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The development of a deep-towed seismic profiling system has been completed after four years of design, fabrication, and testing. This system provides the capability to determine the detailed acoustic character of the sea floor and upper 500–1000 m of subbottom structure. The system is designed for tow depths of 6000 m while operating at an altitude of 100 m above the sea floor. The major components of the system include a sound source located in the deep-towed vehicle, which operates over a frequency range from 260 Hz to 650 Hz at a peak source level of 201 dB re 1 micropascal at 1 m; a 24 channel, 1000 m long array attached as a tail to the deep-towed vehicle; a duplex digital telemetry link to communicate with the deep-towed system over a coaxial tow cable; a digital data record system; a real time engineering data display system; a short baseline navigation system; handling hardware to deploy and retrieve the system; and two instrumentation vans to support system operations. This paper discusses the unique hardware developed for the deep-towed seismic system and focuses on the acoustic subsystems. Also reviewed is a performance prediction analysis initially performed to define geoacoustic parameter measurement improvements achievable with a deep-towed configuration. Field measurement engineering results acquired during the system's final performance evaluation are presented. Data was acquired at tow depths of 4500 m during the September 1984 evaluation.

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Development of a Deep-Towed Array Geophysical System: A New Capability for Deep-Ocean Acoustic Measurements

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Ocean Acoustics and Technology Directorate

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Foreword

The ability to understand the effects of the ocean environment on Navy systems and operations is vital to the fleet. One area of research being carried on by the Naval Ocean Research and Development Activity is the development of definitive models of the ocean floor and subbottom as a transmission media for acoustic energy.

This report covers the Deep-Towed Array Geophysical System and its development as a hardware suite to provide high-resolution data to describe the geological, geophysical, and geoacoustical character of the deep-ocean sea floor and upper subbottom structure.

R. P. Onorati, Captain, USN
Commanding Officer, NORDA

Executive summary

The development of a deep-towed seismic profiling system has been completed after four years of design, fabrication, and testing. This system provides the capability to determine the detailed acoustic character of the sea floor and upper 500–1000 m of subbottom structure. The system is designed for tow depths of 6000 m while operating at an altitude of 100 m above the sea floor. The major components of the system include a sound source located in the deep-towed vehicle, which operates over a frequency range from 260 Hz to 650 Hz at a peak source level of 201 dB re 1 micropascal at 1 m; a 24 channel, 1000 m long array attached as a tail to the deep-towed vehicle; a duplex digital telemetry link to communicate with the deep-towed system over a coaxial tow cable; a digital data record system; a real time engineering data display system; a short baseline navigation system; handling hardware to deploy and retrieve the system; and two instrumentation vans to support system operations. This paper discusses the unique hardware developed for the deep-towed seismic system and focuses on the acoustic subsystems. Also reviewed is a performance prediction analysis initially performed to define geoacoustic parameter measurement improvements achievable with a deep-towed configuration. Field measurement engineering results acquired during the system's final performance evaluation are presented. Data was acquired at tow depths of 4500 m during the September 1984 evaluation.

Acknowledgments

The authors are indebted to all NORDA project members for their technical contributions in the successful development of DTAGS. Thanks are extended to the NORDA field team who participated in the DTAGS final engineering evaluation sea test: Mr. John Cranford, Dr. Charles Rein, Mr. Richard Wilkinson, Mr. Albert Albrecht, Mr. Robert Brown, Mr. William Everard, and Dr. Joseph Gettrust. The processed deep-towed stacked section was provided by Dr. Gettrust. We would also like to recognize Mr. Clark Kennedy of the University of Miami for his outstanding technical support on-board the research vessel ORV COLUMBUS ISELIN during the at-sea test.

Development of a deep-towed array geophysical system: A new capability for deep-ocean acoustic measurements

Introduction

The Naval Ocean Research and Development Activity (NORDA) carries out broadly based research and development in ocean science and technology to understand the effects of the ocean environment on Navy systems and operations. Specifically, one area of responsibility is developing definitive models of the ocean floor and subbottom as a transmission medium that refracts, diffracts and dissipates, as well as reflects, acoustic energy. These models are used to predict, and thus improve, the performance of naval systems that acoustically interact with the bottom. Critical for developing these models is high-resolution data to describe the geological, geophysical, and geoacoustical character of the deep-ocean sea floor and upper subbottom structure. These high-resolution data can be obtained using a low-frequency sound source and multichannel array system capable of operating at an altitude of 100-500 m in ocean depths of 6000 m. This configuration is depicted in Figure 1. A development program entitled ''Deep-Towed Array Geophysical System'' (DTAGS) was initiated in 1981 to provide a hardware suite to meet this high-resolution data requirement.

System performance prediction studies [1, 2, 3, 4, 5] showed substantial improvement in measuring geoacoustic parameters with the DTAGS configuration. A comparison between the deep-towed configuration and a surface-towed configuration for measuring a critical geoacoustic parameter, interval velocity, as a function of layer thickness is given.

The initial hardware development focused on a Helmholtz resonator sound source system. This unit was successfully tested to a depth of 2000 m in December 1981. Subsequent effort concentrated on developing the multichannel hydrophone array (672 m long) and high data rate telemetry system. These systems were integrated with the sound source system and sea tested to a depth of 4500 m during the summer of 1983. The hardware development concluded with extending the array to a total length of 1000 m, fabricating a digital data record system, and incorporating into the system a short baseline navigation system. The total hardware suite was tested to a depth of 4500 m in September 1984.

Performance prediction analysis

The basic objective of the deep-towed system is to provide measurements for extracting the geoacoustic parameters of the near subbottom. Such parameters include sound speed as a function of depth and vertical thickness between

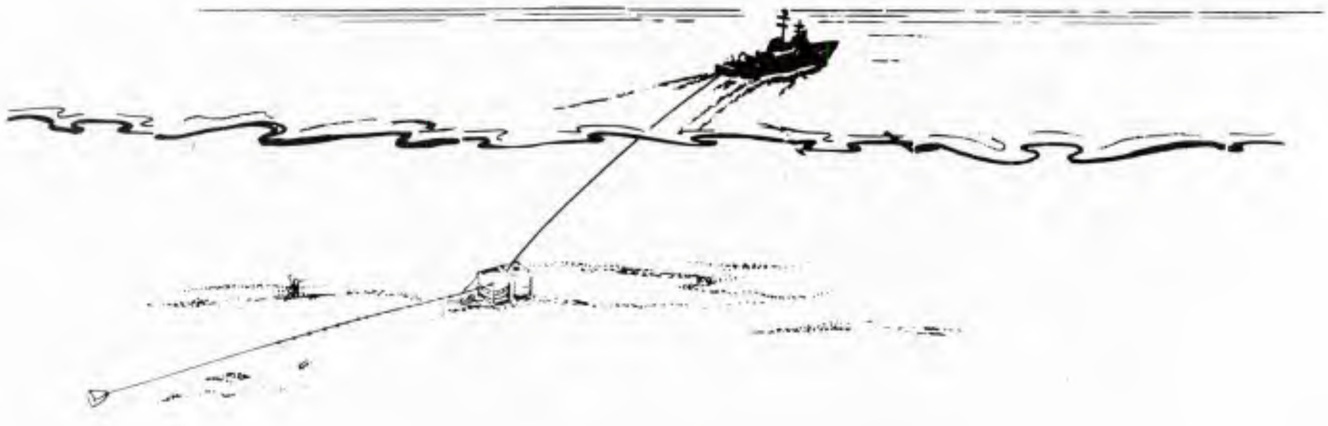

Figure 1. Deep-towed system configuration.

acoustic reflectors. The geoacoustic parameter addressed here is termed interval velocity, where interval velocity is defined as the RMS sound speed in the layer (interval) of interest. For a layer of constant sound speed, the interval velocity reduces to simply the sound speed in the layer. Analysis by Gibson et al. [6] and Gholson and Fagot [4], more advanced than that presented here, addresses the problems associated with estimating sound speed gradients.

Estimating the interval velocity of a layer bounded above and below by acoustic reflectors can be accomplished by exercising the Dix [7] equation shown below:

$$Vi = \left[\frac{V_{A2}^{2}\,T_2 - V_{A1}^{2}\,T_1}{T_2 - T_1}\right]^{1/2} ,$$

Errors in measuring normal incidence travel time (T_1, T_2) were modeled as zero mean independent errors uniformly distributed with bounds ± Tpick where Tpick is the precision of measuring (picking) reflected energy arrival times. Errors in the measured array velocities V_{A1}, V_{A2} are much more difficult to model. The approach was to assume that the fitted T^2 (X^2) curve never departs from the true T^2 (X^2) by more than that associated with the picking error Tpick. Further, it is assumed that the just-mentioned is reliably true over a horizontal span, X, equal to one-half the physical array length. The last assumption is equivalent to assuming the array is one-half its actual length and a moveout curve is successfully fitted (± Tpick) through returns from every hydrophone group. Stoffa [8] and simulations using realistic signal-to-noise ratios indicate the one-half array length assumption to be reasonable for an array with 24 equally spaced groups. This error analysis allowed for system optimization, as well as general system performance prediction.

This type of error analysis was used in comparing a surface-towed system with a deep-towed system. A geoacoustic model, along with a surface versus deep-towed system comparison, is shown in Figure 2. The surface-towed system differs from the deep-towed system both in array length and altitude above the layer of interest. The increasing error for small Z is due to the water column sound speed dominating the measured array velocity. This effect is much worse for the surface-towed system, since the water column is much thicker.

Hardware description

A block diagram of DTAGS hardware configuration is given in Figure 3. The sound source transducer and power amplifier system, telemetry system, and associated electronics are located within a deep-towed vehicle (fish) towed at the head of a multichannel array. The deep-towed system is tethered to the tow ship with a 9150-m long coaxial steel tow cable. A duplex telemetry system communicates via the tow cable with the deep-towed system. Data from the fish system is then digitally recorded at the tow ship. Monitoring of system performance is through a real-time display system. The position of the fish relative to the tow ship is provided by a short baseline navigation system. Global position is obtained through satellite and Loran-C navigation. A tow cable heave accumulator and an array handler winch constitute the system handling hardware. The operation systems are located in a portable van with a maintenance facility and spares storage located in a second van. The component designs of these major subsystems are optimized to meet the basic geophysical data requirement while still maintaining a hardware suite that can be easily deployed, operated, and maintained. A detailed description of the total hardware suite is described by Fagot [9].

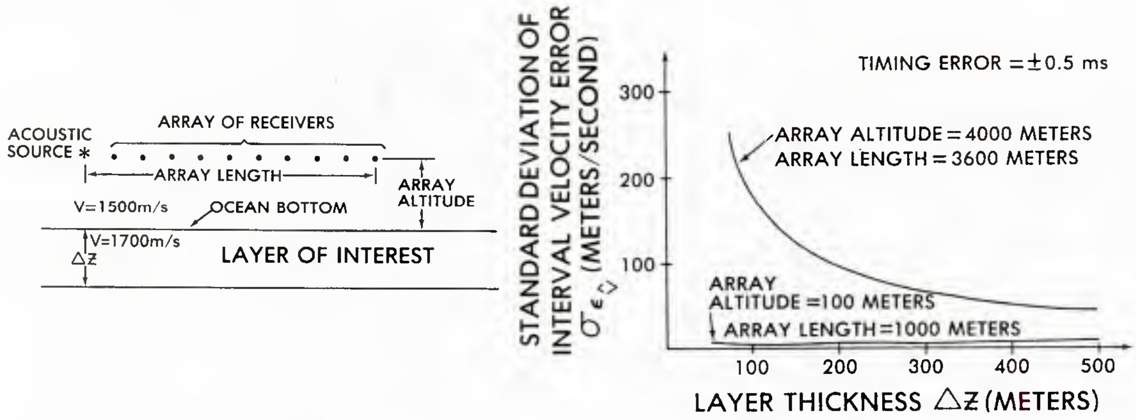

Figure 2. Geoacoustic model and performance comparison between a surface-towed and deep-towed system.

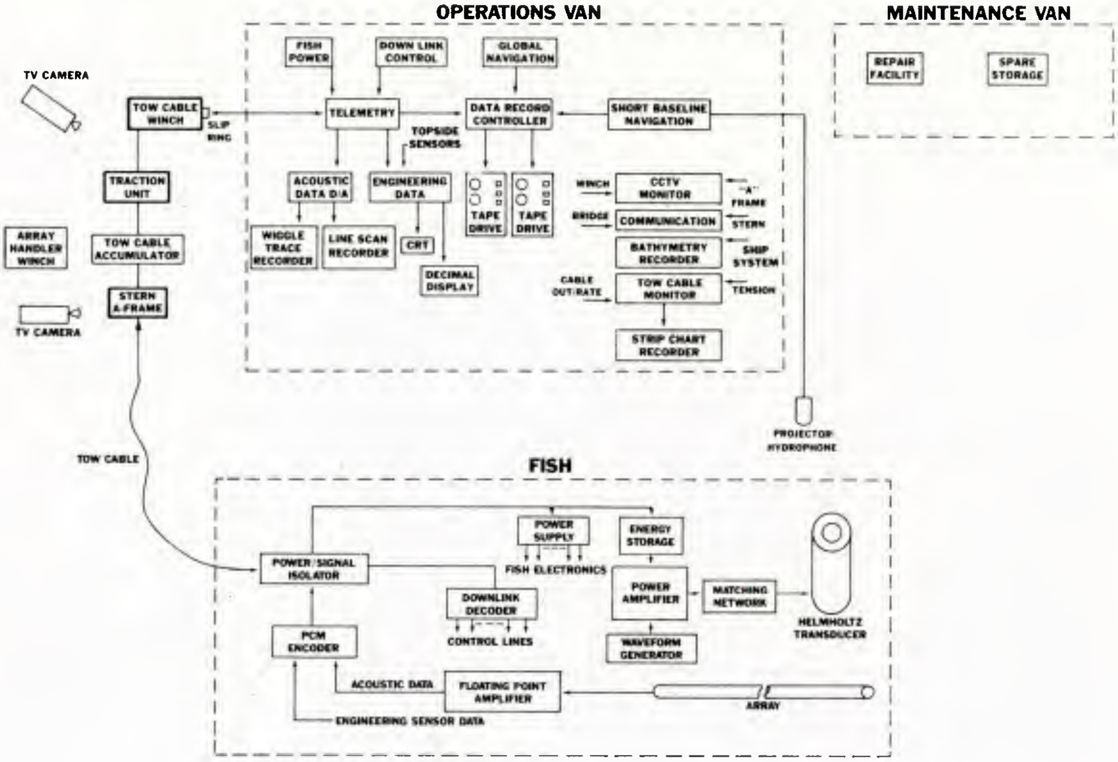

Figure 3. Block diagram of deep-towed system hardware configuration.

Sound source system

The sound source system hardware consists of a piezoelectric Helmholtz resonator transducer and a power amplifier. The amplifier was designed and packaged for operation at full depth. The transducer and power amplifier are mounted together in the deep-towed vehicle (fish) as shown in Figure 4. Also identified are other major subsystems located on the fish.

The sound source system is capable of full performance from near surface to full ocean depth. The system is capable of a nominal peak source level of 201 dB//1 μPa @ 1 m. This level can be achieved over a frequency range from 260 Hz to 650 Hz. Directivity over this range of frequencies is omnidirectional. Output pulse length is programmable from 5-ms minimum to a maximum of 250 ms in duration. The system is capable of a full power 250-ms output pulse once every 12 seconds.

The transducer consists of a Helmholtz cavity and orifice driven by five piezoelectric-segmented ceramic ring drivers. As built, the transducer is approximately 0.7 m in outside diameter, is 1.1 m long, and weighs 800 kg. The design, development, and fabrication of this transducer was performed by the Naval Research Laboratory, Underwater Sound Reference Detachment, and is described by Young [10].

A Class S switching amplifier was chosen as the driver for the Helmholtz resonator transducer due to its small relative size compared to a linear amplifier, such as a Class B. The Class S power amplifier system weighs approximately 232 kg (including pressure vessel) and is housed in a 0.6-m diameter spherical pressure vessel. Due to the inefficiency of a deep-water broadband sound source, the power amplifier is required to deliver 16 kVA of reactive power. Other requirements of the system called for control of output waveshape and frequency. Also due to inaccessibility and remote location of electronics during an at-sea operation, reliability of the power amplifier was of prime concern. The design, development, and fabrication of the power amplifier was performed by NORDA.

The power amplifier system located at the tow vehicle consists of a waveform generator, power amplifier modules, energy storage bank, and a load matching network. Four drive waveforms are stored in an erasable, programmable, read only memory (EPROM) that is programmed prior to deployment. Selection of the source drive waveform, along with the source firing key signal, is accomplished via the downlink telemetry system. Energy for the highpower output pulse is stored in a 0.132 farad capacitor bank. This bank is trickle charged between pulses at an average rate of 300 watts via the tow cable. The power amplifier module controls the power drive level and

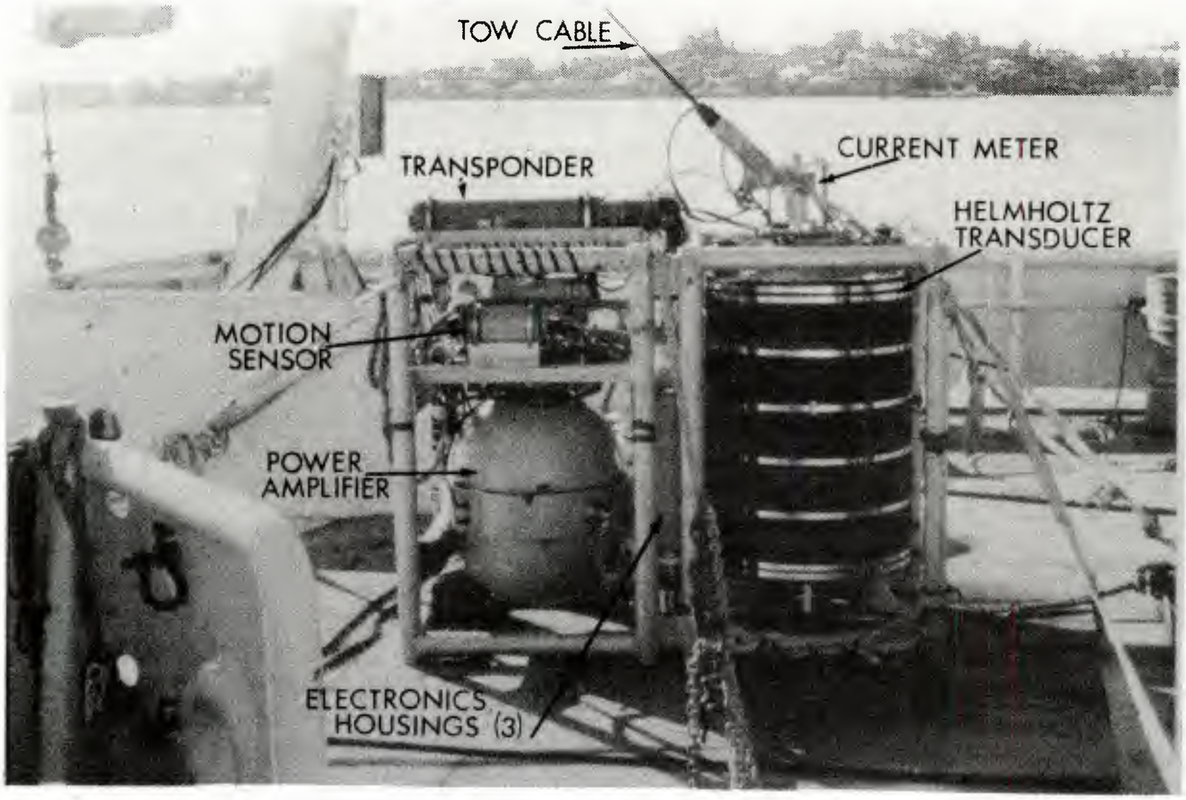

Figure 4. Deep-towed vehicle (fish) with major subsystems identified.

waveshape supplied to the Helmholtz resonator transducer. Power transfer to the source is optimized through the load matching network, which consists of a power factor correction network and an impedance matching transformer. The matching network is housed in a separate pressure vessel.

Array system

The array design selected for the deep-towed geophysical system is a multichannel hydrophone array similar to the type used by the marine exploration community. The standard oil-filled design, hose, spacers, and oil-immersed electromechanical coupling presently used are compatible with high operating pressures. The array is 1000 m long and consists of 12 active sections that contain a total of 48 hydrophone groups. Only 24 groups will be used for a specific configuration to reduce the telemetry data rate requirement. A 2-m interconnect section is located at the head of each 82-m active section. Each 82-m active section has an outside diameter of 4.61 cm; the 2-m interconnects are either 7.62 cm or 10.16 cm, depending on the sensor suite, and a 50-m stretch section at the head of the array has a diameter of 6.6 cm. The entire array is designed to have a tensile strength greater than 1200 kg and for a maximum tow speed of 1.5 m/sec (3 knots). A drogue parachute is attached to the array tail for tow stability. The interconnect sections contain heading sensors, depth sensors, and hydrophone preamplifiers. Each active section contains four hydrophone groups. Figure 5 shows the array on the handler winch.

The array acoustic design is tailored to the deep-tow geophysical system operational performance requirements. Forty-eight hydrophone groups are spaced uniformly along the array with a 21-m separation between adjacent groups. Each hydrophone group consists of six elements with a total length of less than 60 cm. The individual hydrophones are a piezoelectric cylinder type that are tolerant to high operating pressures. Outputs of the hydrophones are connected to the preamplifiers located in the 2-m interconnect section at the head of the associated active section via a twisted pair shielded cable. Because of the large separation between the hydrophone group and preamplifier (approximately 74 m for the last group of each active section) and the low group capacitance, a balanced input charge amplifier is used for the preamplifier to accommodate these conditions. The combined sensitivity of an acoustic channel (hydrophone group plus preamplifier) is a nominal -150 dB//1 V/μPa with a frequency response from 150 to 1000 Hz. The bandwidth is limited by filters in the preamplifier and can be opened to a band ranging

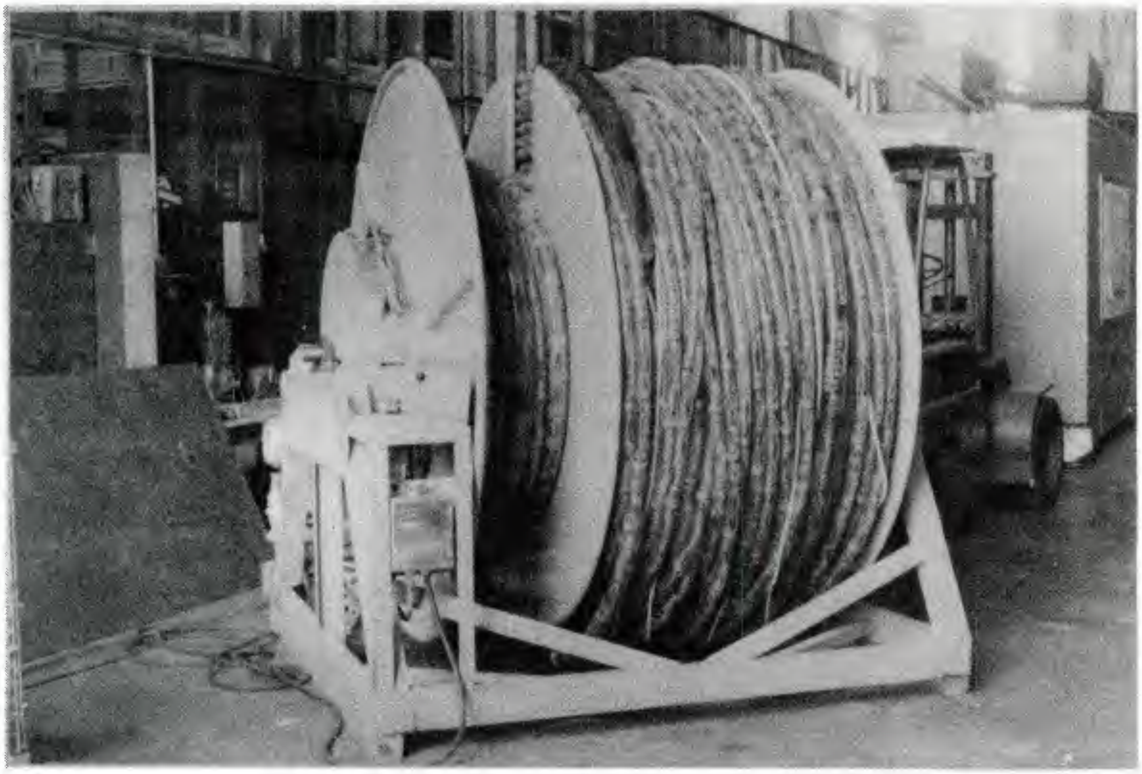

Figure 5. Deep-towed array on the array handler winch.

from 10 to 2000 Hz by appropriate component changes in the preamplifier. The self-noise of each acoustic channel is less than 35 dB (// 1 μPa/$\sqrt{\text{Hz}}$) over the operating frequency band, which is less than deep-ocean Sea State 0 ambient noise. Each channel preamplifier has a built-in calibration oscillator with a unique frequency that provides easy channel identification and an in situ functional check of the entire acoustic channel, including the hydrophone group. Gain of the preamplifiers can also be lowered 20 dB by an external control signal.

The array is equipped with a suite of engineering sensors to measure array tow dynamics, such as array shape, tension, and tow attitude. Each interconnect section contains a depth sensor and four heading sensors are spaced uniformly over the array length. A load cell at the head of the array is used to monitor in-line array tension in real time.

Ancillary systems

A number of other subsystems are required to support the deep-towed operations. An overview of these subsystems is presented.

Telemetry system

The telemetry system for the deep-towed geophysical system provides full duplex communication between the tow ship and the tow vehicle via a 9150-m coaxial tow cable. System requirements call for a data transfer rate of 1.5 M bit/sec. The telemetry system is capable of handling tow fish power (300 W) down the cable, as well as the 1.5 M bit/sec pulse code modulation (PCM) uplink data and low data rate FSK downlink control signals. The acoustic signals from the towed array are digitized by a 12-bit A/D with a 4-bit gain exponent floating point amplifier at a 3125-Hz sample rate. The FSK downlink control system operates at a 10 bit/sec rate. The telemetry equipment contained in the tow vehicle includes the PCM encoder and FSK decoder electronics. Cable equalization circuits are located on the tow ship.

The PCM uplink system provides thirty multiplexed channels for data transmission from the deep-towed vehicle to the tow ship. Twenty-seven of these channels are utilized for transmitting acoustic channel data that has been digitized by a common floating point amplifier (FPA). The FPA low pass filters the data at 800 Hz. The digital outputs of the floating point amplifier are time division multiplexed with two 16-bit frame synchronization words and a submultiplexed engineering sensor channel to form a frame containing thirty 16-bit words. This data stream is Manchester encoded and transmitted to the surface via the tow cable.

The submultiplexed engineering sensor channel is capable of handling 256 sensor channels. Data such as the array depth sensors, array heading, and other engineering sensors are transmitted via these subchannels. The subchannels are also used to transmit subsystem operational status for real-time monitoring by the system operator.

Data record system

The data record system provides the capability to record the high data rate and large volume of data generated by the deep-towed system. The data is tape formatted in the Society of Exploration Geophysicist's SEG-D (Demultiplexed 2½-byte binary exponent word) as defined by the Society of Exploration Geophysicists [11]. The format provides the flexibility through header blocks to record both the global and short baseline navigation parameters simultaneously with the geophysical reflection data. Thus, each data tape will contain all the information required for geophysical processing.

The ability to play back prerecorded data is also incorporated into the system. The engineering sensor data for the deep-towed system is extracted from the recorded data tape in a format directly compatible with the engineering real-time display system. Also, up to 8 channels of acoustic array data can be input directly into the real-time D/A converter for display.

Real-time display system

The capability to monitor the performance of the deep-towed system is provided by a real-time display system. This system, located in the operations van, includes monitoring, displaying, and recording engineering sensor data from the array and fish located sensors; displaying acoustic array data; monitoring and recording tow ship located subsystem sensor data; and closed circuit television monitoring of the deployment/retrieval handling systems.

Navigation system

The navigation suite consists of two subsystems: a short baseline system to position the fish relative to the tow ship and a global system, Satnav and Loran C, to geographically position the tow ship. The output of both systems is fed to the data record system.

Deep-towed vehicle (fish)

The fish is an aluminum open-framed structure (Fig. 4). Since the fish drag is small at low tow speeds (0.5-1.5 knots) in comparison to the tow cable, an unstreamlined structure is employed. The fish envelope size is 1.83 mL X 0.86 mW X 1.35 mH. The fish consists of two substructures of approximately equal size, with a total weight of 1360 kg in air and 1090 kg in water. One substructure houses the Helmholtz transducer, which is shock-mounted to provide vibration isolation. The other substructure houses the sound source power amplifier spherical pressure vessel, two oil-filled junction boxes, motion sensors, a current meter, an array tensiometer, and an acoustic transponder. Three cylindrical pressure vessels containing system electronics are located vertically between the two substructures.

Vehicle heave accumulator system

The ship surge motion effects on the towed system are minimized with a tow cable tension accumulator system. The unit is primarily effective when the fish system is near the sea surface. Incorporated into the system is a cable tension-monitoring sensor. The lead sheave, separate from the accumulator system and located at the tow point, is instrumented with a cable-out sensor.

Array handler winch

The array handler, a large motorized drum (Fig. 5), is used for deployment and retrieval, as well as storage of the array. The winch is mounted near the fish deployment area to facilitate array launch and retrieval.

Tow cable

The tow cable is a coaxial-type construction with two contrahelically wound layers of galvanized, high-strength steel wires wrapped around a coaxial cable core. The core has electrical characteristics similar to RG-8U. The steel wire geometry provides a very low cable torsional characteristic, which eliminates the need for an electrical-mechanical swivel within the tow cable system.

Portable vans

The flexibility to meet a ship-of-opportunity operation scenario is provided by self-contained vans. An operations van and maintenance van are part of the deep-towed hardware suite. The vans are sized to allow air shipment if necessary.

Host ship support

The host ship provides the deep-sea winch, cable traction unit, and the tow point stern "A" or "U" frame. This set of hardware is generally available for ships engaged in deep-sea geophysical research. The deep-sea winch/traction unit must be capable of smooth and precise control of tow cable movement. Slow, creep, cable in/out speeds are required when lifting the fish off or placing the fish on the deck, and then speeds up to 45 m/min are required for deep deployment and retrieval. The ancillary units are highlighted in Figure 3 by heavy, broader outlines. The slip ring assembly incorporated into the deep-sea winch for termination of the coaxial tow cable is a part of the deep-towed system hardware suite. The ship must be capable of making 0.5 knots (relative the water) on any course in a fully developed Sea State 6, with the ship heading within 45° of the course.

Engineering field test

The final engineering evaluation test was performed in September 1984 while on a transit from Miami, Florida, to St. George, Bermuda. This test concluded the hardware development with extending the array to a total length of 1000 m, fabricating the digital record system, and incorporating a short baseline navigation system.

The sound source system again performed reliably during the test. An excess of 20,000 shot-receive sequences were initiated. The predominant source waveform used was a 260 Hz to 650 Hz linear FM slide with 10% leading and trailing amplitude shading on a 125-ms pulse. Some data was acquired with a 400 Hz, 5-ms pulse. A 20-second pulse repetition rate was typical.

The array also performed well during the test. The array shape typically experienced throughout the test is pictured in Figure 6. The real time display system generates this type figure for tow performance monitoring. Depth data is annotated as D1 through D9 on the figure. Fish depth is annotated as DF with the actual depth value given (4343 m in this case). Also, at the top of the figure are critical tow parameters. They include; tow speed (1.22 knots); array tilt (6°); delta depth between DF and D9 (127 m); depth rate of change (0 m/min); and array tension (245 pounds). The dip at D6 was caused by array low fill oil. For the conditions typified by Figure 6 the tow noise was a nominal 65 dB (//1 $\mu Pa/\sqrt{Hz}$) over the operating frequency band.

Figure 7 is an unprocessed reflection field trace for a single array group offset 297 m from the source. This type trace is monitored in the field for quality control. The FM slide source waveform was used for this data section. The apparent bottom slope results from a slight change in system tow depth during the two and one-half hours required for the 5.7 km long profile. Static corrections are necessary to correct for this type change.

The seismic data acquired during this engineering evaluation test is being used to complete the geophysical processing software. A short data section has been processed using DISCO, a standard processing package used principally by the oil exploration community.

A processed data section using this package is presented in Figure 8. This is a short section from the same location as the field trace (Fig. 7). An 11-fold CDP stacked section was generated. A match filter routine was used to collapse the FM slide source signature. No static corrections were made for this section. Although this processed section is only preliminary, it does show the potential of the deep-towed system. In particular, the discontinuity of beds at 0.3 seconds would be difficult to detect with a conventional surface-towed system.

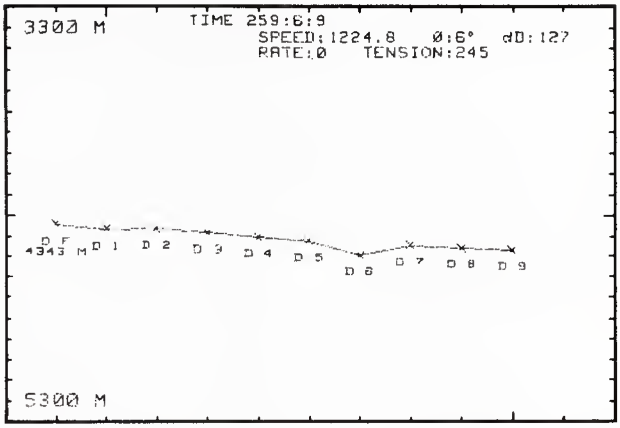

Figure 6. Array shape pictorial generated during field test by real-time display system.

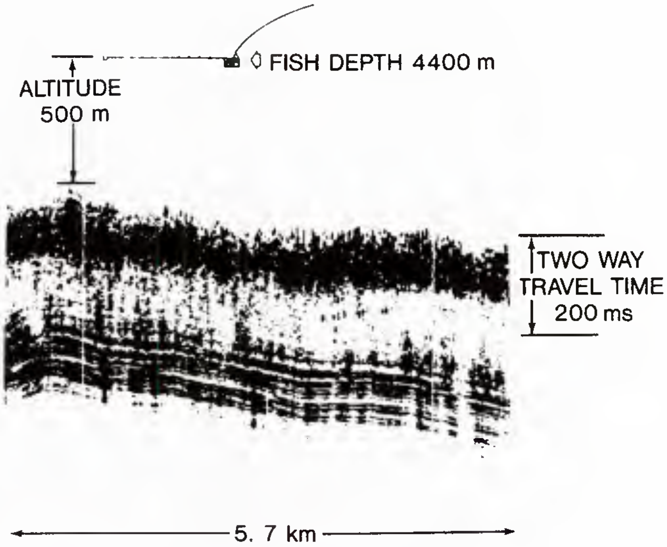

Figure 7. Single channel reflection field trace obtained at a 4400-m system tow depth.

The present effort focuses on optimizing this standard processing software for the deep-tow data set. Areas of concentration include: static corrections using array depth sensors and moveouts measured for the source to sea-surface to array reflection path; deconvolution techniques to optimize source signature collapse; and interval velocity measurement routines for the high-resolution data set.

Summary

A new capability for deep-ocean acoustic measurements is available with the Deep-Towed Array Geophysical

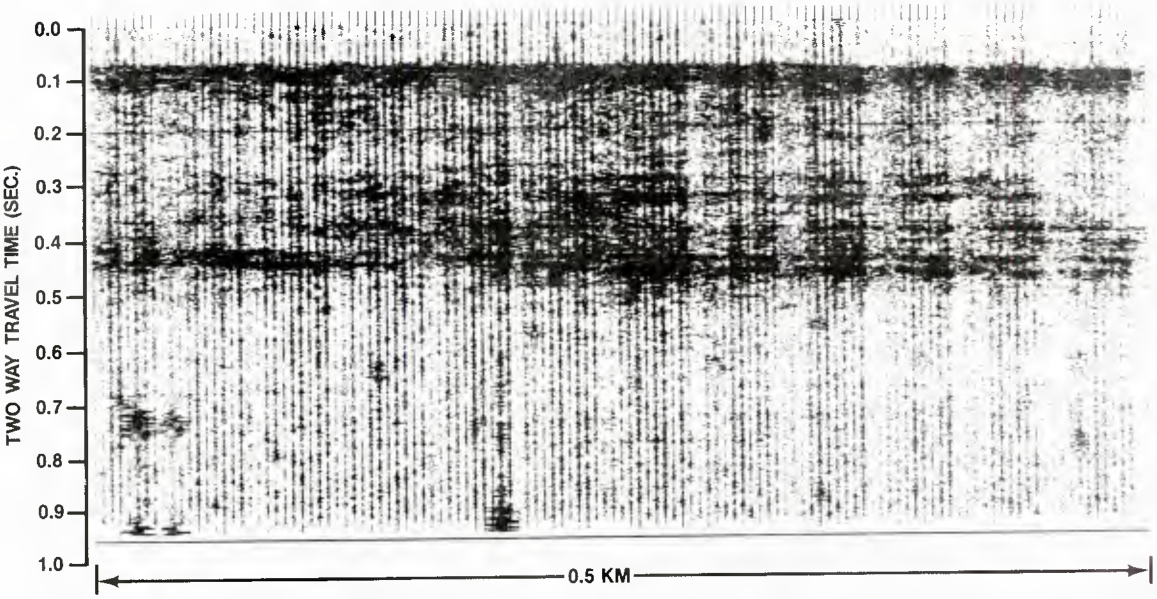

Figure 8. An 11-fold CDP stacked section of deep-tow data acquired at a tow depth of 4200 m.

System. The unique hardware suite provides the ability to extract high-resolution geoacoustic parameters. The deep-towed sound source and array and the ancillary support systems have been developed and tested over the past four years. The final field engineering evaluation test successfully operated the total system to a tow depth of 4500 m. The geophysical data acquired during the test is being used to optimize processing software for the deep-towed application.

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