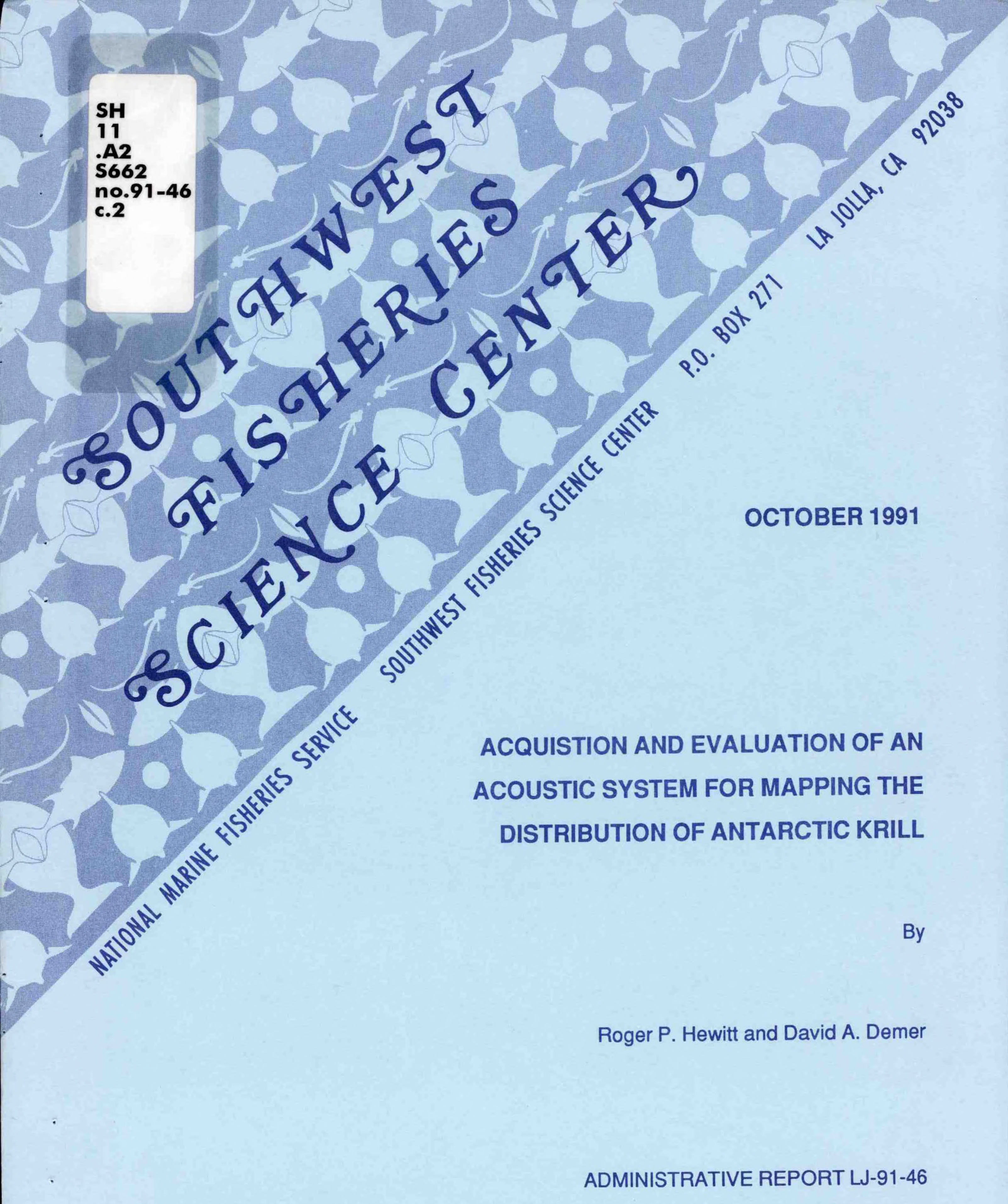

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ACQUISTION AND EVALUATION OF AN ACOUSTIC SYSTEM FOR MAPPING THE DISTRIBUTION OF ANTARCTIC KRILL

By

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Acquisition and Evaluation of an Acoustic System for Mapping the Distribution of Antarctic Krill

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ABSTRACT

A portable acoustic survey system was acquired and evaluated as a tool for mapping the distribution of Antarctic krill and estimating its abundance. This report describes our initial research objectives, system requirements necessary to achieve these objectives, three alternative systems, and the procurement, assembly, testing and field use of the selected system. Plans for modification of the system and refined research questions are also presented. Although some engineering problems remain, the system is capable of producing the kinds of data required to meet our research objectives. By adding multi-frequency capabilities to the system, its use may be extended to fish and micro-zooplankton populations.

INTRODUCTION

The U.S. Antarctic Marine Living Resources (AMLR) program has two principal components: (1) U.S. policy positions on the management of harvested resources in the Southern Ocean are developed and articulated in an international forum established to conserve marine resources; and (2) a field research program is pursued to address critical information needs and to establish scientific credibility.

The current AMLR research strategy is to determine the response of krill predators to changes in the availability of their prey, and to relate these changes to biotic and abiotic features of the epipelagic environment. Within-season and between-season variability has been described for a study site in the vicinity of Elephant Island during the 1989-90 and 1990-91 austral summers. A field team, from NOAA's National Marine Mammal Lab, monitored the reproductive success and foraging patterns of seal and penguin breeding on a small island within the study site. Grants were given to academic investigators for shipboard studies including 1) descriptions of the currents, hydrographic fronts, and water mass boundaries apparent in the upper 750m; 2) distribution of nutrients, phytoplankton biomass, species composition, and primary productivity throughout the study area; 3) direct zooplankton sampling with nets; 4) descriptions of krill length, reproductive condition, sex ratio, maturity stages, molt stages, and feeding condition; and 5) acoustic surveys of the distribution and abundance of krill throughout the study area. The research strategy and the survey cruises were designed and coordinated by scientists from the Southwest Fisheries Science Center (SWFSC).

In 1990, the Director of the SWFSC decided to acquire the capability to conduct acoustic surveys for Antarctic krill; he also stipulated that the system be suitable for mapping zooplankton, nekton and fish populations in other habitats. This report describes progress since that decision, and includes sections on our research objectives, system requirements and components, description and comparison of candidate systems, discussions with other biological oceanographers using acoustic tools, our experiences with procurement, assembly and testing of the selected system, planned modifications and upgrades, research questions yet to be addressed, and a general evaluation of the system as a tool for mapping pelagic populations and biomass estimation.

RESEARCH OBJECTIVES

1. **Map relative and absolute abundance of krill in vicinities of land-based predator monitoring sites.** Our long-term research strategy is designed to elucidate the relationship between krill and its predators. Our current field tactic is to map abiotic and biotic factors, postulated to affect the spatial distribution of krill, and to describe land-based predator response to variations in the local availability of krill. As such, spatial mapping of krill densities is central to our program.

2. **Measure *in-situ* target strengths of individual krill.** The largest potential bias in using acoustic techniques to estimate krill biomass, is associated with the conversion of integrated echo power to absolute numbers of krill reflecting sound. The relationship is a function of the target strength of individual krill which, in turn, is a function of their size, shape, orientation and physiological condition. Consequently, krill target strength data should be collected to a) confirm or modify theoretical models of target strength, b) to classify ensonified populations, assuming a correct model, and c) to reduce the number of net samples required to confirm target classification.

3. **Measure aspects of krill aggregation patterns.** Like many organisms, krill are heterogeneously distributed. Quantitative data on the distribution patterns of krill should be collected to a) improve the reliability of survey designs, distribution maps, and abundance estimates; b) allow comparisons of the dominant scales of krill distribution patterns with those of biotic and abiotic factors in the pelagic habitat postulated to affect the distribution of krill; and c) facilitate comparisons with other data sets to examine variations in distribution patterns between regions and within a region over time.

4. **Map pelagic fish and zooplankton populations and estimate their biomass.** In order to gain broad support for the purchase, development and maintenance of an acoustic system, it should also be suitable for surveying fish and zooplankton populations. Initial design and future development decisions should be biased toward portability and adaptability to other resource assessment problems.

SYSTEM REQUIREMENTS

System requirements follow from the objectives:

1. The system should be based on echo integration technology, a relatively mature methodology for relating total echo power to animal abundance.

2. The system should be portable so that it can be used on a variety of research ships and vessels of opportunity.

3. The system should include either dual beam or split beam transducers and associated software to resolve individual targets, compensate for signal loses, and accumulate target strength data.

4. The system should be down-looking, and expandable to side-looking and up-looking. Such expansion will provide additional spatial information for reconstructing distribution patterns.

5. The system should include a computer with large storage and backup capacities, and a well-developed software package for data collection, archival and analysis. Data collection parameters must be flexible and easily modified. Received echoes should be digitized and archived so that echograms may be recreated and re-analyzed. Processed data should be stored in a form that will facilitate further reduction and display.

6. The system should be expandable to multiple-frequency operations.

7. The system should have a large dynamic range so that echoes from single krill as well as dense swarms may be detected simultaneously.

SYSTEM COMPONENTS

A functional description of the desired system is as follows: The acoustic system should transmit pings into the water, measure echo return as a function of time (depth), apply corrections for transmission losses and system calibration, digitize the analog signal, display and record the echogram, integrate echo intensity, and collect target strength data from individual sound scatterers. The main system components necessary to perform these functions are:

1. Towed body with transducer(s)
2. Towing and deck cables
3. Deployment system, including winch, sheaves, and tension compensator
4. Transceiver(s)
5. Digitizer(s)
6. Signal processor(s)

7. Computer and software for data archiving, analyses, and reporting
8. Calibration setup

ALTERNATIVE SYSTEMS

Three systems were evaluated which met some or all of our requirements:

1. Custom-built system and PC software
2. Biosonics 102 echo sounder and PC software
3. Simrad EK500 echo sounder and UNIX workstation software

1. Custom-Built

An example of a custom-built system is one designed and used by Dr. M. Macaulay, Applied Physics Laboratory, University of Washington. Macaulay's system consists of one to several single-beam and dual-beam transducers connected to a transceiver. Incoming signals are corrected for transmission losses and digitized before being passed to a microcomputer for display. Both a real time echogram (ping by ping) and a compressed echogram (30 ping averages) are displayed so that the user can see the last five minutes in detail or the last two hours in a compressed form; a map of the survey area with transects and current position is also displayed. Echograms are also recorded on a thermal chart recorder and a video cassette recorder. Periodically data are passed to a second computer for archiving and further analyses; positions are checked, echo integration is performed, and distribution maps are generated. The echogram display on the second computer is compiled from pings averaged over five minutes so that several hours of data may be compressed and viewed; this is useful for looking at distribution patterns on a scale of a few km to 10's of km. Additional software is required to process dual beam echo returns for target strength information.

During the 1989-90 and 1990-91 field seasons, two single beam transducers were used (120 kHz and 200 kHz). Some insight into the biological character of the sound scatterers was obtained by visually comparing the echograms from the two frequencies. The transducers were mounted on a 4-foot V-fin towed body which acted as a depressor; when under tow the body tended down and outboard. About

15 m of cable was sufficient to achieve 6-8 m of depth; strain was taken off the cable by a pair of large bungee cords which effectively de-coupled the ship's motion from the towed body. The body appeared to tow at a steady attitude in a wide range of sea states on a variety of vessels. The body was unstable, however, near the surface during recovery operation in heavy seas. Field calibration setup was straightforward and reliable.

Approximate costs for a custom-built system are: $20k for a transducer, transceiver and signal digitizer; $15k for a V-fin towed body with cables and a simple deployment system; $20k for software, plus another $20k for computers, printers, and recorders, for a total of $75k.

Macaulay's system is simple, extensively field tested in the Antarctic, and inexpensive. All components, with the exception of his software, are commercially available. An attractive feature is the simultaneous display of detailed and compressed echograms. This allows comparisons with complementary data sets of coarser resolution (i.e. physical oceanography, primary production and predator foraging).

2. Biosonics

The Biosonics system (Model 102) consists of one or two dual beam transducers connected to a dual transceiver. The transceiver handles more than one dual beam transducer by multiplexing between them on a ping-by-ping basis. The user is offered a limited amount of flexibility in adjusting for signal transmission losses. Analog echo data from the transceiver are passed to a microcomputer where they are digitized. The user specifies data processing parameters, and echo integration and target strength analyses are conducted in real time. An echogram is displayed and saved after averaging over several pings; target strength data are also saved from identified individual scatterers. The echogram can be recreated and both echo integration and target strength analyses can be re-run using different processing parameters. Incoming signals from the transceiver are also displayed on an oscilloscope and recorded on a thermal chart recorder and a digital audio tape (DAT) recorder.

Although Biosonics initially recommended a dead weight towed body that could house both a high frequency down-looking transducer and side-looking transducer, they were willing to design a simple V-fin deployment system including cable, winch, and bungee cords. Biosonics would have also provided engineering assistance to help design calibration procedures, local training for system operators, and an acoustic technician for the duration of the first cruise.

The data collection and analyses software is the most attractive aspect of the Biosonics system. It operates under the Microsoft Windows graphical environment which has several advantages: the required hardware (a 80386 or 80486 based MS-DOS computer) is relatively inexpensive; Windows' memory management and multi-processing overcomes the memory limitations of MS-DOS and allows several processes to be co-running in different windows (e.g. echogram display, echo integration, and target strength data accumulation); and Windows' data exchange capabilities make it easy to port data to other Windows applications for generating spatial maps of biomass density, statistical summaries, graphic data displays, report writing, and data archiving in a relational database.

Approximate costs for the Biosonics system are: $89k for the transducer, transceiver, computer hardware, software, and printer; $22k for side-looking capability including an additional transducer, multiplexor and recorder; $7k for a dead weight body, cables and connections, or $15k for a V-fin towed body with cables and a simple deployment system ($20k for side-looking as well). Thus, a Biosonics system would cost between $96k and $131k depending on which transducer and deployment options were chosen.

Biosonics offered the most complete system for the money; the company has a reputation for solid engineering support; and they were willing to provide a complete range of logistic services.

3. Simrad

The Simrad system (Model EK500) consists of one to three transducers connected to a processing unit. Contained in the processing unit, for each transducer, are a transceiver, a signal digitizer, and software for echo integration and target strength analysis. The user is offered a considerable amount of flexibility in setting both data collection and data analyses parameters. The echogram is displayed on a color monitor and recorded on a color printer. Analyzed data may be output to a MS-DOS personal computer via a serial port or a more expensive UNIX workstation via an ethernet port for archiving. In addition, UNIX workstation software developed in conjunction with the Institute of Marine Research in Bergen, may be used to log raw data, reconstruct the echogram and re-analyze the data.

Simrad initially recommended a relatively expensive, self-contained boom and winch that would swing out horizontally from the side of the ship to deploy a towed dead-weight body (the body is of sufficient size to house both a high frequency down-looking transducer and a low frequency side-looking transducer). This system would be easy to use and minimizes possible damage to the towed body; it would be semi-portable requiring welding to the deck and electrical power connections from the survey vessel. The dead weight body does not exert a downward pull when towed and requires approximately 60 m of cable to achieve a depth of 10 m at 10 kt; this amount of cable would be more cumbersome and time-consuming to recover than a V-fin system. Alternately, Simrad indicated that it could supply a V-fin with a single transducer, but declined to offer a deployment system or calibration setup. Simrad was willing to provide training in Norway, and on-site assistance of an engineer for one week.

Approximate costs for the Simrad system are: $89k for a transducer, transceiver, processor, printer and display; $15k for side-looking capability including an additional transducer, transceiver and printer; $73k for the dead-weight towed body, cable and crane-mounted deployment system, or $15k for a V-fin towed body with cables and a simple deployment system ($20k for side-looking as well). The UNIX workstation for data analyses and logging is $70k (including $40k for the software); whereas a PC for simple data logging is $5k. Thus, a Simrad system would cost between $109k and $253k depending on which transducer, deployment, and data logging/analysis options were chosen.

Of the three systems, the Simrad echo sounder is the most technically advanced as well as operationally flexible. Two features make the system particularly attractive:

1. A very large dynamic range which makes it possible to use the system for both relatively weak targets, such as deep krill layers, and relatively strong targets, such as epipelagic fish schools.

2. Split beam technology which can classify echoes from single point scatters with greater confidence than dual beam technology. This is critical to the accumulation of reliable individual krill target strength data.

COMPARISON OF SYSTEMS

A custom-built system is the least capital investment. The Biosonics system uses more mature software in a popular graphics environment. The Simrad echo sounder is superior to the Biosonics; without a UNIX workstation and software, however, its post-processing capabilities are more limited.

Technical expertise required to maintain the equipment was a consideration. A custom-built system, because it would be one of a kind, would probably require the most attention to technical detail. Biosonics is a small company selling systems to relatively unsophisticated users and would probably require less technical expertise. Simrad has a reputation for over-engineered, highly reliable systems and would probably require the least technical familiarity; however, they are difficult to repair without specific Simrad training.

Ease-of-use and investment in operator training was another consideration. At least two people will be required during each cruise leg to operate the acoustic system and ensure that data are collected correctly. Some field analyses will be necessary to adjust sampling strategy and to plan related work. The degree to which the system is easy to use will be a factor in training the required number of people. In this regard, Biosonics and Simrad are approximately equal; the custom-built system would be substantially more complicated.

Finally, follow-up service was an important consideration. In the beginning, we expected to need a high level of engineering support; as our program developed, we anticipated a desire to expand our capabilities; and as technical advances were brought to the market, we wanted to be able to upgrade the equipment. In this regard Simrad has a very good reputation. Even with the political animosity between Norway and South Africa, Simrad consistently provided good service and equipment upgrades to the Sea Fisheries Institute. On the other hand, there are some questions about the quality of service received from Simrad with the EK400 echo sounder aboard the *David Starr Jordan*. Judging from conversations with people at the Alaska Fisheries Science Center, Biosonics is not as strong with their follow-up service. Charles Greene, at Cornell University, counters this impression by noting that Biosonics is very interested in the success of his field work, offering an extraordinary level of engineering support and follow-up service. Follow-up service with a custom-built system is more problematic; a continuing contract with the designer/builder would be the only way to ensure his interest.

All of the systems have identical calibration requirements.

All of the systems can operate at multiple frequencies. The operating frequency should be high enough to resolve individual krill, yet low enough to detect krill layers at 250 m depth. A commonly used frequency for krill surveys is 120 kHz; there are several target strength studies on krill at 120 kHz as well. Macaulay currently uses both 120 kHz and 200 kHz; Ian Hampton (South Africa's Sea Fisheries Institute) uses 120 kHz and 38 kHz; Inigo Everson (British Antarctic Survey) uses 120 kHz and 38 kHz; the majority of countries reporting acoustic data during FIBEX used 120 kHz. 120 kHz seemed a logical choice; however, the ability to resolve real targets from background noise decays rapidly with range. Lower frequency sound is not attenuated nearly as fast and thus allows detection at deeper ranges. Investigators often use two frequencies: a high one because krill make better targets at high frequencies, and a low one to make sure that deep layers of krill are not overlooked.

OTHER CONVERSATIONS

Jim Traynor, head of the acoustics group at the Alaska Fisheries Science Center, and his electronic engineer, Dan Twohig, were both very pleased with the performance of the Simrad EK500 echo sounder that they recently purchased and used on a pollock survey in the Bering Sea. Twohig considered the Simrad EK500 sounder to be technically far superior to the Biosonics 102 sounder and strongly recommended that we select Simrad on this basis alone. Traynor stated that the operational setup and data collection are very easy and well engineered; he advised, however, that the UNIX workstation analyses software is still under development and requires an intimate familiarity with the UNIX operating system.

Ian Hampton, head of the acoustics group at the Sea Fisheries Institute, reviewed the product literature and technical specifications for both the Biosonics and Simrad systems. Hampton, a physicist with 20 years experience in the design and conduct of bioacoustic surveys, recommended the Simrad system. Paul Smith and Jay Barlow each concurred that the Simrad unit appears to be technically superior to the Biosonics unit and therefore is the better investment.

Charles Greene advised that it was unreasonable to expect to be able to measure the target strength of individual krill from a surface-towed transducer. He cited Weibe and his use of deep submersible transducers mounted on ROV's and nets to measure the target strength of individual zooplankters. Biosonics developed a 420 kHz submersible transducer for this purpose and have collaborated on several projects with Greene. Biosonics also expressed a strong desire to help us develop a practical system (submersible transducers, experimental setups) to make *in situ* measurements of krill target strength as a contribution to acoustic theory. Simrad markets a submersible 38 kHz split beam transducer system and has a 120 kHz submersible transducer currently under development; however, they have yet to express scientific interest in helping us collect krill target strength data. Although he has worked closely with Biosonics, Greene noted the technical superiority of the Simrad echo integrator and stated that if Simrad can build a split-beam transducer that will function at depth that we should procure their equipment.

SUMMARY AND DECISION

The following table summarizes the differences between the three systems:

Consideration	Custom-Built	Biosonics	Simrad
Cost of complete system	Low	Moderate	High
Technical merits of echo sounder	High; custom-built for krill survey work to take advantage of inexpensive components and advanced digital signal processing	Moderate; uses standard echo sounder technology with dedicated computer for signal processing	Very high; state-of-the-art production echo sounder and signal processor
Post-processing capabilities	Good; flexible echogram display	Excellent; extensive data display, archiving, and report generation capabilities	Minimal, without UNIX workstation and software; excellent with workstation.
Engineering support and training during setup and field testing	Unknown	Excellent	Weak support for deployment system and calibration setup
Ease of use; technical expertise required	Least user-friendly; however reduced manpower requirements with contract.	Excellent	Excellent
Follow-up service	Unknown	Conflicting reports	Conflicting reports

In May 1990, a decision was made to procure the Simrad EK500 system with a single split-beam transducer housed in a small V-fin in FY1990. Simrad would also supply the armored towing cable and the deck cable, but the portable winch and other components of the deployment system would be procured separately in FY1991. A lack of adequate lead time, available funds, and experience with echo integration technology contributed to the decision to procure only one transducer and a simple deployment system. It was further decided to use the system on an experimental basis during the 1990-91 field season; a grant would be given to Macaulay to participate on the cruise with his system and to provide acoustic data on krill distribution.

We subsequently learned that several other institutions and government agencies working in the Antarctic had made similar decisions. Australia's Antarctic Division, the British Antarctic Survey, Chile, and Ecuador have all acquired Simrad EK500 echo sounders.

No decision was made on whether to purchase a computer for data archiving, and, if so, what computer architecture and software would be optimal.

PROCUREMENT, ASSEMBLY, AND TESTING

System specifications were prepared and a requisition was submitted to the NOAA procurement group in Seattle on May 17, 1990. We anticipated one month to prepare the solicitation, one month to advertise and award the contract, and six weeks for the winning vendor to build and deliver the equipment; a delivery date of September 1 was thus specified. Our expectations were too optimistic. The solicitation was not issued until June 29; the award was made to Simrad on September 11; and the equipment was delivered during the first week in November.

Bids were received from Biosonics and from Simrad. Although neither vendor was fully compliant with the specification, a Source Evaluation Board recommended on August 3 that the contract be awarded to Simrad. NOAA procurement overruled, asking for another round of bids. Simrad was ultimately awarded the contract, but a devaluation of the U.S. dollar relative to the Norwegian kroner increased the cost by 10% before negotiations were completed.

Meanwhile, various alternatives for data archiving and post-cruise analyses were considered. The Simrad EK500 outputs color echograms and periodic tables of each integration and target strength accumulations. These data products are sufficient to reconstruct the survey and produce a descriptive report. The data are not, however, permanently archived in a digital format. A simple data logging procedure could be written to log ensemble-averaged ping data on an MS-DOS personal computer via the serial port; the computer and logging software would be relatively cheap, but ping-by-ping resolution would be lost and additional software would be necessary to perform any post-survey analyses. A second alternative would be to capture the data stream from every ping through the ethernet port to an MS-DOS computer equipped with a an ethernet board. The basic hardware would be cheap, but development of data logging software and additional data storage capacity would add considerably to the cost. Furthermore, the anticipated volume of data throughput could be pushing the limits of MS-DOS computer technology, and it would still be necessary to develop additional software to perform any post-survey analyses. A third alternative would be to capture the ping-based data stream through the ethernet port to a UNIX workstation. This made the most sense because UNIX was designed with built-in capacities for managing and archiving high volume data streams, and because the price difference between a UNIX workstation and an MS-DOS computer is rapidly shrinking. Although data logging would be relatively straightforward with a UNIX workstation, questions still remained regarding the complexity, cost and time required to develop software for post-cruise data extraction and analyses.

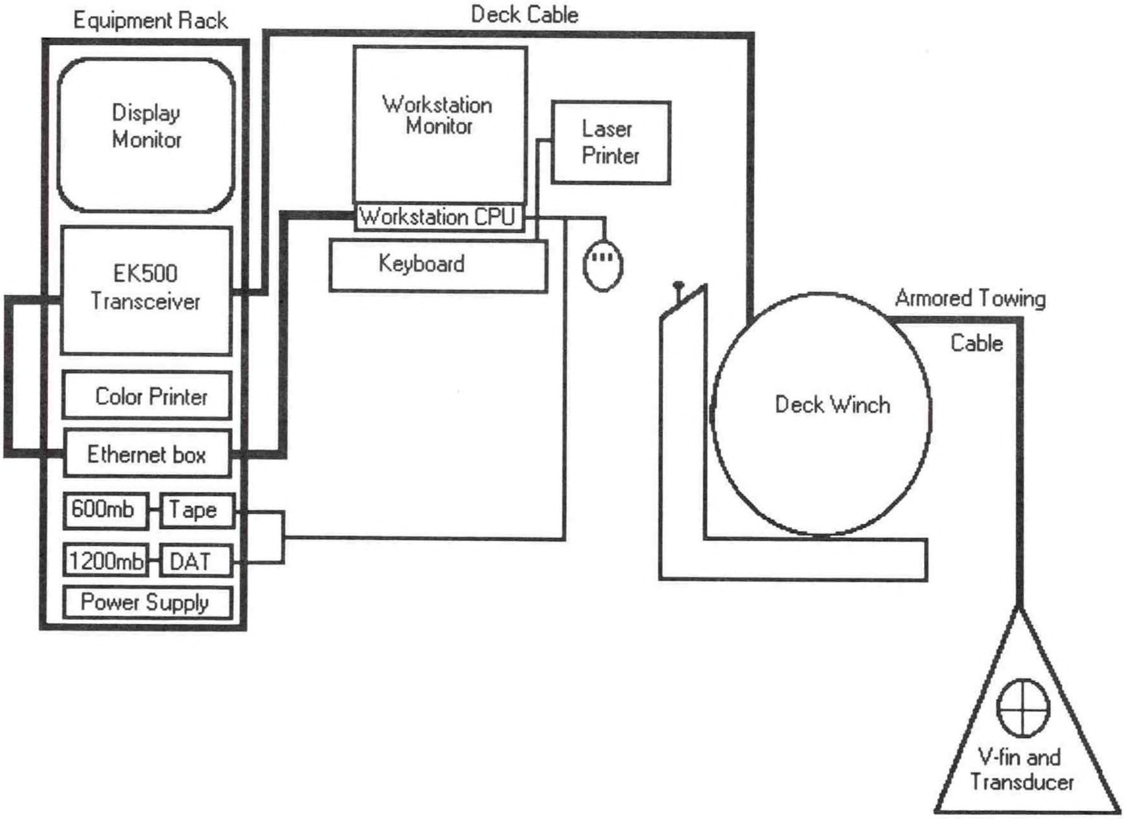
Ultimately it was decided to purchase a UNIX workstation in FY1990 and the Bergen Integrator software in FY1991. It was expected that the software would perform several functions: control of the echo sounder, control of data logging and archiving, selected data extraction and display, echo classification using graphical analyses tools, and report generation. The software had been developed over several years as a joint project between the Institute of Marine Research and the Christian Michelsen Institute, both in Bergen; Simrad assisted in adapting it to the new EK500 echo sounder and eventually took over both the development and marketing of the software, calling it the BI500. Although the software was expensive and not bug-free, it would be available before the 1991 field season at a fixed price. We could be assured of neither if we attempted our own software development.

A UNIX workstation was procured in August 1990. It was recognized that it would be necessary to recruit technical assistance to set up and administer the new computer, as well as to assist with the assembly, testing, and operation of the acoustic system. A position description was developed and several contacts were made with local groups working in the field of underwater acoustics.

In September 1990, the first author (RPH) visited Horten, Norway to talk with Simrad's engineers about the EK500 echo sounder, and Bergen, Norway to talk with colleagues about the BI500 software. Simrad's engineers indicated that the small V-fin might not be adequate for work in heavy seas, but they were not certain and it was too late to acquire a different towed body. The EK500 appeared to be a well-developed instrument, capable of meeting our requirements. The BI500 software was not nearly as mature, but Simrad promised a high level of support and unlimited upgrades without cost.

In response to the annual budget crisis, the new position was canceled in October, 1990. Fortunately, a Scripps graduate student in ocean engineering (second author, DAD) volunteered his time in exchange for access to the equipment and ship time to develop a PhD thesis. During the next six weeks, system software was loaded on the new computer and user accounts were set up; a laser printer, digital tape drive, high capacity disk drives, and other peripherals were purchased and installed; an equipment rack and power supply was procured; a portable winch, cable sheaves, and other deck rigging supplies were acquired; the EK500 echo sounder (including transceiver, monitor, power regulator, color printer, transducer, towed body, towing cable, deck cable, and various connectors) was received, assembled and bench tested; and a calibration rig was designed and built.

The system is described in the following schematic diagram:



Simrad's chief engineer for the EK500 and BI500 projects visited La Jolla in late November, 1990 and brought the latest version of the BI500 software and documentation. Loading the software was more troublesome than expected and most of the one week planned for training was spent in program debugging. Two days at sea with the full system was spent aboard the Navy R/V *DeStieger*. A system calibration was conducted and underway tests were performed. All components, including the towed body, worked well.

Total cost of the system prior to the 1991 field season:

EK500 echo sounder, including transceiver box, display monitor, color printer, deck and towing cables, V-fin, transducer, voltage transformer, and power regulator	$110k
Deck winch, sheaves, tension compensator system, and rigging	7k
UNIX workstation, disk drives, tape drives, laser printer, and equipment rack	25k
BI500 software	46k
Total	$188k

DEPLOYMENT IN ANTARCTICA DURING 1990-91 AUSTRAL SUMMER

The system was deployed in the Antarctic during the 1990-1991 field season aboard the NOAA Ship *Surveyor*.[1] Another system, operated by Macaulay, was the primary source for acoustic data describing the distribution of krill over the study area. The SWFSC system was operated in tandem with Macaulay's and qualitative comparisons were made between the systems as the surveys progressed. The study area was approximately 13,000 square nautical miles centered on Elephant Island, just north of the tip of the Antarctic Peninsula. This area was surveyed once during each of two 30-day cruise legs in 1991. Two additional surveys covering approximately 2700 square nautical miles on the north side of Elephant Island were

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[1] For details see Rosenberg and Hewitt. 1991. AMLR 1990/91 Field Season Report: Objectives, Accomplishments and Tentative Conclusions. SWFSC Admin. Rep. LJ-91-18: 97p.

conducted, once during each cruise leg. The system was calibrated at Admiralty Bay, King George Island at the beginning of the first leg and at the end of the second leg; it was also calibrated before and after the cruise at the Scripps Institution of Oceanography.

Operational problems were encountered with the V-fin towed body. Although deployment and recovery operations were, for the most part, trouble free, the body was not stable at survey speeds (6 to 8 knots). Mechanical vibration weakened the electrical connection between the transducer leads and the towing cable. This connection had to be repaired several times in the field, causing gaps in the survey coverage. A second towed body and transducer was received between cruise legs as a backup in the event that the first body was lost or failed completely.

Although survey coverage was incomplete, there was good qualitative agreement between the systems as to the definition of areas of high krill density. A more formal evaluation of the outputs of the two systems is in preparation; included are comparisons of krill density histograms, distributional maps, and biomass estimates.

A very useful data set was collected at 5 knots in an area of high krill density. A closed spaced (0.2 n.mi.) series of transects was run over an area 1 n.mi. square. Data were collected to 250m depth so that a volume of water 1 n.mi. by 1 n.mi. by 250m was ensonified. The grid was occupied three times over a 12-hour period with ambient light levels ranging from full daylight to twilight to darkness. Changes in the position, shape, and density of krill swarms were evident. A description of these changes, using volume visualization techniques, is in progress.

At the same time, *in-situ* measurements of krill target strength were obtained. The measurements extended the results of controlled experiments on constrained animals, and confirmed predictions based on theoretical models. The measurements are the first reported of individual animals in the wild, and are of interest to both acousticians and krill biologists. Scientific correspondence describing these observations was recently published in *Nature*[2].

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[2] Hewitt and Demer. 1991. Krill abundance. Nature 353:310.

PLANNED UPGRADES AND MODIFICATIONS

A new dead-weight towed body was recently procured. The design is expected to provide more stable behavior at high ship speeds and sea states. In addition to a down-looking configuration, the transducer may be oriented to operate in side-looking or up-looking modes. This provides additional flexibility and the capability to conduct some directed experiments (see below). The deck winch was traded in on a new one, which allows finer operational control and compensates for the added weight of the new towed body. The new winch is also equipped with slip rings, rather than a plug, for transferring the electric signal from the towing cable to the deck cable; this enhances both the safety and efficiency of deployment and recovery operations.

The workstation operating system, the EK500 firmware, and the BI500 software have all been upgraded at least twice during the past year. These necessary upgrades are time-consuming and often introduce unexpected bugs and incompatibilities with previously-collected data sets. As the EK500 and BI500 are refined, however, additional upgrades should occur with decreasing frequency.

There is an ongoing, but as yet unfulfilled, requirement for spare circuit boards and backup components. Now that the configuration has been set, and research objectives have been further elaborated (see below), critical components can be specified. In particular, the towed body, towing cable, transducers, signal processor and transceiver boards, color printer, and workstation CPU should be backed up.

Expansion of the system to include additional acoustic frequencies is desirable, but not currently funded. Additional frequencies would provide the observation range required to survey pelagic and bentho-pelagic fish populations and the resolution necessary to survey zooplankton populations. Lower frequencies are necessary to detect krill below 250m depth, and higher frequencies may assist in separating echoes of krill from that of other zooplankters.

RESEARCH QUESTIONS

After one year's experience with the new acoustic system, we can review our research objectives, identify specific issues that should be addressed, and prioritize future work.

1. Map relative and absolute abundance of krill in vicinities of land-based predator monitoring sites. With the new towed body sub-system, we expect to have solved most of the major engineering problems associated with assembling an acoustic mapping tool. Several issues concerning survey methods and data analyses, however, remain to be addressed:

a. Procedures need to be developed for generating distribution maps and estimating abundance during the course of the surveys. This information is necessary for allocating direct sampling effort, for interpreting ancillary data sets, and for making adjustments to the cruise plan. Furthermore, the general problem of how to best estimate abundance and its variance from line-transect measurements of density, particularly without sacrificing the spatial relationships contained in the data set, is of interest to biologists using acoustic stock assessment tools in any aquatic habitat. The approach will be to apply existing statistical methods for describing spatial pattern to observed transects, interpolate and contour the underlying density field, and estimate abundance as the volume under the fitted surface. The procedures will also be applied to simulated density fields to test the efficiency of the methods and to verify estimates of variance.

b. At any one time, an unknown quantity of krill are either above or below the vertical range of observation (10m to 250m). Possible approaches for assessing the amount of krill in the upper 10m are the use of up-looking and/or side-looking towed transducers, vertically stratified net sampling, and remote self-contained acoustic systems (e.g. bottom-moored, buoy-mounted, or free drifting). The same approaches could be used to assess the amount of krill below 250m; lower frequency acoustic transducers would be necessary to achieve the required range.

c. Krill surveys may also be biased if the animals react to the approach of the ship by adjusting their position and/or orientation. Possible approaches to assessing avoidance include the use of repetitive survey patterns to detect changes in the position and/or density of krill swarms, frequency analysis of echo returns from krill swarms to detect and quantify Doppler shift, and the use of moored acoustic systems to observe the change in distribution in reaction to the passage of a survey vessel.

d. Three groups of organisms are responsible for most of the acoustic return observed in the epi-pelagic zone of the Elephant Island study area: nekton (including several species of euphausids and myctophids), zooplankton (primarily copepods), and thaliaceans (salps). Directed net sampling has been used to help interpret echo returns from krill and other scatterers. Other approaches may be to make use of the return from transducers operating at several frequencies. In addition to complex signal processing methods, visual interpretation of the difference in return received by 120 kHz and 200 kHz transducers may be useful in distinguishing krill from salps.

e. The acoustic integration method assumes that the total observed echo energy is the sum of echoes from individual scatterers. This assumption may be violated in the case of high density zooplankton swarms and fish schools. Complications may include multiple reflections of the returning echo, absorption of sound within the aggregation, and shadowing of one portion of the aggregation by another. The sensitivity of the method to this assumption may be investigated by comparing krill density estimated from acoustic return with that estimated from direct samples or photographs, over a range of aggregation shapes and densities

2. Collect *in situ* target strength measurements of individual krill. The system has proven to be capable of collecting krill target strength measurements. The limited data set obtained in March, 1991 has already contributed to an improved definition of krill target strength at the July meeting of the CCAMLR Working Group on Krill. Future work (also recommended by the Working Group) should address the following issues:

a. Krill target strength varies as a function of body volume and physiological condition. In order to better define these dependencies, *in-situ* measurements of target strength will be obtained over a range of animal lengths and physiological condition, including gender, sexual maturity, molt stage, and feeding condition. In conjunction with the measurements krill specimens will be obtained with high-resolution directed net sampling gear.

b. Krill target strength also varies as a function of animal orientation and body shape. One promising approach to investigating these dependencies is to simultaneously photograph and acoustically ensonify a volume of water containing krill.

c. Although theoretical models of sound scattering by krill have incorporated various aspects of animal size and physiological condition, they have been verified only to a limited degree. The observed distributions of krill lengths, condition, orientation and body shape will be input into theoretical models so as to predict the distribution of individual target strengths that would be expected from a natural aggregation of animals. This will be compared with observed distributions and the models adjusted or redefined as appropriate.

d. The accuracy of target strength measurements is very sensitive to system calibration. A series of experiments is planned to measure the response of the system gain to changes in the pulse length and water temperature, salinity and depth. The difference between a calibration sphere made of copper versus one made of tungsten carbide will also be measured.

3. Collect measurements of krill aggregation sizes. The system's current ability to collect and archive acoustic data on a ping-by-ping basis allows the description of swarm structure with a resolution of approximately one meter. Data can also be averaged for pattern description on coarser scales and we have done a limited amount of these kinds of analyses. Future analyses will address the following issues:

a. The details and variability of krill aggregation patterns have not been well described, and are necessary to understanding all aspects of krill biology and well as for planning efficient surveys. Descriptions of swarm dimensions, density and inter-swarm spacing will be generated from the survey data. Observed seasonal, diurnal and spatial variability in these parameters will also be described. Three-dimensional imagery will be used to aid in the perception and description of aggregation patterns and their change with time.

b. Pronounced, but inconsistent, diurnal changes in krill swarming have been observed, but not well described. The position, shape and density of swarms appears to change in response to changes in ambient light, although phototaxism may not be the only proximate cause. Detailed observations of swarms throughout one or more day cycles, and associated measurements of other parameters, will be obtained. Three-dimensional imagery has already been used to describe one data set, and will be applied to additional observations.

c. Testable hypotheses need to be developed regarding the effects of both biotic and abiotic factors on the spatial distribution of krill. Factors which may influence the distribution of krill include bathymetric features, water mass boundaries and frontal zones, phytoplankton biomass, species composition and production rates, and zooplankton volumes and species composition. Possible approaches to the identification of dominate factors include correlation statistics (e.g. principal component analysis, step-wise regression) and scale comparisons (e.g. spectral analysis, autocorrelation).

4. Map spatial biomass of pelagic and bentho-pelagic fish stocks and zooplankton populations. The experience and procedures developed for mapping krill in the Antarctic can be directly transferred to other species and other habitats. The system is portable and can be deployed on any vessel with adequate power, GPS navigation control, and facilities for deploying the towed body. The instrument is capable of resolving echoes throughout the water column as well as very near the bottom. There are some issues, however, that should be addressed when considering other populations:

a. No single frequency is ideal for all depth ranges and target species. Lower frequency transducers (e.g. 38 kHz) would be required to conduct surveys of fish populations at depths greater than 250m. Higher frequency transducers (e.g. 200 kHz) would be required to accurately resolve zooplankton scatterers. The new towed body will accommodate a 120 kHz transducer and a 200 kHz transducer together or a 38 kHz transducer by itself. Use of a frequency other than 120 kHz would require installation of a second transducer and transceiver; use of multiple frequencies would require new cables and the specification of procedures for processing data from multiple sources.

b. In some survey situations it may be preferable to position the transducer closer to the animals of interest. The approach would be to procure transducers capable of making accurate measurements under high pressure and to investigate alternative deployment vehicles (ROV's, benthic sleds, nets).

c. Information from additional sensors (e.g. cameras, fluorometers, optical plankton counters, depth and attitude indicators, light meters) may assist in the interpretation of echo returns. To add these capabilities it would be necessary to modify the existing towed body (or design a new one) and to procure cables with sufficient signal bandwidth.

EVALUATION AND EXTENSION TO OTHER RESOURCE PROBLEMS

The main elements of an acoustic system for mapping the distribution of Antarctic krill have been specified, procured, assembled and tested. Although some engineering problems remain to be addressed, the system meets our requirements and has already been used to collect new information on the target strength of krill.

Future work can be organized under three general headings:

Engineering, including incremental improvements and upgrades to the system, and incorporation of additional frequencies;

Survey methodology, including determination of survey biases, and definition of acoustic target strength;

Data analyses, including description of aggregation patterns, and identification of causal factors.

The system will be used during the 1991-92 austral summer to map the distribution of krill biomass in the vicinity of Elephant Island, Antarctica. The experience gained from this field work and the procedures developed to analyze the data will be directly transferable to mapping pelagic populations in other habitats.

Three general concerns should be addressed when using this system in any resource assessment situation: 1) apportionment of echo return to target species and other sources, 2) determination of the portion of the population that is not detected acoustically and 3) implication of observed pattern on biomass estimates.