellowfin tuna school, some other fish species, a bubble cloud from a breaking wave, or whatever.

Rapid advances in computer technology make possible relatively sophisticated signal processing based on inexpensive desktop systems available at your local computer store.

All signal processing can be viewed as the application of a filtering process to the data from the hydrophones. The filter selects against background noise and passes only genuine signals of pulses reflected from the desired yellowfin tuna. A perfect filter (not physically achievable, of course) would, in essence, return the exact range and bearing of a yellowfin tuna school if the school were present and in range, and return zero if no school was present in range. The filter matches the observed data from the hydrophones with an expected pattern or algorithm to accomplish this selectivity.

Standard beamformers

Standard beamformers assume that the acoustic energy arriving on the array is in the form of a perfect plane wave crossing the array. Assuming that the propagation speed across the array is constant, the time lag between any given wavefront crossing two adjacent sensors is a constant, with the constant determined by the angle of arrival of the plane wave. For a continuous signal at a given frequency, this is equivalent to the statement that there is a constant phase difference between adjacent elements across the array for a plane-wave arrival.

This expectation of a constant time difference for any given wavefront between adjacent sensors, or equivalently a constant phase lag, is the filter that a standard beamformer applies to interpret the acoustic energy arriving on the array.

One way to view the process is as follows. To filter for a plane wave arriving at angle theta relative to the array axis, the output of all elements is summed, but with a time delay from element to element appropriate for the theta plane wave. If there is in fact a plane wave signal present on the array at frequency f, the addition will be in phase (coherent), and sum positively to produce an amplified signal. If there is no plane wave signal present at frequency f, the addition will be a sum of random numbers, which averages to zero (after any constant bias is removed). The summed output with the theta delay forms a theta "beam"; that is, the output corresponds to a frequency f plane wave arriving from a theta direction.

Noise discrimination

The signal processing attempts to maximize the amount of signal (a pulse scattered from a tuna school) relative to the noise (any other acoustic energy on the array). The key quantity is the signal to noise ratio, which is the amount of acoustic power corresponding to the signal relative to all other acoustic power. After processing, the signal to noise ratio must be greater than one in a time-varying environment in order to successfully extract the signal from the noise - that is, in order to detect the fish school.

The optimal technique for extracting an expected signal from an incoming signal if the expected signal is known is through replica correlation. If there is no systematic component of the noise that mimics the expected signal, then the inner product of the expected signal with the actual data from the array at any given time will be, on average, zero if only noise is present on the array. On the other hand, if the data from the array exactly matches the expected signal, then the normalized inner product of the data and the expected signal is 1. For the normalized inner product, all other values fall between zero and one. Here the inner product refers to the integral of the product of the expected and actual data sets over time; that is, the total area of the product (where negative values have negative areas). Two data sets that vary randomly with respect to each other have, on average, equal probabilities of being relatively positive or negative, and so average to zero.

In a replica correlator system, the expected waveform pattern is continually correlated with the data pattern on each beam. If there is a match to the expected waveform, the correlator output registers a quantity near 1. Any correlator output over a threshhold value is considered a match and is reported to the operator.

Typically the expected waveform is taken as the broadcast waveform. At long ranges in the ocean waveguide, the waveguide itself has strong dispersive qualities and modifies the structure of the received pulse due to multipathing (separate arrivals of acoustic energy at the receiver), boundary interaction, and scattering (see, for example, the predicted first-order one-way modifications in a frequency chirp, which has a flat frequency response between the start and stop frequencies). If one has faith in one's understanding of the media propagation characteristics, one can use the predicted propagated waveform to form the correlation instead of the broadcast waveform.

This is one way that classification can be done on type of fish school: given predictions or measurements of scattering from yellowfin tuna schools, and knowledge of the local propagation environment, expected received waveforms can be predicted for yellowfin tuna. If these expected waveforms differ sufficiently from returns from other fish species or schools, or differ depending on size of yellowfin tuna school, or so forth, then a correlator match with the expected waveform is a positive identification of a yellowfin tuna school.

While a correlation technique is processor-efficient if the expected waveforms are reliable, scattering at distance from a yellowfin tuna school carries many unknowns and may be too variable for appropriate correlator use. In this case a variation of replica correlation that allows the equivalent of the correlator replica to be obtained through an iterative process with feedback can be used. Neural nets

currently are being used in a number of "ill-determined" systems to allow classification and pattern recognition when direct analytical prediction is poorly understood for a system. Neural nets have been successfully applied to undersea detection systems (Dr. Robert Kolesar, NRaD, is one expert in this field) and would be a good candidate for classification in a fisheries acoustic detection system.

Processing requirements, Phase coherence

Standard beamforming assumes phase coherence across the array, as described above. To the authors knowledge, it is unknown whether phase coherence applies in the ocean at the frequencies and distances under consideration. Certainly phase coherence applies very well at lower frequencies (below 1 kHz) and is the basis of many operational systems deployed in the field today.

However there are troublesome unknowns and causes of worry here. The central problem is that at these relatively high frequencies (high compared to most ocean long distance acoustic systems) the near-surface ocean environment may be fundamentally different than that for lower frequencies. The relevant quantity is the scale of inhomogeneities and surface features compared to that of a wavelength of sound. For 200 Hz, a wavelength is roughly 7.5 meters, while for 5 kHz, a wavelength is roughly 0.3 meters. While 7 meters is on the same order or large compared to scattering features on the ocean surface (capillary waves, breaking waves, etc), 0.3 meters is more than an order of magnitude smaller and some surface features and inhomogeneities will be large comparitively. To put it picturesquely, while lower frequencies see the ocean surface as a relatively flat but jagged surface, the frequencies under consideration here might see the same surface as mountainous alps.

Also an acoustic array that operates at lower frequencies is large compared to these inhomogeneities; for example, a 20-element array cut for 200 Hz would be 75 meters long. Conversely, the small aperture of a phase-coherent array at these frequencies is a different story.

The different length and time scales involved could produce different propagation characteristics that would make phase-coherent processing impractical at the long distances under consideration and small aperture. Whether this is a problem or not is unknown. Certainly it is dubious whether acoustic models can reliably predict results on a small aperture array at these frequencies. Experimental results would be required to address the question.

It is for this reason that the configuration study was carried out using a thinned long array, where processing is done in the time domain and phase coherence is not an issue. The thinned long array predicted results are expected to be reliable in any case. If phase-coherent processing on a small-aperture array is feasible, it would be expected to have superior operating characteristics to the thinned long array but lower noise resistance, due to the fact that the widely-separated elements in the thinned long array can be considered to be in statistically-independent noise fields, while the short-aperture coherent array cannot.

Real-time interface

Overall system control and interface would be through a more-or-less standard desktop PC system.

Actual processing would be done either in DSP-add ons or plug-in cards, or in an interfaced VME-based system in the same rack as the source control electronics. Display would be on a standard monitor. The processing/control system would be housed in a convenient interior area or on the bridge. The footpad could be as small as 2 feet by 2 feet if all components, including computer and display, can be integrated into a single rack; otherwise an area on the order of 2 feet by 5 feet would suffice.

The system should monitor and report the health and status of all components, including source, source power, hydrophones, etc. An alarm should be given if serious problems are detected so that components can be retrieved promptly.

Raw incoming data rate is expected to be on the order of 400 kb for the real time processor for coherently-processed array data. The raw data rate would be much lower for a time-based thinned long array, roughly on the order of 10-100 kb, depending on the binning accuracy chosen. The modeled array performed adequately at the 10 kb rate. These data rates can be readily handled by available DSP cards. If processing is done onboard the ship, the data would be multiplexed and transmitted to the on-ship rack receiver, which would demultiplex and process. Sampling of the hydrophones is typically done at several times the highest frequency to be analyzed with an averaging stage to smooth out local noise.

The preamplifier output of each hydrophone is amplified to a voltage level appropriate for an analogue to digital (A/D converter) converter. A 12-bit conversion provides accuracy of 2 parts in 10000, a 16-bit converter 1 part in 100000. Power output of each channel should be monitored by a watch-process to identify any dead channels, notify the operator, and possibly alter the processing to compensate. It can also be useful to watch for railed (maxed-out) channels, and other warning signals.

Beamformer

The beamformer should generate sufficient beams to close efficiently on the target and permit good target direction identification. Results with the end-to-end simulation with the thinned long array indicated that for that system in the low-data-rate configuration achievable effective beamwidths would be on the order of 3 degrees on a 90-degree beam, 8 degrees on 60- and 120- degree beams, 10 degrees on a 30-degree beam, 20 degrees on a 150-degree beam, and 50 degrees on 0-degree beam. These effective thinned-array beamwidths are out to 20 km and for good propagation conditions. Effective beamwidths about half these would be available inside of 10 km for good propagating conditions. All beams are labeled relative to 0 degrees, taken as the ship-to-array direction.

The phase-coherent array would be more narrowly confined to the 90-degree direction.

Either system would generate on the order of 20-30 beams.

For the thinned long array this would imply about 200 kips and could easily be handled on a single processor. For coherent processing this implies about 4 mips and is probably doable on a single processor but might have heavy loading and require more.

Display interface

All data and processing results would be displayed on the PC monitor. Standard display techniques consist of a top-level menu choice screen, with various subscreens that monitor system status, beam results, estimated locations, provide frequency-spectrum displays, tracking results, or whatever is deemed of interest. At any level, it should be possible for the system to transmit alarms or notices to the user.

Ease of use would be essential for actual operations on a tuna boat. Options should be well-defined, clear, and not too many in number. It should not be necessary to have detailed knowledge of the system design, electronics, or other features to use the system (although detailed system-level screens can be useful for system debug, checkout, and maintenance by an expert under these special circumstances).

The most useful display would be cumulative tracking results in range and bearing for potential targets, and any associated classification information for those targets. Other displays might include raw beam data, frequency data on a beam, estimated noise levels, and so forth.

Some type of automatic notification of a potential target would be highly advisable, since the array system could be in use for long periods of time and it would be unrealistic to expect constant monitoring of the system. In addition one of the best uses of an acoustic detection system could be at night, when such a system could still probe the full volume of water while other systems are of limited or no use. Schools could be tracked throughout the night and closed on when day arrives. If multiple schools were being tracked, the cumulative record of the school's positions would constitute a track useful to start a new search after one school had been closed on.

It could be useful to have direct access to the hydrophone output (with the direct signal from the source screened out, of course) so that an operator could listen to the output. Human ears and brains are still a preeminent pattern detection system. A set of earphones would suffice, with the input taken from a preselected hydrophone or selected hydrophone. The earphone option would probably only be practicable if the real-time processing system were on ship.

Software design

Difficulties and challenges in software design are consistently underestimated in software development projects. Either a prepackaged processing software suite should be used or an experienced software designer for array systems should develop the software suite. Software costs can be highly significant. It is difficult to reliably estimate a software cost for the proposed system, but a minimum estimate would be $100K for development and implementation.

VI. Testing Procedures

As has been noted, there are many pieces of information that would be extremely useful in developing a tuna acoustic towed-array active detection system. As mentioned above, constraints on phase-stable coherent processing at these frequencies and ranges are unknown to the author, and some experiments to clarify these issues would be highly desirable. Questions of phase stability could be answered with some simple experiments with a few hydrophones and an appropriate source with a few days experimental work and approximately three weeks of data analysis, assuming all equipment functioned properly.

Testing scattering off of known tuna targets would be invaluable in system design, checkout, and calibration. It is important to ascertain the behavior of tuna schools when subject to these types of acoustic pulses. For example, do tuna run away from the acoustic source (probably unlikely at the low duty cycles projected for typical system use, but possible)? Are there waveforms that produce characteristic features when scattering off of yellowfin tuna - knowledge which would be invaluable in classification? How do different sizes of fish or numbers of fish in a fish school or other combinations impact the scattering? There are many questions which can be addressed through use of a preliminary system, a model system, or a phase-1 development system.

Although it is considered unlikely that tuna would generate enough acoustic energy to make it practical to operate a towed array in passive mode at anything other than very close ranges, it might be that certain tuna activities (such as feeding on a prey school) would generate sufficient acoustic energy, or the prey might generate characteristic calls or other acoustic markers. It is also interesting to speculate that passive array use might be useful in closing on a tuna school at short ranges. Passive testing of a towed array would clarify these issues.

Testing with components of the system would be extremely useful for system development also. The entire envisioned fish school acoustic detection system would not have to be fully implemented for meaningful testing and experimentation to be carried out. For example, a towed array could be tested with a borrowed source, or a source with a borrowed array or even single hydrophones. Developing components of a system individually increases the likelihood of success of the total system and permits lower per-year funding, as knowledge gained from constructing and operating individual components is applied to future-developed components.

Typical active tests would start with scattering off of a target of convenience, such as a ship or buoy. Testing could proceed to small buoys or flotation balloons chosen to mimic yellowfin tuna swim bladder characteristics. Incremental testing would continue up to actual tests with fish schools. Initial tests of system components and a full system would best be done not off of an operating tuna boat but off of a research vessel equipped to handle in-water acoustic tests and interpret the results.

An accumulated repertiore of system component tests and full system tests also provides the needed information for system calibration. There are also various acoustic ranges operated by the US Navy that can perform calibration functions.

Once a specific system design is set at a component level, it is possible to assemble a software simulator for the electronic components, and by playing in either recorded waveforms or modeled waveforms, to assess the design at a software level. Such software system simulations must usually be developed in conjunction with a hardware system to provide truly useful information due to the large amount of specific information required.

VII. Costs

The following cost estimates are preliminary and may be subject to significant revision. Two classes of cost estimate are given, one with maximum use of available off-the-shelf components and technology to minimize cost, and another with some customized work.

Estimates by system

Source			
Transducer:	$10K	to	$50K
Electronics:	$10K	(includes waveform generator & power amplifier)	
Housing:	$5K	to	$10K
Cabling:	$1K		
Labor:	$100K	to	$200K
Test&Cal:	$50K		
Array			
20 hydrophones @ $1K to $5K each:			
	$20K	to	$100K
A/D	$5K		
MUX		$4K	
Elec (misc):	$5K		
Housing,etc:	$2K		
Labor:	$100K	to	$200K
Test&Cal:	$50K		
Real-time			
Processor Cards: $10K			
Elec (misc):	$5K		
Interface:	$1K		
Control			
PC/Display:	$5k	to	$10K
Rack/Cables:	$10K		
Power Sup/conv: $5K			
Labor (real+cont):	$20K		
Tow Cable:	?		
Spooler:	$2k	to	$5K
Software:	$100K	to	$300K
Integration:	$50K		
TOTAL:	$570K	to	$1103K
(Optional CTD):	$5K	to	$10K

VIII. Operations

The tuna acoustic detection system could be operated in several modes, including detection mode, tracking mode, minimization of acoustic impacts, and maximization of detection.

Also the advisability of acoustic profiling of a tuna boat is briefly discussed in this section.

Detection Mode

In detection mode, array operations would be concentrated on initially detecting a fish school. Assuming good propagation conditions, the ship would travel to the area where it is desired to start a search. The array would be deployed and the ship would cruise in search mode at a slow speed with the source and array operational for long enough to determine that no schools were being detected out to the expected detection range, say 20 km. This time is estimated to be on the order of 100 pulses, or roughly one hour.

When no detection was verified, one of two optional choices could be made. If it was felt that the area was unfavorable and it might be better to move to a farther area, the array and source would be retrieved and the boat would cruise at high speed for roughly half the outermost perpendicular scanned distance at the largest range, or 6 km. The array would then be redeployed and a new search begun.

In a more conventional operational mode, the boat would continue to cruise with the array in the water but at higher speed until a new area was reached.

Thus detection mode consists either of continuous cruise or a series of jumps to the next search area.

Tracking Mode

In tracking mode, array and source operations are optimized to maintain a track - that is, an estimated location over time - on a target, which may or may not be a target yellowfin tuna school. During this time as much information as possible is gathered to determine whether or not the target being tracked is a desired school. The boat navigates in such a way as to keep the target visibile to the towed array system while information is gathered on frequency response, etc. Tow course and speed are adjusted to keep the target visible. In addition, if there is a right-left ambiguity (it is uncertain whether the target is on the left or right side of the array), small heading changes on the order one or two beamwidths will resolve the ambiguity by noting the change in the target beam.

At some point (usually after a definite indicator of a desired target is seen, or sufficient time has passed that it seems unlikely a definite indicator will be seen) a decision is made as to whether the target is sufficiently promising to pursue or not. If the target is deemed promising, then the boat begins course changes to close on the target while still keeping the target in view of the array system. If not promising, the boat returns to cruise-search mode and discards the target.

Minimization of Acoustic Impacts

In operations to minimize acoustic impacts, the boat starts search operations at low source acoustic power and close range (shorter cycle time). After ascertaining that there are no targets (fish, whales, marine mammals, etc) of concern within the near area, the source power is stepped up and the search broadened to a wider area. In this way the search is stepped outward to larger ranges (meaning higher acoustic power in the water near the boat) in increments, with each increment verifying that it is "safe" to increase source power.

Note that this assumes that most of the water volume insonified by the source is visible to the array, as the array itself is being used to detect targets of concern. This also assumes that targets of concern will be detected by the array a high percentage of the time and hopefully identified as such.

This type of stepped-outward search is intrinsically "safe" for targets of concern if the stepping is slow enough, because the affected target of concern will leave the area if impacted. Note that this is a "failsafe" consideration; if operated effectively for minimization of acoustic impact, the array system detects targets of concern before they are significantly impacted and maintains source levels below the predetermined significant impact level.

Additional techniques for minimizing acoustic impacts include visual scanning of the boat vicinity for any targets of concern, or other survey techniques (such as helicopter) for potential targets of concern.

Maximization of Detection

In maximization of detection operations, the source is operated at full intensity at all times, and the boat maneuvers so that the maximum amount of water volume is searched by the acoustic detection system. This is in essence a sinuous forward path, with straight cruising while in search mode.

Tuna boat noise profiling

It would be extremely useful to profile an operational tuna boat to see what noise spectrum it emits at a variety of speeds. This would help to operate the array in a favorable noise bandwidth, avoid any sharp noise lines emminating from the boat, and determine the best tow length to the receive section behind the boat. A ship of opportunity could be profiled at a Navy range.

Appendix A

Detailed results on acoustic intensity at various ranges and depths from the operation of an acoustic source in a fisheries active acoustic system.

1. Tables of acoustic intensity at ranges from 1 to 40 km from the acoustic source and at depths from 10 to 100 meters. Tables are presented for each of 8 characteristic geographic and temporal environments representing the ETP, given in the table header as Jan grp 0, Jan grp 1, ..., Jly grp 3. All tables are for a source frequency of 6 kHz, which is representative of results at all frequencies in the studied band. All tables are for an acoustic source of 200 dB intensity; results for other source levels SL can be found by adding (SL-200) to the table values. One table is presented for each characteristic environment group for the source located at 10 meter depth (shown in the table header, for example, as "src = 10m"), 20 m depth, ..., up to 100 m depth. The predicted average intensity at a range and depth is then found by locating the appropriate range-depth entry for a selected characteristic group and source depth.

These tables are averaged in a concluding set of tables which show the *average* predicted acoustic energy in the top 100 meters of water at ranges from 1 to 40 km and for source depths of 10 to 100 meters. These tables show the strong impact source depth can have on acoustic energy in near-surface waters. One table is presented for each characteristic environment group.

2. Figures for each of the characteristic environment groups show the distribution of acoustic energy throughout the entire water column for a source as above, with a source depth of 20 meters and a horizontal full beamwidth of 80 degrees. Acoustic intensity is shown for all depths and ranges out to 10 km by a grayscale representation; the lighter the coloring, the higher the intensity. A colorbar for each plot shows the translation from predicted acoustic intensity to shade of gray.

Appendix A. continued. Page

Tables of acoustic energy in the top 100 meters of water by range and depth
Source Depths: 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 meters
Sound Speed Profile - January Group 0 61
Sound Speed Profile - January Group 1 71
Sound Speed Profile - January Group 2 81
Sound Speed Profile - January Group 3 91
Sound Speed Profile - July Group 0 101
Sound Speed Profile - July Group 1 111
Sound Speed Profile - July Group 2 121
Sound Speed Profile - July Group 3 131

Tables of average predicted acoustic energy in the top 100 meters of water by range and depth
Source Depths averaged over 10-100 meters
Sound Speed Profile - January Group 0 141
Sound Speed Profile - January Group 1 142
Sound Speed Profile - January Group 2 143
Sound Speed Profile - January Group 3 144
Sound Speed Profile - July Group 0 145
Sound Speed Profile - July Group 1 146
Sound Speed Profile - July Group 2 147
Sound Speed Profile - July Group 3 148

Figures for each characteristic Sound Speed Profile Environment showing the distribution of acoustic energy throughout the top 100 meters of water using a source at 20 meters and a horizontal full beamwidth of 80 degrees

Sound Speed Profile - January Groups 0, 1, 2, 3 149
Sound Speed Profile - January Group 0 150
Sound Speed Profile - January Group 1 151
Sound Speed Profile - January Group 2 152
Sound Speed Profile - January Group 3 153
Sound Speed Profile - July Groups 0, 1, 2, 3 154
Sound Speed Profile - July Group 0 155
Sound Speed Profile - July Group 1 156
Sound Speed Profile - July Group 2 157
Sound Speed Profile- July Group 3 158

Appendix B

Representative pulse waveforms and their distortion at various ranges in the ocean waveguide when used in a fisheries active acoustic system.

1. Representative waveforms are shown in the time and frequency domains. For illustrative purposes a 0.04 sec pulse is shown. All pulses are chosen to lie in the 6 to 8 kHz bandwidth region. The frequency power spectrum is shown immediately below the time representation. One figure shows the pulse as broadcast by the source; waveforms illustrated include a pure 6-kHz tone, a hyperbolic-frequency modulation pulse (which is doppler-invariant), a uniform-distribution pulse which decays with time, a frequency chirp (which has a linearly-increasing instantaneous frequency with time), and a comb pulse with equal components at 6, 6.25, 6.5, 6.75, and 7 kHz. Following each pulse illustration are the predicted arrivals, propagating in good propagation conditions for the ETP, for ranges of 4 km to 20 km. The predicted arrivals are a first-order calculation only, incorporating only multipath structure, to illustrate typical ocean waveguide waveform distortion. This is a one-way prediction including only waveguide effects; that is, pulse effects from reflection from a target and propagation back to a receiver are not included.

For the propagated pulses, the title line information can be read as follows: (1) the first entry is the characteristic SSP used, (2) the source depth in meters is given after "SD", (3) the target depth in meters is given after "TD", (4) the range in meters from the source is given after "R", (5) the effective source level is given after "SL=". Arrival times are shown relative to the start of the source pulse broadcast.

Appendix B. continued. Page

Pure Tone waveform in time and frequency domains for the January Group 0 Sound Speed Profile environment, by range

Pure Tone Waveform 162
Range 4000 meters 163
Range 8000 meters 164
Range 10000 meters 165
Range 12000 meters - 1st arrival 166
Range 12000 meters - 2nd arrival 167
Range 12000 meters - 3rd arrival 168
Range 14000 meters - 1st arrival 169
Range 14000 meters - 2nd arrival 170
Range 16000 meters - 1st arrival 171
Range 16000 meters - 2nd arrival 172
Range 18000 meters - 1st arrival 173
Range 18000 meters - 2nd arrival 174
Range 20000 meters - 1st arrival 175
Range 20000 meters - 2nd arrival 176

Hyperbolic-frequency modulation waveform in time and frequency domains for the January Group 0 Sound Speed Profile environment, by range

Hyperbolic-frequency modulation Waveform 177
Range 4000 meters 178
Range 8000 meters 179
Range 10000 meters 180
Range 12000 meters - 1st arrival 181
Range 12000 meters - 2nd arrival 182
Range 12000 meters - 3rd arrival 183
Range 14000 meters - 1st arrival 184
Range 14000 meters - 2nd arrival 185
Range 16000 meters - 1st arrival 186
Range 16000 meters - 2nd arrival 187
Range 18000 meters - 1st arrival 188
Range 18000 meters - 2nd arrival 189
Range 20000 meters - 1st arrival 190
Range 20000 meters - 2nd arrival 191

Appendix B. continued. Page

Uniform-Distribution Pulse waveform in time and frequency domains for the January Group 0 Sound Speed Profile environment, by range

Uniform-Distribution Pulse Waveform 192
Range 4000 meters 193
Range 8000 meters 194
Range 10000 meters 195
Range 12000 meters - 1st arrival 196
Range 12000 meters - 2nd arrival 197
Range 12000 meters - 3rd arrival 198
Range 14000 meters - 1st arrival 199
Range 14000 meters - 2nd arrival 200
Range 16000 meters - 1st arrival 201
Range 16000 meters - 2nd arrival 202
Range 18000 meters - 1st arrival 203
Range 18000 meters - 2nd arrival 204
Range 20000 meters - 1st arrival 205
Range 20000 meters - 2nd arrival 206

Frequency Chirp waveform in time and frequency domains for the January Group 0 Sound Speed Profile environment, by range

Frequency Chirp Waveform 207
Range 4000 meters 208
Range 6000 meters 209
Range 8000 meters 210
Range 10000 meters 211
Range 12000 meters - 1st arrival 212
Range 12000 meters - 2nd arrival 213
Range 12000 meters - 3rd arrival 214
Range 14000 meters - 1st arrival 215
Range 14000 meters - 2nd arrival 216
Range 16000 meters - 1st arrival 217
Range 16000 meters - 2nd arrival 218
Range 18000 meters - 1st arrival 219
Range 18000 meters - 2nd arrival 220
Range 20000 meters - 1st arrival 221
Range 20000 meters - 2nd arrival 222

Comb Pulse with equal components waveform in time and frequency domains for the January Group 0 Sound Speed Profile environment, by range 223

Appendix C

Modelled thinned long line array detections and tracking efficiency in the ETP when used in a fisheries active acoustic system; detailed plots.

1. This series of plots show the simulated response of a thinned long-line acoustic array operating for detection of yellowfin tuna schools in the ETP in an edge-detector configuration. Results were assessed for ranges of 3 to 20 km on the 0, 30, 60, 90, 120, and 150 degree radials. The coordinate system is such that the source represents 0 range and 0 degrees bearing is along the array axis away from the tow direction, progressing to 180 degrees in the tow direction. Four plots are given for each simulated configuration: a detection estimation plot, first-arrivals plot, and peak- and average-power on the array plots. The detection plot shows each estimated detection as a line drawn from the true target location to the processor's estimated location. Failure to detect is indicated by a black dot. The tendency of estimated detections to fall towards 90 degrees is an artifact of the assumption of perfect hemispheric resolution and in reality errors would be distributed around the radials. The remaining plots are by radial as a function of range. The radial label (in degrees) adjoins its label line at the label's lower right corner. The first-arrival plots show first arrivals on the array in terms of processor time bin number; peak and average power plots show peak and average powers on the array for the processor's detection. Lack of detection is again shown by a black dot.

Plot titles can be read as follows: (1) the first entry is the characteristic SSP used, (2) the configuration number (following "C") shows source, target, and receiver depths in tens of meters ("0" represents 100 m), in that order, (3) the pulse central band frequency in Hz follows "F", (4) the processor sampling frequency in Hz follows "H", (5) the array configuration follows "A" as A*Ne:lag.Ds*, where *Ne* is the number of elements, *lag* is the distance from source to first element in meters, and *Ds* is the element spacing. The final item is the source level ("SL=*sl*") in decibels.

Appendix C. continued. Page

Plots of thinned, long line, array detections and tracking efficiency for Sound Speed Profile environments, by selected configurations of Source Depth, Target Depth, and Receiver Depth for a 12 element array, 500 meters from Source with elements spaced at 20 meters

Sound Speed Profile - January Group 0
Range, Angle test locations 227
Configurations 223, 243, 263, 283, 203 228
Configurations 225, 245, 265, 285, 205 233
Configurations 227, 247, 267, 287, 207 238
Configurations 229, 249, 269, 289, 209 243

Sound Speed Profile - January Group 1
Range, Angle test locations 248
Configurations 223, 243, 263, 283, 203 249
Configurations 225, 245, 265, 285, 205 254
Configurations 227, 247, 267, 287, 207 259
Configurations 229, 249, 269, 289, 209 264

Sound Speed Profile - January Group 2
Range, Angle test locations 269
Configurations 223, 243, 263, 283, 203 270
Configurations 225, 245, 265, 285, 205 275
Configurations 227, 247, 267, 287, 207 280
Configurations 229, 249, 269, 289, 209 285

Sound Speed Profile - January Group 3
Range, Angle test locations 290
Configurations 223, 243, 263, 283, 203 291
Configurations 225, 245, 265, 285, 205 296
Configurations 227, 247, 267, 287, 207 301
Configurations 229, 249, 269, 289, 209 306

Sound Speed Profile - July Group 0
Range, Angle test locations 311
Configurations 223, 243, 263, 283, 203 312
Configurations 225, 245, 265, 285, 205 317
Configurations 227, 247, 267, 287, 207 322
Configurations 229, 249, 269, 289, 209 327

Appendix C. continued. Page

Sound Speed Profile- July Group 1
Range, Angle test locations 332
Configurations 223, 243, 263, 283, 203 333
Configurations 225, 245, 265, 285, 205 338
Configurations 227, 247, 267, 287, 207 343
Configurations 229, 249, 269, 289, 209 348

Sound Speed Profile - July Group 2
Range, Angle test locations 353
Configurations 223, 243, 263, 283, 203 354
Configurations 225, 245, 265, 285, 205 359
Configurations 227, 247, 267, 287, 207 364
Configurations 229, 249, 269, 289, 209 369

Sound Speed Profile - July Group 3
Range, Angle test locations 374
Configurations 223, 243, 263, 283, 203 375
Configurations 225, 245, 265, 285, 205 380
Configurations 227, 247, 267, 287, 207 385
Configurations 229, 249, 269, 289, 209 390

Appendix D

Processor detection output summarized in terms of scored (weighted average) plots for all combinations of target depth, range, and SSP to assess optimum source and receiver depths.

1. Scored plots provide a uniformly-weighted average across different parameters so that the relative impact of chosen parameters can be assessed for system impact and optimization. Plots are presented scoring simulated detection peak power, average power, and range and bearing estimation accuracy. These results are presented in two forms on each figure: as raw numeric scores, and in grayscale form to aid the eye in choosing optimal configurations. All results show scored assessments as a function of source and receiver depths. A perfect (optimal) score would have numeric value 255; a failure to detect is represented by a black dot. In the grayscale plots, solid black represents a perfect score with decreasing scores represented by lighter shades. Thus high scores and black/dark areas represent optimal configurations. For a detailed discussion of the scoring method, see the report text.

For compactness, target depth, range and SSP are all represented by corresponding index values in the plot titles. Index values correspond to parameters as follows: (A) range: 0=4 km, 1=7 km, 2=10 km, 3=14 km, 4=18 km; (B) target depth: 0=20 m, 1=30 m, 2=40 m, 3=50 m, 4=60 m, 5=70 m, 6=80m, 7=90 m, 8=100m; (C) SSP: 0=jan0, 1=jan1, 2=jan2, 3=jan3, 4=jly0, 5=jly1, 6=jly2, 7=jly3. The scored plot titles indicate which parameters have been averaged over to form the plot by the range of target depth indices following "TD", range indices following "R", and SSP indices follow "SSP". For example, "SSP0-7" would indicate all SSPs were averaged over, "SSP4-7" would indicate all jly group SSPs were average over, and "SSP0-0" would indicate that no averaging over SSP was done - SSP index 0 (jan0) was used.

Appendix D. continued. Page

Weighted average plots of the probability of detection, by target depth and Sound Speed Profile environment, for range averaged 0- 18 kilometers
Target Depths: 0, 20, 30, 40, 50, 60, 70, 80, 90, 100 meters

Sound Speed Profile - January Group 0 397
Sound Speed Profile - January Group 1 406
Sound Speed Profile - January Group 2 415
Sound Speed Profile - January Group 3 424
Sound Speed Profile - July Group 0 433
Sound Speed Profile- July Group 1 442
Sound Speed Profile - July Group 2 451
Sound Speed Profile - July Group 3 460

Weighted average plots of the probability of detection, by range and Sound Speed Profile environment, for target depths averaged 0- 100 meters
Ranges: 4, 7, 10, 14, 18 kilometers

Sound Speed Profile - January Group 0 469
Sound Speed Profile - January Group 1 474
Sound Speed Profile - January Group 2 479
Sound Speed Profile - January Group 3 484
Sound Speed Profile - July Group 0 489
Sound Speed Profile- July Group 1 494
Sound Speed Profile - July Group 2 499
Sound Speed Profile - July Group 3 504

Weighted average plots of the probability of detection, by Sound Speed Profile environment, for target depths averaged 0- 100 meters and range averaged 0- 18 kilometers

Sound Speed Profile - January Group 0 509
Sound Speed Profile - January Group 1 510
Sound Speed Profile - January Group 2 511
Sound Speed Profile - January Group 3 512
Sound Speed Profile - July Group 0 513
Sound Speed Profile- July Group 1 514
Sound Speed Profile - July Group 2 515
Sound Speed Profile - July Group 3 516

Weighted average plots of the probability of detection for all Sound Speed Profile environments combined, for target depths averaged 0- 100 meters and range averaged 0- 18 kilometers 517

RECENT TECHNICAL MEMORANDUMS

Copies of this and other NOAA Technical Memorandums are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22167. Paper copies vary in price. Microfiche copies cost $9.00. Recent issues of NOAA Technical Memorandums from the NMFS Southwest Fisheries Science Center are listed below:

NOAA-TM-NMFS-SWFSC- 241 The Hawaiian monk seal in the Northwestern Hawaiian Islands, 1995.
T.C. JOHANOS and T.J. RAGEN
(June 1997)

242 Plankton sampling during the whale habitat and prey study 10 July-4 August 1996.
W.A. ARMSTRONG and S.E. SMITH
(July 1997)

243 Benthic Invertebrates of four Southern California marine habitats prior to onset of ocean warming in 1976, with lists of fish predators.
J.R. CHESS and E.S. HOBSON
(August 1997)

244 Fishes collected by midwater trawls during two cruises of the *David Starr Jordan* in the Northeastern Pacific Ocean, April-June and September-October, 1972
J.L. BUTLER, H.G. MOSER, W. WATSON, D.A. AMBROSE, S.R. CHARTER, and E.M. SANDKNOP
(September 1997)

245 Mapping benthic habitats and ocean currents in the vicinity of Central California's Big Creek Ecological Reserve
M. YOKLAVICH, R. STARR, J. STEGER, H.G. GREENE, F. SCHWING, and C. MALZONE
(September 1997)

246 The physical oceanography off the Central California coast during May-June, 1996: A summary of CTD data from pelagic juvenile rockfish surveys.
K.M. SAKUMA, F.B. SCHWING, K. BALTZ, D. ROBERTS, and S. RALSTON
(September 1997)

247 Killer whales of California and Western Mexico: A catalog of photo-identified individuals.
N.A. BLACK, A. SCHULMAN-JANIGER, R.L. TERNULLO, and M. GUERRERO RUIZ
(September 1997)

248 U.S. Pacific Marine Mammal Stock Assessments: 1996
J. BARLOW, K.A. FORNEY, P.S. HILL, R.L. BROWNELL, JR., J.B. CARRETTA, D.P. DeMASTER, F. JULIAN, M.S. LOWRY, T. RAGEN, and R.R. REEVES
(October 1997)

249 Analysis of agency costs attributable to the recovery plan for Sacramento River winter-run chinook salmon.
C. THOMSON
(October 1997)

250 A report of cetacean acoustic detection and dive interval studies (caddis) conducted in the southern Gulf of California, 1995.
J. BARLOW, K. FORNEY, A. VON SAUNDER, and J. URBAN-RAMIREZ
(December 1997)