BIOMAPER-II: An Integrated Instrument Platform for Coupled Biological and Physical Measurements in Coastal and Oceanic Regimes

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Abstract—**The BIo-Optical Multi-frequency Acoustical and Physical Environmental Recorder or BIOMAPER-II is a newly developed towed system capable of conducting quantitative surveys of the spatial distribution of coastal and oceanic plankton/nekton, near surface bubble fields, and turbulence, as well as field verification studies of theoretical plankton reverberation models. The system consists of a multi-frequency sonar (up-looking and down-looking pairs of transducers operating at five frequencies: 43, 120, 200, 420, and 1000 kHz), a video plankton recorder system (VPR), an environmental sensor system (CTD, fluorometer, transmissometer), and several other bio-optical sensors (down- and upwelling spectral radiometers, spectral attenuation, and backscattering, and absorption meters). The lower four acoustical frequencies utilize split beam technology and are able to make target strength and echo integration measurements. Also included are an electro-optic tow cable, a winch with slip rings, and a van which holds the electronic equipment for real-time data processing and analysis. The vehicle is capable of operating to a depth of 300 m at 4–6 kn, while near the surface it may be towed at speeds up to 10 kn. The system can be operated in a surface-towed down-looking mode, in a vertical oscillatory "tow-yo" mode, or in a subsurface up/down-looking horizontal mode. To enhance the performance and utility of BIOMAPER-II in high sea states, a winch, slack tensioner, and over-boarding J-frame assembly are integrated with the system for deployment and handling. Wire tension records and the power spectra demonstrated the substantial protection that the slack tensioner system provided against excessive shock loading of the cable and the vehicle in sea states that would otherwise prevent work. The scientific capability of the vehicle is illustrated with acoustic, environmental, and bio-optical data sets collected from the Gulf of Maine on cruises in 1997 and 1999.**

Index Terms—**Bioacoustics, echo integration, nekton, target strength, towed body, video, zooplankton.**

I. INTRODUCTION

UNDERSTANDING the dynamics of marine planktonic populations requires a knowledge of their spatial and temporal distribution and abundance, and their birth, death, advective loss/gain, and growth rates. These fundamental properties are determined through complex interactions and couplings with both the physical and the biological elements in which a species occurs [1]. The vast dimensions of the oceanic realm and the limited nature of traditional sampling systems (nets, pumps, and other discrete sampling systems) have severely limited the spatial and temporal scope of most sampling programs, so that small- to large-scale distributions of plankton are inadequately known for most ocean areas. This is a widely recognized problem and a number of groups of investigators have been working to develop a variety of new sensors to extend the biological sampling capabilities of traditional systems.

Acoustical and optical imaging systems are the most capable *in situ* remote sensing technologies currently available and are essential for observing the dynamical physical and biological processes at work in the ocean's interior. A principal objective is to make rapid high-resolution measurements of the abundance, biomass, size structure, and taxonomic composition of plankton, seston, and nekton over scales from centimeters to hundreds of kilometers [2]–[6]. A companion objective is to produce high-resolution data suites that contain unique information about the physical and biological environmental structure of the water column that will aid in interpreting the relationship between the biological distributions and environmental structure in both shallow water and deep ocean areas.

In order for acoustical systems to be usefully applied to the biological aspects of this problem, the spatial and temporal variability of the backscattering must be related to the variability of the distribution of biological sound scatterers. This relationship involves the long standing problem of identifying and quantifying sources of acoustic scattering in the ocean. There are a variety of scatterers in the ocean including marine organisms, bubbles, turbulence, and suspended sediment [7]. Description of the scattering physics associated with these objects is quite complex and remains a challenge [8]–[13]. Another challenge involves resolving the ambiguities in the acoustic scattering data due to similar scattering levels from different scatterers or types of scatterers.

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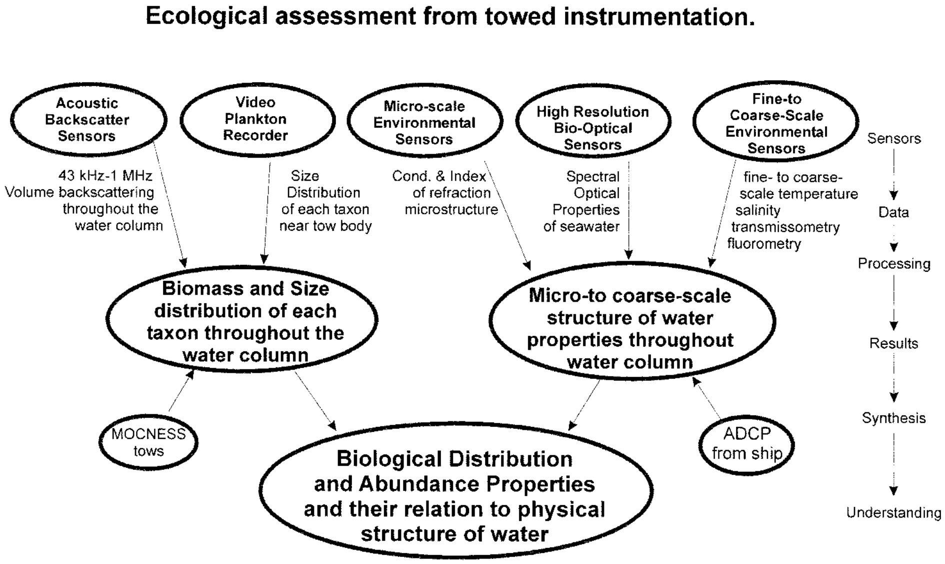

Fig. 1. The integrated collection of acoustic, optical, and environmental data, and the processing and analysis needed to develop an understanding of the coupling between animal distributions and their environment (modified from [7]).

There are various approaches toward reducing the ambiguities in the acoustic data. One approach includes the coupled use of acoustic and optical systems. By integrating these two types of sensors, the optical data can be used to "ground truth" the acoustic data. It is important that the sensors be co-located. A second approach employs multifrequency acoustic sensors. Through the use of multiple acoustic frequencies, there are in essence, more channels of acoustic information. Since the acoustic scattering properties of finite objects are a function of frequency and those functional dependencies vary between types of scatterers, it is advantageous for the acoustic system to span a substantial range in frequencies. Finally, the simultaneous collection of hydrographic and other bio-optical data provides essential information about the environment to interpret the patterns of distribution and abundance produced by the acoustic/optical system (Fig. 1). In addition, in the cases where the physical properties of the water, such as turbulence, also scatter sound, these data can help identify the sources of scattering and further reduce the ambiguities.

One approach toward simultaneous collection of a diverse set of data involves use of a tethered sensor system. Tethered sensor systems are part of a broad class of systems that have very powerful capabilities for sampling various aspects of the ocean. The tether can serve to deploy the system, provide electrical power, and allow data transfer between the ship and vehicle. The cable may contain both electrical conductors for powering the vehicle's sensors as well as optical fibers for high-speed two-way data communication. Because of the typically high strength of the tow cable, high-power delivery ability of the conductors, and high data rate capabilities of optical fibers, tethered sensor systems can have a diverse suite of sensors permitting dense sampling of a correspondingly diverse array of quantities. The potentially large number of sensors and high data rate capability of the system permits the data sets from the various sensors to be co-located—a very desirable scenario.

The objective of this paper is to describe a tethered sensor system for the simultaneous collection of acoustical, optical, and various environmental properties of the ocean. This system, the BIo-Optical Multi-frequency Acoustical and Physical Environmental Recorder (BIOMAPER-II) is a sophisticated towed survey system developed specifically to conduct high-speed, large-area surveys of zooplankton and environmental property distributions. The system represents an advancement through the integration of the acoustic, optical, and environmental sensors. In addition to allowing all data to be co-located, the integration permits ground truthing of the acoustic data so that the sources of sound scattering can be identified, quantified, and differentiated. This platform can help solve some of the long standing issues of identifying sources of scattering in the ocean.

In addition to the description of the vehicle, we also present details of the associated handling/motion-compensation system that permits use of BIOMAPER-II to survey zooplankton and environmental variables in high sea conditions. A suite of data collected by BIOMAPER-II is used to illustrate the use of the system as a survey tool.

II. DESCRIPTION OF THE SYSTEM

The BIOMAPER-II system consists of three main subassemblies: 1) the vehicle; 2) the control van; and 3) the tow cable, winch, and tow frame/handling system (Figs. 2–8). BIOMAPER-II is a significant extension over an early prototype, BIOMAPER, which consisted only of a vehicle, tow cable, smaller winch, and a small subset of the sensors described below [7]. The primary vehicle sensors of BIOMAPER-II are the Acoustic Backscatter Sonar System (ABSS), Video Plankton Recorder (VPR), and the Environmental Sensor System (ESS). The ABSS was built by Hydroacoustics Technology Inc., Seattle, WA (HTI) and the VPR and ESS were supplied by SeaScan Inc., Falmouth, MA. Integration of the diverse complementary sensors allows realization of the goal of complete ecological assessment (Fig. 1). The entire system is self-contained, so that it may be operated off of ships of

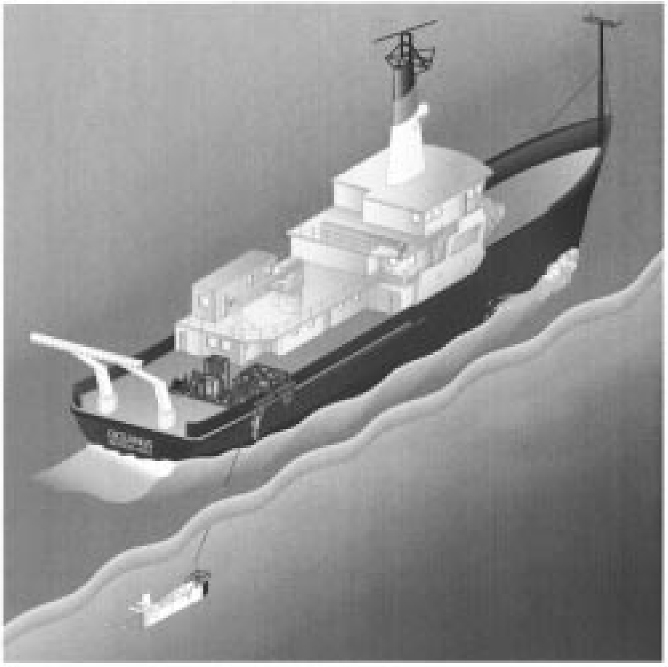

Fig. 2. Conceptual drawing of the BIOMAPER-II vehicle integrated with a tow cable, winch/handling system, control van, and ship.

opportunity, with electrical power being the only ship-supplied requirement. All data acquisition and processing surface consoles are installed in the BIOMAPER-II Control Van.

The overall design philosophy of the system is to provide for a moderate cost assembly with high reliability and ease of maintenance and modification at sea. This philosophy was realized through the use of many commercially available components.

A. The Vehicle

The structure of the BIOMAPER-II tow body is similar to that of the proto-type BIOMAPER [7]. The vehicle is a free-flooded open-frame architecture with an outer skin in the form of easily removable flat plastic panels (Fig. 3). It weighs approximately 2000 lb in air and 1200 lb in water, has a length of 3.78 m, a height of 0.85 m for the main framework, a height of 1.19 m to the top of the VPR framework, and an overall height of 2.0 m to the top of the towing bail. The body is 0.55 m wide at the nose (not including the side rails which add 0.22 m overall) and is 0.27 m wide at 0.6 m in front of the tail. The frame is made of welded aluminum angles in an open box-type shape that allows for simple installation of and access to instruments and wiring. For pitch stability, most of the dead-weight is located near the bottom of the vehicle just forward of the towing bail. A shock mount is installed in front of the vehicle for protection during launch and recovery. In addition, 19-mm stainless steel round stock was used to form side rails that act as side fenders and provide access points for handling lines.

The frame (Fig. 3) has four "bays" which are described as follows.

1) Nose Bay#1: Located at the very front of the vehicle is a fiber glass shell with aluminum reinforcing struts that is hinged on one side to the main body of the vehicle and bolted on the other. Unbolting the shell allows it to swing forward providing access to the nose itself, and to the forward end of Bay #2 where all the ABSS and telemetry connectors are located.

2) Bay #2: Located between the nose and the tow point, this is where the large electronics bottles and the oil-filled junction-box(s) are located.

a) Telemetry/power bottle : This aluminum pressure case contains all the dc/dc converters for generating the various system power supplies from the dc tether voltage. The dc tether voltage is 300 V dc, with no load, and will drop to 200 V dc with a maximum load of 2 kw in the vehicle (based on 1 km of 0.68-in Rochester cable). At this time, the load is less than 500 W, thus there is a good reserve of power available for future additions to the sensor load.

The telemetry/power pressure case also contains the video and data telemetry interfaces to the fiber-optic tow cable. Two channels of video are supported using the Force, Inc. model 2768T fiber-optic video modulators; two cameras are currently being used in the Antarctic surveys.

Data telemetry is ethernet only via a TC Communications model TC3100 ethernet single mode fiber optic transceiver. This converts ethernet onto two optical fibers operating at 1300 nm wavelength for uplink and 1550 nm wavelength for downlink. This allows both directions of ethernet to be mixed onto a single fiber with wave division multiplexing. A twisted pair MAU (media adapter unit) with four or eight ports is attached to the fiber-optic transceiver. This allows multiple ethernet devices in the vehicle to share the network. At this time there are four ethernet devices: the ABSS, the vehicle control computer (a PC-104 computer stack in the telemetry/power bottle), and two bio-optical acquisition systems. The vehicle control computer provides control I/O for various vehicle functions such as power switches, voltage and current monitors, ground fault detection, and water leak detectors. In addition, it serves as a pass-through for the serial interface for the ESS system. A Serial Ascii Interface Loop (SAIL) to RS-232 converter is included for the ESS interface. The power/telemetry bottle also contains a Lantronix Micro Serial Server (model MSS100). This server allows any serial device to be connected to the TCP/IP network. Microsoft Windows-based software on a shipboard computer redirects a local serial port to the remote MSS100 enabling normal serial communication with the underwater sensor.

b) ABSS electronics bottle: The ABSS electronics are housed in a large titanium pressure case of approximately 40.6 cm (16 in) OD by 50.8 cm (20 in) long. The ABSS consists of the acoustic transducer transmit and receive electronics for up to six frequency channels, and the case provides bulkhead connectors on its front end cap for two transducers per channel. There is also a power/data connector for control in, data out, power in, external trigger in, and sea water switch leads. An oil-filled cable and connector mates to the power/data connector, and routes to the oil-filled junction-box through a hose barb (this is an XSL type connector for oil-filled applications). All the transducer cables go directly to their respective transducers. This connector end-cap is immediately accessible by simply opening the vehicle nose cone. Two probes are mounted on the front top of Bay#2 as penetrators to sense submergence in sea water. This is a safety interlock to prevent the ABSS from transmitting in air.

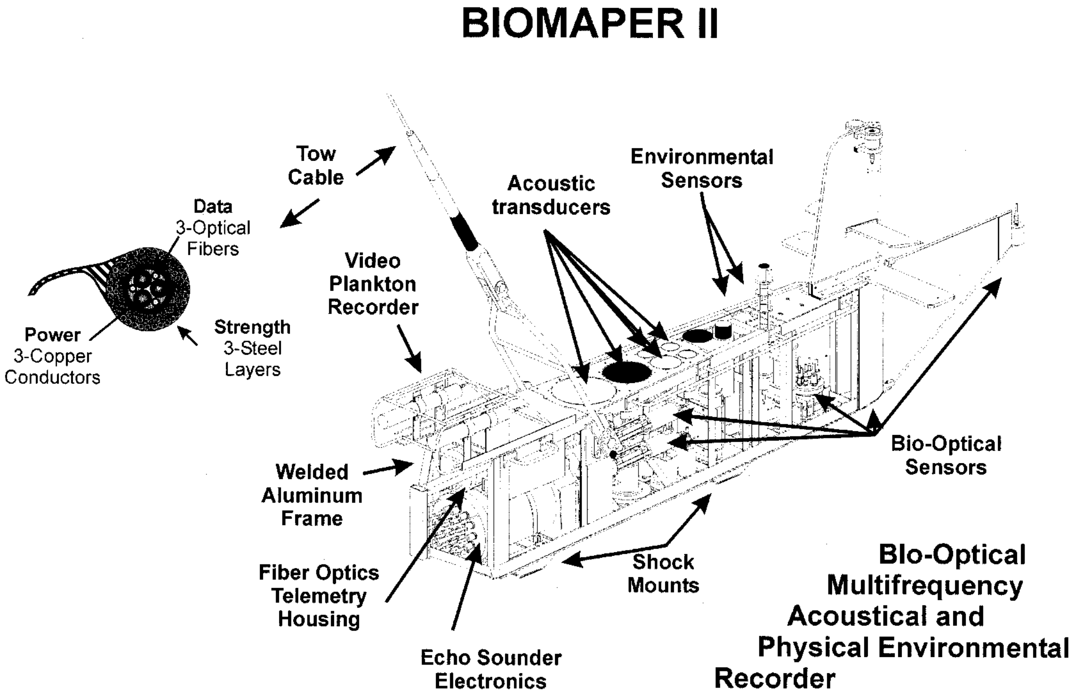

Fig. 3. Schematic drawing of BIOMAPER-II with the skins removed. Nose bay #1 not showing. A schematic drawing also illustrates the cross-sectional structure of the BIOMAPER-II tow cable.

c) Oil-filled junction box: There is a single shallow oil-filled box located on the side of this bay, with an aluminum cover. Power comes in through the tether as dc, and routes directly to the telemetry/power bottle for distribution. This junction box consists of terminal strips for the tether and for all of the frame wiring between the telemetry/power bottle and the sensor systems. It also contains three ST type fiber-optic couplers mounted on a bulkhead inside the box to allow for easy attachment and removal of the tether. From the junction-box, there are three discrete D. G. O'Brien (DGO) "steelite" pigtail connectors which mate to three DGO single-mode fiber-optic bulkhead connectors on the telemetry/power bottle front end-cap. A compensation bladder is mounted below the box in Bay#3 on a quick disconnect oil fitting to provide pressure compensation to the oil-filled system, and to act as a sump for water to fall into in the event that there is a leak in the box cover or stuffing glands. An oil-filled hose routes from the box to a multi-pin connector to plug into the telemetry/power bottle.

d) VPR hardware: The cameras and strobe are mounted above the top surface of Bay #2 in front of the towing bail, so that the video images are taken in undisturbed water. The cameras and strobe housings are attached to a framework, made from a solid stainless steel rod that protects these parts during launch and recovery without disturbing the water in the field of view of the VPR camera. VPR video signals route through the oil-filled junction-box to the telemetry/power bottle. Power and control command interfaces come from the ESS system in Bay #3.

3) Bay #3: Located in the center of the vehicle between the tow point and the tail are all of the ABSS transducers except one. There are ten transducers, five looking up and five looking down. The frequencies used are 43, 120, 200, 420, and 1000 kHz. The down-looking transducers are arranged with the 43 kHz at the forward end of the bay, followed by the 120 kHz, then the remaining three at the aft end of the bay. The up-looking ones are arranged so that the 120 (located in Bay#4) and 43 kHz transducers are furthest aft and the higher frequencies are forward. All cables are routed forward to the ABSS electronics bottle connector end cap. The ESS electronic bottles, a 12.5 kHz transponder, and the ac-9 optical sensors (see description below) are also mounted in Bay#3.

4) Bay #4: This is the aft-most bay, and includes the tapered section at the tail. This bay serves as the location for all of the ESS sensors. The ESS system connects to the telemetry bottle for power and SAIL connections. The SAIL interface is converted to RS-232 and fed into the telemetry PC-104 computer for transmission to the surface over the ethernet. Since the VPR electronics in Bay#4 is essentially an ESS module, cables route from this bay to the hardware mounted above Bay #2 for the VPR power and data control link. The HydroScat-6 optical backscattering sensor is also mounted down-looking in this bay. Spectral radiometers are mounted on top of the tail fin over Bay#4 (downwelling irradiance) and on an aluminum frame extending aft from the end of the vehicle (upwelling radiance).

5) Vehicle Deployment Modes: A versatile winch allows the system to be towed in several modes: fixed depth, tow-yo, or a hybrid of the two (Fig. 4). Certainly the simplest and most common mode of deployment is the one involving fixed depths. In this mode, the direct sampling devices, such as the optical sensors, are only sampling at a constant depth while the acoustical sensors are sensing the water at depths above and below the vehicle extending for the two lower acoustic frequencies out 200 m. For cases in which direct sampling of the entire water column is desired as well as sampling with the shorter range higher frequency acoustic transducers, tow-yoing is performed. Here, the depth of the vehicle is constantly changed (either positively or negatively) so that the system undulates up and down

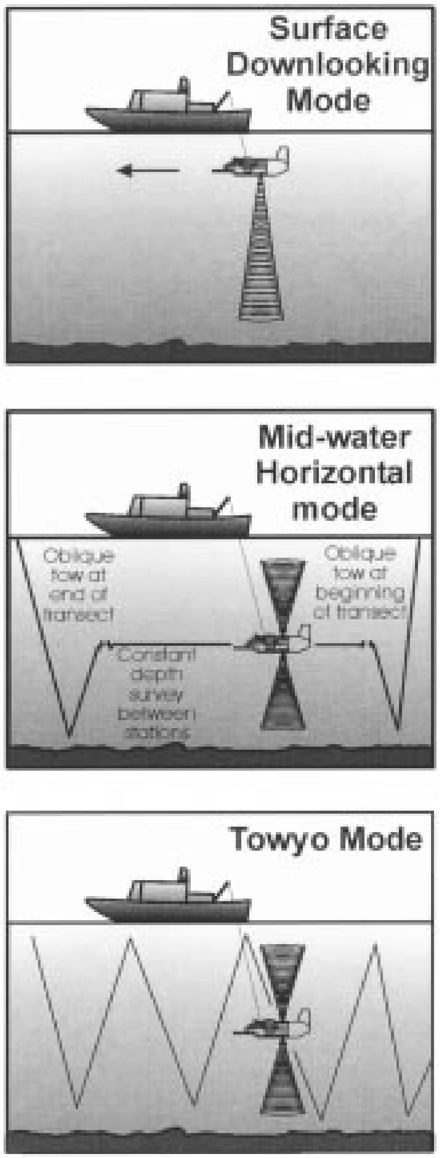

Fig. 4. Schematic drawing of vehicle deployment modes.

throughout the desired portion of the water column. Although it may be desired to tow-yo constantly, there may be practical limitations imposed by highly irregular bathymetry, high sea states, or surface ice fields. In that case, a hybrid approach may be used where most of the transect is performed at constant depth and a small subset of the transect involves an undulating path.

B. The Sensor Systems

The vehicle contains a wide range of acoustical, optical, and environmental sensors.

1) The Acoustic Backscattering Sonar System (ABSS): The high-frequency acoustics system in BIOMAPER-II is housed in a titanium pressure vessel containing most of the electronics and a combination of distributed and centralized processing units. The underwater housing contains all of the signal processing hardware associated with the Acoustic Backscattering Sonar System (ABSS). A large end cap contains an array of 12 transducer connectors. Inside, these connections are routed to a multiplexor board that selects which of the (up to) 12 transducers is to be currently active. The multiplexor connects the active transducer to one of six dedicated frequency receiver channels. Four of the receiver channels are dedicated to split-beam transducers, and the last two channels are for high-frequency (1 MHz and an optional 2 MHz), single-beam transducers. Each receiver board includes a multi-channel time varying gain (TVG), bandpass filtering, quadrature demodulation, and 12-bit analog-to-digital (A/D) conversion of the baseband signal. Once the signal has been digitized, all further filtering and echo processing is performed by distributed digital signal processors (DSPs) for such functions as matched filtering, echo-integration, target detection, and target tracking. There are two transmitter boards required, one to cover the low-frequency range of 43–200 kHz and a second to cover the high-frequency range of 420 kHz–2 MHz. The transmit signal is routed through the multiplexor board to the selected transducer connector. A local PC-104 micro-computer formats the acquired data for transmission to the surface, and also receives commands and new firmware downloads from the surface console, via a 10 Base-T ethernet connection.

Both the transmitter and receiver processing are under DSP control. The standard firmware and control software includes operator selection of frequency, pulse length, and chirp options, allowing the user to take full advantage of the available transducer bandwidth to improve the signal-to-noise ratio (SNR) at the receiver output. The ABSS has a maximum of 1440 depth bins that can be allocated amongst the 10 transducers for each duty cycle. Currently there are 800 allocated for the 43- and 120-kHz frequencies (each transducer has 200 depth bins), 300 allocated for the 200-kHz frequency (150 depth bins for each transducer), 200 for the 420 kHz frequency (100 depth bins for each transducer), and 70 for the 1000-kHz frequency (35 depth bins for each transducer). In the Gulf of Maine surveys, all depth bins were 1 m, but for work in the Antarctic, the 43- and 120-kHz depth bins were 1.5 m.

The surface control console, a Pentium-based PC running HTI system control and processing software, is connected onto the ethernet communications link to the subsea vehicle, allowing it to send commands and receive data from the ABSS. A Microsoft Windows-based program allows full control of multiplexor sequencing and ping rates, as well as providing multi-window color displays for echo-integration data, target tracking, and target-strength statistics. Data may be logged locally to the PC hard drive or remotely to another network drive for global access.

Calibration of the acoustic system has been done periodically by HTI, Inc., at their test facility in Seattle, WA (Table I). Standard target calibration spheres have also been used before or after a cruise as a check on the facility calibration [14]).

2) The Environmental Sensing System (ESS): The ESS consists of temperature and conductivity sensors (SeaBird, Inc.), a SeaBird pump, a fluorometer (WetLabs, Inc.), a transmissometer (SeaTech, Inc.), and a downwelling irradiance sensor. The conductivity, temperature, fluorometer, and pump are connected in series with tygon tubing and the pump draws water past these sensors. Data are gathered on the SAIL at selectable speeds ranging from 0.25 to 4 Hz. The surface control console is a PC running a Microsoft Visual Basic system control and processing software program.

TABLE I
THE HTI MODEL 344 ECHO-SOUNDER CHARACTERISTICS AND CALIBRATION DATA USED IN THIS STUDY. THE SYSTEM WAS OPERATED ON ALL FIVE FREQUENCIES WITH TEN CHANNELS

Frequency (kHz)	-3dB Transducer Nominal Beamwidth (degrees)	Maximum Transmit Power Source Level (dB)*	Receive Sensitivity (dB)†
Down-Looking Transducers			
43	6	224.32	-132.91
120	3	229.44	-141.97
200	3	227.53	-149.35
420	3	222.12	-148.69
1000	3	217.9	-161.65
Up-Looking Transducers			
43	6	223.07	-133.18
120	3	226.94	-146.4
200	3	227.22	-149.25
420	3	221.5	-149.01
1000	3	217.9	-164.07

* re: 1µPa at 1 m

† re: 1V/µPa

3) The Video Plankton Recorder (VPR): The VPR (Sea Scan, Inc.) is a high-resolution video camera imaging system designed to unobtrusively quantify the distribution and abundance of zooplankton and bubbles encountered along the tow path at 60 fields per second [15]. The VPR has an adjustable viewing volume that is currently set to approximately 6 cm^3. Illumination is provided by a collimated 80-W xenon strobe which incorporates a parabolic reflector. Dark-field illumination is provided by the oblique angle between the camera and strobe. The high resolution of the camera (570 horizontal × 485 vertical TV lines) and short (≈ 1 μs) pulse duration of the strobe permits detailed imagery of target organisms moving in relation to the camera. The resolution of the images depends on the dimension of the field of view, water clarity, and the optical properties of the targets, however, given typical pixel dimensions of 30 μm, the system is capable of resolving objects down to 75–100 μm. The video data are transmitted to a VCR and recorded on SVHS tape for postprocessing on most cruises, although real-time processing has been done recently [16].

4) Other Bio-Optical Sensors: The other bio-optical sensors include two ac-9 dual-path spectral absorption and attenuation meters (WetLabs, Inc.), a spectral downwelling irradiance sensor (OCI-200 series, Satlantic, Inc.), a spectral upwelling radiance sensor (OCR-200 series, Satlantic, Inc.), and more recently a HydroScat-6 optical backscattering sensor (HobiLabs, Inc.). One of the ac-9s measures whole-water properties and the other, configured with an in-line 0.2-μm water filter, measures absorption by dissolved material. The instruments are configured with matching wavelength bands selected to cover the visible spectrum and to reflect those on the SeaWiFS ocean color sensor [ac-9s: 412, 440, 488, 510, 532, 555, 650, 676, 715 nm; radiometers: 412, 443, 490, 510, 555, 665, 683 nm]. The data acquisition system for the ac-9s and radiometers is based on a subsurface PC-104 and includes two serial ports, a 16-channel/16-bit A/D converter, an 8-MB flash disk, and an ethernet adapter for communication with the BIOMAPER-II Lantastic network. Data files are logged on a desktop PC aboard the ship. The RS232 serial data stream from the HydroScat-6 is collected on a separate shipboard PC via the Lantronix Micro Serial Server in the power/telemetry bottle.

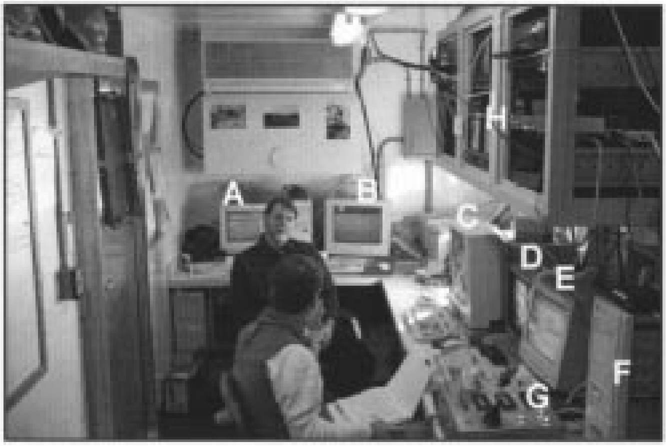

Fig. 5. Interior of the control van during a BIOMAPER-II survey in the Gulf of Maine—Peter Wiebe (facing camera) and Charles Greene. (A) BIOMAPER-II engineering status computer display. (B) Post-processing computer display. (C) Digital echo sounder display. (D) Deck camera display. (E) Environmental sensor computer display. (F) VPR processing computer. (G) Moveable winch controller box. (H) Instrument rack.

C. *The Control Van*

The BIOMAPER control van is a 8 × 20 ft ISO container finished off on the inside as a lab (Fig. 5). The van has seating for five individuals and computers for six operations: ABSS data acquisition, ABSS processing, ESS acquisition, bio-optical data acquisition, VPR processing, and hardware monitoring (Fig. 6). In the center is a set of 19-in rack mounting rails, hung from the ceiling on shock isolators. The rack has three adjacent bays, having an inside height of 21 in. The 19-in rack holds the BIOMAPER dc power supply, which is an Electronic Measurements, Inc. EMS300-8-2-D. Also, the 19-in rack holds two color monitors which display the output from two deck cameras used to observe the winch and the launch and recovery and tether angle for the towed body. The rack also holds a VCR and a time code generator for the VCR and an output strip for a 12-channel Rockwell Zodiac Global Positioning System (GPS) receiver. Under counter platforms are provided for four mini tower PC chassis and at both ends of the bench is a set of tool and storage drawers. A Sanyo air conditioner/heat pump is mounted at the far end in a recessed box for both cooling and heating.

Power for the Van is 440–480 VAC, single phase. A 10-KVA step-down transformer provides 220 V single phase with a neutral to the circuit breaker panel.

D. *The Tow Cable*

A steel armored tether made of 1000 m of the standard 1.73 cm (0.68 in) OD cable (Rochester, Inc.) is spooled on the winch. Its specifications are: outer armor—36 wires galvanized extra improved plow steel (GEIPS), middle

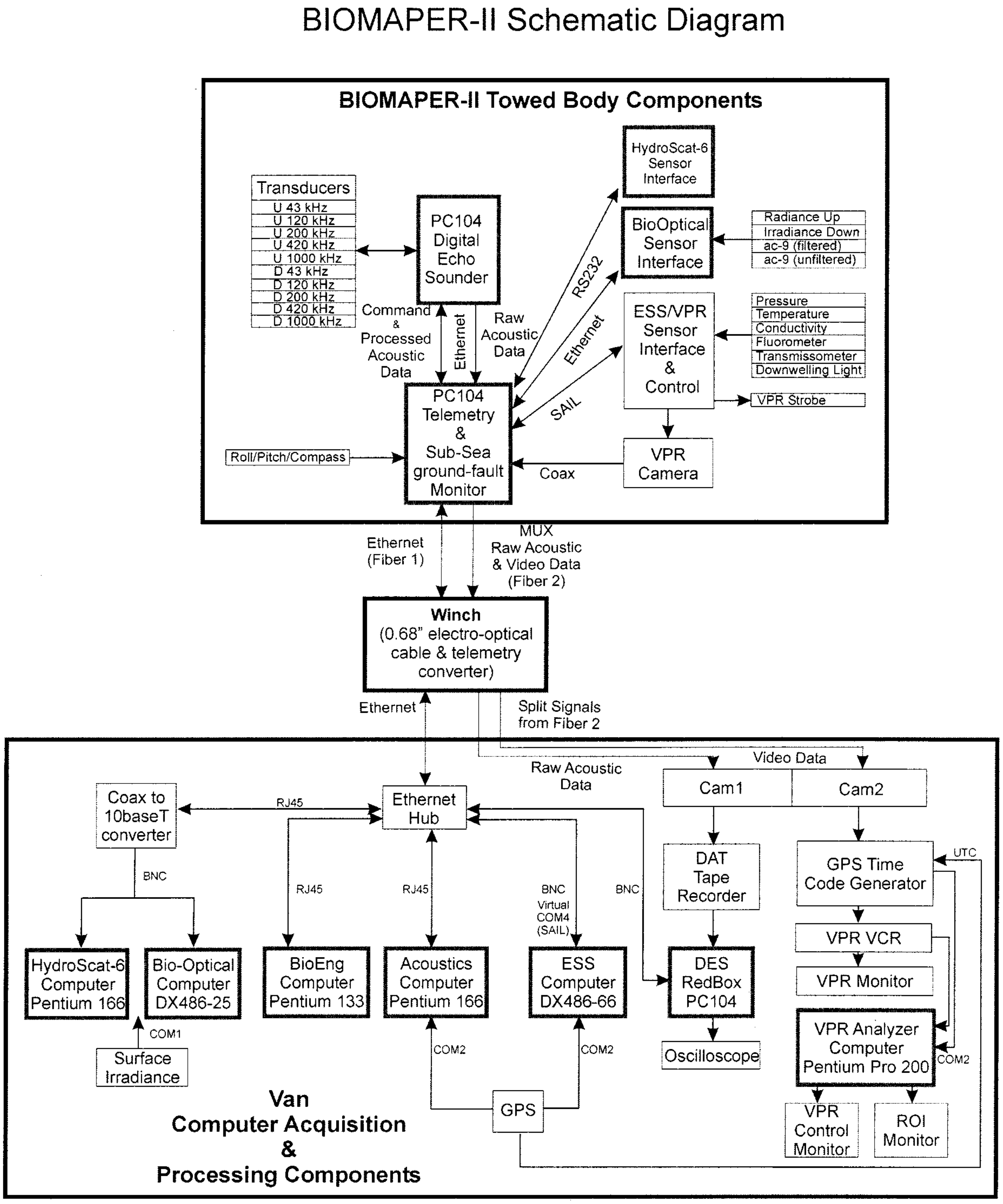

Fig. 6. Schematic drawing of the BIOMAPER-II sensor systems and the control van's computer data acquisition and processing layout.

35 wires (GEIPS), and inner 35 wires (GEIPS); weight in air—1114 kg/km; weight in water—906.7 kg/km; specific gravity (seawater)—5.6; temperature range −30 deg. C to +80 deg. C; breaking strength—46 000 lbf; working load @ 3% strain—10 000 lbf. The tow cable contains three single mode optical fibers and three copper power conductors (Fig. 3) and is known for its superior strength and very good performance and power transmission capability. One fiber (using two wavelengths) carries multiplexed data and the other video. The third fiber is currently unused and serves as a spare. A cable termination, matched to meet the strengths of the towing cable and the vehicle's towing bail was designed and built at WHOI, is a poured fitting using Cerrobend, a low-melting-point metal alloy.

E. The Winch and Handling System

During the first three cruises, the BIOMAPER-II winch was a single entity that included an outside control console, with the capability of adding a remote control interface in the control

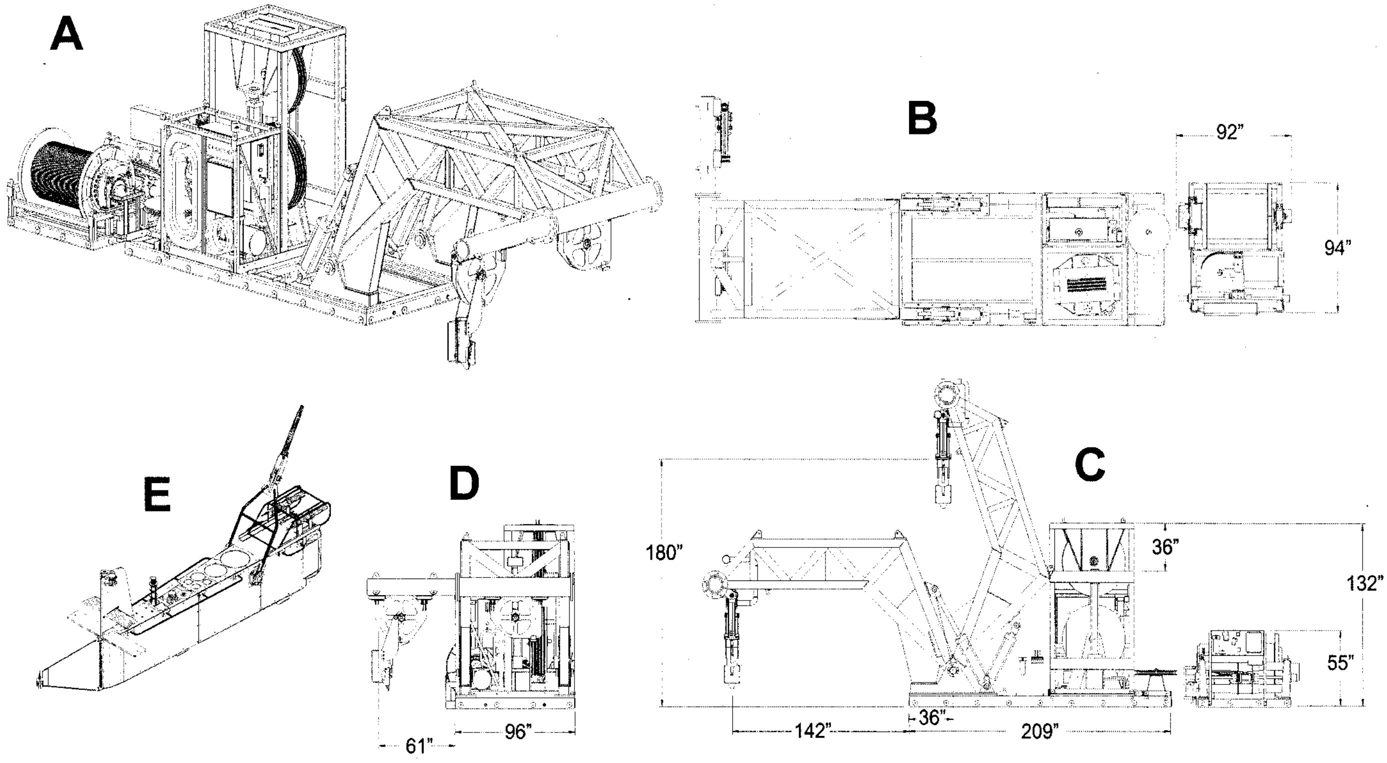

Fig. 7. Schematic drawing of the Dynacon BIOMAPER-II winch, slack tensioner, and deck handling system. (A) A 3-D view. (B) Top view. (C) Side view showing both the inboard (up) and outboard (down) positions of the J-frame. (D) end view. (E) BIOMAPER-II in approximate position for towing.

van. The electro-optic tether core terminated in a rotating junction-box in the drum core. This junction-box contained the following modules: TC3100 AUI to fiber optic transceiver, AUI to twisted pair MAU, two WDM's, and two Force 2768R-O-BFST fiber optic video receivers. These are all small, flat modules, which packed into the rotating junction-box and removed the need to have a fiber-optic slip ring. A deck cable consisted of 2 coaxial wires and a 12-V power supply pair routed from the slip ring junction-box to the control van. These coaxial wires were: an ethernet and one video channel. The slip ring (Focal Technologies) had three power rings @ 480 V, 20 amps, two small signal coaxial rings, and four twisted pair rings. This arrangement provided for one spare power, one spare coax, and two spare twisted pair rings.

Since October 1999, there have been four BIOMAPER-II cruises which have deployed, towed, and recovered BIOMAPER-II using a unique self-contained handling system built by Dynacon, Inc specifically for BIOMAPER-II (Fig. 7). It is powered and controlled electrically, and driven hydraulically.

The system consists of a winch and electro-optical cable, slack tensioner, J-frame/docking mechanism, power pack/hydraulic system, and local and remote controls. The J-frame, slack tensioner, and power pack are all mounted on a single structural steel tubing platform with a base of 2.4 m (8 ft) by 5.3 m (17.5 ft).

The stand-alone hydraulically driven drum winch has a core diameter of 0.8 m (32 in), a core width of 1.2 m (48 in), and a flange diameter of 1.2 m (48 in) [Fig. 8(A)]. It has a bolt-on drum liner (Liebus grooving) grooved for 17.3 mm (0.68 in) electro-optical cable. The winch is designed to hold 1500 m of this cable. The drum shaft is hollow to accommodate slip rings and a water proof junction-box is mounted externally within the confines of the drum flange metal structural supports. The winch gearbox has a hydraulically released failsafe brake and there is additionally, a hydraulically actuated caliper disk brake installed on the drum assembly.

The level-wind assembly is a separate unit that bolts onto the front of the winch base support. Wire leads off the winch drum and into a level-wind sheave/carriage assembly which is driven by an ACME screw. The sheave is equipped with sensors to measure wire tension, line speed, and line count. Wire coming out of the level-wind sheave goes to a horizontal turning sheave where it is led into fixed input sheave of the slack tensioner.

The structural steel tubing framework for the slack tensioner has a rectangular base 1.7 m (67 in) by 1.4 m (56 in) and a height of 3.2 m (125 in) [Fig. 8(C)]. Within the frame are seven 1.2–m (48 in) diameter polyamide sheaves with four sheaves mounted in a fixed position at the bottom and three sheaves positioned above them on a vertical-traveling carriage assembly. Two 1.2-m (48 in) stroke hydraulic cylinders, secured to the rigid base and the carriage, drive the top three sheaves in response to the motion of the ship. The hydraulic cylinders are connected to two piston style accumulators. Cable tension is controlled by hydraulic oil movement between the cylinders and nitrogen charged accumulators. The slack tensioner can take up 7.3 m (20 ft) of cable.

The J-frame is also constructed of structural steel tubing and has dimensions of length 5.1 m (200 in), width 2.2 m (87 in), and height (when in the lowered overboard position) 2.9 m (113 in)

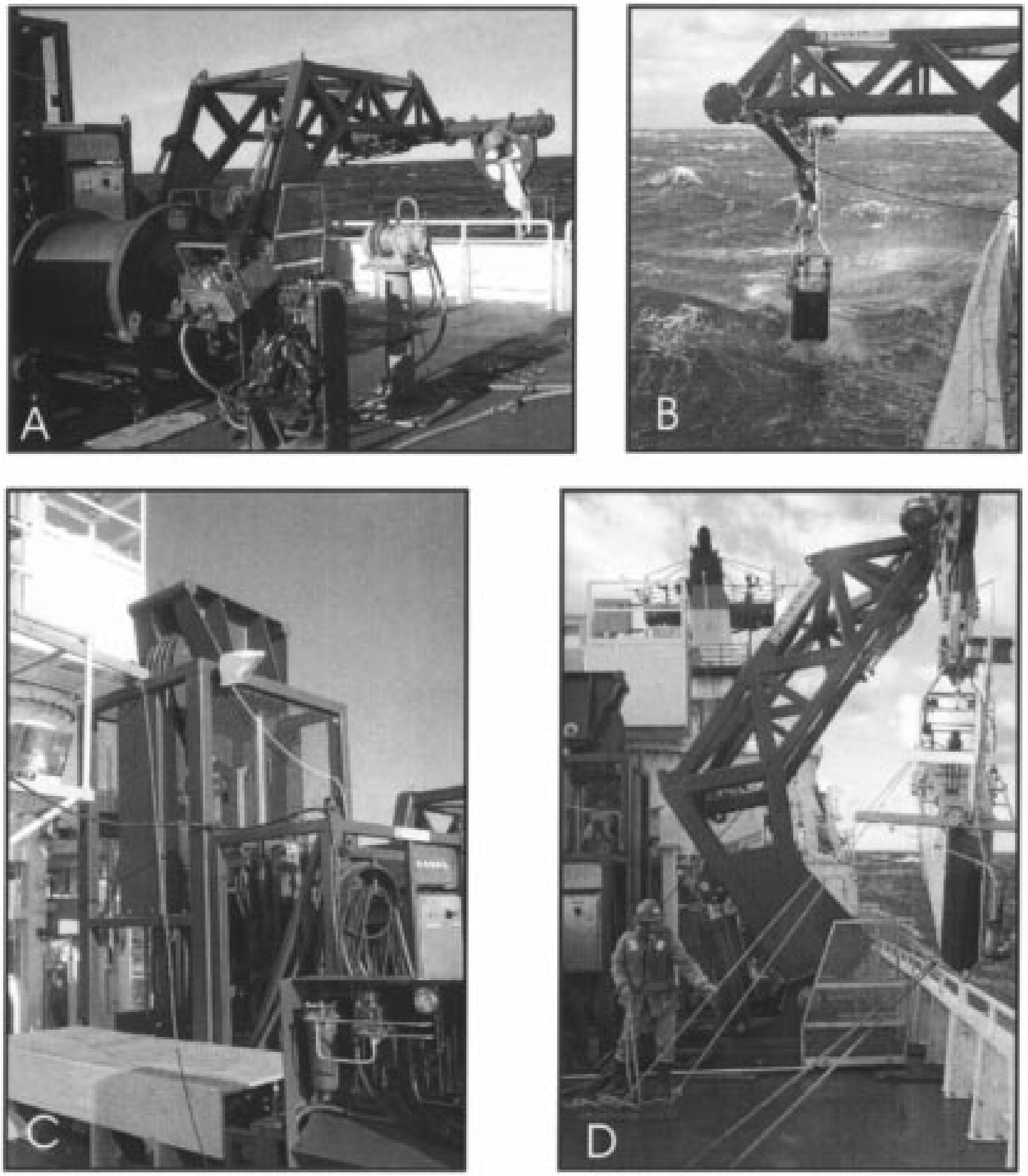

Fig. 8. BIOMAPER-II handling system on R/V ENDEAVOR (cruise 331, December 1999). (A) The local control system on a pedestal (foreground), the winch with 0.68-in electro-optical cable, and the J-frame in the overboard position towing BIOMAPER-II. (B) BIOMAPER-II locked in the docking mechanism and ready to be brought on board. (C) The slack tensioner and hydraulic power pack. (D) The J-frame at the start of the deployment of BIOMAPER-II.

[Fig. 8(D)]. The J-frame extension makes the overall width of the over board end of the frame 4.2 m (164 in) The framework is attached to a base plate with a pivot-pin assembly that allows the frame to rotate approximately 60 degrees from horizontal to its most vertical position. Two double-acting cylinders are attached to the base plate and inner structural frame members and are extended to move the frame to the outboard position. On the outer portion of the frame is a turning sheave which leads to an over-boarding sheave. The over-boarding sheave is part of an assembly that mounts in a steel cylinder welded into the outer margin of the framework and provides the J-extension. Below the over-boarding sheave is a docking mechanism for BIOMAPER-II which enables the towed body to be deployed or recovered with very restrained motion even in rough seas. The docking mechanism captures and latches the cable termination and the upper part of the BIOMAPER-II towing bail [Fig. 8(B) and (D)]. There are two remote controlled hydraulic pistons on the docking assembly. One is used to operate the latch and the other is used to adjust the fore/aft alignment of the docking assembly and the towing wire.

The power pack/hydraulic system is a 23-kW (30 HP) unit mounted in a separate framework [length 1.7 m (66 in), width 1 m (38 in), height 2 m (77 in)] that bolts onto the main platform [Fig. 8(C)]. It houses the hydraulic reservoir, electric motor and pump assembly, heat exchanger, and circuitry for high voltage electric supplies and low voltage control modules. The system requires 460 VAC 3 phase 60-Hz electrical power.

The local control station (a M/D TOTCO LM 2000) mounts on a movable pedestal that enables flexible placement in the vicinity (8 m–25 ft) of the handling system [Fig. 8(A)]. Controls to operate the winch, J-frame, and docking mechanism hydraulic rams are located on a stainless steel enclosure. A panel displays line tension, line out, and line speed. The unit provides for the setting and activation of alarms to indicate when parameter values exceed minimum or maximum limits. The data are output for computer logging via an RS232 bus at up to 4 Hz. A remote control unit on a 45-m tether (150 ft) is also available for operation of the winch and for displaying and logging of the data. A switch is present on the local unit to enable/disable the remote control unit. Normally, the local unit is used for launch and recovery of BIOMAPER-II and the remote unit is used to “fly” the vehicle from the BIOMAPER-II control van.

The sub-units have weights of: J-frame assembly—9136 kg (20 100 lb), slack tensioner—5118 kg (11 260 lb), hydraulic power unit—1546 kg (3400 lb), winch—2241 kg (4930 lb—without cable), 1000 m of cable—1114 kg (2450 lb), level wind—1155 kg (2540 lb), and turning sheave—218 kg (480 lb). Total weight is about 20 527 kg (45 160 lb).

F. Other Features

1) Troubleshooting: All systems on the vehicle power up when the BIOMAPER-II power supply is energized at the surface. A PC running a Visual Basic program displays the BIOMAPER-II status and includes information such as ground fault and water leak status, and pitch and roll angle. Water leaks are sensed in the telemetry/power bottle and the junction box. Troubleshooting is accomplished by powering subsystems off, unplugging systems, installing dummy connectors, and re-deploying in sea water. All systems are isolated to assist in ground fault trouble shooting. Therefore, it is possible to distinguish whether the fault is in the tether or on the vehicle (ABSS, ESS, VPR, etc.). If the fault is in the vehicle, it will most likely be one of many connectors. To determine which system is at fault, the user simply powers down each individual system (remotely) until the fault goes away. Once the system is found, the individual connectors in that system need to be inspected and cleaned as a first step in fixing the problem.

2) Future Sensors: Provisions are made in the wiring of the oil-filled box and the telemetry/power bottle to accommodate a future high sample rate probe. A likely candidate is a microstructure sensor for high resolution sampling of temperature, conductivity, and optical index of refraction. A 200-kHz maximum sample rate A/D board is included in the PC-104 stack for miscellaneous I/O. Spare analog channels are wired in for these future probes. A program could be written to sample these ports and send the data up the ethernet to a surface computer for logging.

Several other sensor systems are currently under consideration as well. To enhance BIOMAPER-II’s capabilities, broadband acoustic transducers are an option. Although there is wide coverage of frequencies in the current system, each transducer involves a discrete frequency. Much more information can be extracted for classification from broadband transducers [17]. Multi-beam acoustic systems also offer promise. The existing sampling volumes ensonified by BIOMAPER-II’s transducers result from the narrow beams of sound looking directly above or below the vehicle. It would be greatly advantageous to incorporate a multi-beam system that uses many beams to span a large volume of water at high resolution. Additional optical systems with a higher sampling volume would be advantageous. The current VPR has extremely small sampling volumes. As a consequence, it may under sample sparsely populated organisms [18]. Also, it is not at all practical to image large animals such as fish with this sensor because of their size and their avoidance capabilities. What is needed is an imaging system with a wider field of view for a larger sampling volume for zooplankton and micronekton. In addition, another type of optical system, such as a laser line scan system, is needed for visualizing fish at a distance (Coles, private communication). These short comings are currently addressed by ancillary use of a separate towed net system (MOCNESS—[19]), which has a large sampling volume. Even if these other optical systems were added, use of a net would remain important for direct analysis of the caught specimens. To complement the bio-optical sensors, there needs to be either an on-board system to enable mapping of dissolved nutrients or chemical tracers, or a modified towing cable with a tube to permit pumping of water for real-time seawater chemistry. Finally, as discussed above, micro-structure sensors are needed. Although the acoustic scattering is sensitive to micro-structure in the water, the current physical sensors can only provide information on temperature and conductivity at larger scales (meters). The addition of sensors that can provide information on centimeter-scale fluctuations (or smaller) in the water would better complement the acoustic data (Fig. 1).

G. Data Processing and Display

All data are co-registered with time and GPS navigation data. Data from each sensor package are displayed in real time on a monitor. These displays include data from the acoustical, VPR, ESS, and HydroScat-6 sensors, as well as engineering data regarding status of the BIOMAPER-II vehicle and tow cable. For example, echograms of acoustic volume backscattering strength are plotted on the computer monitor in real time while that information, as well as target strengths are stored. The close proximity of these displays allows operators to rapidly respond to phenomena of interest. For example, BIOMAPER-II can be guided into acoustical features so that their constituent scatterers can be identified with the VPR and physical conditions quantified. Significant post-processing is performed on the video data. Post-processing involves digitization of each video field followed by detection and extraction of in-focus targets. These in-focus targets, termed “regions of interest” (ROI), are subsequently measured and classified into taxonomic groups using neural network processing that requires training data sets [16]. During data collection, ROIs are presented on the computer monitor in real time. On the Antarctic cruises in 2001, the system has used the software for real-time processing of the ROIs.

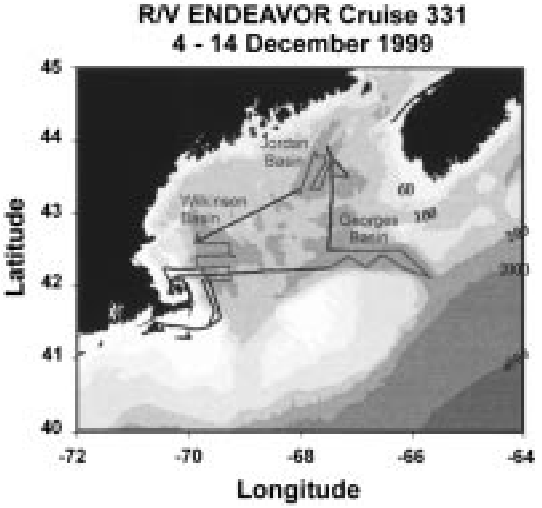

Fig. 9. The trackline for the R/V Endeavor cruise 331 which is similar to the other four cruises on which BIOMAPER-II was deployed in the Gulf of Maine.

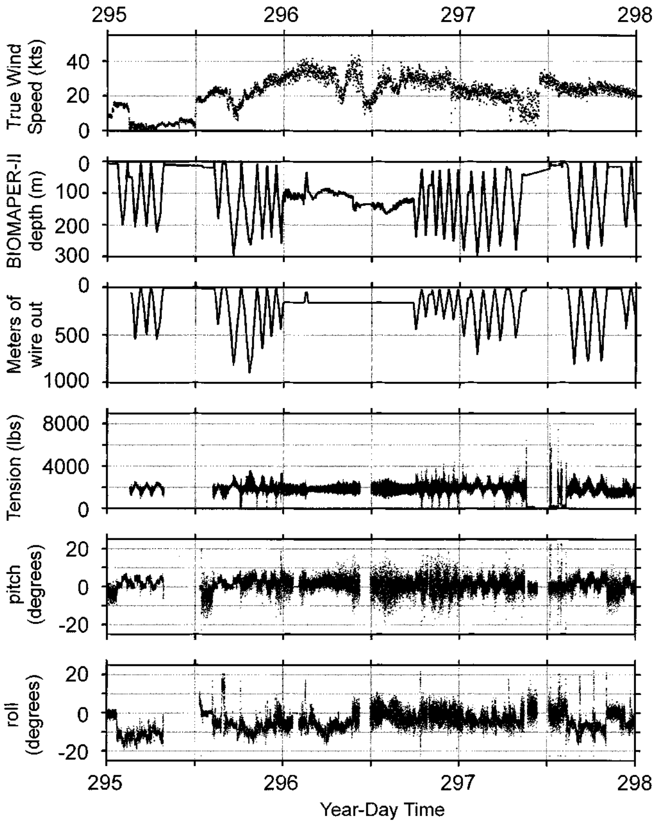

Fig. 10. BIOMAPER-II tow engineering data collected during a gale in Georges Basin, October 22–24, 1999. Wind speed data were collected at 1-min intervals; wire tension and line out data were collected at 0.25-s intervals; BIOMAPER-II depth, roll, and pitch data were collected at 4-s intervals.

III. Field Operations

BIOMAPER-II underwent sea trials on an engineering test cruise during July 1997. During the first actual science mission in October, 1997, the vehicle successfully performed a large-area survey of the major ocean basins located in the Gulf of Maine, off of the New England coast. Since then, BIOMAPER-II has been used for surveys of the Gulf of Maine in October 1998 and 1999, in December 1998 and 1999 (Fig. 9), and in broad-scale surveys of the continental shelf and Marguerite Bay area off the Western Antarctic Peninsula in 2001. Calibration of the sensors was either performed at dockside or by the manufacturer.

As a survey tool, BIOMAPER-II has typically been tow-yoed between the surface and 15–30 m above the sea floor or a maximum of 300 m depth. The normal tow-yoing procedure is to lower or raise BIOMAPER-II at approximately 6 m/min while the ship's speed is between 4 and 6 kn. This provides for the measurement of properties throughout the water column with the vehicle's point source sensors while collecting acoustic data throughout most of the water column. Although the VPR is used to provide the information about the numbers and size of the taxonomic animal groups present in the water column, the MOCNESS is also currently being used to provide samples of zooplankton that can be used to evaluate the performance of the VPR and to assist in the interpretation of the acoustics data. During a MOCNESS tow, BIOMAPER-II is usually brought to near the surface and operated at a fixed depth in a down looking mode.

1) Evaluation of Handling System Performance: An extended period of high winds and rough seas in Georges Basin between October 22–24, 1999 on R/V ENDEAVOR Cruise 330 provided an opportunity to make observations of the effectiveness of the motion compensation system under sea states that would normally render over-the-side operations impossible (Fig. 10). Work in Jordan Basin constituted a baseline for comparison because winds were light and seas nearly calm. During that period, the wire tensions during tow-yos of BIOMAPER-II between 0 and 200 m (1 to $\sim$ 500 m of wire out—mwo) were between 445 and 1168 kg (980–2570 lb—Table II). The pitch of BIOMAPER-II varied between 0 and 5 degrees while the roll had an offset of about 10 degrees (Fig. 10). The latter was caused by a misalignment of the tail which was corrected later in the cruise. Both the roll and pitch varied with the paying out or hauling in of the towing cable. There was a tendency for the nose to be pointed down a few degrees while paying the cable out and for it to be pointed up while hauling in. The roll bias tended to be minimized close to the surface and to increase with wire out (Fig. 10). The power spectra for the wire tensions (collected at 4 Hz) revealed two peaks. Most of the variance was centered at the frequency of the tow-yo, i.e., the maximum variation in wire tension was associated with the paying out and hauling in of the wire [Fig. 11(A)]. A secondary maximum in variance, three to four orders of magnitude lower, was between 5 and 10 s and was associated with the roll and pitch motion of the ship.

In Georges Basin, a tow-yo survey began while winds and seas were still moderate. As the wind and seas picked up, the slack tensioner began to fail to compensate for the ship's motion when BIOMAPER-II neared the surface. As the tension was reduced by the smaller amount of cable over board and the motion of the ship increased the wire tension variation, the slack tensioner reached the maximum upward excursion and the cable momentarily went slack. Adjusting the gas pressure reduced, but did not entirely fix the problem [Fig. 11(B)]. Still, the mean wire tension remained low and the maximum wire tensions only

TABLE II

SUMMARY OF WIND SPEED AND WIRE TENSION FOR BIOMAPER-II HANDLING SYSTEM PERFORMANCE (SEE FIGS. 10 AND 11 FOR DATA USED TO COMPUTE STATISTICS)

Time Period		Wind Speed (kts)			Wire Tension (lbs)			Comment
Start	end	min	mean	max	min	mean	max	
295.0	295.3	0	3.6	7.5	980	1975	2570	Light winds in Jordan Basin- towyo (Figure 11A)
295.6	296.0	16.1	29.0	41.8	30	2030	3600	Increasing winds in Georges Basin -towyo (Figure 11B)
296.0	296.4	9.6	28.0	43.7	10	1864	2780	Sustained high winds - horizontal tow (Figure 11C)
296.5	296.7	21.3	29.2	39.3	960	1875	2890	Sustained high winds - horizontal tow (Figure 11D)
296.7	297.0	4.9	24.0	37.1	20	1971	4400	Decreasing winds - towyo (slow ship speed) (Figure 11E)
297.0	297.4	3.2	20.1	35.3	20	2004	3820	Sustained Moderate winds - towyo (Figure 11F)
297.6	298.0	12.9	21.3	28.9	950	1818	4210	Sustained Moderate winds - towyo (only two tension points above 3380 lbs (Figure 11G)

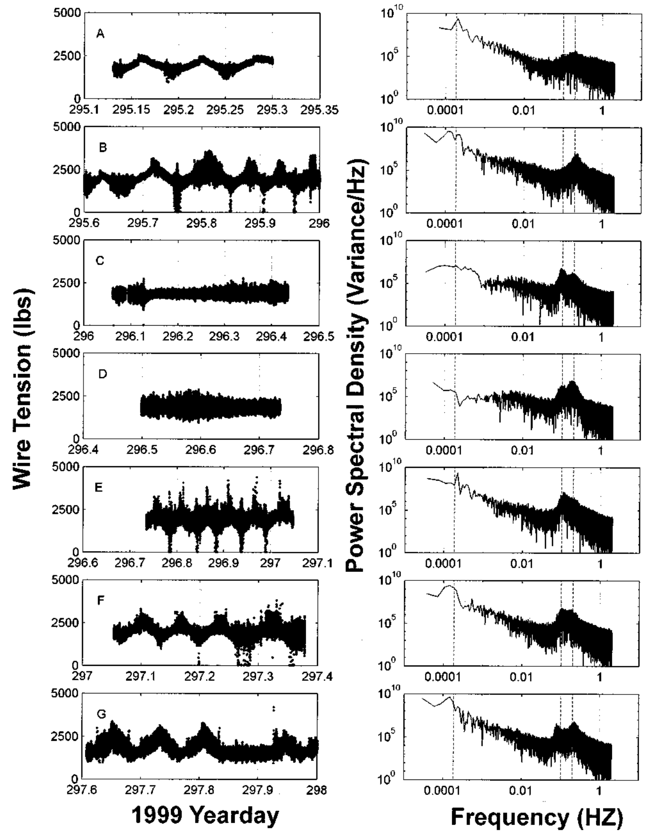

Fig. 11. Wire tension data and power spectra from sections of the data collected during the period October 22–24, 1999 and shown in Fig. 10. (A) Tow-yo during light winds in Jordan Basin. (B) Tow-yo with increasing wind at the start of work in Georges Basin. (C) Horizontal tow during high sustained winds in Georges Basin. (D) Continuation of horizontal tow in high sustained winds. (E) Resumption of tow-yos with decreasing winds. (F) Tow-yo during sustained moderate winds. (G) Tow-yo during sustained moderate winds after BIOMAPER-II VPR repair. The dotted vertical lines in the power spectra plots mark the approximate position of the tow-yo frequency and the positions of the 5-s and 10-s frequencies that typically span the range of the ship's roll and pitch motion.

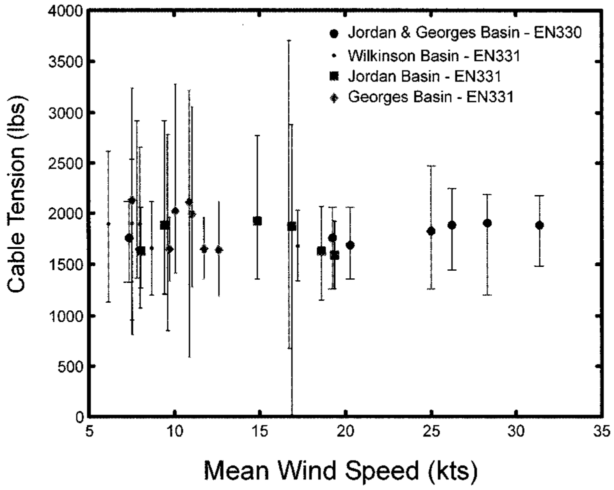

Fig. 12. Wire tension measured during a wide range of wind speeds and sea conditions during the towing of BIOMAPER-II on two cruises to the Gulf of Maine on R/V ENDEAVOR (October and December, 1999). The vertical bars and symbols near the middle of each bar correspond to the maximum, minimum, and mean values. These data illustrate that the Dynacon BIOMAPER-II handling system very significantly eliminates effects on the cable tension due to sea surface/ship motion when towing BIOMAPER-II.

reached 1636 kg (3600 lb). By midnight on October 22, the tow-yos were discontinued due to the high sea state in favor of a horizontal towing mode with BIOMAPER-II at about 100 m, which lasted about seventeen hours. Variations in BIOMAPER-II's depth were determined mostly by variations in ship speed. In spite of considerable vessel motion in seas of 4.5 to 6 m (15 to 20 ft), wire tension during this period was maintained by the slack tensioner in the same range as experienced during light winds in Jordan Basin (Table II). The power spectra during horizontal towing were dominated by ship's motion in the 5-10-s range and no significant contribution was evident at lower frequencies [Fig. 11(C) and (D)].

Resumption of tow-yoing resulted in some increase in the wire tension variation, but the mean wire tension level stayed nearly constant [Fig. 11(E)–(G)] and there was no evidence of shock loading of the wire or spiking. Wire tensions experienced during the recovery and subsequent launch were significantly higher than any observed during the towing. In summary, there

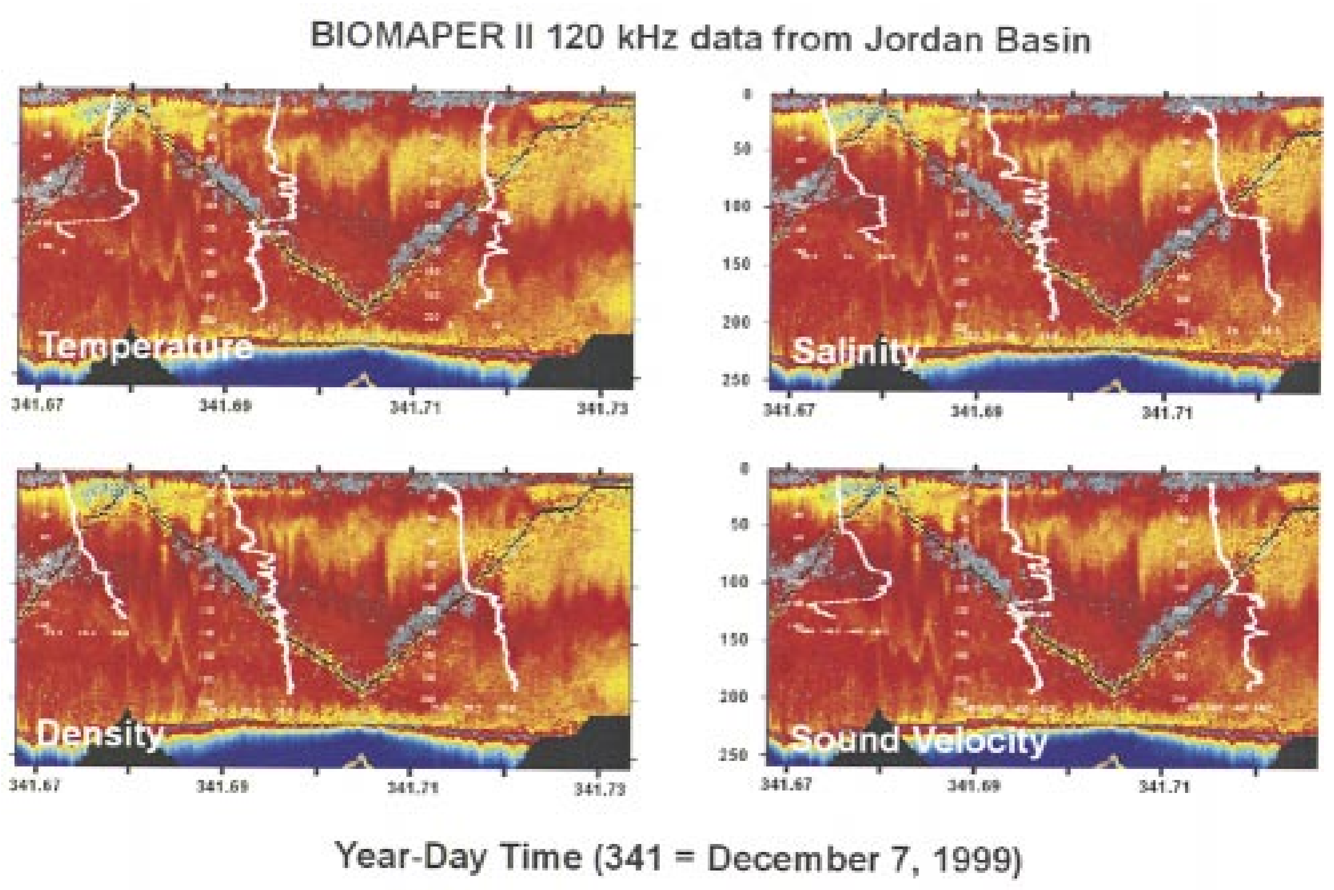

Fig. 13. Temperature, salinity, density, and sound velocity profiles from each of the BIOMAPER-II tow-yo legs overlain on the 120-kHz echogram of an internal wave in Jordan Basin (R/V Endeavor cruise 331—December 1999).

was no change in the performance of the handling system under calm to fairly extreme sea conditions (Fig. 12). The wire tension records and the power spectra demonstrate the substantial protection the slack tensioner system provides against excessive shock loading of the cable and the vehicle in sea states that normally prevent work.

The relative stability of the tow vehicle throughout this range of conditions also had implication regarding the possible need to compensate the acoustic data for errors caused by the motion of the transducers. For a sufficiently large angular displacement (roll/pitch) of the beam between the times of transmission and reception, the echo integration values will be reduced due to the directivity of the beams and require compensation [20]. The maximum deviation of roll and pitch angles of the vehicle were roughly 10° from the mean (Fig. 10). However, those deviations were on a cycle corresponding to the tow-yo frequency (scale of hours). The relevant angular deviations were on the short-term scale of seconds and those deviations were generally well within about 3° of the mean. For a 200-m range from the transducer and at the maximum swing rate corresponding to a 3° amplitude and a 5-s roll/pitch period, the angular deviation between transmission and reception is about 1°. This 1° deviation would correspond to about a 1-dB error in the echo integration value [20]. On average, the error would be less than 1 dB for the 3° deviation case, since one needs to average across the entire period which includes low angular velocities at the end-points of the deviation. Also, since most deviations were less than 3°, the overall error of the echo integration analysis due to motion of the acoustic transducers was well within 1 dB.

2) Survey Data and Preliminary Analysis: Five scientific surveys were conducted with BIOMAPER-II in the Gulf of Maine during the years 1997–1999 totaling approximately 40 days of survey time. During each survey, all sensors on the system collected data simultaneously producing a wealth of complementary data. For example, acoustic data were collected during tow-yo transects while at the same time the temperature, conductivity, and other physical properties of the water were measured throughout the water column (Fig. 13). Interestingly some aspects of the observed spatial variations in acoustic scattering were also evident in optical properties of the water column (Fig. 14). There were strong correlations between optical and physical properties and, based on comparisons between chlorophyll fluorescence, light absorption, and light scattering, it is apparent that different water constituents (i.e., phytoplankton, other particles, dissolved materials) are important in different layers. These data show layers of elevated acoustic scattering coincident with structure in the physical properties in an internal wave that extended throughout the water column. The video plankton recorder detected a wide range of animals throughout the water column (Fig. 15). These images complemented the net samples collected with the MOCNESS system.

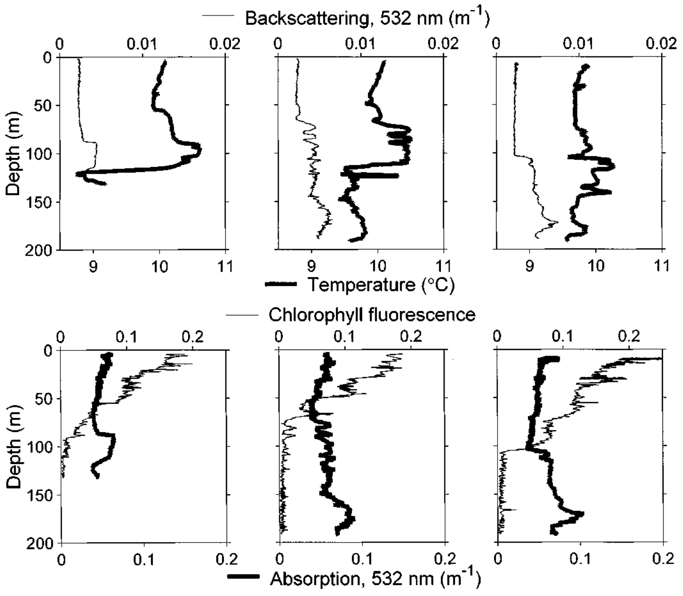

Fig. 14. Optical backscattering and absorption at 532 nm (m^{-1}), chlorophyll fluorescence, and temperature profiles from the same BIOMAPER-II tow-yo legs overlain on the 120 kHz echogram in Fig. 13.

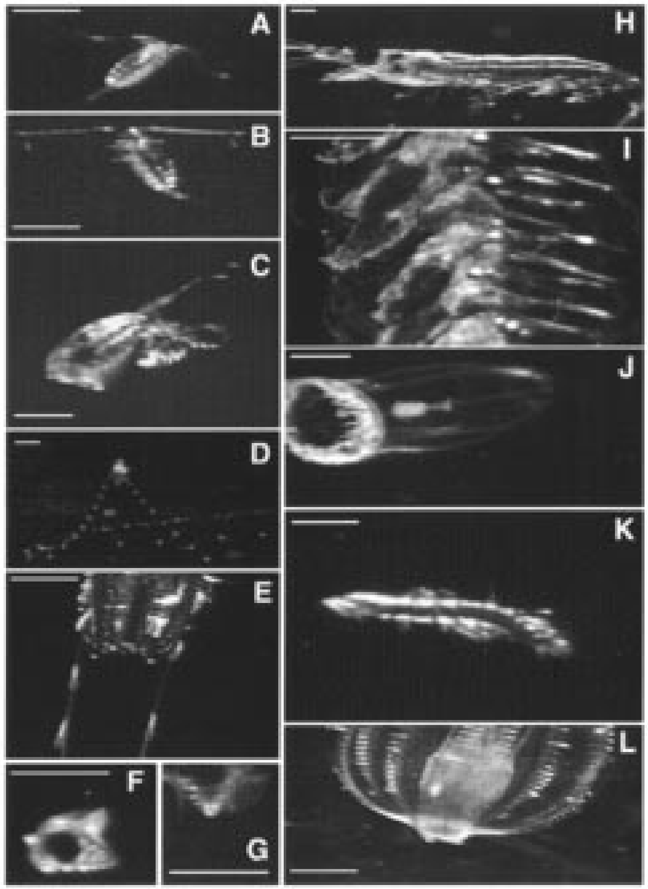

Fig. 15. VPR images of individual zooplankton present in the Gulf of Maine (R/V Oceanus cruise 332—October 1998 [(B)–(D), (G), (H)] and R/V Endeavor cruise 331—December 1999 [(A), (E), (F), (I)–(L)]). (A)–(C) Copepods. (D) Siphonula. (E) Ctenophore. (F), (G) Pteropods. (H) Euphausiid. (I) Portion of a siphonophore. (J) Medusa. (K) Polychaete. (L) Ctenophore. Siphonulae were recorded throughout the Gulf including portions of the water column near the internal wave displayed in Fig. 13. A 1-mm scale line is on each image to indicate animal size.

There are striking results that have been uncovered through the use of this system. First, in at least one region, the spectral properties of the multifrequency acoustic data have distinctly different characteristics in different parts of the water column, indicating different sources of scattering dominating the echoes. Second, certain animals not readily identified from the net samples were shown, through use of the video camera system, to be prevalent in the water and, through use of scattering models, were shown to be significant sources of scattering. Both of these phenomena are currently being studied in separate investigations and are summarized below.

In the survey of the Wilkinson Basin in October 1997, an internal wave was studied through use of the BIOMAPER-II and MOCNESS systems. The upper portion of the internal wave was observed to have a distinctly different frequency dependence of the acoustic scattering than that of the lower portion (Fig. 16). The upper portion had a frequency response that decreased monotonically with frequency while the response of the lower portion increased with frequency. These scattering characteristics are indicative of two different sources of scattering present [9]. The spectral response with a negative slope is consistent with acoustic scattering by sound speed microstructure. The positive slope is consistent with scattering by marine organisms that do not contain gas.

The sources of scattering were investigated through analysis of the direct measures of the physical properties of the water and the net samples. The CTD data indicated significant small-scale variability in the physical properties of the water in the upper portion of the water column. This variability is attributed to mixing processes that normally occur due to wind-wave interactions. Furthermore, there was a wide range of animal types collected through the water column, such as copepods, euphausiids, pteropods, siphonophores, and medusae. The proportions of animal types and overall biomass was a strong function of depth. Physical data were manipulated through a process involving Thorpe scaling so that estimates were made of the dissipation rate of turbulent kinetic energy (ε). The net samples were counted and sized according to major taxonomic zooplankton groups. Once both the physical properties and distribution of zooplankton were determined, acoustic predictions were made to determine the amount of acoustic scattering that each animal group and the microstructure produced. The predictions involving the animals were done in a manner similar to that described in [6] while the method involving microstructure is described in [21]. The results indicate that the microstructure dominated the scattering in the upper portion of the water column and euphausiids dominated in the lower portion.

The analysis was taken further by performing an inversion of the acoustic data to estimate properties of the dominant sources of scattering. In this approach, we assumed that the scattering in the upper portion of the water column was due solely to microstructure and that euphausiids were the sole contributors to the scattering in the lower portion. Then, predictions of acoustic scattering versus frequency were fit to the data in a least squares sense. The fitting was done by varying one or two parameters in the predictions and generating classes of curves (scattering versus frequency) that were compared with the corresponding

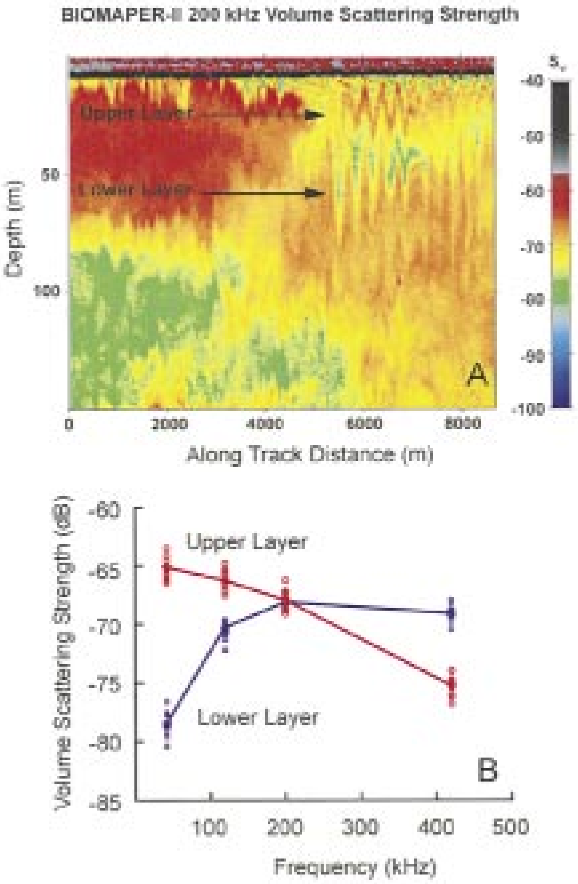

Fig. 16. (A) BIOMAPER-II 120-kHz echogram of a transect through an internal wave in Wilkinson Basin Gulf of Maine(R/V Endeavor cruise 307—October 1997). (B) The upper and lower layers, observed in the internal wave, have patterns of measured S_v at four acoustic frequencies that are consistent with the interpretation that the upper level is dominated by backscatter from microstructure and the lower level is dominated by backscatter from zooplankton. Figure redrawn from [21].

TABLE III
OBSERVED AND PREDICTED PROPERTIES OF ANIMAL SIZE AND DISSIPATION RATE OF TURBULENT KINETIC ENERGY BASED ON THE INVERSION OF BIOMAPER-II ACOUSTIC DATA FROM AN INTERNAL WAVE OBSERVED ON R/V ENDEAVOR CRUISE 307 (OCTOBER 1997)

	Acoustic Estimate	Directly measured/calculated
Animal Size (cm)	1.47	1.5
Dissipation rate (ϵ - watts/kg)	1×10^{-7}- 1×10^{-6}	2.5×10^{-7}

data. For the scattering by the microstructure, the dissipation rate was varied. For the scattering by the euphausiids, size and numerical density were varied. The fits produced reasonable agreement for inference of dissipation rate of the microstructure and excellent agreement when inferring size of the euphausiids (Table III).

In the December 1999 survey of the Gulf of Maine basins, the VPR detected the presence of siphonulae, a larval form of siphonophores (Fig. 15). These juveniles contain gas inclusions of the order 0.2 mm in diameter. The remainder of the animal is fragile gelatinous tissue. These animals were not always obvious in the net samples because of the fragile nature of the tissue and their amorphous appearance after preservation. Much of their tissue is damaged by the strong agitation caused by the towing of the net, and hence these types of animals are usually under represented by net systems such as the MOCNESS. Although the gas inclusion is small compared with the wavelength of the highest frequency of BIOMAPER-II, the resonance frequency of these inclusions is near 120 kHz, the frequency of one of the transducers of BIOMAPER-II. Our predictions (not shown) of the scattering by these animals show levels of acoustic scattering consistent with many of the measured values where the animals were present [22].

Each of the above observations is very important to the use of acoustic systems for surveying the water column since they demonstrate that the inherent ambiguities of acoustic techniques can be reduced through use of this advanced system. By combining the acoustic data with video, physical, and net data, and through the use of acoustic scattering models, the dominant sources of scattering were estimated. Until recently, the traditional interpretation of acoustic data has been that variations in the echo level were directed related to variations in the biomass of whatever was caught in the net. Our experience over the past several years has demonstrated that what was caught was not necessarily the dominant source of scattering. In one case, the microstructure dominated the scattering and in another case, an animal that was detected in the video system, but not easily classified through net sampling, was a significant source of the scattering.

IV. SUMMARY AND CONCLUSION

An advanced towed instrument platform and associated winch and handling system have been developed and used in oceanographic studies. This system has a great capability for surveying marine life because of the diverse suite of sensors (acoustics, video, environmental), high-data-rate telemetry (fiber optic), and automated handling system which allows it to be used over a wide range of weather conditions. Because of the wide range of acoustic frequencies, one can discriminate between the scattering by zooplankton and microstructure. By using co-registered video and environmental data as well as simultaneous net sampling, the acoustic data can be used in a meaningful way to produce quantitative estimates of biological and physical parameters such as length and numerical density of zooplankton and dissipation rate of turbulent kinetic energy of the microstructure.

One important aspect with regard to the success of inversion of the acoustic data was the strategic choice of acoustic frequencies. The range of frequencies was designed so that typical turning points between the low-frequency scattering and high-frequency scattering for both the zooplankton and microstructure was within the frequency range. The observed value of the location of the turning point and the overall level of scattering could then be used in combination with the video and environmental data to provide an adequately constrained inversion of the data.

BIOMAPER-II was constructed with a modular architecture so that sensors can be changed or added. Future expansion of this system could include adding more acoustic beams at a given frequency to increase spatial coverage, adding more acoustic frequencies to extend the range of frequencies which would provide more flexibility in the location of the turning point, adding more frequencies within the existing frequency range to provide more information, adding broadband transducers which provide more information than a single frequency transducer (but at the sacrifice of sensitivity), adding microstructure sensors to help ground truth physical phenomenon, and adding one or more optical imaging systems with a larger field of view (but lower resolution) to complement the existing one.

In conclusion, this multisensor system represents the current state of the art in technology for surveying marine life. The complementary video and environmental sensors, as well as ancillary use of net systems and CTD casts, reduce the ambiguities in the interpretation of acoustic data. The modularity of the design allows the system to be modified or expanded for different applications in the future. With these and the other capabilities discussed above, this system is capable of surveying a wide range of organisms under a wide range of sea conditions.

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Terry Hammar, photograph and biography not available at the time of publication.