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## **Coastal Structure Inspection Technologies**

### **Investigation of Multibeam Sonars for Coastal Structure Surveys**

*by Terri Prickett*

**WES**

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|    | <u>Problem Area</u>           |    | <u>Problem Area</u>       |
|----|-------------------------------|----|---------------------------|
| CS | Concrete and Steel Structures | EM | Electrical and Mechanical |
| GT | Geotechnical                  | EI | Environmental Impacts     |
| HY | Hydraulics                    | OM | Operations Management     |
| CO | Coastal                       |    |                           |

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# **Coastal Structure Inspection Technologies**

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by Terri Prickett

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Final report

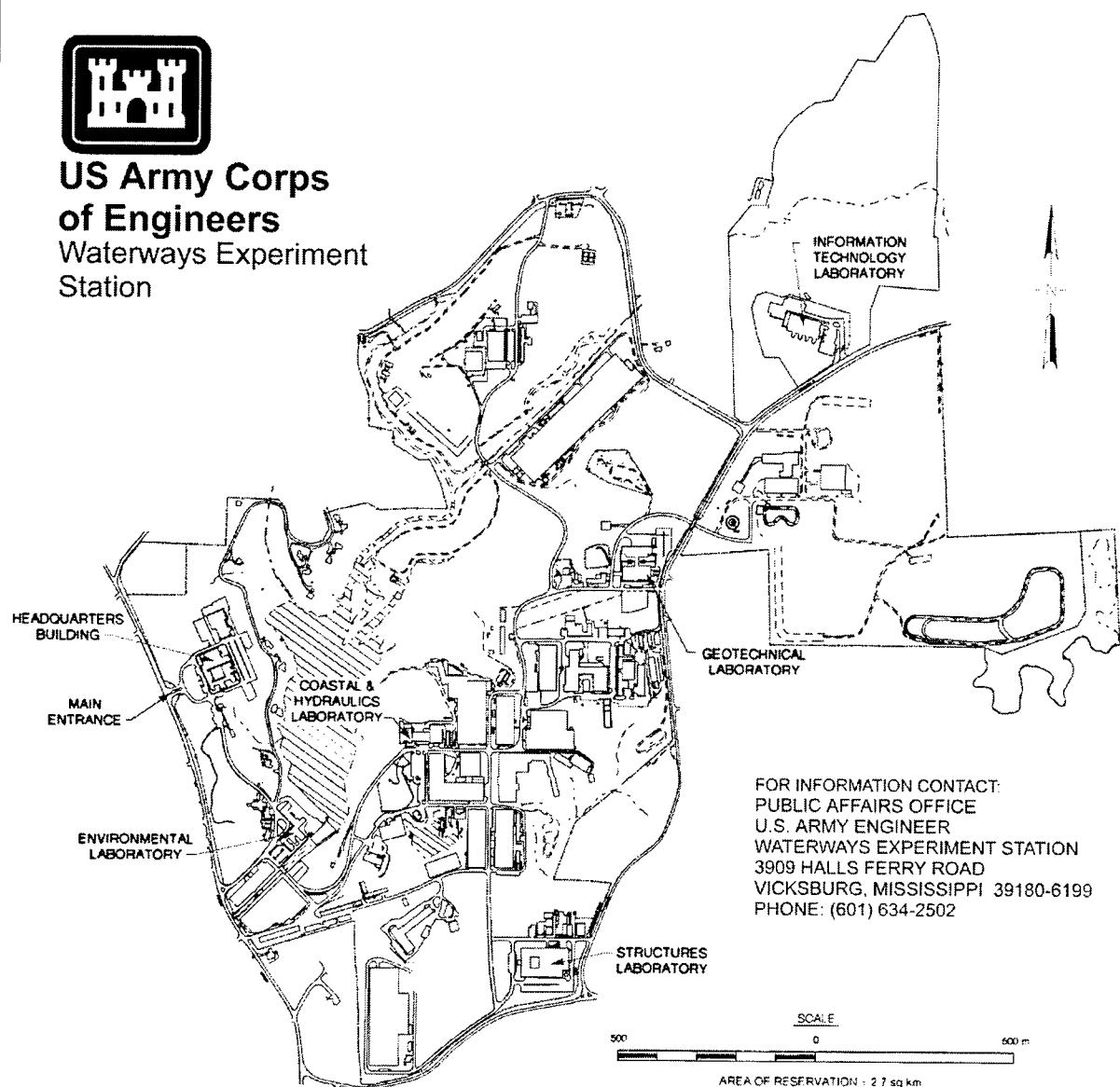
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# Preface

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The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE) as part of the Coastal Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Civil Works Research Units 32326, "Evaluation of Damage to Underwater Portions of Coastal Structures," from Fiscal Years (FY)1984 to 1989 (REMR-I) and 32661, "Quantitative Imaging and Inspection of Underwater Portions of Coastal Structures," from FY1990 to 1995 (REMR-II) for which D.D. Davidson, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Waterways Experiment Station (WES), is the Problem Area Leader. The CHL was formed in October 1996 with the merger of the WES Coastal Engineering Research Center and Hydraulics Laboratory.

Dr. Tony C. Liu is the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Harold C. Tohlen and Dr. Liu serve as the REMR Overview Committee. Mr. William F. McCleese, WES, is the REMR Program Manager. This study was conducted under the general supervision of Dr. James R. Houston, Director, CHL, and Messrs. Richard A. Sager and Charles C. Calhoun, Jr., Assistant Directors, CHL, and under the direct supervision of Mr. William L. Preslan, Chief, Prototype Measurement and Analysis Branch (PMAB), Coastal Sediments and Engineering Division (CSED), CHL, and Mr. Thomas W. Richardson, Chief, CSED.

Mr. Gary L. Howell, PMAB, was Principal Investigator (PI) of the REMR-I work unit during prototype conception, development, and field testing of the Coastal Structure Acoustic Raster Scanner (CSARS) and was assisted by Mr. Jonathan W. Lott, formerly of PMAB. Mr. Lott was PI of the REMR-II work unit for final CSARS development, investigation of new technology for monitoring coastal structures, and field demonstrations and tests. He was assisted by Mr. Paul T. Puckette, also formerly of PMAB. Mr. Timothy Welp, PMAB, assisted in field testing and production of documentary video. Ms. Terri L. Prickett, PMAB, authored final report documentation.

This report summarizes research conducted to develop and investigate survey equipment for the purpose of collecting quantitative hydrographic data to more accurately determine underwater coastal structure conditions. Technical review was conducted by Mr. Lott and Mr. Preslan.

Dr. Robert W. Whalin was Director of WES at the time of publication of this report. COL Robin R. Cababa, EN, was WES Commander.

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# Conversion Factors, Non-SI to SI Units of Measurement

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Non-SI units of measurement used in this report can be converted to SI units as follows:

| Multiply              | By         | To Obtain         |
|-----------------------|------------|-------------------|
| degrees (angle)       | 0.01745329 | radians           |
| feet                  | 0.3048     | meters            |
| knots (international) | 0.51444444 | meters per second |
| miles (U.S. nautical) | 1.852      | kilometers        |
| miles (U.S. statute)  | 1.609344   | kilometers        |

# 1 Introduction

---

This report discusses research conducted to investigate and develop hydrographic survey equipment for objective, detailed, and quantitative definition of the underwater shape of coastal structures. This research was conducted at the U.S. Army Engineer Waterways Experiment Station (WES), Coastal and Hydraulics Laboratory (CHL)<sup>1</sup> under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

Research and development were executed in two phases: (a) from fiscal years 1984 to 1989 (REMR-I) by the work unit "Evaluation of Damage to Underwater Portions of Coastal Structures," and (b) during REMR-II from FY1990 to 1995 by the work unit "Quantitative Imaging and Inspection of Underwater Portions of Coastal Structures." The main objective of the REMR-I work unit was hardware identification, evaluation, and prototype design and development. The REMR-II work unit focused on developing hardware and software tools to make quantitative inspections of underwater portions of coastal structures a routine procedure requiring minimum levels of skill, training, and experience to produce useful, high-quality results with an emphasis on the product and the process of such inspections. Both work units investigated present-day and newly emerging survey technologies.

## Problem Statement

Most damage to coastal structures, e.g. rubble-mound breakwaters, jetties, and groins, typically occurs to the underwater portion of the structure. While above-water damage is easily observed and surveyed, underwater damage such as scour, settlement, and scattering and breakage of armor units is not often evident subaerially, and damage can progress until a major structural collapse occurs. Figures 1, 2, 3, and 4 are examples of coastal structures exhibiting damage. Inspection of submerged portions of coastal structures is essential for early detection of structural damage and deterioration. Detection of underwater damage and deterioration is cost-effective for coastal engineers in terms of

---

<sup>1</sup> The CHL was formed in October 1996 with the merger of the WES Coastal Engineering Research Center and Hydraulics Laboratory.



Figure 1. 1982 breakwater damage at Crescent City, CA. Note the broken dolos and scattered armor stone



Figure 2. Scour damage on Shinnecock Inlet jetty, Long Island, New York

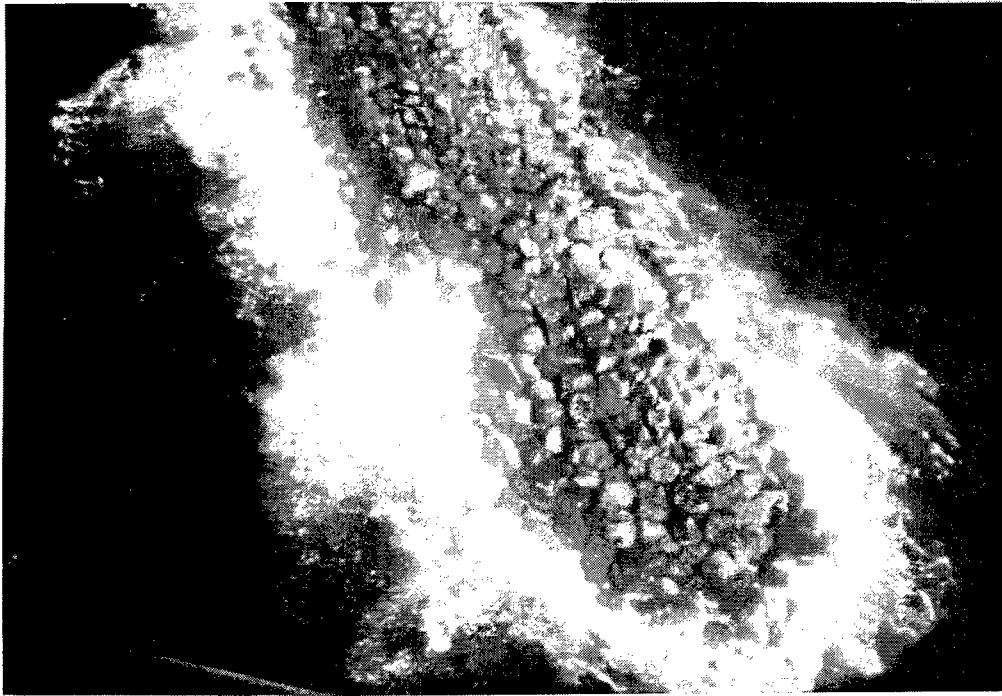


Figure 3. Yaquina Bay north jetty, Newport, OR, damaged by waves and currents



Figure 4. Breakwater damage at King Harbor, Redondo Beach, CA

planning for structure repairs and rehabilitation, and management of coastal structures over their lifetimes.

Using divers for underwater inspection or surveys of coastal structures is often difficult and risky because of the normal occurrence of waves, current, and limited visibility around the structure. Diver surveys are costly and time-consuming, and only provide subjective information sparse in spatial detail. Side-scan sonars (SSS) were investigated and proved a viable tool for structural surveys (Kucharski and Clausner 1990). Although SSS surveys provide good spatial coverage, the results are semi-quantitative and often sketchy and distorted because of energetic wave and current conditions around the structure. To guarantee quality, underwater structural inspection using both divers and SSS often requires onsite involvement of numerous skilled, trained, and experienced personnel, making these efforts costly and time-consuming. Additionally, typical fathometer surveys, while low in cost, are difficult to perform and yield ambiguous data on the steep, irregular slopes typical of coastal structures.

While detecting changes is now often possible, the potential for rapid and cost-effective quantitative underwater inspection is now being realized. Quantitative comparison of data from successive annual inspections could help detect incipient damage conditions such as toe scour, and would provide information needed for planning of structure rehabilitations.

## **Scope of Report**

Chapter 1 of this report is the introduction and problem statement. Chapter 2 provides a general introduction to REMR equipment and multibeam sonar technology developed and tested for use in performing high-resolution, quantitative surveys of coastal structures. Chapter 3 describes equipment demonstrations, and major field trials and results, and Chapter 4 provides a brief summary of the entire investigation.

## **2 Equipment Description and Development**

---

### **Coastal Structure Acoustic Raster Scanner (CSARS) System**

Prior to REMR-I, surveying technology had not yet advanced to the point where objective, detailed and quantitative data could be obtained to determine the underwater condition of coastal structures. Established to research and develop equipment capable of meeting the needs of the U. S. Army Corps of Engineers (USACE) surveying community, the REMR-I work unit conceived and developed the Coastal Structure Acoustic Raster Scanner (CSARS) system.

The CSARS system is a remote, bottom-deployed system consisting of a tripod containing a single, pointable 300-kHz acoustic transducer unit with a driving pan-and-tilt motor. The tripod also contains peripheral sensors, including a compass and inclinometer for orientation accuracy, and a pressure sensor to provide water depth. CSARS specifications are provided in Table 1.

The transducer head transmits a narrow beam of acoustic energy in a conical beam pattern towards the structure, mapping the underwater target as a two-dimensional array or raster of ranges which, once processed, results in a data set of x-y-z coordinates. Range errors resulting from boat and wave motion are eliminated because the bottom deployment provides a stationary platform. The CSARS-instrumented tripod is cabled to an operator-controlled shipboard computer system allowing for real-time graphical display and onsite data post-processing. Figure 5 is a photograph of the CSARS-instrumented tripod and computer system.

CSARS field deployment involves lowering the tripod to the seafloor from a boat fitted with a suitable boom or A-frame in a series of set-downs spaced along the coastal structure. A helicopter was also considered as a vehicle for CSARS field deployment, but was not field tested. Data collected from the set-downs would provide a continuous data set through overlapping scans. This concept is illustrated in Figure 6. CSARS field trials were conducted in 1988 and 1989 using prototype versions of the system in several man-made tanks; the Atlantic Ocean near Wilmington, North Carolina; Cleveland Harbor on Lake Erie; and

| <b>Table 1</b><br><b>CSARS System Specifications</b><br><b>(Lott, Howell, and Higley 1990)</b> |                                                                |
|------------------------------------------------------------------------------------------------|----------------------------------------------------------------|
| Underwater Unit                                                                                |                                                                |
| Beam width                                                                                     | Conical beam, 1.7° <sup>1</sup> , at 3 dB down points          |
| Frequency                                                                                      | 300 kHz                                                        |
| Minimum step size                                                                              | 0.45°, both horizontal and vertical                            |
| Scan limits                                                                                    | ±90° horizontal, and ±45° vertical                             |
| Range                                                                                          | 3 to 150 m (10 to 500 ft)                                      |
| Operational depth                                                                              | 30 m (100 ft)                                                  |
| Water temperature                                                                              | 0 to 35° Celsius                                               |
| Shipboard Unit                                                                                 |                                                                |
| Power                                                                                          | 115 VAC, 60 Hz, 4 amp sine wave                                |
| Humidity                                                                                       | 10 to 90° non-condensing                                       |
| Air temperature                                                                                | 0 to 35° Celsius                                               |
| Resolution                                                                                     | Range dependent, timing resolution reported to 0.03 m (0.1 ft) |

Crescent City, California, resulting in the evolution of a prototype system capable of collecting and processing three-dimensional (3-D) digital range data from steeply sloped structures such as rubble-mound breakwaters. A more detailed description of the CSARS system and its development is found in Lott, Howell, and Higley (1990) and Lott (1991).

The REMR-II work unit continued CSARS system development, thereby improving hardware, data collection software, and deployment techniques. In addition to CSARS system development, the REMR-II work unit also investigated newly emerging technology for monitoring coastal structures, resulting in discovery of new, high-resolution multibeam sonar systems in the commercial market. These commercially available systems proved superior to the still-prototype CSARS system, and CSARS development ended in 1993. REMR focus was directed towards investigation of multibeam sonar system applications for inspection and surveying of coastal structures.

## Multibeam Sonar Systems

### Background

By the late 1970s, echo sounding had evolved from single-frequency, single-transducer acoustic systems, to dual-frequency, multi-transducer units called “sweep systems,” that are able to provide 100 percent swath coverage and

<sup>1</sup> A table of factors for converting non-SI units of measurement to SI units is provided on page vii.

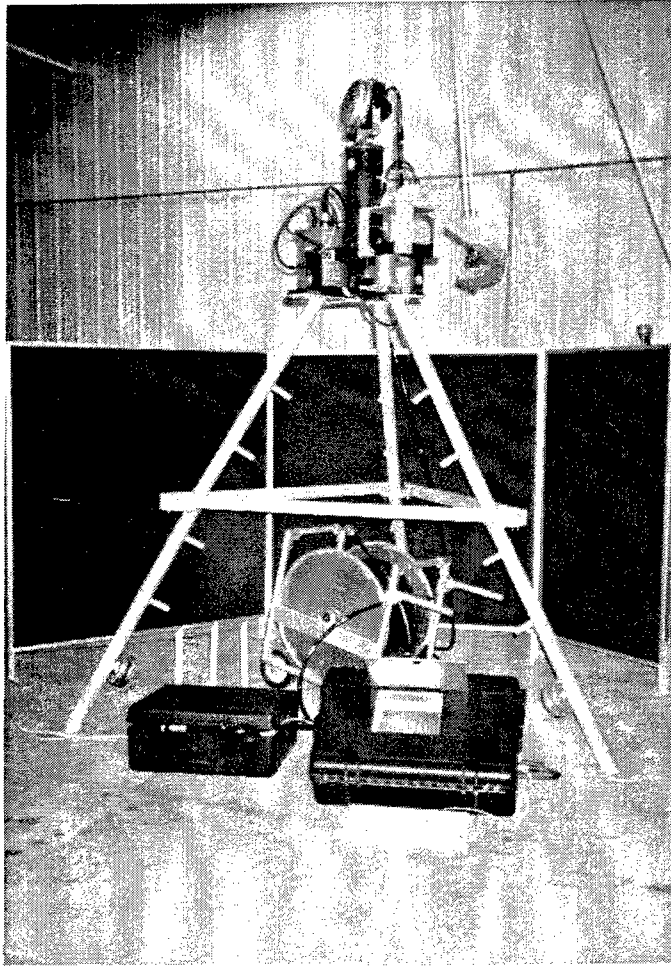


Figure 5. CSARS system

simultaneous, overlapping bathymetric measurements. Sweep systems have been used by USACE in the last 20 years and consist of multiple transducers mounted in a vertical series on a boat and/or on boom attachments. The sweep systems are typically used during project condition surveys to search for navigation hazards or obstructions (also known as “strikes”) and for Class 1 dredge payment surveys in which they are able to provide more accurate quantity computations (Headquarters, Department of the Army 1994). Drawbacks to the sweep systems include problems with transducer spacing and boom deployment, and the next logical step was to develop a new class of sweep systems that consolidated the transducer array onto a single mount (Rougeau 1991).

Single-transducer multibeam swath survey technology was developed by the Navy in the 1960s, but was only used for deepwater bathymetric mapping. Shallow-water, single-transducer systems were first developed in the 1970s and continued to improve through the 1980s, but remained restricted by limited positioning accuracies, ship motion, and data-processing capabilities (Topographic Engineering Center 1996).

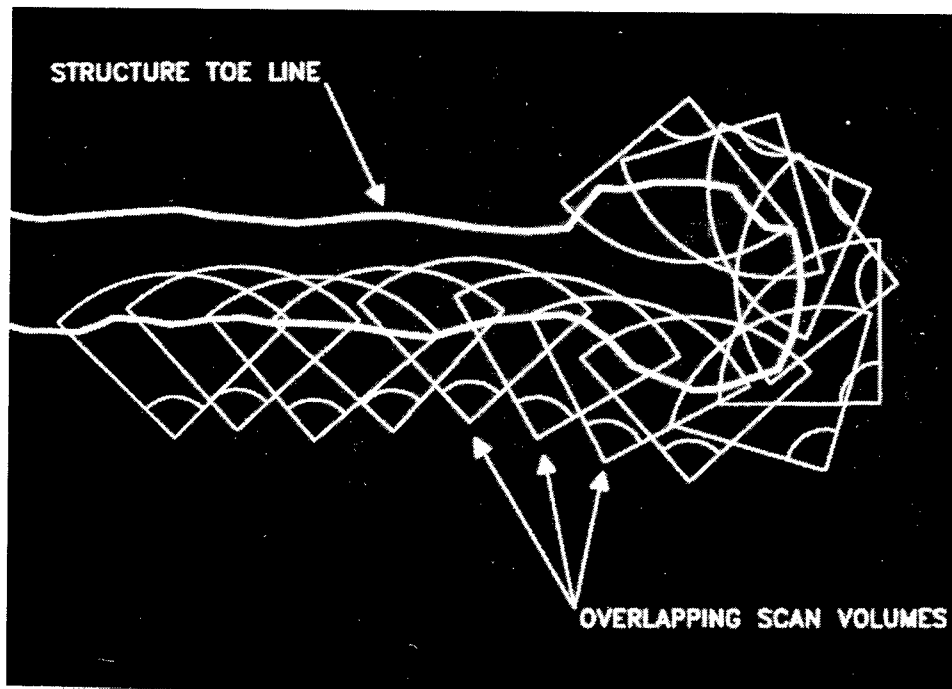


Figure 6. Illustration of overlapping scan data from CSARS set-down series

In the early 1990s, high-resolution multibeam sonar systems found their way into the commercial market, having evolved along with technological advances on several fronts, including the development of the Differential Global Positioning System (DGPS); advanced computer hardware and software capable of collecting, storing and processing dense data sets; and motion compensators with improved roll, heave, and pitch sensors. Combining the new sonar technology with advanced positioning and motion sensors has resulted in state-of-the-art swath systems suited for shallow-water survey applications such as condition-assessment surveys of coastal structures.

Private companies and surveying contractors have been instrumental in developing hydrographic surveying systems (hardware and software) for use in shallow-water applications. In 1990, John E. Chance & Associates (JECA) from Lafayette, Louisiana, conducted a study of single-transducer swath systems aimed at combining the new technology with advancements in beam forming, interferometry techniques, data processing and acoustic imaging (Rougeau 1991). JECA's research resulted in the development of a multi-discipline survey system with advanced surveying capabilities called the Hydrographic Inland Marine Acoustic Platform (HI-MAP). The HI-MAP system utilizes the Krupp-Atlas Fansweep multibeam system for topographic data collection. Typical HI-MAP applications are pre- and post-dredge payment surveys, condition surveys, and general reconnaissance surveys of navigation projects, bridge scour investigation and pipeline location surveys. REMR field-tested the JECA HI-MAP system in Los Angeles, California. The Los Angeles field test is discussed in Chapter 3 of this report.

Another survey contractor successfully utilizing multibeam sonars is C & C Technologies, also of Lafayette, Louisiana. C & C Technologies system uses the Simrad EM-950 which has side-looking capabilities (190-deg ensonification feature) allowing for surveying up to the water's edge. Upon completing development of its integrated bathymetry and imagery system in 1993, C & C Technologies demonstrated their new multibeam capabilities during the Flood of '93 in the Missouri and Mississippi Rivers as part of the flood relief effort. The multibeam survey system, deployed on the 26-ft *Inland Surveyor* was able to rapidly provide critical levee scour and breach information (Williams 1993). C & C Technologies also constructed the 12-m (40-ft) *Coastal Surveyor* with multibeam capabilities and active roll stabilizer fins for coastal work.

The SeaBat 9001 multibeam sonar system, developed by RESON, Inc., of Goleta, California, came into the commercial market in 1992. Although originally developed for high-resolution, Remotely Operated Vehicle (ROV)-mounted surveys, the SeaBat looked promising for adaptation to small vessel deployment. Additionally, the SeaBat was more compact and less expensive than other multibeam systems. For these reasons, the SeaBat 9001 multibeam sonar system was selected for testing in this investigation. REMR-II funds were not sufficient for a comparative evaluation of the other multibeam systems. We presume that other commercially available multibeam systems are generally similar to the SeaBat. However, see Chapter 3 for an evaluation of the Krupp-Atlas Fansweep conducted by JECA.

### **SeaBat 9001 system description**

The SeaBat 9001 is a portable, downward and forward-looking single-transducer multibeam sonar system. The main component of the SeaBat system is an acoustic sonar head operating at 455 kHz that transmits 60 sonar beams spaced at 1.5 deg in a fan pattern to provide a maximum sounding swath of 90 deg. This configuration enables swath coverage of 2 to 4 times the water depth. Typically, the sonar head is vertically deployed from a fixed mount off the side of a small vessel, although vessel-mounting systems vary between surveyors. Figure 7 shows the SeaBat sonar head prior to deployment. The sonar head is cabled to an external computer or data logger that controls display, data processing, and output in real time. A pointer device such as a trackball or joystick is used for operational control of the sonar head. The sonar head is tiltable for mapping steeply sloped or vertical structures to the water's edge. The SeaBat mounting and beam configuration are illustrated in Figure 8. In the down- or bottom-looking mode, the SeaBat serves as an echo sounder, profiling or imaging the seafloor below the transducer. To image sloping structures, the SeaBat transducer head is typically oriented horizontally in the side-looking mode to provide a plan view image of the surveyed structure. The transducer head is tilted manually to change the operating mode.



Figure 7. SeaBat sonar head

The SeaBat 9001 system can take 60 simultaneous soundings at a rate of over 15 profiles per second (over 800 data points per second). SeaBat depth precision, in ideal conditions, is 0.04 m (0.13 ft) below the sensor and 0.09 m (0.3 ft) at the outermost beams at vessel speeds up to 6 m/sec (12 knots) (Headquarters, Department of the Army 1994). SeaBat images can be viewed in real time and videotaped for data post-processing quality checks.

In addition to the SeaBat data, simultaneous measurements of vessel position, heading, and motion (heave, pitch, and roll) are required for post-processing geometric data corrections. Bathymetric data corrections are necessary to produce accurate measurements of true depths, referenced to vertical and horizontal datum, for individual beams. Computer time tags of all data are also necessary. An overall system configuration is illustrated in Figure 9.

For structural surveys, the SeaBat has three operational options:

- a. "Visual" inspection of an underwater structure (side-looking mode).
- b. Least-depth bathymetric surveys (down-looking mode).

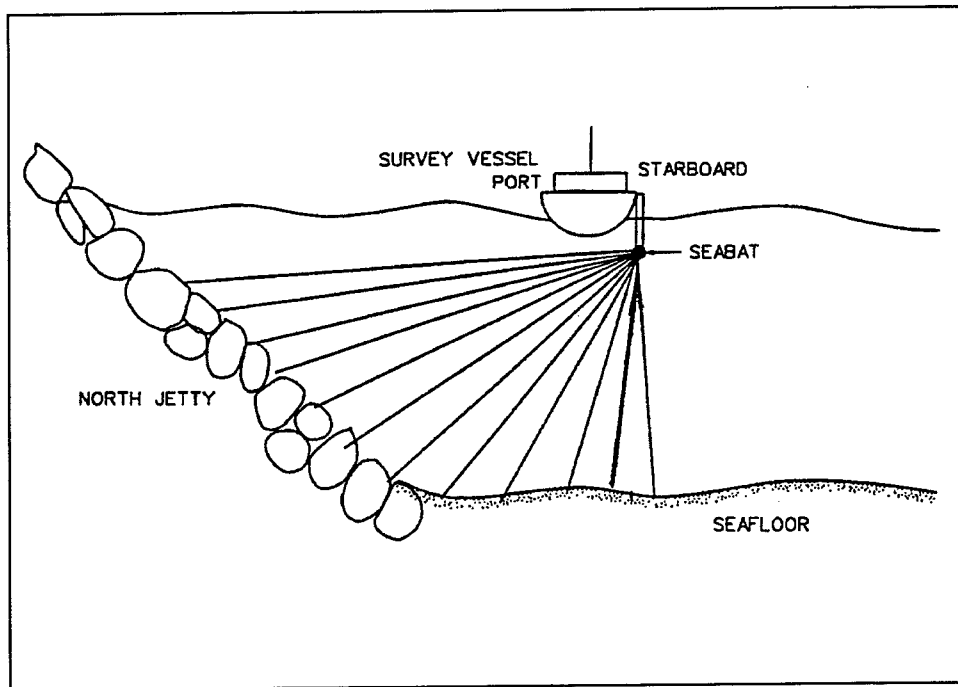


Figure 8. SeaBat mounting and beam configuration on steeply sloping structure (Hughes et al. 1995)

c. High-resolution, underwater structural mapping (side-looking mode).

Option *a* requires simultaneously recording SeaBat output on videotape and separately videotaping the surface area being surveyed for correlation. For this option, the SeaBat data and surface video should be time stamped for post-processing. Options *b* and *c* require a data acquisition system for data collection, storage, and post-processing to generate an x-y-z data set. Recording the raw SeaBat output and videotaping the surface area are also recommended for Options *b* and *c*.

Once geometrically corrected and processed, the SeaBat provides a dense data set of x-y-z coordinates of point data (spot elevations). From this data set, a 3-D mesh surface connecting the spot elevations called a digital elevation model (DEM, also called digital terrain model or DTM) can be created in addition to specified cross sections and contour maps. Various terrain modeling software programs are available on the market for this purpose.

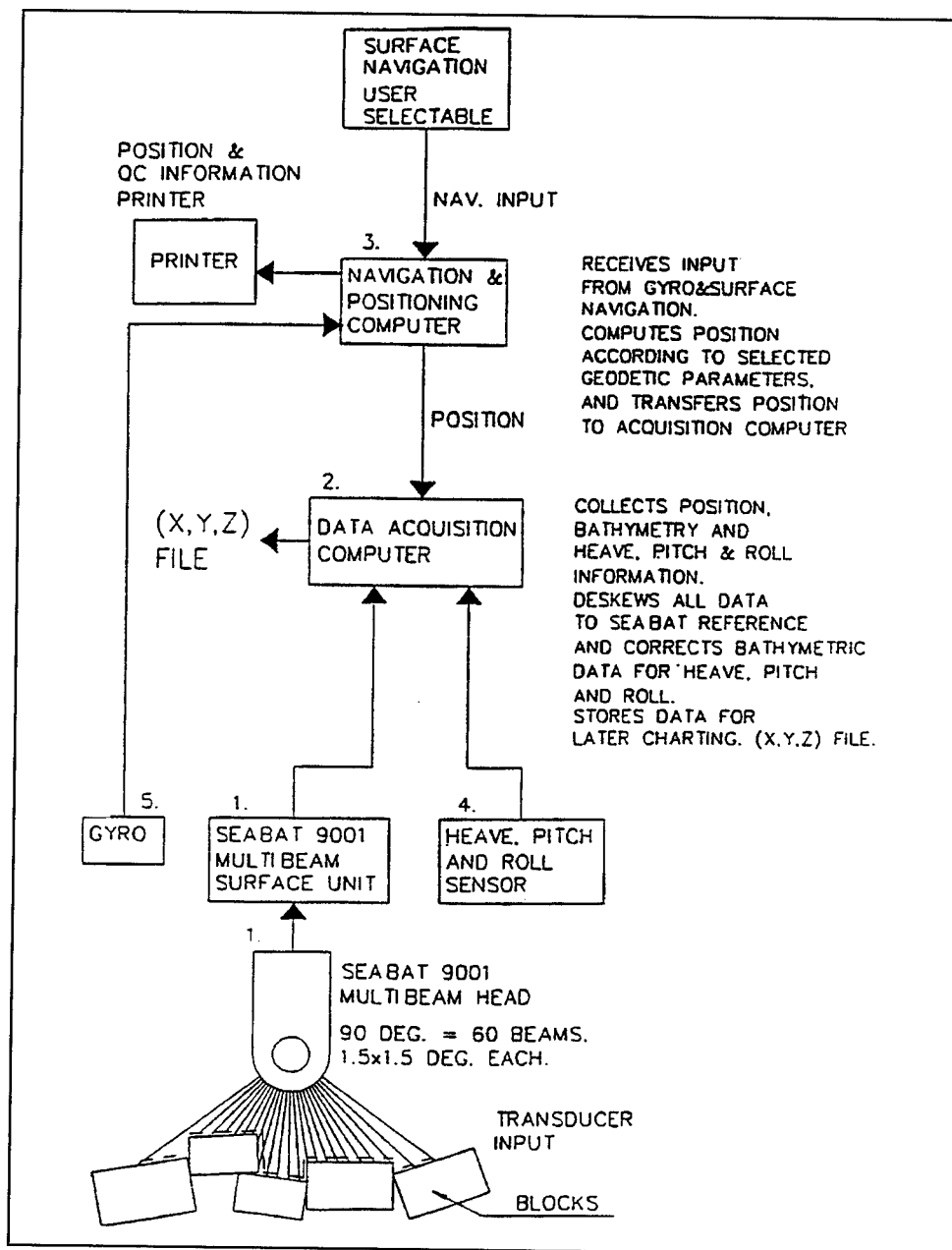


Figure 9. SeaBat overall system configuration (RESON, Inc. 1993)

## 3 Field Demonstrations and Trials

---

### SeaBat Demonstrations

Beginning in early 1993, the Quantitative Imaging work unit began disseminating information about the potential uses of the SeaBat system throughout the hydrographic survey community. As a result, several USACE Districts and hydrographic survey contractors sponsored or conducted SeaBat system demonstrations for varied applications.

One of the first CE Districts to examine the newly emerging multibeam sonar technology for shallow-water applications was the U. S. Army Engineer District, Los Angeles (SPL). The SPL mission, as with many other Corps Districts, encompasses a continual need to conduct coastal and oceanographic measurement and surveying. This effort includes pre- and post-dredging and structure condition surveys (breakwaters, jetties, groins), structure reconnaissance surveys, and sub-bottom classification.

SPL, in cooperation with the REMR work unit, hosted a SeaBat equipment demonstration in June 1993 at the Los Angeles, Long Beach Harbor complex in California. The harbor complex is a combination rubble-mound and fitted-stone breakwater. SPL supplied the survey boat and operator, and the SeaBat equipment and operator were furnished by the manufacturer, RESON, Incorporated. Demonstration participants included representatives from WES/REMR, SPL, and a private survey contractor.

An attempt to integrate the SeaBat data with SPL's hydrographic survey package (HYPACK, by Coastal Oceanographics, Inc.) was unsuccessful because of software difficulties. Nonetheless, the SeaBat equipment (with real-time data display) demonstrated that the multibeam sonar indeed had potential as a tool for coastal structure surveying. The demonstration also resulted in subsequent improvements in the SeaBat transducer mount and HYPACK software integration as well as development of a data processing module.

Following the demonstration in Los Angeles, several other SeaBat demonstrations were conducted in 1993 and 1994 throughout the country. The SeaBat performed successfully when applied to varied applications such as bridge pier

scour and dolos surveys. Table 2 lists those demonstrations attended by WES personnel. Demonstration attendees included personnel from other USACE Districts, academia, and private hydrographic surveyors.

| <b>Table 2<br/>SeaBat Demonstrations</b>                         |                   |                                                        |
|------------------------------------------------------------------|-------------------|--------------------------------------------------------|
| <b>Sponsor</b>                                                   | <b>Location</b>   | <b>Application</b>                                     |
| USACE District, Los Angeles                                      | Los Angeles, CA   | San Pedro Breakwater                                   |
| USACE District, Memphis/EMC, Inc.                                | Memphis, TN       | Bridge Pier Scour on the Mississippi River             |
| Oceaneering, Solus Schall Division<br>(Upper Marlboro, Maryland) | St. Louis, MO     | Missouri River Bridge Pier Scour (after Flood of 1993) |
| EMC, Inc.<br>(Greenwood, Mississippi)                            | Crescent City, CA | Harbor entrance survey (dolos inspection)              |
| Ocean Surveys, Inc.<br>(Old Saybrook, Connecticut)               | Old Saybrook, CT  | Connecticut River Entrance on Long Island Sound        |
| WES                                                              | Duck, NC          | CHL Field Research Facility                            |

## SeaBat Field Trials

The Quantitative Imaging work unit also facilitated use of the SeaBat system during 1993 and 1994 for five field trials of Corps structural surveys (Table 3). Several of the field trials are described below. As with the demonstrations, the survey applications were varied. For all of the field trials, the SeaBat system was able to provide valuable, previously unknown information on the underwater condition of the structures.

| <b>Table 3<br/>SeaBat Field Trials</b> |                 |                                                           |
|----------------------------------------|-----------------|-----------------------------------------------------------|
| <b>Sponsor</b>                         | <b>Location</b> | <b>Application</b>                                        |
| USACE District, Buffalo and WES        | Cleveland, OH   | Cuyahoga River Retaining Structure Reconnaissance Survey  |
| USACE District, Los Angeles and WES    | Los Angeles, CA | Los Angeles (San Pedro) Harbor and Long Beach Breakwaters |
| USACE District, New York               | Long Island, NY | Shinnecock and Moriches Inlets                            |
| USACE District, Philadelphia           | Rehoboth, DE    | Indian River Inlet                                        |
| WES and USACE District, Portland       | Newport, OR     | Yaquina Bay North Jetty Survey                            |

## Los Angeles, Long Beach Harbor breakwater system

Following the demonstration in Los Angeles, SPL and REMR jointly sponsored a multibeam sonar field trial conducted in August 1993 and March/April 1994. The objective of the field trial was to evaluate individual multibeam sonar systems, data collection procedures, data density requirements, and processing techniques (John E. Chance & Associates 1994).

JECA was contracted to conduct a comprehensive structural condition survey of both the above-and below-water parts of the “San Pedro,” “Middle,” and “Long Beach” breakwaters that protect the Los Angeles, Long Beach (LA/LB) Harbor complex, located approximately 35.4 km (22 miles) south of central Los Angeles in Los Angeles County, California (Mesa and Brooks 1994). Figure 10 is an illustration of the LA/LB Harbor complex. The San Pedro breakwater primarily consists of laid-up (fitted) stone construction, and the Middle and Long Beach breakwaters are detached, rubble-mound structures. Total length of breakwater coverage at the project site is 9,708 m (31,850 ft). Water depths along the three breakwater toes range from 0 to about 18.3 m (60 ft).

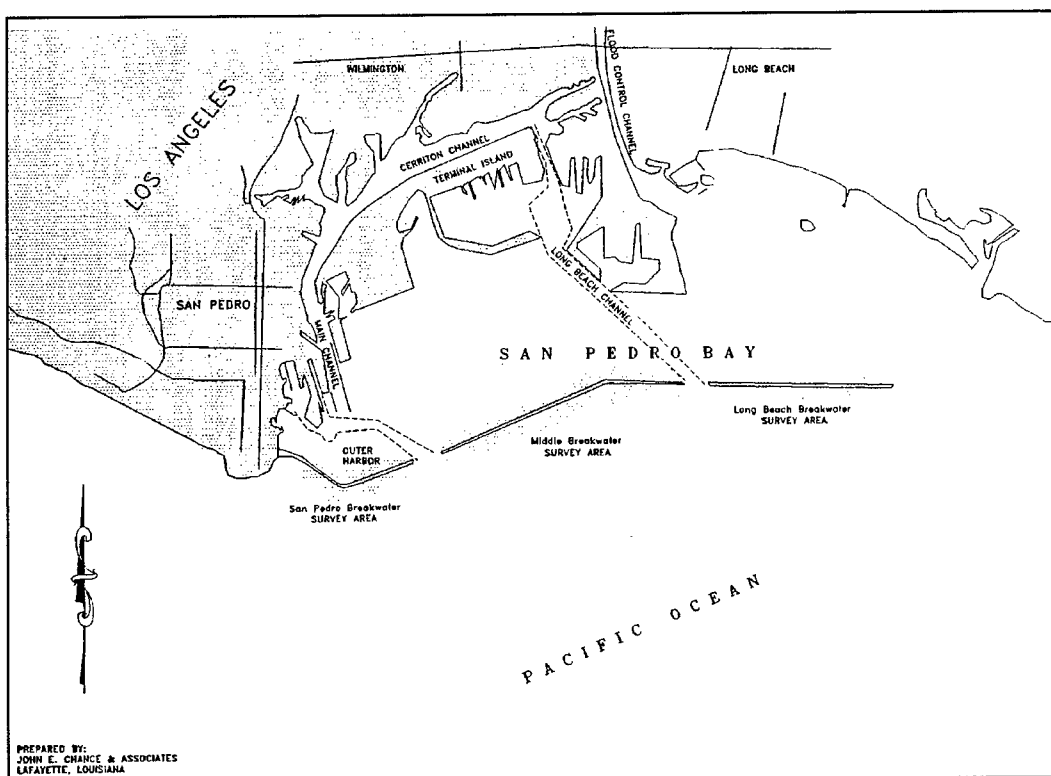


Figure 10. LA/LB breakwater system

Under the project scope, JECA was to provide swath coverage extending from the water's edge of the breakwater structures at high tide to the natural seafloor. Tide, vessel position, motion, and attitude (heave, pitch, and roll) data were to be collected to establish coordinates of individual beams with accuracies within 1.5 m (5 ft) horizontal and 0.2 m (0.5 ft) vertical absolute.

JECA executed the breakwater surveys onboard its own HI-MAP II, a 10-m (32-ft) v-hulled survey vessel, equipped with a Krupp-Atlas Fansweep multi-beam system. The Fansweep is ram-mounted at the center of the survey vessel and operates at approximately 200 kHz from 52 beams with 2.5-deg spacing. The swath width of 128 deg provides maximum coverage of four times the water depth (up to 200 m (656 ft)). Fansweep data are collected every 850 msec. JECA included the SeaBat 9001 multibeam system (described in Chapter 2) for evaluation and comparison with the Fansweep. Figure 11 shows the SeaBat transducer head and mounting system on the HI-MAP II.

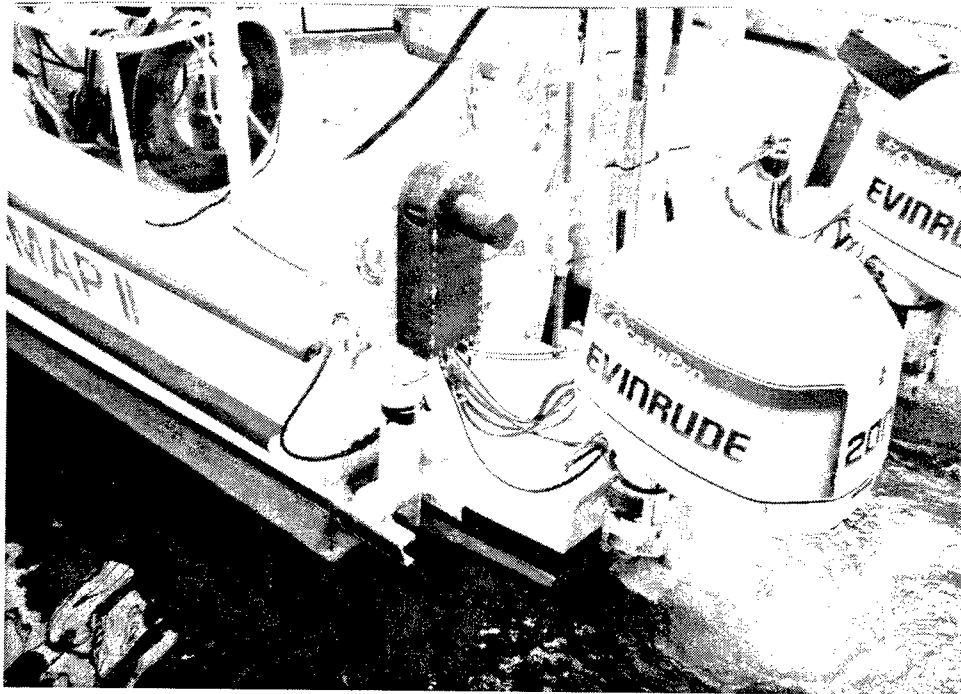


Figure 11. SeaBat transducer head mounted on HI-MAP II

To collect comprehensive data from the sea bottom to the water's edge, the Fansweep and SeaBat transducer heads were deployed in both down- and side-looking orientations. Side-looking data were obtained from both systems by tilting the transducer heads and surveying during high tide. The mounts for both the Fansweep and SeaBat transducers were modified to allow for tilting of 50 and 60 deg to port, respectively. Data were collected using JECA-developed software.

During other survey periods, extra lines were run along the structures with the sonar systems in the down-looking mode. The data from these extra lines were used as redundant data for the kinematic Global Positioning System (GPS) processing and quality control in post-processing.

Following the August 1993 survey, JECA determined that the Fansweep was impractical for surveying the breakwater structures because of insufficient coverage to the water's edge and data density. To obtain the required data

resolution with the Fansweep, the survey vessel would have to repeatedly collect data over the area at a lower vessel speed. In addition, the side-looking Fansweep data required more processing because raw, individual beam data consisting of take-off angles and ranges were not available from the Fansweep. For these reasons, Fansweep side-looking data were not collected during the March/April 1994 survey. However, the Fansweep provides sufficient data for conventional bathymetric surveys. Additional project details are given in John E. Chance, & Associates (1994) and Mesa and Brooks (1994).

**Data post-processing.** Data from the August 1993 survey were processed after completion of the survey. During the March/April 1994 survey, data were downloaded and processed at the end of each data-collection day to catch potential data-collection errors.

During the August 1993 survey, several equipment problems occurred that delayed both SeaBat and Fansweep data post-processing. A computer glitch resulted in the loss of several days of GPS data, preventing kinematic post-processing for the affected days. SeaBat data post-processing was hampered by timing errors that occurred during the data logging. Data gaps in the Middle and Long Beach breakwater surveys occurred when the logging program overflowed causing the computer to lock up. This data loss was not obvious until data post-processing. To eliminate the timing errors, JECA developed a Contag box which was used during the March/April 1994 survey to precisely time tag the SeaBat data within 1 msec.

After difficulties experienced from the first survey, data post-processing procedures were changed to include interpolation and filtering routines to reduce the SeaBat data set. A reduction factor of two was selected (by choosing every second sweep) and little difference was observed whether 50 or 100-percent data were used when modeling the data. Reducing the data set also greatly diminished processing time without degrading the accuracy of the surface models. Also, the co-linearity of the beams was inspected along with the quality indicator. These inspection procedures were established to eliminate poor data and reduce the data set size to a manageable size for modeling. During LA/LB data post-processing, JECA developed a thinning algorithm for logical thinning of data rather than systematic point elimination without inspection of relativity with neighbors. A portion of the data set was thinned using the new algorithm and compared to the 50-percent data set, resulting in a standard error reduction.

When both systems were deployed in the side-looking mode, kelp collected above the transducers, resulting in data loss from the outer beams. The outer beams for both systems could also have been affected by aeration and multi-path from the beams bouncing off the water's surface. Data loss from one or possibly a combination of these factors was estimated at approximately 10 percent. Additionally, JECA observed many more rejected beams in the side-looking data from the Middle and Long Beach rubble-mound breakwaters than in the San Pedro data set, possibly due to the rubble-mound construction (versus the San Pedro breakwater laid-up (fitted) stone construction).

JECA (1994) provided recommendations resulting from the LA/LB project pertaining to equipment setup, data collection, and data post-processing. Those recommendations included:

- a. Extensive and careful setup, mounting, and alignment of SeaBat with navigation and motion sensors prior to data collection is crucial to data accuracy.
- b. All data should be time-tagged for post-processing correlations.
- c. Videotaping of SeaBat data and surveyed surface area is valuable for post-cruise analyses.
- d. For data analysis, desired model accuracy must be initially defined rather than just reducing the data set to a more manageable size.

The SeaBat was successful in providing detailed information about the underwater condition of the different-type breakwater structures (both fitted and rubble-mound) at the Los Angeles breakwater system. The SeaBat data, in combination with data collected by other, more conventional methods (side-scan sonar, airborne laser mapping surveys, and visual and photographic observations) allowed SPL to conduct a comprehensive structural assessment of the LA/LB breakwaters. Figure 12 is a photograph of the San Pedro breakwater taken from a landward perspective and Figure 13 shows a complete above- and underwater DEM of the San Pedro breakwater (from an aerial perspective) that merges the underwater SeaBat data and the above-water airborne laser mapping survey data. The upward projection in Figure 13 is the lighthouse located at the

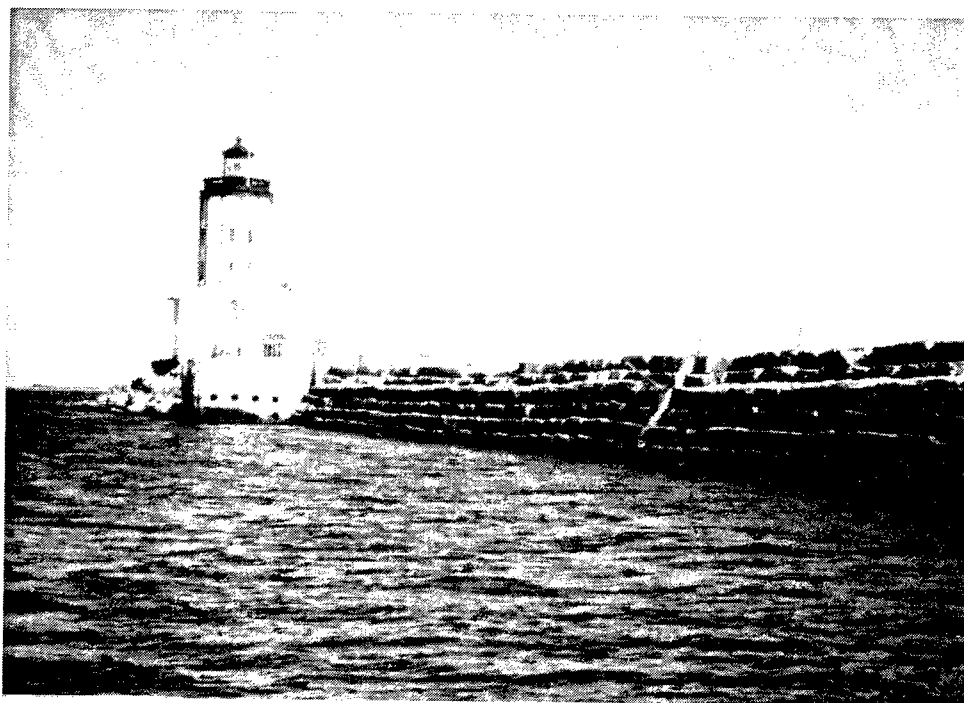


Figure 12. San Pedro breakwater (from landward perspective)

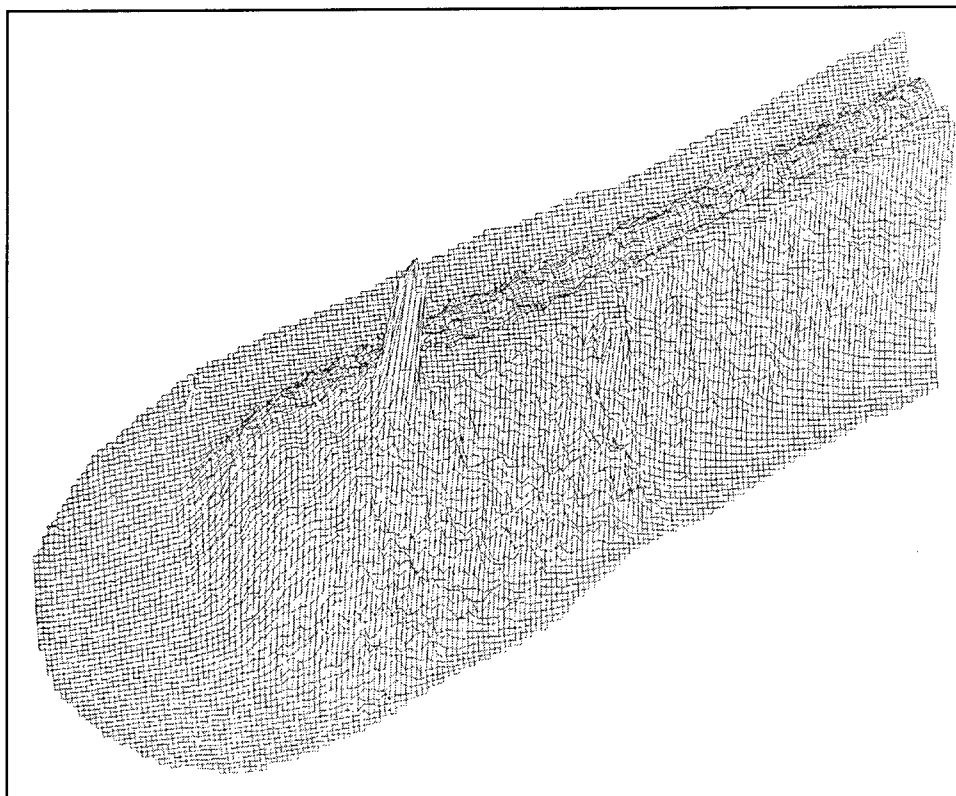


Figure 13. DEM of above- and below-water portions of San Pedro breakwater (by Chuck Mesa, U.S. Army Engineer District, Los Angeles)

end of the breakwater. Additional information concerning the condition survey is found in U. S. Army Engineer District, Los Angeles (1996).

### **Cuyahoga River retaining structure reconnaissance survey**

Also in August 1993, the CHL, in support of the U.S. Army Engineer District, Buffalo, utilized SeaBat and a side-scan sonar to conduct a general condition reconnaissance of the retaining structure network along the Cuyahoga River Federal Project located near Cleveland, Ohio. The Federal Project encompasses the river entrance channel at Lake Erie to approximately 11.1 km (6 miles) upstream, with water depths ranging between 7 and 8.2 m (23 and 27 ft). The objective of the reconnaissance study was to identify above- and underwater areas with structural weaknesses. Because of the large area of the Federal Project, time and funding constraints, and limited underwater visibility, it was impractical to use divers to conduct the study.

Real-time SeaBat and side-scan sonar profiles were obtained while simultaneously videotaping the above-water structure. Figures 14 and 15 are examples of structures surveyed along the Cuyahoga River. At times, data collection was minimized or totally eliminated by docked vessels, certain retaining wall configurations, water turbulence from outfalls, and shallow-water bathymetry. During the survey, a Remotely Operated Vehicle equipped with a



Figure 14. Ribbed sheetpiling retaining structure at Cuyahoga River



Figure 15. Concrete structure along Cuyahoga River

videocamera was deployed in an attempt to observe the underwater conditions of the structure and verify observations from the SeaBat output. Water clarity was poor, making the video pictures unclear. The surveyors relied on the SeaBat and side-scan sonar for the remainder of the survey.

During post-processing, both the SeaBat data (screen output) and surface videotape were time stamped, synched, and spliced together to produce a presentation screen. This was the first time the SeaBat had been used for this type application and analysis of the data was partly based on experience gained while conducting the study. The profiles provided acoustic images of different types of retaining walls and structures that included staggered pilings, inclined walls, and ribbed sheetpiling. Profile analysis indicated anomalies such as openings, protrusions, indentations in retaining walls and scour at the base of some structures. This study is presented in a documentary video (Welp 1994). Figures 16 and 17 are example presentation screens from the video. SeaBat output in Figure 17 indicates an underwater ledge near the river bottom.

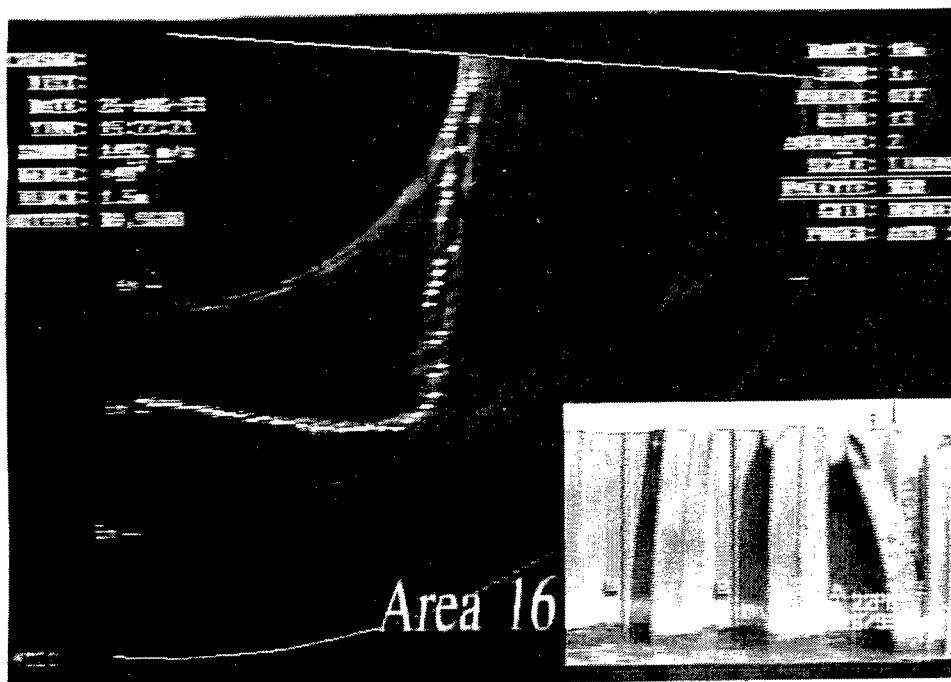


Figure 16. SeaBat raw data output together with surface video of ribbed sheetpiling

By using the SeaBat multibeam system, CHL was able to quickly provide real-time information on structural conditions along the banks of the Cuyahoga River at least cost to the Buffalo District. In addition, the SeaBat data complemented and enhanced standard side-scan sonar data used to map the river bottom.

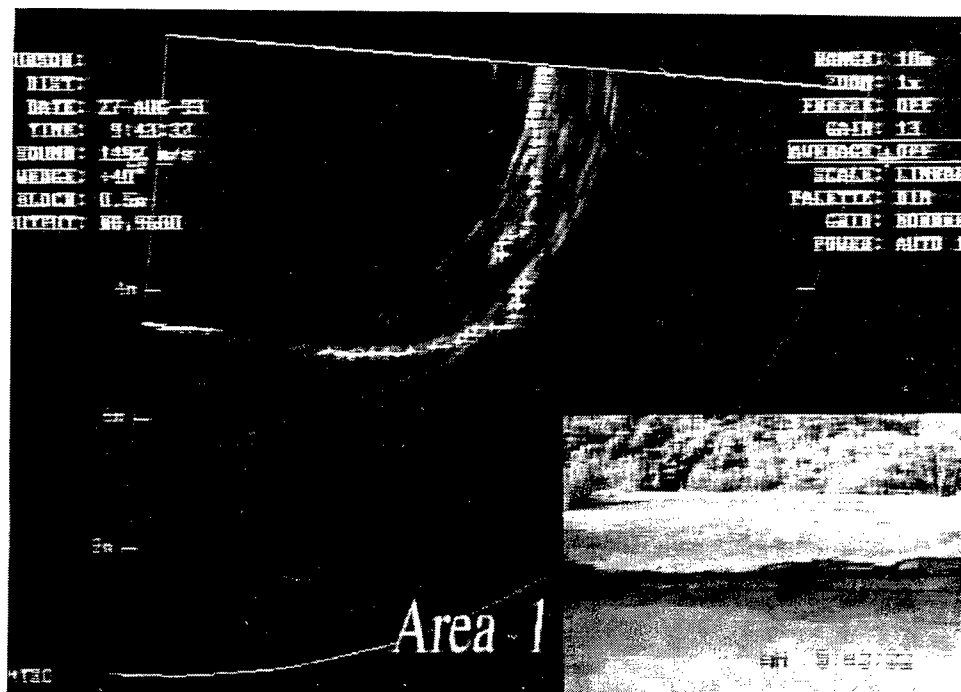


Figure 17. SeaBat raw data output and surface video of concrete structure along Cuyahoga River

### Shinnecock and Moriches Inlets

The REMR work unit advised the U.S. Army Engineer District, New York (NAN) on multibeam sonar applications and, in April 1994 NAN contracted Ocean Surveys, Incorporated (OSI) to conduct hydrographic surveys using the SeaBat multibeam system at Shinnecock and Moriches Inlets located on the southeast side of Long Island, New York. Both inlets are protected by parallel jetties extending into the Atlantic Ocean. The survey objective was to investigate scour damage along the jetty structures. The surveys were successful, and OSI provided NAN with video of SeaBat data and surface (video) insets, 3-D images and contour plots of the inlets and jetty structures, and soundings and trackline data.

### Indian River Inlet navigation channel and jetty survey

The Indian River Inlet, approximately 500 ft wide and formed by parallel jetties, is located on the Atlantic coast of Delaware connecting the Atlantic Ocean with Indian River Bay (approximately 17.7 km (11 miles) north of the Delaware-Maryland state line) and is shown in Figure 18. A 4.6-m (15-ft)-deep navigation channel runs through the inlet, though generalized scour in the channel has been observed since construction of the jetties in the late 1930s. Accelerated scour has been observed since the 1970s, forming scour holes with depths ranging from 24 m (80 ft) to greater than 30 m (100 ft).

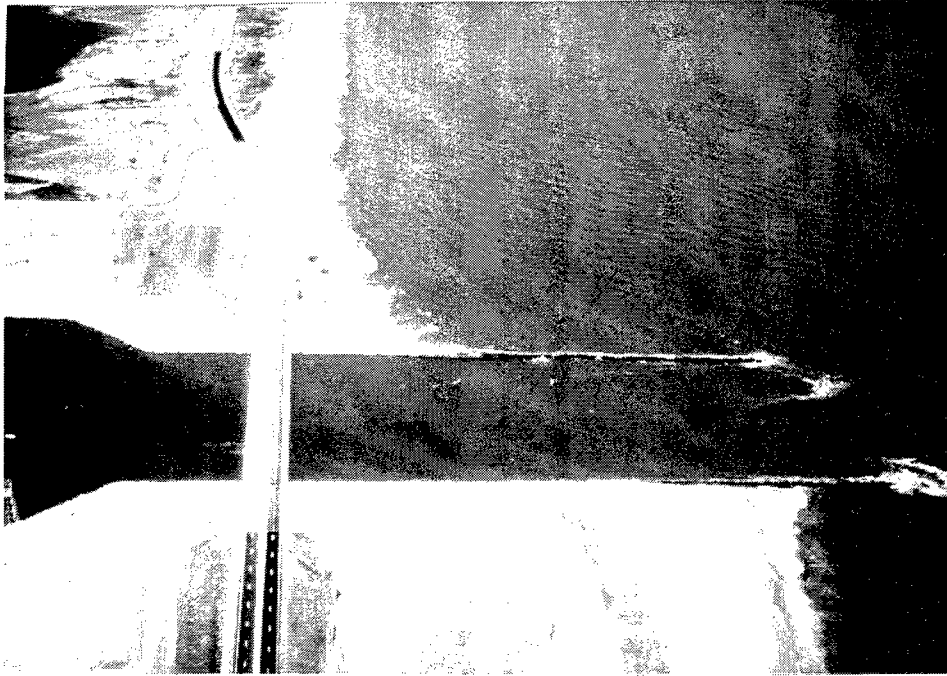


Figure 18. Indian River Inlet and jetties

In May 1994, supplied with information and encouragement from the REMR work unit, the U.S. Army Engineer District, Philadelphia (NAP) contracted OSI to conduct a detailed high-resolution hydrographic survey using the RESON SeaBat in the Indian River Inlet navigation channel and jetty areas. The survey objective was to investigate progressive scour occurring in the channel in order to a) determine if jetty stone loss was related to the scour, and b) confirm conclusions from the Committee on Tidal Hydraulics (1994) that inlet rehabilitation was not necessary. Concern was also expressed as to whether the scour would undermine cofferdams supporting piers of the Delaware State Route 1 bridge, which spans the inlet. Additional studies included inlet velocity measurements, subsurface borings, and geotechnical analyses of channel bottom and side slope stability (U.S. Army Engineer District, Philadelphia 1994).

Bathymetric maps created from SeaBat data, when compared to data from previous bathymetric surveys collected using single-beam, fathometer-type sonar equipment, revealed in greater detail that known scour areas had deepened and new scour was occurring. Figure 19 is a bathymetric map of the Indian River Inlet project site created with SeaBat data from the 1994 survey. The inlet entrance begins at the top of Figure 19. Figure 20 is a closeup of the project area and indicates scour areas in the inlet before and behind the supporting piers (the areas of white) of the Route 1 bridge. Figure 20 also reveals a possible slope failure in the upper right corner, close to the bridge pier on the right. The SeaBat data also indicated jetty stones had unraveled in place and did not appear to have rolled into the scour holes (U.S. Army Engineer District, Philadelphia 1994).

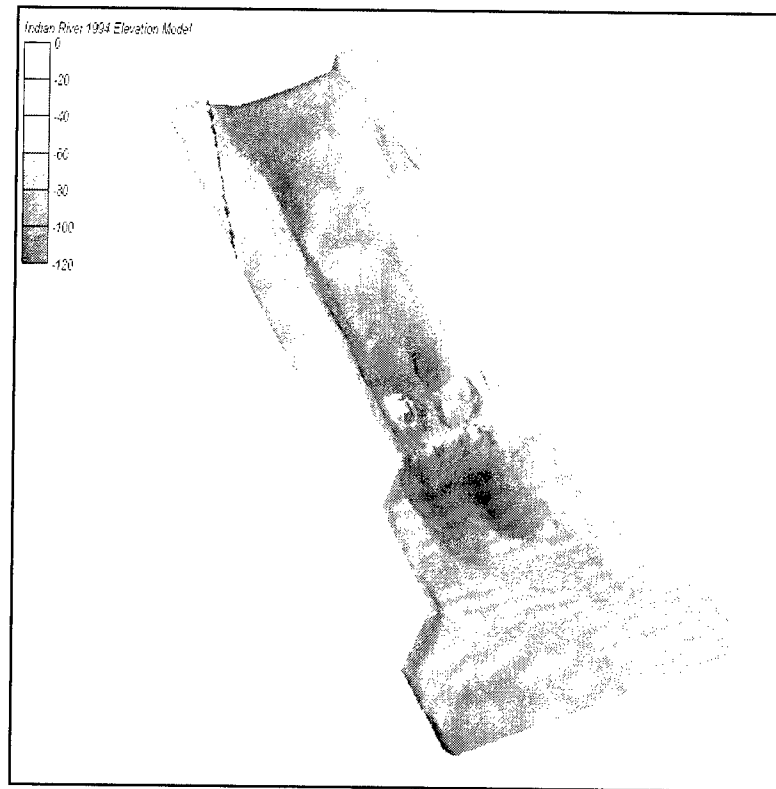


Figure 19. Bathymetric map from Indian River Inlet 1994 SeaBat survey (graphic by Glen Stevens, USAE District, Philadelphia)

The high-resolution SeaBat bathymetric data provided more detailed information unavailable from previous survey data, allowing the NAP to verify the results of the Committee on Tidal Hydraulics (1994). Other recommendations to continue monitoring the project conditions resulted in a second SeaBat survey by OSI in September 1996. The NAP plans to continue using multibeam sonar systems for future bathymetric surveys.<sup>1</sup>

### Yaquina Bay north jetty survey

In June 1994, the SeaBat was utilized by David Evans and Associates (DEA), to collect bathymetric data at the Yaquina Bay entrance north jetty at Newport, OR. The SeaBat survey was a principal element in a joint study by CHL and the U.S. Army Engineer District, Portland, conducted through the Monitoring Completed Navigation Projects (MCNP) research program.<sup>2</sup> The objective of the CNP effort was to determine why, after several rehabilitations, the north jetty at the entrance to Yaquina Bay continued to experience chronic damage. The project area is shown in Figure 21. A comprehensive summary and results of the MCNP study are provided in Hughes et al. (1995). The SeaBat survey

<sup>1</sup> Personal communication, Glen Stevens, USAE District, Philadelphia.

<sup>2</sup> The Monitoring Completed Coastal Projects Program was renamed the Monitoring Completed Navigation Projects (MCNP) research program in October 1996.

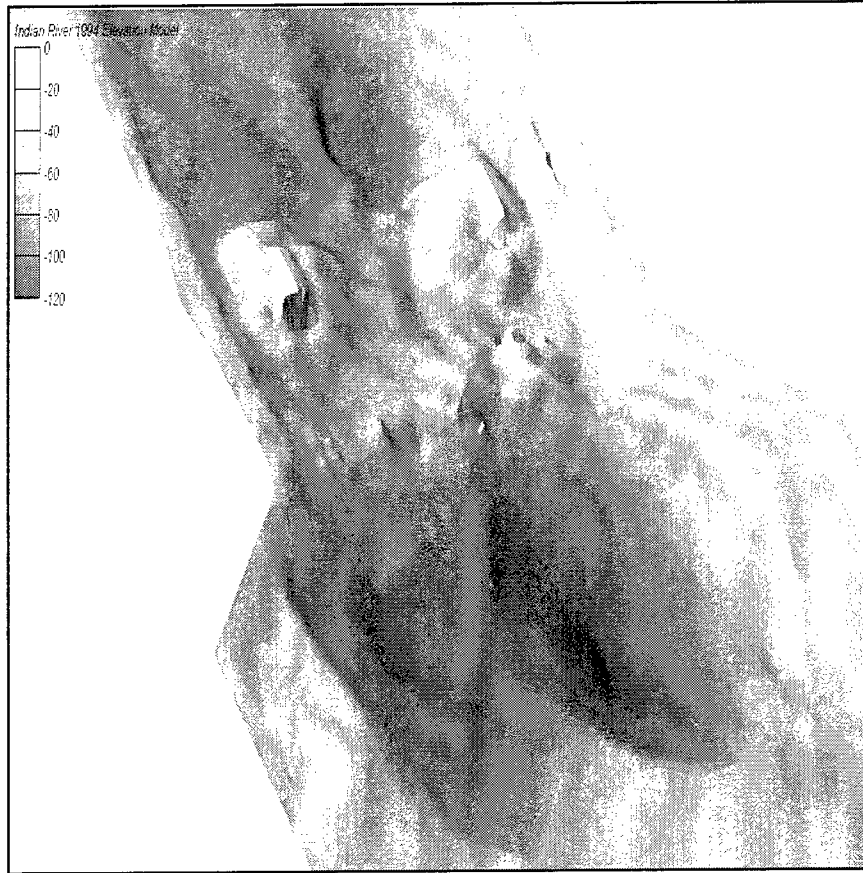


Figure 20. Closeup of Indian River Inlet bathymetry (graphic by Glen Stevens, USAE District, Philadelphia)

objectives at Yaquina Bay were to map the generally unknown underwater morphology of the north jetty structure and adjacent rock reef and further develop and improve SeaBat survey field procedures and data processing technologies.

The jetties protecting Yaquina Bay are rubble-mound structures, both of which have undergone extensive repairs and extensions since construction over 100 years ago. Present lengths of the north and south jetties are 2,130 m (7,000 ft) and 2,620 m (8,600 ft), respectively, from the shoreline. The tip of the north jetty is intersected by the Yaquina Reef, formed from a basalt flow (see Figure 21).

During the survey, SeaBat tracklines were run along the north side of the north jetty parallel to the jetty center line and continued around the jetty tip to the channel side. Additional tracklines were run parallel to Yaquina Reef, more or less along the reef center line. Onboard displays of SeaBat profile images were videotaped for possible future reference and for post-survey data quality checks. SeaBat data were corrected for sensor depth and motion and combined with position data to provide an underwater view of the north jetty as it intersects Yaquina Reef (Hughes et al. 1995). Figure 22 is a DEM of the jetty

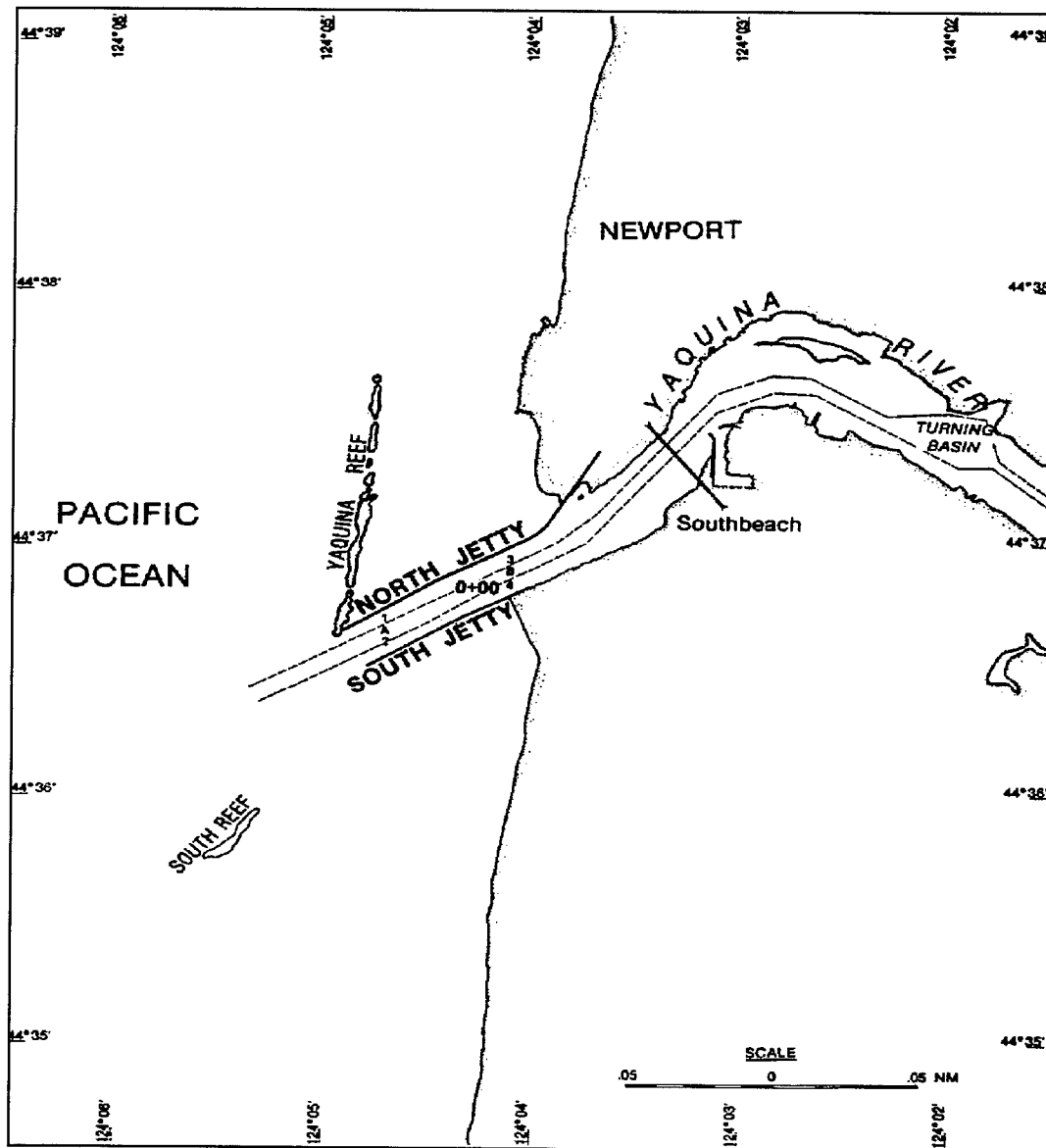


Figure 21. Yaquina Bay navigation channel jetty system (Hughes et al. 1995)

and reef bathymetry from an onshore perspective. Field and data post-processing procedures for the Yaquina survey are summarized in David Evans and Associates, Inc. (1994).

The Yaquina SeaBat survey was successful in providing previously unknown underwater information on the jetty and reef intersection. Hughes et al. (1995) concluded:

Deployment of the SeaBat multibeam bathymetric sonar provided the first detailed picture of the underwater configuration of the Yaquina Bay north jetty and its positioning relative to Yaquina Reef...demonstrating the utility of the SeaBat sonar for gathering important monitoring information

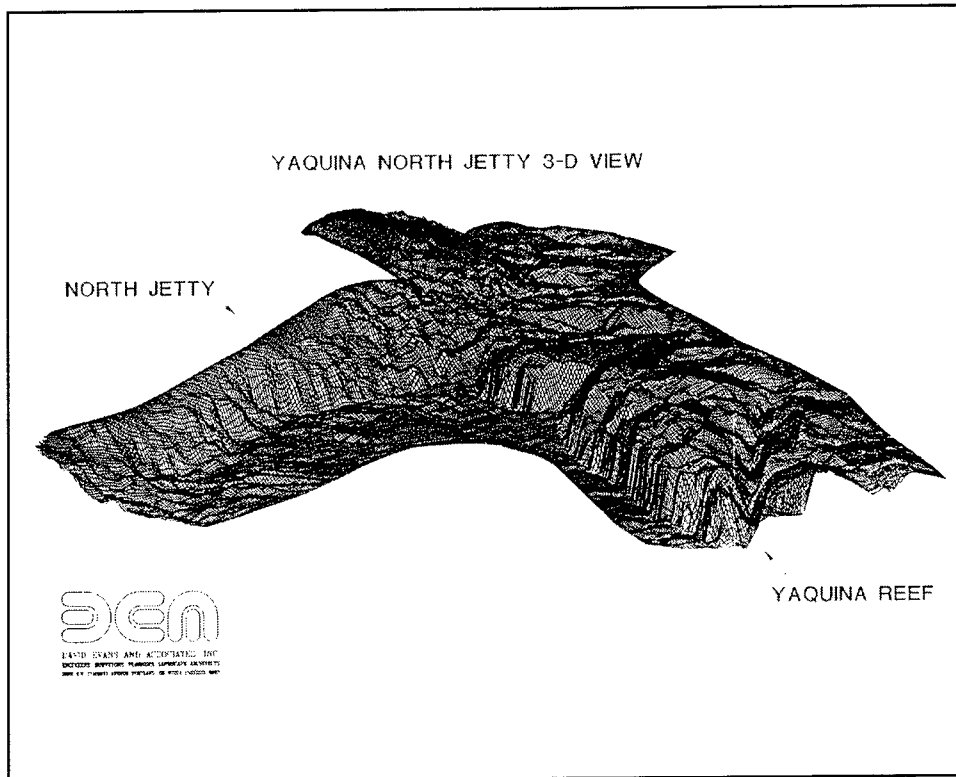


Figure 22. DEM of Yaquina Bay north jetty and Yaquina Reef below-water bathymetry

at sites where more conventional structure surveying techniques are not likely to be successful due to harsh environmental conditions.

and,

...the SeaBat profile information will prove invaluable for any future physical modeling efforts of the north jetty structure, and the data have provided Portland District a means for more accurately estimating stone requirements for potential jetty rehabilitation.

## 4 Summary

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Much information was gained from CSARS development such as system and data requirements, and deployment procedures and techniques. However, the capabilities of commercially available multibeam systems like RESON's SeaBat surpassed the still-prototype CSARS, and the REMR work unit concentrated its investigation on multibeam sonar systems for coastal structure survey applications.

The REMR work unit, working in cooperation with CE Districts, RESON, and private survey contractors such as JECA and DEA, evaluated the SeaBat multibeam sonar equipment through field demonstrations and tests in typical Corps survey applications (structural condition assessment). The field efforts resulted in improved equipment and data collection capabilities for application to CE coastal structures and shallow-water surveys, in addition to providing the Districts information for their operation and maintenance needs.

### System Improvements

The SeaBat system was successful in providing accurate, high-resolution hydrographic data on the underwater condition of various structures: rubble-mound breakwaters and jetties, retaining walls, bridge piers, and channel scour. As the system was demonstrated and tested, development of the SeaBat multibeam sonar system and its application to coastal structure surveys resulted in improvements of:

- a.* Equipment mounts for the SeaBat transducer head.
- b.* Equipment interfaces with standard hydrographic software.
- c.* Equipment deployment techniques.
- d.* Data collection techniques.
- e.* Data post-processing techniques.

## System Limitations

As the system was tested, difficulties were encountered because the SeaBat system provided such a dense data set. Data processing was constrained by limited computer storage capacity and computing capability. During post-processing, data filtering (decimation) and interpolation were used to thin the data set. However, computer technology is now advancing with increased storage and computing capabilities. New and enhanced data acquisition and processing software packages are becoming available in the commercial market, which will reduce the need for filtering or decimation routines during data post-processing. These advances will enable surveyors to completely utilize the expansive data sets provided by multibeam systems for modeling structures in greater detail.

Cost is relatively high for multibeam surveys. Most Corps survey work is done using standard hydrographic equipment such as fathometer (single-beam) sonars, that are less expensive than a multibeam system. Cost is also greater because more time is required to post-process the huge multibeam data set. Advantages of the multibeam system, however, are more rapid collection of a high-resolution data set that provides 100-percent bathymetric coverage to the water's edge.

## Conclusions

The equipment demonstrations and success of the field trials have proved that the commercially available SeaBat multibeam system can be applied for use in coastal structure underwater surveys. The REMR research also showed the two types of sonar systems (side-scan and multibeam) can be operated simultaneously from a single vessel. SSS produces a real-time, detailed picture of the seafloor and adjacent structures from which one can ascertain structural characteristics, roughness (i.e. sediment ripples), and physical properties of sediment. The dense, high-resolution multibeam data set complements and substantiates SSS imagery, resulting in a more comprehensive picture of the underwater shape of coastal structures, in addition to time and cost savings. Additional details of the SeaBat 9001 and description of other multibeam swath systems employed on USACE hydrographic survey contracts are provided in Engineer Manual 1110-2-1003, "Hydrographic Surveying" (Headquarters, Department of the Army 1994) which provides guidance to Corps of Engineers Divisions and Districts.

The SeaBat multibeam system and others like it are fast becoming standard equipment for shallow-water surveying applications. At the time of this report publication (1998), several CE Districts have purchased multibeam systems or are including multibeam sonars in specifications for private survey contractors. RESON has also developed a SeaBat 9001s that allows the equipment operator to interchange between the down- and forward-looking modes. Other models have been developed that include operator mode-switching and the capability of simultaneously collecting side-scan sonar and multibeam imagery.

Other research on multibeam sonars has been conducted by the Topographic Engineering Center, Topographic Applications Laboratory, resulting in the development of procedures for sensor calibration and standards and recommendations for using multibeam sonars and data processing. Additionally, Coastal Oceanographics, Inc., developer of the HYPACK data acquisition software, conducts an annual surveying conference that includes multibeam sonar discussions for a large portion of the conference.

Hydrographic surveying using state-of-the-art multibeam swath systems provides nearly 100-percent bathymetric coverage of the structure up to the water's edge, resulting in detailed and quantitative definition of the underwater shape of coastal structures. Information and products resulting from the use of multibeam sonars will permit USACE Field Operating Agencies to improve the operation and maintenance of their coastal structures by better quantifying existing structure conditions below the waterline, changes due to damage or repairs, and required volumes of repair materials. They will also be better equipped to identify problem zones on structures, damage sequences and mechanisms, and repair alternatives. With multibeam sonar systems, it is now possible to have types of survey information that were previously impractical to obtain or were unattainable, leading to safer, more cost-effective management of coastal structures over their lifetimes.

## **Acknowledgements**

Recognition is given to Mr. Jonathan W. Lott, who participated in the REMR-I CSARS investigation and was the principal investigator of the REMR-II work unit until 1995. His superb research and technology transfer efforts resulted in escalating the development of multibeam sonars as a state-of-the-art tool for underwater surveying of Corps of Engineer coastal structures.

The author would like to thank RESON, Inc., manufacturer of the SeaBat multibeam system, for their considerable cooperation and assistance during the REMR investigation. RESON's technical expertise and support were vital elements in the success of this investigation.

Thanks are also given to John E. Chance and Associates, David Evans and Associates, C & C Technologies, Ocean Surveys, Inc., and other private survey contractors for contributing their time and effort in support of the REMR investigation to test and demonstrate the applicability of multibeam sonars for surveying coastal structures.

Specialty Devices, Inc., of Plano, Texas, is acknowledged for their efforts in CSARS system development by upgrading and improving CSARS software and hardware to provide a "second-generation" system.

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# REPORT DOCUMENTATION PAGE

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| <b>13.ABSTRACT (Maximum 200 words)</b><br><p>This report discusses research conducted to investigate and develop hydrographic survey equipment for objective, detailed, and quantitative definition of the underwater shape of coastal structures. The research included development of and investigation of the Coastal Structure Acoustic Raster Scanner (CSARS) system. Although much information was gained from CSARS development, the capabilities of commercially available multibeam systems like the SeaBat 9001 multibeam sonar system surpassed the still-prototype CSARS. Therefore, this investigation concentrated on multibeam sonar systems, and field demonstrations and trials were conducted with the SeaBat system. The SeaBat system was successful in providing accurate, high-resolution hydrographic data on the underwater condition of various structures. With multibeam sonar systems, it is now possible to have types of survey information that were previously impractical to obtain or were unattainable, leading to safer, more cost-effective management of coastal structures over their lifetimes.</p> |                                                                |                                               |                                                                               |
| <b>14.SUBJECT TERMS</b><br>Coastal Structure Acoustic Raster Scanner (CSARS) System<br>Coastal structures<br>Hydrographic surveys<br>Multibeam sonar systems<br>SeaBat 9001 multibeam sonar system                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                |                                               | <b>15.NUMBER OF PAGES</b><br>42                                               |
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