Marine Physical Laboratory

Large Aperture Acoustic Arrays in Support of Reverberation Studies

John A. Hildebrand

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In preparation for a major field experiment in FY92, this report addresses the development of acoustic arrays which are needed in order to make carefully controlled and well-documented measurements of bottom reverberation. The purpose of these measurements is to study the physics of the backscattering process and to quantify backscattering characteristics as a function of physically meaningful parameters (e.g. ensonified area, grazing angle, bottom material properties, bottom roughness, etc.).

Specific array systems which are addressed include the following: (a) towed horizontal array, (b) horizontal and vertical array, (c) ship-tethered 64-element vertical array, and (d) self-contained, 16-element vertical array.

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LARGE APERTURE ACOUSTIC ARRAYS IN SUPPORT OF REVERBERATION STUDIES

Final Report to Office of Naval Research Grant N00014-89-J-1935

John A. Hildebrand (Principal Investigator)

Abstract

In preparation for a major field experiment in FY92, this report[1] addresses the development of acoustic arrays which are needed in order to make carefully controlled and well-documented measurements of bottom reverberation. The purpose of these measurements is to study the physics of the backscattering process and to quantify backscattering characteristics as a function of physically meaningful parameters (e.g. ensonified area, grazing angle, bottom material properties, bottom roughness, etc.).

Specific array systems which are addressed include the following: (a) towed horizontal array, (b) horizontal and vertical array, (c) ship-tethered 64-element vertical array, and (d) self-contained, 16-element vertical array.

Objective

Our scientific objective was to understand the interaction between acoustic energy and the seafloor. The development of several acoustic arrays enabled us to make field measurements of the scattered wavefield from the ocean bottom/subbottom.

Background

Although seafloor scattered wavefields have been studied previously, many of the seafloor characteristics important to their understanding have not been measured concurrently. Scattering may vary spatially in the ocean due to variations in seafloor roughness, sediment cover, and water depth.

The scientific plan for the bottom reverberation component of the Acoustic Reverberation Special Research Program (SRP) has placed special emphasis obtaining a detailed description of the bottom in the "natural laboratory" where acoustic experiments are to be conducted. The SRP natural laboratory will provide a setting where adequate environmental control is available to understand the connection between seafloor characteristics and scattering characteristics.

[1] This report originally appeared as a proposal (UCSD 901004) to the Office of Naval Research for the bottom reverberation component of the Acoustic Reverberation Special Research Program (SRP).

Approach

We propose the development of several acoustic arrays in preparation for a FY92 experiment where the objective will be to study the interaction of low-to-mid frequency acoustic wavefields and the ocean bottom/subbottom. The proposed effort is broken down into four areas each of which is discussed separately: (a) acoustic reverberation measurements with towed horizontal array, (b) horizontal and vertical array configurations for bottom reverberation experiments, (c) ship-tethered 64-element vertical array, and (d) self-contained, 16-element vertical array.

A. Acoustic Reverberation Measurements with a Towed Horizontal Array

Objective

Provide a large aperture, horizontally-towed hydrophone array to measure the directional spectrum of seafloor scattered wavefields.

Approach

As part of the ONT-sponsored, 1987 SVLA experiment, we constructed a vertical acoustic array of 120 elements and 900 m length (half-wavelength element spacing at 100 Hz). This array was designed for deployment from the research platform FLIP in a moored configuration. A unique capability of the array is acoustic element location with an accuracy of a few meters. Estimates of array shape and element position are required because element location contributes to the signal phase needed for beamforming. Acoustic element positioning is needed for large aperture arrays where a rigid mechanical structure is impractical. This array can be used as a large-aperture, horizontal array for the SRP bottom reverberation experiments.

As a initial step we modified the 120 element vertical array for deployment as a towed horizontal array. Key advantages of this array include its ability to be towed at any depth up to 6000 m, and precise array element location. For operation as a horizontal array, modifications are necessary to allow vertical array element positioning. Operated as a vertical array, an acoustic pulse initiated near the surface determines element depth. In a horizontal configuration, the element depths are more easily determined by pressure sensors distributed along the array. Pressure sensors with adequate depth resolution (1 m) are based on a quartz crystal oscillator and are moderately priced (e.g. Paroscientific - $5K per sensor). A total of 12 pressure sensors incorporated into the array would provide a depth determination at 75 m spacing.

While the vertical array has been operated inside a small field of navigation transponders, the horizontal towed array configuration would be done with multiple sets of transponders so that a substantial tow range could be achieved without having to reverse course. It takes a good deal of time to stabilize the towed array once a course change is executed. Extended range transponder fields have been used with Deep Tow so there is experience already at MPL with this aspect of acoustic navigation.

We tested the 120-element horizontal-towed array during a 10-day expedition. The test was conducted in close proximity to seafloor sources of scattered energy including the continental slope, seamounts, and lineated abyssal hills. Narrow-band acoustic sources (e.g. HX-90) as well as broad-band impulsive sources (e.g. explosive shots) will be used as sound sources deployed from the tow ship. This mode of operation allowed observation of the receiver depth dependence of reverberant energy.

We analyzed the data from the FY90 engineering test, corrected problems encountered with the array hardware during the FY90 field test, and conducted a second 10-day engineering test. Data analysis will include statistical analysis of single element data to determine variation of omni-directional reverberant signal levels as well as beamformed coherent combination of all array elements to determine directional variation of reverberant signal levels. All beamforming will incorporate array element locations determined from acoustic lateral positioning and pressure sensor depth positioning.

B. Horizontal and Vertical Array Configurations for Bottom Reverberation Experiments

Objective

The simultaneous deployment of large-aperture horizontal and vertical arrays for observation of seafloor scattered energy.

Approach

Two methods will be described by which vertical and horizontal acoustic arrays can be deployed together for making bottom reverberation measurements. The first method (proposed) makes use of the R/P FLIP as the platform from which to deploy and record from both arrays, as shown in Figure 1. The second method (not proposed but discussed in Appendix A) consists of using a subsurface float as a common point of support as well relaying telemetry data to a surface float for radio transmission to a receiver for recording, presumably on a ship near enough for reception without contaminating the acoustic data, as shown in Figure 2. We are proposing the first method over the second on the basis of our best estimates of the associated costs involved and risk to the experiment due to potential deployment difficulties.

The Marine Physical Laboratory has been deploying various vertical hydrophone arrays from R/P FLIP for over twenty years for acoustic propagation and ambient noise measurements. These have ranged from sparse twenty element analogue arrays to the latest one, a 200 element digital array uniformly spaced over 3000 meters, and incorporating acoustic navigation for array element location.

Starting in 1977, under ONT funding, development of a large aperture, high gain, high resolution, neutrally bouyant horizontal array commenced in order to study residual noise, that is, non shipping noise. Originally conceived of as a 1500 meter 200 element array cut for 100 Hz, it was tested for horizontal deployment from FLIP several years ago with the USNS NARRAGANSETT, T-ATF 67. Position keeping of the T-ATF in the weather we encountered was inadequate for the degree of control we needed for emplacement of the anchor at the bitter end of the array.

To investigate two dimensional aspects of acoustic reverberation from bottom roughness, we propose to deploy horizontal and vertical arrays from FLIP with simultaneous recording of data from both arrays on board FLIP. Recent experience with position keeping by the R/V NEW HORIZON in deployments of the RUM III vehicle demonstrated a 20 meter watch circle capability in deep water in sea state 3 conditions. The key to success was a display of ship position within a 100 meter radius circle based on acoustic navigation from which the Captain maneuvered the ship. The Captain has indicated he could maintain similar position keeping in higher sea states, up to and including state 5 with a new dynamic positioning system that is being worked on. The Captain indicated that for this type of array deployment he could maintain his heading within +/- 15 degrees, well inside the +/- 90 degrees of freedom of the large radius flume on the fantail through which the array is deployed. For safety of the group deploying the horizontal array, it is necessary to have the vessel heading into the weather. The large bow and weak bow thruster on the NARRAGANSETT made it fall off in such a way that we could not recover without aborting the deployment. Deployments backing into the wind proved too dangerous, rendering the vessel and personnel vulnerable to casualties such as those incurred near Point Loma.

What is entailed, therefore, is the use of separate ships for the mooring and array deployment operations. The smaller NEW HORIZON has the position keeping and maneuvering capabilities required for array deployment but cannot handle the 80 tons of gear required for putting FLIP into a three-point mooring in deep water.

We have also considered the use of a tether between the NEW HORIZON and FLIP so that we could virtually eliminate any danger to the acoustic array from overstressing it and enable us to work in higher sea states. For this mode of deployment, the array would be below the surface at all times and the tether would have to remain at the surface so that it could not foul the array. We have discussed this mode of operation with the Marine Superintendant. This involves a constraint on ship maneuverability which, if the tension in the tether is kept low, may not seriously degrade its maneuverability. Some testing of these deployment concepts needs to be done with a dummy horizontal array before deploying the real array.

The sequence of deployment without a tether would be as follows:

- The array vessel would come near FLIP and receive the bitter end of the electromechanical cable for attachment to the telemetry package, Norwegian float and weight. The float is to compensate initially for the weight so that the array will remain at the surface until it is all paid out.
- The telemetry package is attached to the array which is flaked out in storage boxes. The horizontal array requires a strength member external to it and 1/2" Kevlar line is used for this purpose. Control of the tension in the Kevlar strength member is with an air actuated line puller with a maximum pull capability of 1000 pounds. (This could be another type of constant tension device.)
- The array will be attached to the Kevlar line between the line puller and the flume mounted at the stern.
- Once the array is paid out and checked electrically, an anchor line and hard floats are attached to the bitter end of the array. Anchor line is paid out so that when the deployment is complete, the horizontal array will be at the depth of the sound axis, the same depth as the center of the vertical array.
- Anchor weights and acoustic navigation gear are attached to the end of the anchor line away from the array and a crown line is used to lower the anchor. At this point the array begins to submerge and as electromechanical wire is paid out from FLIP the weight of the electromechanical wire eventually causes the Norwegian float to submerge and collapse.
- With maneuvering guided by acoustic navigation, the ship places the anchor weight on the bottom in a predetermined location so that the array will be deployed horizontally.
- A recovery float and marker are attached to the crown line once the array position has been determined to be satisfactory. At this point the deployment of the array is complete and the vessel is released for other duties.

Recovery of the array is essentially the reverse of the deployment process and full control of the array position is key to avoiding fouling problems.

Appendix A: Autonomous Deployment

The autonomous deployment would capitalize on the past experience with the IWEX subsurface tri-moor at Woods Hole. This involves precision deployment of mooring legs which is accomplished with acoustic navigation of the anchors for each mooring leg. The same system for precision mooring deployment is proposed for array element location for the vertical and horizontal arrays. As discussed in Berteaux's book, after deploying two legs of the tri-moor, the subsurface float is still on the surface. At this point we would deploy the vertical array through the hole in the middle of the buoy (as shown in Figure 2) or else through a tube at the edge of the buoy which could be next to the ship. The only ships capable of manuevering adequately for the intended operations are the *R/V Melville* or the *R/V Knorr*. Once the vertical array is deployed and checked out from aboard the ship via a hard wire link, the vertical array would be connected to the buoy power supply and the surface telemetry buoy would be deployed. The radio telemetry link then would be checked out for the vertical array. This not only would monitor the performance of the array but also would give a measure of own ship noise as a function of range.

Since the telemetry buoy would drift downwind, this causes a problem in the deployment of the horizontal, neutrally bouyant array. That is, we propose to deploy this on the surface downwind from the subsurface float which at this point, with only two legs in, is still on the surface. The way to solve this problem is to keep the telemetry buoy adjacent to the subsurface float until the horizontal array is fully deployed.

The horizontal array would be attached to the autonomous power supply and mechanically made fast to the subsurface float. The horizontal array would then be paid out from the stern of the vessel as is slowly increases range from the buoys; the radio telemetry link would be monitored during payout to check out array elements and acoustic navigation sensors. At the bitter end of the array, hard floatation would be attached and deployment of the anchor line would commence. Once the anchor line is paid out the vessel would have to acoustically navigate the anchor to the precise location so that when the upwind leg of the subsurface float mooring is in place, the horizontal array is indeed horizontal. A crown line to the anchor would be used to locate the anchor and also to recover the anchor line. The crown line would have a surface float, light and radar reflectors for recovery and warning.

Once the horizontal array is deployed, the upwind mooring leg is deployed next unless some direct action is required to release the telemetry buoy from the subsurface buoy. It may be necessary to have a weight on the electromechanical wire to the array to keep in below the surface in order to prevent fouling with the telemetry buoy when the 400-600 meter tether to the subsurface float is released, since both the telemetry buoy and the horizontal array are downwind. Deployment of the third leg would then pull the subsurface float and the horizontal array down to the desired depth and it would be possible to monitor the telemetry via radio to be sure all the electronics and navigation systems are working before dropping the third anchor. Crown lines on all anchors to recoverable surface floats would be used to recover the arrays in the opposite sequence.

It is easy to see the value of the weight on the horizontal array during recovery since both the horizontal array and telemetry buoy would both be on the surface as soon as the subsurface float surfaces; the weight would keep the telemetry tether from fouling the horizontal array.

C. Ship-Tethered 64-Element Vertical Array

Objective

The use of a bottom-moored, ship-tethered vertical array within the scattering region in order to provide local measurements of the ensonifying acoustic field and the corresponding scattered energy. These measurements will enable a direct comparison to be made of the experimental data and predictions made by models being developed which can account for the detailed physics of of the bottom interaction process. Such measurements also will enhance our ability to interpret the observations made of the backscattered field at longer range by other arrays participating in the experiment.

Approach

As part of the Surface Reverberation SRP project, we have proposed to modify an existing MPL 64-element digital array for use in the FY92 surface reverberation experiment. The modifications will consist of: (a) shortening the the interelement spacing so that it is half-wavelength at 1 kHz, (b) increasing the sampling rate to 2.5 kHz, and (c) incorporating 14 bit A/D converters into the digitizing electronics. In addition, we will add four self-recording tilt/heading/pressure sensors at equally-spaced locations along the array.

Beyond the array modifications, topside data acquisition and recording will be enhanced to accommodate the higher sampling rate. Data will be recorded on 4 mm cartridge tapes as well as being available for real-time quick-look analysis.

With a small additional investment, this array also could be used in the Bottom Reverberation SRP. Specifically, a new set of interelement cables would need to be cut (making the interelement spacing half-wavelength at 500 Hz) and a subsurface float with soft tether to the surface for connection to the support ship would need to be designed and fabricated.

The 64-element array originally was designed to present a low drag profile (so that it could be deployed from FLIP while drifting). It is very well suited to be a bottom moored, surface tethered array.

D. Self-Contained 16-Element Vertical Array

Objective

The use of a self-contained, bottom-moored vertical array within the scattering region in order to provide local measurements of the ensonifying acoustic field and the corresponding scattered energy. These measurements will enable a direct comparison to be made of the experimental data and predictions made by models being developed which can account for the detailed physics of of the bottom interaction process. Such measurements also will enhance our ability to interpret the observations made of the backscattered field at longer range by other arrays participating in the experiment.

Approach

Currently, MPL is completing the development of a self-contained, seafloor recording capsule which will have several gigabytes of data storage capacity. We propose to fabricate a 16-element vertical array whose data will be stored by this recording capsule. The array will have an interelement spacing equal to a half-wavelength at 500 Hz, a 1.5 kHz sampling rate, and 14-bit A/D converters. In addition, we will add two self-recording tilt/heading/pressure sensors - one at the top and one at the bottom of the array.

APPENDIX A

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Large Aperture Digital Acoustic Array

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Large Aperture Digital Acoustic Array

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(Invited Paper)

Abstract—A digital array of 120 acoustic channels and 900 m in length has been constructed to study low-frequency (20–200 Hz) ambient noise in the ocean. The array may be deployed vertically or horizontally from the research platform *FLIP* and the array elements are localized with a high-frequency acoustic transponder network. This paper describes the instrumentation, telemetry, and navigation systems of the array during a vertical deployment in the northeast Pacific. Preliminary ambient noise spectra are presented for various array depths and local wind speeds. Ambient noise in the frequency band above 100 Hz or below 25 Hz increases with local wind speed. However, in the frequency band 25–100 Hz ambient noise is independent of wind speed and may be dominated by shipping sources.

Keywords—acoustic array, ambient noise, acoustic navigation, low frequency.

I. Introduction

A DIGITAL ARRAY of 120 acoustic channels and 900 m in length has been constructed for the study of low-frequency (20–200 Hz) ambient noise. A large aperture array is required for high-resolution directional information at low frequencies. A well-filled array is required to provide low side-lobe levels for the study of ambient noise. This paper describes the characteristics of a large aperture linear array of hydrophones which may be deployed vertically or horizontally from the research platform *FLIP*. Preliminary observations of low-frequency ambient noise from a vertical deployment of this array in the northeast Pacific during September 1987 are described.

Oceanic ambient noise is the prevailing sustained background of sound in the ocean. These noise levels place constraints on the operation of acoustic sensors in the ocean. For this reason, it is valuable to understand the sources generating the sound, the absolute levels, and the spectral shapes of ambient noise. Low-frequency noise is particularly important because of its low attenuation and therefore its ability to propagate over long distances. Only recently has it been practical to investigate the directionality of ambient noise sources at low frequency (less than 100 Hz) due to power, size, and cost constraints.

The following have been identified as sources of low-frequency noise in the ocean [1]: shipping, wind and waves, seismic disturbances, and nonlinear ocean wave interactions. In the frequency band between 20 and 100 Hz, shipping is thought to be the dominant noise source where shipping sources are present [2], [3]. This component may include reverberative paths, perhaps related to prominent bottom topographic features, as well as forward scattering and channeling of the shipping sources. The variation of shipping noise may depend on whether the sources are of single-ship or multiple-ship origin and whether they are local or distant.

At frequencies between 100 and 200 Hz, sea surface noise generated by wind and waves may be dominant. The reported contribution by local wind sources in this band is quite variable, ranging from a difference in spectral level of approximately +18 to −4 dB/μPa/$\sqrt{\text{Hz}}$ [1], [4]. The sources responsible for this variation may be identified by examining the vertical and horizontal directionality. Distant storms and noise generated at the edges of the ocean due to waves breaking on cliffs, rocks, or beaches as well as the nonlinear generation due to interference of incoming and reflected coastal swell may produce an azimuthally nonuniform contribution; local wind should induce a vertically variable contribution.

The unique capabilities of the array described in this paper allow its deployment as a high-performance vertical or horizontal array. Arrays previously used to measure low-frequency vertical directionality are listed in Table I to facilitate comparison. The number of elements (120) and large aperture (900 m) of our array is substantially greater than previously reported vertical arrays. This large aperture will allow higher resolution vertical directionality than was previously available. Horizontal directionality is usually measured using large aperture towed arrays. Our array can be moored horizontally because of its neutrally buoyant design. When operated in the horizontal configuration, the flow noise affecting our array is significantly less than for towed arrays, leading to improved array performance.

II. Array Description

This section describes the array electrical and mechanical design. The array has a modular design, which facilitates assembly and transportation and allows for a variable aperture. It is separable into identical hose sections of ten elements each, joined together by in-line interchangeable pressure cases. Each of the ten elements consists of two hydrophones, a preamp, a filter, and a line drive submerged in insulating noroma oil. The oil-filled hoses are neutrally buoyant in seawater, necessary for horizontal deployments. The interelement spacing is 7.5 m and the elements are secured within the 2.54 cm diameter urethene hose by a kevlar line which is terminated near each end of the hose subsection. In-line pressure cases are located between each hose section of ten hydrophones. The pressure cases are 45 cm long with a 7.6 cm outside di-

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TABLE I
COMPARISON OF VERTICAL ARRAYS

Number of Elements	Aperture meters	Hydrophone Spacing	Frequency Range Hz	Deployment Depth (actual) meters	Deployment Platform	Reference
120	900	uniform	70-200	400-3100	*FLIP**	this paper 1988
11	34	nested subarrays	62.5-1K	200	free floating	[14] Buckingham and Jones 1987
48	115	uniform	0-450	sound channel	*FLIP*	[15] Hodgkiss and Fisher 1986
27	93	uniform	0-600	sound channel	*FLIP*	[15] Hodgkiss and Fisher 1986
31	180	nested subarrays	20-800	300	free floating	[3] Burgess and Kewley 1983
31	310	uniform	45-100	1500	surface ship	[16] Wales and Diachok 1982
12	237	logarithmic	<200	300-3100	free floating	[17] Browning, *et al* 1982
20	<560 (variable)	uniform	5-400	700-4800	*FLIP*	[18] Tyce 1982 [19] Anderson 1979
40	97	geometric	112-1414	4400	anchored to bottom	[20] Axelrod, *et al* 1965

* *FLIP* (Floating Instrument Platform) is a manned 109 meter spar buoy stable platform operated by the University of California, San Diego, Marine Physical Laboratory.

ameter providing a low-profile cross section. These pressure cases house nonpressure tolerant electronics for processing and telemetering the hydrophone signals. Hydrophone data are transmitted asynchronously along the ray to a telemetry module near the *FLIP* end of the array. This module buffers the data and synchronously transmits it through a double-lay armored electrical cable to the surface where it is recorded by the data acquisition computer (LSI-11). The tension carried by the electrical support cable is transferred at the telemetry module to a 1.5 cm diameter kevlar line. During vertical deployment, the hoses and pressure cases are attached to the kevlar line, which has 1500 kg at its bottom to maintain verticality. The array is deployed from the research platform *FLIP*, which maintains station by a multipoint moor. The array is suspended from a hydrographic winch which allows it to be lowered to a specified depth below *FLIP*. Fig. 1 shows a schematic of the array configuration during vertical deployment.

The coaxial armored uplink electrical cable carries frequency-multiplexed data in three bands: uplink data, downlink commands, and dc power. The spectrum allocated for the uplink data is from 100 kHz up to approximately 1.5 MHz. The uplink data rate is 1 Mbit per second encoded using a Miller code to reduce the bandwidth required to approximately 500 kHz. The downlink spectrum is from 100 kHz down to 1.5 kHz. The downlink data is encoded on a 20 kHz carrier which is used to synchronize the data sampling clocks, and a command synchronization bit sequence is transmitted every 2 ms. The cable simultaneously carries the dc power for the array. Each section of the array has dc-to-dc converters that produce 5 V at 600 mA and ± 15 V at 150 mA to power the electronics and hydrophone elements. The sections are in series so that they use the same current; the voltage necessary for the complete array is 5.1 V times the number of sections. The power loss in the armored uplink cable is proportional to the current and does not change as the number of array sections changes.

A. Uplink Data Stream

This section describes the uplink of acoustic data from the array hydrophones to the topside electronics. The data stream

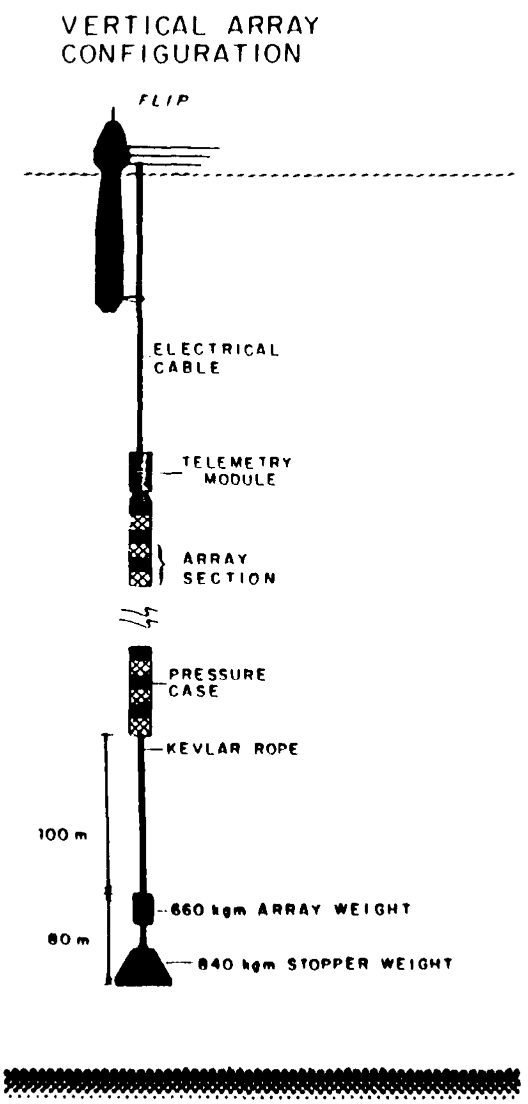

Fig. 1. Vertical deployment configuration of the low-frequency digital acoustic array from the research platform *FLIP*.

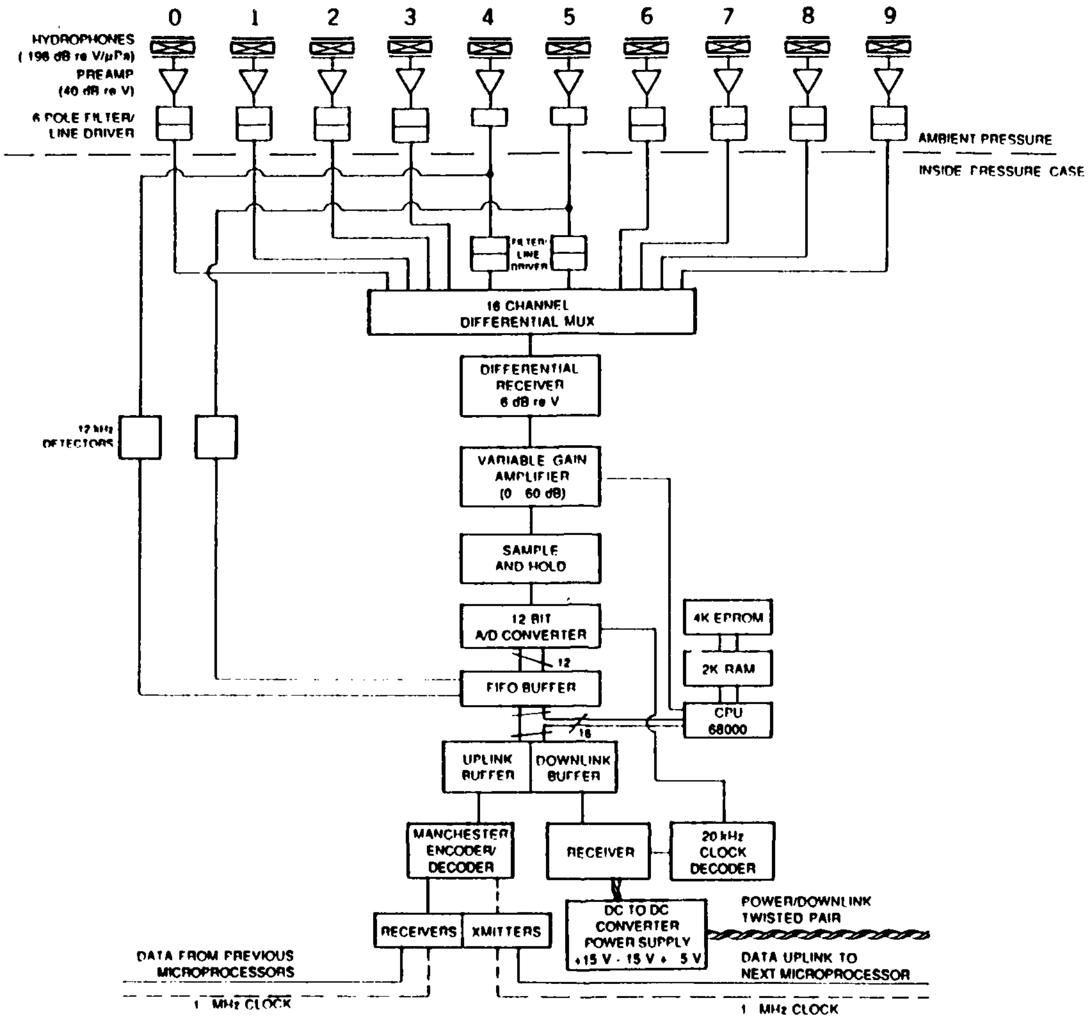

Fig. 2. Array Section Block Diagram. The hydrophone signals are amplified and filtered at the element except for hydrophones 4 and 5 which are filtered within the processor pressure case to allow detection of 12 kHz navigation signals. The low-frequency acoustic signals are multiplexed, amplified, captured by the sample and hold, and converted to digital format before being transmitted to the surface.

originates at the hydrophones. It is amplified, filtered, converted to a digital signal, reformatted, and finally transmitted to the surface, as shown schematically in Fig. 2. The hydrophones are an Aquadyne AQ-1 with sensitivity of −204 dB re 1 V/μPa and a capacitance of 12 nf. AQ-1 hydrophones have been calibrated with respect to pressure, temperature, and frequency and exhibit a well-behaved response over the range of operating conditions [5]. There is a 2 to 3 dB re 1 V/μPa sensitivity increase from low pressure (near surface) to high pressure (6000 m), a 0.2 to 0.3 dB re 1 V/μPa sensitivity increase from 0° to 22°C, and a ±0.2 dB re 1 V/μPa sensitivity variation across a frequency band of 10 to 1000 Hz. There are two hydrophones per array element wired in series for an element sensitivity of −198 dB re 1 V/μPa. Tested at a constant depth (1830 m), the relative phase of the hydrophones is within 0.2°C; changing the depth from just below the surface to full operating depth (3000 m) induced a relative phase change between hydrophones which was less than 0.6°C. The hydrophone output is applied to a very low noise FET preamplifier with 40 dB of gain. The minimum expected acoustic noise level is approximately 45 dB re 1 μPa at 100 Hz [6], and the electrical noise in the preamp is approximately 15 dB below this level. The output is filtered by a six pole low-pass phase-matched filter with a corner frequency at 220 Hz and whose in-band gain is 1. The preamp has a low-frequency cutoff below 10 Hz. A differential line driver is used to transmit the signal a distance of up to 33.75 m to a processor pressure case. There are ten elements per 75 m section with each processor receiving five inputs from the hose on either side. The two elements immediately adjacent to a processor pressure case are filtered within the pressure case rather than at the element to provide 12 kHz acoustic information required for navigating the array.

In the processor pressure case the hydrophone inputs are

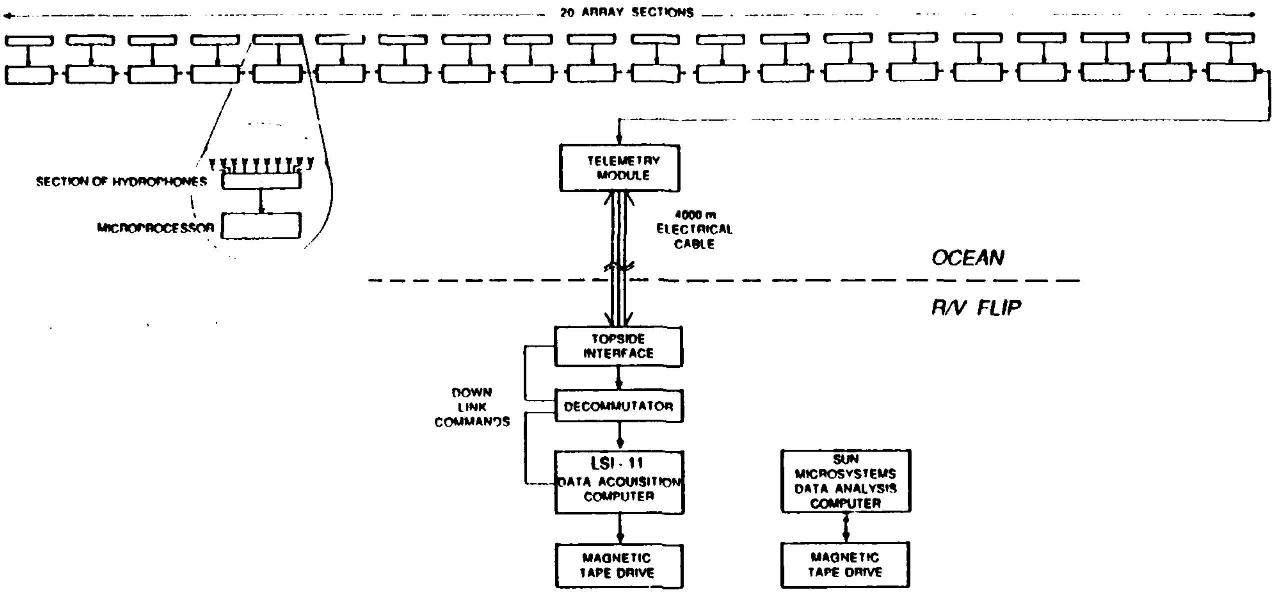

Fig. 3. Array System Diagram. The data path from the hydrophones through the telemetry module to the magnetic tape drive is shown. Further analysis of the data is accomplished by a Sun Microsystems computer.

selected sequentially by a differential multiplexer, converted from differential to single-ended signals, amplified by a programmable variable gain amplifier, captured by a sample-and-hold circuit, and converted to 12-bit digital form. The programmable analog to the digital converter (A/D) clock is synchronous with the 20 kHz downlink carrier and the A/D outputs are stored in a 16-word first-in, first-out (FIFO) register before the processor is interrupted to take the ten data words. Of the 16 bits per word stored in the FIFO, 12 bits are data, 2 bits are from the navigation detectors, and 2 bits are hardware status flags. Prior to low-pass filtering, the signals from the hydrophones adjacent to the pressure case are routed to a 12 kHz detection circuit. This circuit compares the signal level in a narrow band receiver at 12 kHz to the level of a broadband receiver to determine the presence or absence of a 12 kHz acoustic transponder signal. The 1-bit detection from each circuit is multiplexed in with every 12-bit hydrophone word as it is stored in the FIFO. The CPU is a Motorola 68000 operating at 4 MHz with 4K ROM and 2K RAM available. The 4 MHz clock is derived from a 16 MHz crystal which is phase-locked to a 1 MHz clock signal from the telemetry module. The software is interrupt driven with the highest priority interrupt responding to the A/D. The second highest priority interrupt transmits the processed data, and the lowest priority services the downlink synchronization sequence. The signal data are loaded from the FIFO into a large RAM buffer and the CPU then processes the data before presenting it to a Manchester code repeater/encoder for transmission.

The array processors are synchronized by a downlink pattern at a 500 Hz rate. At synchronization, the farthest processor from *FLIP* transmits a synchronization word and the processed data. Each sequential processor repeats the data bit stream from the processor before and inserts its data, followed by a unique ID within a specified time window. At the *FLIP* end of the array is a telemetry module which contains a Manchester decoder, a FIFO, and a synchronous data transmitter. The telemetry module converts the asynchronous data along the array to a continuous data stream up the cable to *FLIP*. It adds frame sync words and null data when the FIFO is empty or busy. The data are driven up the cable at a 1 MHz rate by a high-power amplifier (10 W) to overcome the cable attenuation of approximately 45 dB re 1 V. A bit stream containing data from all the array sections is available every 2 ms at *FLIP*.

B. Topside Electronics

This section describes the topside data acquisition system (Fig. 3). The uplink data are presented to an array interface module where they are amplified and filtered to remove cable phase distortion. A Decom Systems bit synchronizer/decommutator locks to the frame sync word in the data bit stream, and decodes the data to present it to the data acquisition computer (LSI-11). The decommutator hardware transfers data by direct memory access (DMA) to a ring buffer initialized by the LSI-11 data handler software. An 8-word header containing a buffer ID and the timing sequence information are prepended to the ring buffer prior to the transfer to magnetic tape. The tape transfer is a DMA directly from the ring buffer, thus avoiding the overhead in an intermediate-user buffer transfer. A buffer counter tracks the number of transfers and when the tape is full, the handler automatically begins accessing a second tape drive without loss of data. Confirmation of the buffer ID, buffer counter, frame sync word, and processor ID during data processing verifies the integrity of the telemetry system.

C. Downlink Command Stream

This section describes the downlink of commands from the topside data acquisition computer to the array processors. The commands are entered at the operator terminal or from a set of switches on the array interface box and may be sent at any time while the array is operating. The maximum downlink command data rate is limited to 550 baud to ensure accuracy of transmission. Downlink commands may be specified to selected processors or broadcast to all processors. There are three categories of commands as shown in the Appendix: diagnostic, control/initialization, and data format. The diagnostic commands assist in localizing errors in individual processors. Allowable functions are to test memory, read specific memory locations, enter and execute additional machine codes, alter the processor position in the uplink bit stream, turn off the transmitter of the addressed processor so the bit stream is passed around it, and full or partial resets. The control/initialization commands modify array operational parameters. The *select* command determines the order in which hydrophones or other sensors are digitized, allowing selection of other sensors such as depth gauges. The *scan off* command causes only one hydrophone to be digitized per section. The *A/D rate* command selects the rate at which the A/D will digitize the incoming data. The *variable gain* command selects specific gain outputs of a two-stage amplifier. Gains between 5 and 1000 are obtained by selecting a gain of 1, 5, 10, or 20 from the first stage, and 5, 8, 12, or 20 from the second stage. The *data format* command determines the data format to be transmitted. The formats available transmit some combination of test data, hydrophone data, navigation data, and a processor ID. The *navigation receiver* commands select which navigation receiver signal is digitized when the choice of data format restricts the number of navigation bits transmitted.

D. Navigation

Array acoustic navigation is accomplished by detecting the return signals of near-bottom acoustic transponders [7]. A minimum set of three transponders are interrogated from *FLIP* at unique frequencies and their replies are detected by the array. The time of arrival of each reply corresponds to the range between the transponder and the array element. A set of ranges are determined for each array navigation element and input to a program which calculates the element position [8].

The transponders employed were developed for navigation of the MPL deeptow fish [9]. For navigation of the array these transponders are deployed in roughly a one nautical mile equilateral triangle about *FLIP*. They are anchored above the seafloor by a 100 m length of line. To increase the reliability of detection in a noisy environment, the receive circuitry in the transponders (as well as in the array) compares the energy in a narrow band (200 Hz effective bandwidth) about the interrogation frequency to the total energy received in a passband of approximately 1.5 kHz. By adjusting the bandwidth and Q of the recognition circuitry, a short recognition time (> 1 ms) and high-noise rejection are achieved. The interrogation signal for each transponder is unique and upon detection the transponder replies with a 3 ms 12 kHz pulse which is received and recorded by *FLIP* and the array.

The transponder locations must be surveyed to determine their relative positions before using them to navigate the array. The transponder locations are adjusted relative to an arbitary origin by an iterative approach which alternately determines ship positions from known transponder positions and transponder positions from known ship positions using a least squares approach. The initial transponder positions are derived from the GPS satellite navigation positions of the surface ship as each transponder is deployed. A data set containing slant ranges, depths, and initial positions is input to the navigation program. The difference between the calculated and measured positions defines the error.

The horizontal projection (Fig. 4) of the slant range between a given transponder and a given surface ship position (or *FLIP* or an array element) is

$$Hproj(ntr,\ npos) = \sqrt{S^2 - D^2}$$

where ntr indicates a particular transponder, $npos$ indicates a particular fix or position of the surface ship, S is the slant range from the source to that transponder, and D is the transponder depth minus the source depth. The mean squared error is

$$E_{mse} = 1/\hat{N}\Sigma(rngxy - Hproj)^2$$

$$\text{where } rngxy = \sqrt{(x_{ss} - x_{T1})^2 + (y_{ss} - y_{T1})^2}.$$

The horizontal range $rngxy$ is determined by the initial X–Y positions where x_{ss} and y_{ss} represent the position of the surface ship, and N is the number of transponders. If the RMS errors are large the position is adjusted and the process iterates. The adjustment is calculated using the method of steepest descent to follow the mean squared error gradient to a minimum. For known transponder positions, the perturbed ship position in the x direction is

$$x_{ss} = x_{ss} + hE'_{mse}(x_{ss},\ y_{ss})$$

$$x_{ss} = x_{ss} + h * (x_{ss} - x_{T1}) * (rngxy - Hproj)/(rngxy * N)$$

where x_{ss} is the surface ship position, h is the step size, and E'_{mse} is the derivative of the error function with respect to x. The y-direction adjustment is calculated similarly. When the RMS error becomes small the current position is saved.

Assuming the ship positions are known parameters, the transponder positions are adjusted using the same technique. Upon completion of the adjustment loops, the RMS error for all the transponders is evaluated. If this error is not acceptable then the RMS errors associated with each ship position are examined, and any position with an error greater than a specified value is deleted and the process begins again. This method

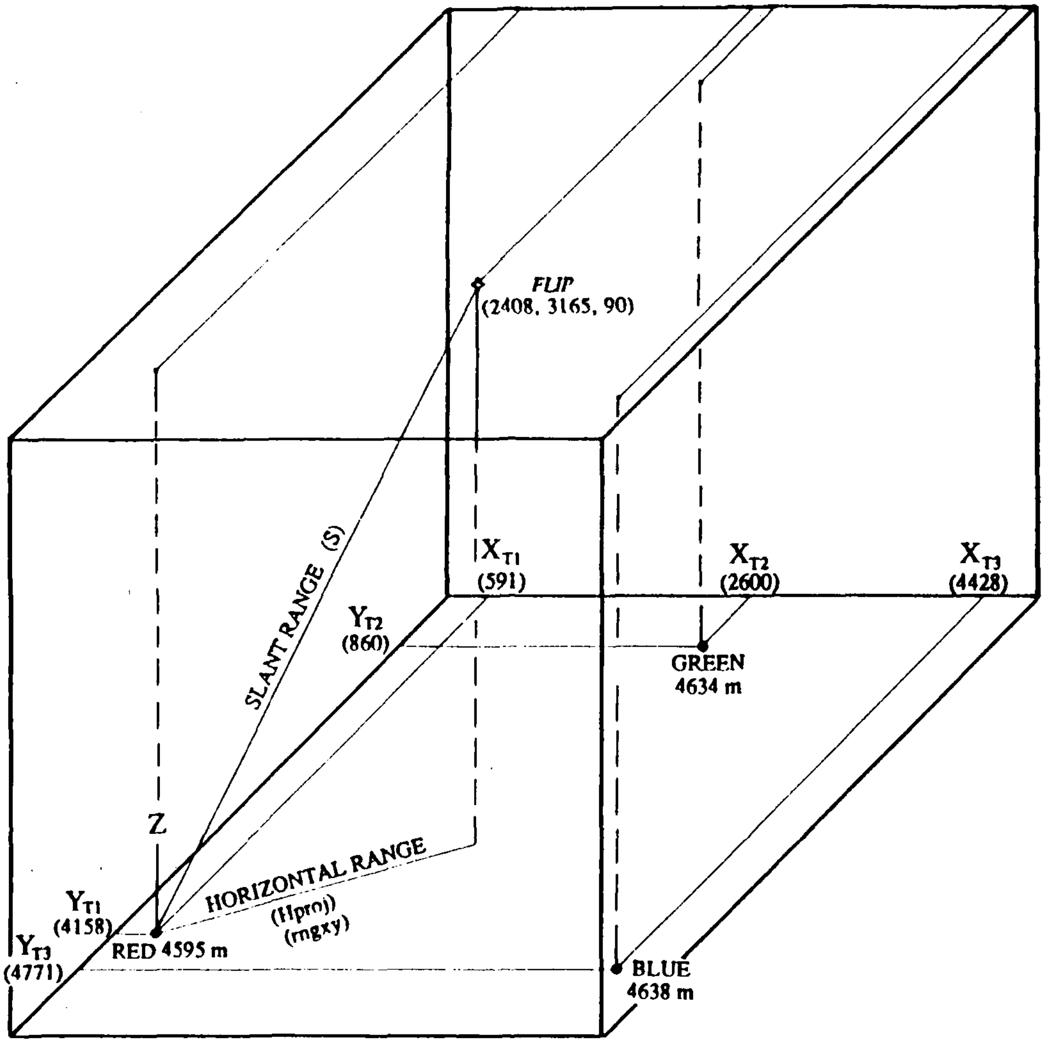

Fig. 4. Navigation Overview. The horizontal projection is estimated first by using the slant range and depths (*Hproj*) and then with the initial *X-Y* positions (*rngxy*).

gives the best transponder locations in a least squares sense which are consistent with the available data.

The array and *FLIP* are navigated similarly. A hydrophone located at the bottom of *FLIP* transmits a series of transponder interrogation sequences (TIS). A TIS consists of four interrogation pulses at 10 second intervals followed by a silent interval. The first three pulses are at the interrogate frequencies of the bottom transponders (10, 10.5, and 11 kHz). Upon receiving an interrogation pulse a bottom transponder replies with a 3 ms pulse at 12 kHz. The fourth TIS pulse is at 12 kHz and is received by the array navigation elements to indicate array depth. The array therefore receives four consecutive 12 kHz pulses, whose timing indicates the transponder ranges and depth beneath *FLIP*. The array samples the 12 kHz pulses at an operator selected rate (typically 0.4 ms). The CPU decimates the data, if necessary, to provide a continuous time series consistent with the number of bits allowed for navigation. The interrogation sequence is synchronized with the data-sampling timebase in the array and the initiation time of the sequence is recorded. The navigation time series establishes the range from each navigation element to each transponder after removal of the *FLIP* to transponder ranges [10]. The ranges are corrected for a varying sound speed profile by integrating over the ray path.

Calculation of the hydrophone position begins by determining the two intersections of the horizontal projection arcs. The third transponder range determines which intersection is used as an initial position. The data are iterated as described above to reduce the RMS errors. Array element relative-location accuracies of a few meters may be achieved by this method. Examples of array element positions from the September 1987 experiment are displayed in Fig. 5, demonstrating the relative motion. The symbols represent the array at 4-hour increments spanning a 24-hour period. There is less than 1° tilt from vertical across the 900 m array aperture. The motion of *FLIP* (Fig. 5(a)) appears to be driven by the increasing northerly wind over the time analyzed (see Fig. 7(h)). The north-south motion of the array (Fig. ...

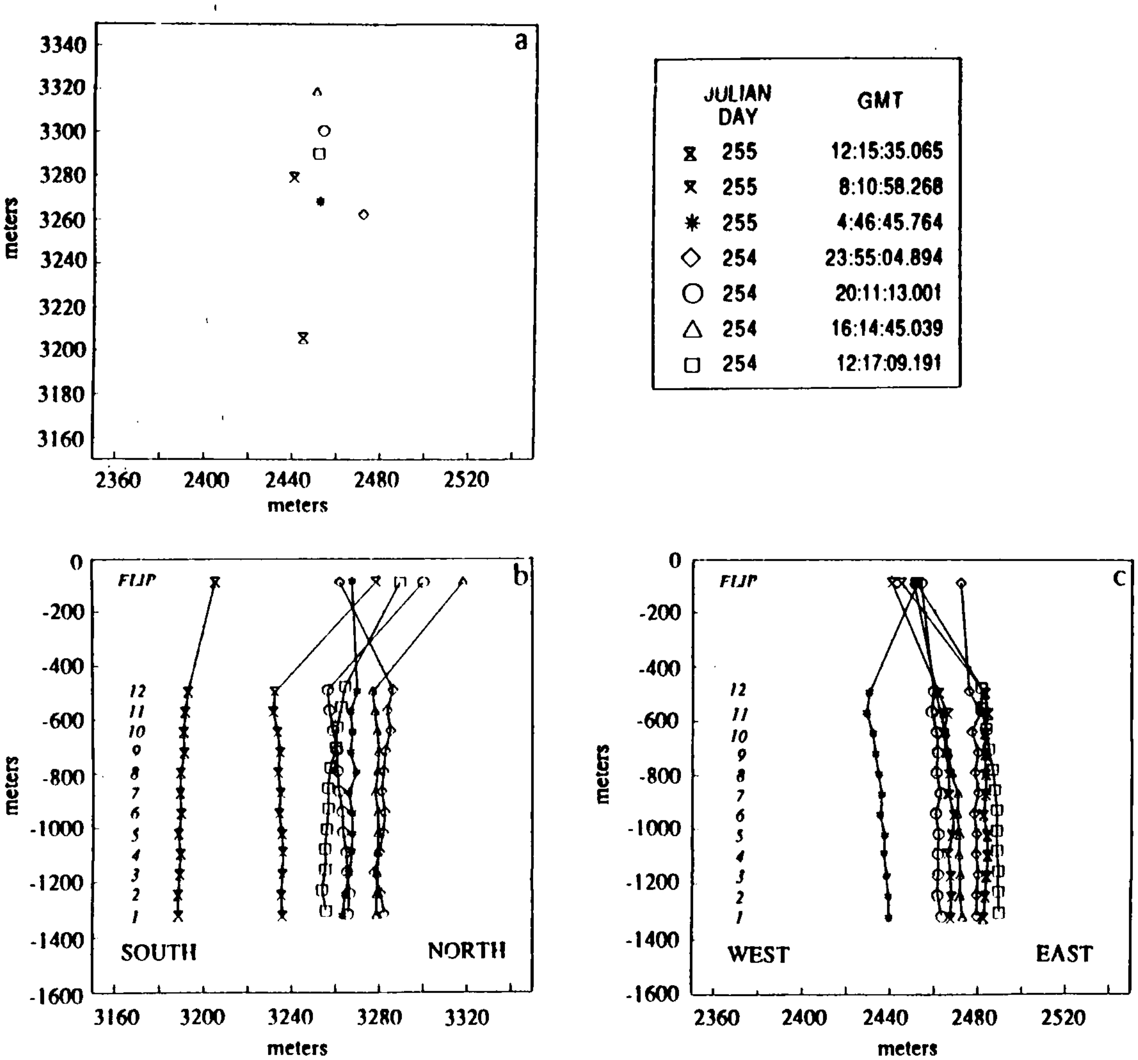

Fig. 5. Navigation Results. A time series of the array position sampled approximately every four hours. The three plots represent (a) a plan view in X (increasing toward the east) and Y (increasing toward the north), (b) X versus depth, and (c) Y versus depth. The scale in (b) and (c) is enhanced in the vertical direction by 8:1.

motion of *FLIP* as well as by tidal motion. The east-west array motion (Fig. 5(c)) is primarily tidal driven, with a semidiurnal period.

III. Experimental Results

Ambient noise data are presented from an experiment conducted in the northeast Pacific during the month of September 1987. Data were collected for 20 days, approximately 400 km southwest of Monterey in 4700 m of water. The programmable data sampling rate was selected at 500 Hz. The array was deployed at various water depths spanning the water column from 400 to 3100 m. Fig. 6 shows the array depth superimposed on the sound speed profile.

Representative hydrophone spectra illustrate the ambient noise variation with depth and wind speed (Fig. 7). The local wind speed varied from 4 to 28 knots during the experiment, as shown in Fig. 7(h). The spectra were obtained by incoherently averaging 11 8192-point FFT's with 50 percent overlap of a Kaiser-Bessel ($\alpha = 2.5$) windowed time series. The nearly uniform spectral level with depth is consistent with previous investigation [1], [11]. There is a distinct difference in the spectral level as wind speed increases (Fig. 7(a)). The spectra at a nominal depth of 1300 m at low wind speed (Fig. 7(c)) and high wind speed (Fig. 7(d)) were bin-averaged and subtracted to provide a measure of wind speed dependent variations. Significant variation in ambient noise was observed for frequencies above 100 Hz and below 25 Hz. Above 100 Hz at all depths, an increasing amplitude and distinct whitening of the spectra are observed at high wind speeds. The observed spectral difference is consistent with previous observations which are diverse in this frequency band (see Table II). Another effect of the wind is the level of mechanical vibration or strum which increases with wind speed. This source is important to the spectral shape below 25 Hz at all wind speeds

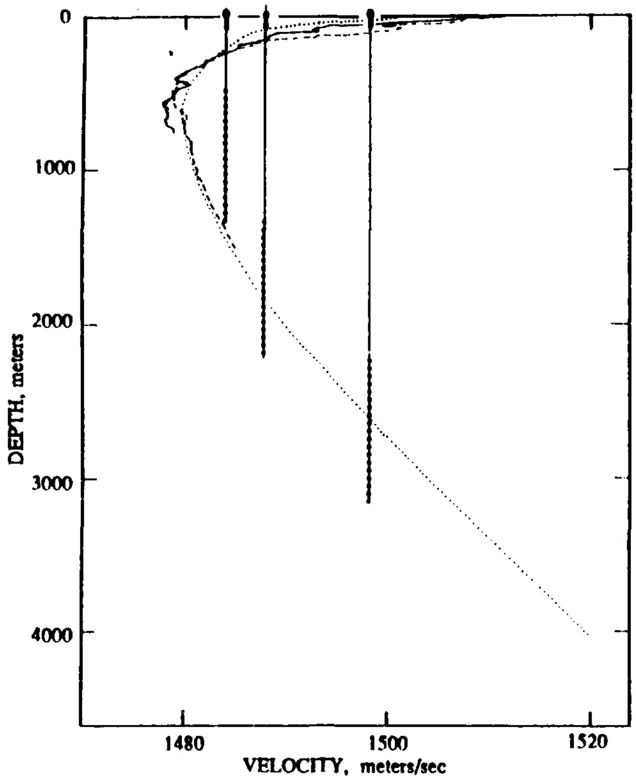

Fig. 6. Array deployment depths for the September 1987 sea test. The three curves represent (a) the historical sound speed profile (dotted) obtained from the National Oceanographic Data Center [12] for the experimental area and time of year (designated area 25C), (b) the sound speed (dashed) obtained from a conductivity, temperature, and depth (CTD) cast deployed from a surface ship approximately 40 km northwest of the array, and (c) the sound speed (solid) calculated with the Clay and Medwin [13] equation using the historical salinity data and an expandable bathymetric thermistor (XBT) deployed from *FLIP*.

but may contribute energy between 25 and 50 Hz at higher wind speeds. The bandwidth of the strum-contaminated noise increases with wind speed and decreases with depth. Preliminary analysis indicates that frequency-wavenumber filtering is effective in removing this noise source as the vibrational modes travel at velocities other than that of acoustic energy. In the band between 20 and 100 Hz the spectral amplitude was independent of wind speed. Shipping may be the dominant noise source for this band as the experiment was in an area of high shipping density. The characteristic spectral "hump" due to shipping noise was observed throughout the experiment. Narrow band 60 Hz harmonics are seen in the spectra and are generated either mechanically or electrically by *FLIP*. There was no evidence of 60 Hz lines during laboratory studies of the array self-noise. The 60 Hz harmonics are narrow band and do not degrade the broadband signal analysis.

A graphic display of the output of 120 acoustic channels recording an air gun source at a range of 500 km is shown in Fig. 8. In this plot, a compressive pressure field or positive voltage excursion is represented as a filled line, and a rarefactive pressure field or negative voltage is represented as an unfilled line. The air gun is seen as a series of impulsive arrivals that appear as both downward-propagating and upward-propagating wavefronts across the array. In addition, two modes of mechanical vibration (strum) are identified in Fig. 8. The first mode is a longitudinal vibration of the kevlar support cable, probably due to vertical motions of *FLIP* pulling on the support cable. This mode propagates with a phase velocity of 1800 m/s and appears as a downward-propagating transient in Fig. 8. The second mode is a transverse vibration of the kevlar support cable, probably excited by water currents. This mode propagates with a phase velocity of 40 m/s and appears as a series of shallow-dipping lines with an interference pattern every 75 m, corresponding to the spacing of the inline pressure cases.

The air-gun array is seen as a contaminant in the spectra of the ambient noise data in Fig. 9(a). Since the operating area of the air run array was shallow, the ocean bottom altered the arrival, part of which is coupled into the deep-sound channel by down-slope conversion and arrives at the array in a multipath structure at a variety of angles. The effect of the profiler is significant in the 125 to 250 Hz band where it dominates the spectra, clearly distorting the 10 dB/octave roll-off of the ambient noise. The profiler was extracted (Fig. 9(b)) by removing the visible signal from the array time series, padding

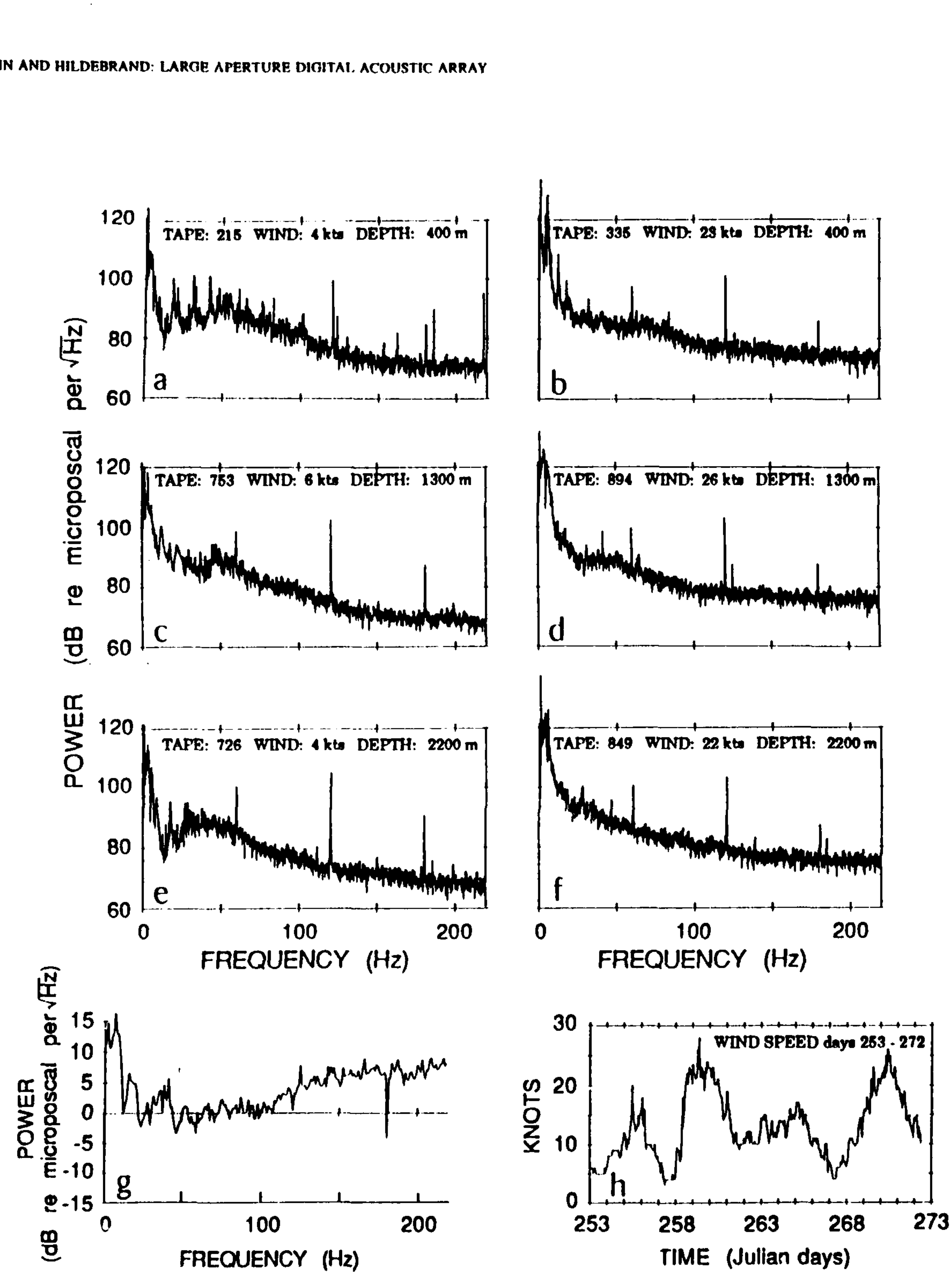

Fig. 7. Ambient Noise variation with respect to wind and depth. Depths indicated are nominal for the top of the array, the hydrophone shown is 675 m deeper. Data were extracted on different days to obtain similar environmental conditions. The narrow band signals are interference from equipment aboard *FLIP*. (a) Wind: 4 kts, Depth: 400 m, Jday: 257. (b) Wind: 28 kts, Depth: 400 m, Jday: 259. (c) Wind: 6 kts, Depth: 1300 m, Jday: 267. (d) Wind: 26 kts, Depth: 1300 m, Jday: 270. (e) Wind: 4 kts, Depth: 2300 m, Jday: 267. (f) Wind: 22 kts, Depth: 2300 M, Jday: 269. (g) Representative spectral difference with wind. (h) Wind speed (kts) versus Julian Day (Jday).

TABLE II
AMBIENT NOISE SPECTRAL VARIATION WITH WIND SPEED

Change in Spectral Level	Change in Wind	Frequency	Reference
dB//μPa/√Hz	kts	Hz	
+18	4-6 to 28-33	200	[1] Urick 1983
+9	10-40	200	[3] Burgess and Kewley 1983
+7	4-6 to 22-28	200	this paper 1988
+7	10-30	150	[11] Morris 1978
+5	18-28	177	[21] Shooter and Gentry 1981
+4	5-28	177	[22] Perrone 1969
0	6-22	200	[15] Hodgkiss and Fisher 1986
-4	low-high	165	[4] Wilson 1983

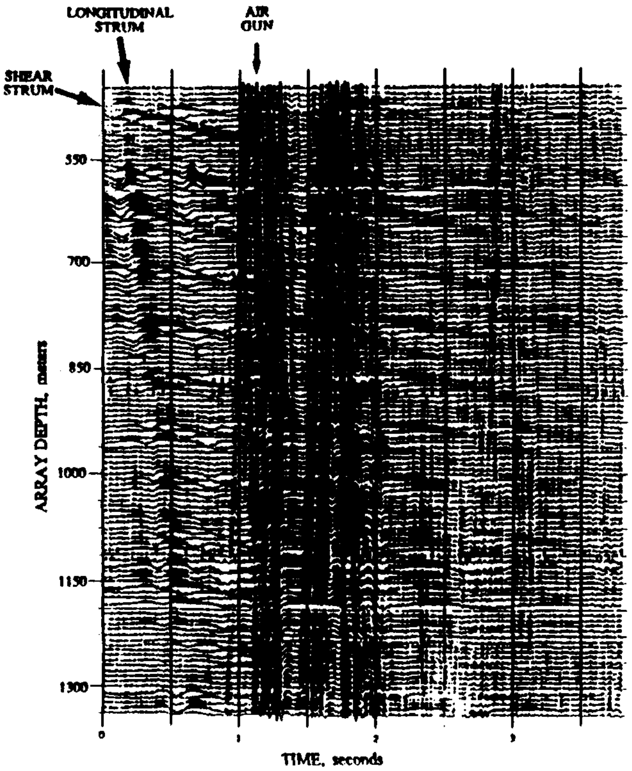

Fig. 8. Time series display of acoustic channels. A graphic display of the acoustic channels shows an air-gun source at a range of 300 miles as well as longitudinal and transverse (shear) strum modes. The time record displayed is 3.5 s. The array hydrophone depths span 400 to 1300 m.

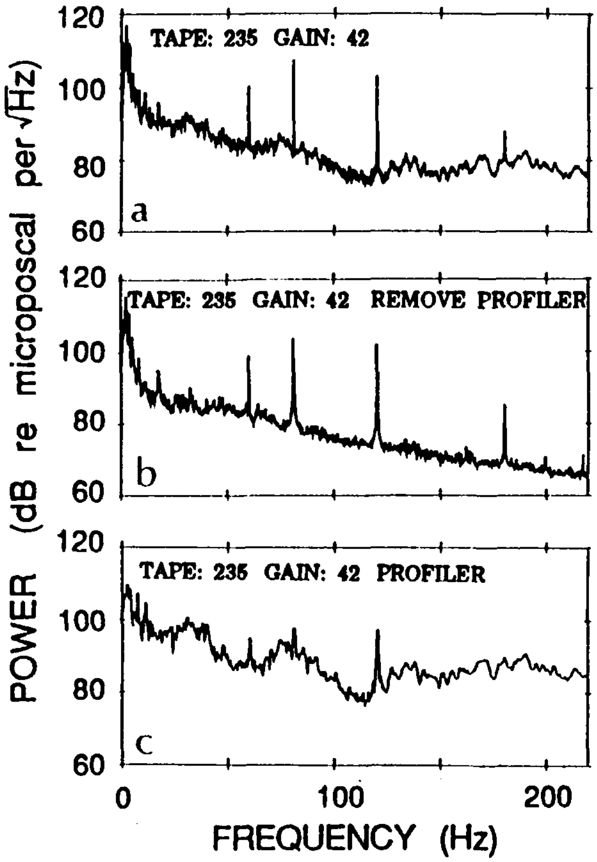

Fig. 9. Seismic profiler contamination. The effect of the air gun signal is seen to be clearly contaminating the ambient noise spectra. (a) Original data acquired at array channel 24. (b) Same data as (a) with profiler signal removed. (c) Profiler signature as seen at the array.

the remaining data to 8192 points, and producing the spectrum as described above with no overlapping. The profiler spectra in Fig. 9(c) was calculated from 800 data points and a rectangular window and shows the ambient noise spectra uncontaminated by the profiler.

IV. Summary

This paper describes the low-frequency digital acoustic array designed and built at the Marine Physical Laboratory. A sea test has been conducted to verify the vertical deployment, telemetry, acoustic navigation, and ambient noise measurement capabilities of the array. Navigation of the array was conducted within an acoustic transponder net. Ambient noise spectra from single array elements were consistent with previous observations of shipping noise in the frequency band between 20 and 100 Hz. At frequencies above 100 Hz sea-surface noise generated by local wind and waves was observed. Current efforts are underway to investigate the vertical directional spectra of low-frequency noise measured by the array.

Appendix

Available array commands are listed below. The left-most hex number is the command byte sent by the data acquisition computer to the array. The last column indicates the type of command: Diagnostic, Initialization, or data Format.

APPENDIX
Available Array Commands

41	DIAG 2 ON		memory test then full init	D
42	SHOW HWID		hwid pos swid oooo	D
43	DIAG 1 ON		analog data test	D
44	DIAG 1 OFF			D
45	SCAN ON		scans through phones	I
46	SCAN OFF		selects only one phone	I
47	SOFT INITIALIZE			D
48	AD RATE	OFF		I
49		5K		I
4A		10K		I
4B		20K		I
4C	NAV RCVR 0			I
4D	NAV RCVR 1			I
4E	ENABLE RAM PROGRAM			D
50-5F	SEL HYD N		N=0 through F	I
60	VAR GAIN	1	stage 1	I
61		5		I
62		10		I
63		20		I
64		5	stage 2	I
65		8		I
66		12		I
67		50		I
68		1000		I
69	DATA FORMAT	6	send 5's (nav0) or A's (nav1)	F
6A		5	10 phones + nav	F
6B		4	2 nav words + 8 phones	F
6C		3	10 phones	F
6D		2	test tape	F
6E		1	listen	F
6F		OFF		F
70-7F	NEW POSITION = N		N=0 through F	DI
80	DIAG 3	OFF	get data from memory location:	D
81		2000	(adad aaaa cccc) address, contents	D
82		2200		D
83		2400		D
84		2820		D
85		28D4		D
86		2900		D
87		2940		D
88		2980		D
89		29C0		D
8A		-----		D
8B		-----		D
8C		2F00		D
8D		2FC0		D
8E		----		D
8F	INCREMENT ADDR IN DIAG 3 ABOVE			D
90	UPLINK OFF			D
91	UPLINK ON			D
92	STORED SINUSOID ON			D
93	STORED SINUSOID OFF			D
99	FULL RESET			D

Acknowledgment

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