High Resolution Bathymetric Sidescan Sonar

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I. Introduction

In the 1990s, development of the Bathymetric Sidescan Sonar (BSSS) hit significant road blocks. First, bathymetry error in the nadir region is so large that deemed useless; second, in a complicated environment, for example with channel-introduced multi-path propagation, or with complex bottom topography, there can be two or more simultaneous echo returns from different directions, which cannot be separated by the conventional BSSS system [1 2].

Later 1990s, the above issues were investigated and some solutions were proposed. First, it was commonly recognized that echo return is from a thin layer of bottom rather than bottom surface alone [1, 2, 3]. The phase term in sonar array time-spatial correlation function shall be expressed as \( \eta = k d \sin (\theta - \theta_m) + \xi \). The first term \( \phi = k d \sin (\theta - \theta_m) \) is commonly used in literatures as the correlation phase, where \( k \) is the acoustic wavenumber, \( d \) is the element spacing in sonar array, \( \theta \) is the grazing angle of acoustic incidence, and \( \theta_m \) is the mounting angle (horizontal plane to the norm of the sonar array). For typical BSSS system, a large \( d \) is often chosen so that a small variation of \( \theta \) will cause a large variation of \( \phi \), thus improving the accuracy in measuring \( \phi \). In reality, however, the correlation phase should include \( \xi \), a term attributed to certain sound penetration into the seafloor. \( \xi \) is a function of \( \theta \) and \( d \); it can be ignored only if \( d \leq \lambda \), where \( \lambda \) is the acoustic wavelength; in other cases, \( \xi \) does matter, particularly in the nadir region, where \( \xi \) contributes more than that by \( \phi \), causing large error in bathymetry measurements. It was demonstrated that BSSS with multiple parallel line arrays equally spaced at \( \frac{\lambda}{2} \) can make the bathymetry measurements at nadir as accurate as by a digital echo sounder [1, 2, 3]. Second, by exploiting high-resolution signal direction-of-arrival (DOA) estimation techniques, the new system design can resolve echo returns simultaneously arriving from different directions. This makes it possible to retrieve the desired echo signal from the multi-path returns caused by acoustic channel propagation and/or bottom topography [1, 2, 4, 5, 6, 7].

To obtain high-precision bathymetry chart, a complete set of signal processing package is required combining the DOA estimation with bathymetric sidescan operation. We call the resulted system High-Resolution Bathymetric Sidescan Sonar (HR-BSSS). With its advantages of being high-resolution, small-size, less-weight, low-power and platform along-side (long-axis) installed, the HR-BSSS is particularly suited for applications involving AUV, UUV, ROV and towed body. The platform can navigate at a low
altitude, obtaining high-resolution mapping of the bottom topography and geomorphology.

In this paper, we introduce an HR-BSSS system including lake test results. This is a joint effort by the Institute of Acoustics, Chinese Academy of Sciences and RD Technologies (Shanghai), a sub-company of the RD Instruments, San Diego, USA.

II. Brief Description of the HR-BSSS

II-1 HR-BSSS System Hardware Architecture

Fig. 1 displays the block diagram of the BSSS system hardware architecture. The system includes two independent transducer arrays – one for port and one for starboard, and an transducer interface module is packaged into the backside of each array. The subsea unit includes a pressure canister and an electronics sub-unit. The subsea electronics consists of twelve Printed Circuit Board (PCB) modules as shown below:

- PC104+ Computer Assembly (including an Ethernet 100Base-TX network port)
- FPGA Controller PCB
- HDD & Interface PCB (to mount 3?? hard disk)
- PCI Interface PCB
- Dual Transmitter PCB
- Transducer Interface PCB
- Quad Receiver PCB (4)
- Data Acquisition System (DAS) PCB
- Input Power Conditioner PCB
- 5.0 V Power Supply PCB
- 3.3 V Power Supply PCB
- Backplane PCB

![Diagram](image-url)

Figure 1: BSSS transceiver hardware & functional block diagram
Fig. 2 shows the structure of the 150 KHz sonar array ((a): face view; (b): side view; (c): photo of the transducer array). Each array includes an electronics cavity, housing the Transducer Interface PCB, and an array cavity, consisting of eleven acoustically identical and independent line elements. Elements 2-9 are receiver transducers, Element 11 functions as a transmit transducer, and Elements 1 and 10 are dummy ones used for impedance matching. Each line element consists of a line of 100 diced square faced transducer sub-elements.

(a) Face view

(b) Side view

(c) Photo of the transducer array

Figure 2: Transducer array physical configuration

II-2 HR-BSSS System Software Architecture

The block diagram of the BSSS system software architecture is shown in Fig. 3, where the corresponding hardware modules are denoted by circle. Software packages developed include host computer (surface) digital signal processing software, host computer server software, sonar operation driver software, and subsea control software. Also developed include terminal debug/testing software 1 for host computer server debug/testing, terminal debug/testing software 2 for sonar operation driver debug/testing, and sonar simulation software. Besides, the system GUI (Graphic User Interface) and post-processing software was purchased from the OIC, Inc., USA.
The HR-BSSS system software has demonstrated very reliable performance during the lake test, capable of implementing real-time data collecting and processing. The raw data, backscattering data, bathymetry data and various sensor data are further combined and processed using the system GUI and post-processing package. The end result is an accurate and fine-scale mapping of the bottom topography and geomorphology, meeting the design specifications.

Individual software packages are summarized below.

The host computer digital signal processing software is to implement processing of the digitally sampled data, generating the bottom bathymetry and geomorphology data. Among them is a novel development of multiple-sub-arrays-based bottom automatic detection and sub-space fitting signal processing algorithm.

The sonar operation driver software is to provide an interface for 1) the host computer server software and terminal debug/testing software, enabling both to control the operation of the sonar; 2) the subsea main control software, sending operation instructions and receiving data from the subsea computer (PC104+); and 3) the host computer digital signal processing software, controlling its operation flow.

The host computer server software is to provide an interface between the sonar operation driver software and the system GUI software, converting the user operation requests to sonar operation instructions/parameters and sending them to the sonar operation driver software, also receiving the processed data from the digital signal processing software and sending them to GUI.

The terminal debug/testing software is to implement debug and testing of the entire sonar system.

The sonar simulation software is to implement simulation of the external interfaces without hooking up the subsea hardware device. It is used for the development/testing of the host computer server software and the system GUI software.

The system GUI software is to 1) implement real-time compensation/correction for the data from the digital signal processing software and generate the mapping results; 2) provide an interface to the host computer server software, sending sonar operation instructions and receiving the processed data from the digital signal processing software; and 3) provide an interface to input/output devices, sensor devices, and storage devices.

The post-processing software is to implement fine-tuned post-processing of the entire data set collected during a test, form into a mosaic, and produce the final isobaths and geomorphology map.

The subsea sonar control software is to implement control of the subsea electronics. It provides an interface via Ethernet port to the host computer sonar driver software, receiving operation instructions/parameters and sending sampled data and hardware...
operation status/testing information. It also provides an interface to the FPGA Controller PCB, controlling its operation; with the FPGA programmed based on the FPGA firmware, implementing system transmit/receiving operation.

Figure 3: HR-BSSS system software block diagram

II-3 HR-BSSS Main Technical Specifications

The main technical specifications of the HR-BSSS system include:

- Operating frequency: 150 KHz
- Transmit pulse: linear modulation (Chirp)
- 3-dB beamwidth: 100° vertical
  1° horizontal
- Mounting angle: 20° ~ 30°
- Swath width: 2×300 m (bathymetry mode)
  2×400 m (sidescan mode)
- Cross-track resolution: 5 cm
- Minimum height detectable: 10 cm
- Multiple target detection: Yes
- Maximum operation depth: 6000 m

III. Experiment Results
In this section, we present some tank test results (see also Refs. [1] and [2]); the focus, however, is the results from the lake test conducted at the Thousand-Island Lake in eastern China.

III-1 Tank Test

To verify the minimum height detectable by the sonar array, a tank test was conducted in early December 2003. The test configuration is displayed in Fig. 4. The transducer array is installed on a supporting frame, about 3 m above the bottom, with mounting angle of 30°. A target of 24×24×11 (length×width×height) cm³ (cf. Fig. 5) is laid down on the bottom, about 2.6 m away horizontally from the transducer array. The result is shown in Fig. 6, where the thick black line represents the real tank floor, the red line represents the result with target present, and the blue line represents the result with target absent. By comparison, it is demonstrated that the HR-BSSS can tell if a 10 cm-height target is present or not on the tank floor, i.e., the system is capable of detecting the existence of a 10 cm-height target.

Figure 4: Target tank test configuration to verify the minimum height detectable

Figure 5: Small target used in tank test
III-2 Lake Test

From Nov. 2\textsuperscript{nd} to 30\textsuperscript{th}, 2003, a test of the HR-BSSS was conducted at the Thousand-Island Lake in China. This sub-section presents the main results from the test.

a. Brief description of the hardware system

The hardware system used in the testing includes HR-BSSS port/starboard transducer arrays, the subsea electronics canister, Octans 6000 motion sensors, Nexus fiber-optical multiplexer surface unit and deck unit, GPS, computers and UPS power supply, as shown in Fig. 7.

Figure 6: Tank test results

Figure 7: HR-BSSS Thousand-Island Lake test system block diagram
HR-BSSS port/starboard transducer arrays and the motion sensor are mounted on a supporting fixture, laid down to the water about 4.7 m deep via a three-piece connected pole, whose top end is tied to the towed boat as illustrated in Fig. 8. The mounting angle of the transducer array is 30°. Fig. 9 displays the photo taken after the installation of the HR-BSSS port/starboard transducer arrays and the motion sensor. HR-BSSS electronics canister and the fiber-optical multiplexer underwater unit are laid down on the deck of the test boat, while the surface operation platform, high-power DC supply, fiber-optical multiplexer surface unit and the UPS power supply are set up in the onboard laboratory. The port/starboard transducer arrays are connected to the electronics canister via a 20 m cable; the motion sensors are connected to the fiber-optical multiplexer underwater unit via a 20 m cable as well. Magellan GPS is used for navigation and positioning in the test.

Figure 8: Transducer array and motion sensor lake test configuration

Figure 9: Photo of the HR-BSSS port/starboard transducer array and motion sensor installation
b. Test Results

This sub-section presents results from the moving test conducted on Nov. 24, 2003. Fig. 10 shows the navigation window in GeoDAS GUI, which displays in real-time the sonar testing coverage while the platform is moving. The abscissa and ordinate correspond to the longitude and latitude coordinates, respectively, with data provided by the GPS. The red area is the testing coverage for the port transducer; while green for the starboard.

![Figure 10: Location of the test region](image)

Fig. 11 is a typical GUI operation display. As pointed by the arrows in the figure, the GUI simultaneously displays the topography map, geomorphology map, real-time bottom tracking, sidescan operation data, and various sensor data, for real-time operation inspection. Seen from the figure, the bathymetry data at nadir measured by both port/starboard transducer arrays agree very well, demonstrating that very good nadir region measurements are obtained by the HR-BSSS.

![Figure 11: GUI software operation display](image)
Figs. 12 and 13 are example screen copies of the GUI operation displays. Fig. 12 shows the operation range in sidescan mode is up to 400 m on each side, while Fig. 13 shows 300 m each side in bathymetry mode.

Figs. 14 and 15 display example real-time inlaid depth chart and three-dimensional isobaths chart, respectively, where different colors represent different depths: deeper the color, deeper the bottom.
Figure 15: Real-time three-dimensional isobaths chart

Fig. 16 shows the geomorphology mosaic of the test region compiled by GeoDAS GUI. Fig. 17 shows the isobaths mosaic compiled by the post-processing software, where the spacing between two adjacent lines of equal depth is 2 m.

Figure 16: Geomorphology mosaic

Figure 17: Isobaths mosaic
As shown in Fig. 18, the bathymetry data is shown in the bottom panel; the arrow on the left points to a puddle about 2 m deep, whose depth variations are seen from over ten depth points, fully demonstrating the high resolution of the HR-BSSS bathymetry measurements.

Fig. 19 displays the results of testing the resolvability of specific targets. In this stationary test, a water-filled cubic target of 0.5 m side length is laid down in a pre-determined location (see the top-right panel). The top-left panel shows the sidescan map covering the region of target including some target parameters extracted; the bottom-left panel gives a profile of the bathymetry measurements with arrow pointing to the target position. Having had corrected the target prolongation raised by the horizontal angular beamwidth, the measured target size is about 0.61×0.54×0.51 m$^3$, where the length dimension is in the along-track direction. Obviously the measurements agree very well with the true target dimension.
IV Conclusion
The above results have demonstrated that the HR-BSSS is capable of collecting in real-time depth and geomorphology data of the bottom, and through post-processing, generating depth chart and geomorphology chart, measuring small variation of the bottom topography, and producing high-resolution regional topography and geomorphology map. For a small man-made target on the lake floor, the experimentally measured size agrees very well with the true one.

References