

The Seafloor Borehole Array Seismic System (SEABASS) and VLF Ambient Noise

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Abstract: The Seafloor Borehole Array Seismic System (SEABASS) has been developed to measure the pressure and three-dimensional particle velocity of the VLF sound field (2–50 Hz) below the seafloor in the deep ocean. The system consists of four three-component borehole seismometers (with an optional hydrophone), a borehole digitizing unit, and a seafloor control and recording package. The system can be deployed using a wireline re-entry capability from a conventional research vessel in Deep Sea Drilling Project (DSDP) and Ocean Drilling Project (ODP) boreholes. Data from below the seafloor are acquired either on-board the research vessel via coaxial tether or remotely on the seafloor in a self-contained package. If necessary the data module from the seafloor package can be released independently and recovered on the surface. This paper describes the engineering specifications of SEABASS, the tests that were carried out, and preliminary results from an actual deep sea deployment. VLF ambient noise levels beneath the seafloor acquired on the Low Frequency Acoustic-Seismic Experiment (LFASE) are within 20 dB of levels from previous seafloor borehole seismic experiments and from land borehole measurements. The ambient noise observed on LFASE decreases by up to 12 dB in the upper 100 m of the seafloor in a sedimentary environment.

Introduction

The Seafloor Borehole Array Seismic System (SEABASS) was developed to measure the pressure and three-dimensional particle velocity of the VLF sound field (2–50 Hz) below the seafloor in the deep ocean (water depths up to 6 km). (A summary of common acronyms used in this paper is given in Table I.) The system can be deployed from a con-

ventional research vessel in Deep Sea Drilling Project (DSDP) and Ocean Drilling Project (ODP) boreholes (which have re-entry cones) using the wireline re-entry capability (Spiess *et al.*, 1989a, 1992). Data from below the seafloor are acquired either on-board the research vessel via coaxial tether or remotely on the seafloor in a self-contained package.

A review of borehole seismic measurements in the deep sea up to 1987 is given by Mutter and Balch (1987). Prior to the development of the SEABASS system, borehole seismic measurements in the deep sea either were obtained at only a single fixed depth, as in the Marine Seismic System (MSS; Harris *et al.*, 1987; Adair *et al.*, 1987) and the Ocean Sub-bottom Seismometer (OSS; Byrne *et al.*, 1987), or were obtained directly from the drill ship and were contaminated by ship and drill pipe noise (for example, Stephen *et al.*, 1980; Stephen and Harding, 1983; Stephen and Bolmer, 1985). There had been an indication from previous seismic work, both at sea and on land, that borehole seismometers had two major advantages over surface or seafloor seismometers: both ambient noise levels and signal-generated noise levels (bottom reverberation or coda) decreased with depth below the solid surface and signal quality, particularly on horizontal components, was better for borehole receivers because of improved coupling to true earth motion. SEABASS was developed to provide conclusive, *in situ*, quantitative observations to test these hypotheses in a deep sea environment.

TABLE I

Some common acronyms used in this paper

A12G4	CGG Recording Format
BCU	Bottom Control Unit
BIP	Bottom Instrument Package
BRG	Borehole Re-entry Guide
BSF	Below the Seafloor
CIEM	Communication and Interface Electronic Module
CGG	Compagnie Générale de Géophysique
DRU	Data Recording Unit
DSDP	Deep Sea Drilling Project
DTU	Data Telemetry Unit
GOES	Geostationary Operational Environmental Satellite
IU	Interface Unit
LFASE	Low Frequency Acoustic-Seismic Experiment
LOPACS	Low Power Acquisition Control Storage System
MSS	Marine Seismic System
OBS	Ocean Bottom Seismometer
ODP	Ocean Drilling Project
OSS	Ocean Sub-bottom Seismometer
ROSE	Rivera Ocean Seismic Experiment
SOPEMEA	Société pour le Perfectionnement des Matériels et Equipements Aérospatiaux
UTC	Universal Time, Coordinated
VHA	Vertical Hydrophone Array
VSP	Vertical Seismic Profile

SEABASS itself consists of four borehole sondes and a data telemetry unit, based on the Multilock Seismic Tool (Géomécanique and Compagnie Générale de Géophysique, 1987), and a Bottom Instrument Package (BIP), designed and built at Woods Hole Oceanographic Institution (Koelsch *et al.*, 1990; Stephen *et al.*, 1993). Each of the borehole sondes consists of a three-component seismometer (with a natural frequency of 4.5 Hz) and a clamp, to couple the sonde to the borehole wall. The top sonde can have an optional borehole hydrophone attached. The Bottom Instrument Package is designed to internally record up to 41 hours of data (600 Mb) and to operate SEABASS autonomously on the seafloor for periods up to two months.

SEABASS is deployed in the configuration shown in Figure 1. The wireline re-entry technique requires a Borehole Re-entry Guide (BRG) below the borehole array, to locate the borehole on the seafloor, and a thruster above the Bottom Instrument Package, to position the array prior to re-entry. (The BRG and thruster were designed, built and operated by the Marine Physics Laboratory of

Scripps Institute of Oceanography (MPL/SIO). MPL/SIO also carried out the bottom navigation, ship dynamic positioning, borehole re-entry and data telemetry from the BIP to the surface ship.) When SEABASS is in place the four seismic sondes are clamped at fixed positions in the borehole and the Bottom Instrument Package sits in the re-entry cone. During shipboard recording the thruster is maintained within a 100 m watch circle and it is connected to the BIP by a 'slack tether'. The thruster is supported from the surface vessel by an armored, coaxial cable. For autonomous seafloor recording, the 'slack tether' is disconnected from the BIP. Recovery is accomplished by grappling, using the thruster and a hook. If grappling fails, the Data Recording Unit (DRU) alone, a sub-component of the BIP, can be released acoustically, allowing it to float to the surface for recovery.

The system was successfully deployed in the Blake-Bahama Basin (off the coast of Florida) in August–September, 1989, as part of the Low Frequency Acoustic Seismic Experiment (LFASE; Spiess *et al.*, 1989b, 1992; Stephen *et al.*, 1989, 1990). Prior to deployment of the complete system, subsystems were tested in shake-table studies (in Paris, France), two land borehole tests (near Marolles, France, and Traverse City, Michigan) and a system wet test (off Martha's Vineyard, Massachusetts).

This paper presents the specifications of SEABASS, reviews the development and testing procedures that were carried out, and gives examples of the results.

The Modified Multilock Array

OVERVIEW

The borehole array components of SEABASS are based on the Multilock Seismic Tool (Institut Français du Pétrole (1987); Géomécanique and Compagnie Générale de Géophysique, 1987). [The Multilock seismic system was designed by Institut Français du Pétrole. It is presently built by Ateliers Mécaniques de Saint-Gaudens (AMG) and Géomécanique and it is marketed by Compagnie Générale de Géophysique (CGG).] The Multilock system was developed as a Vertical Seismic Profile (VSP) tool for the petroleum industry. VSPs provide interval velocities, at seismic frequencies, of the formation around the borehole and can be used to trace the origin of subsurface reflectors. They are

Seismic Array Deployed and in Tethered Mode

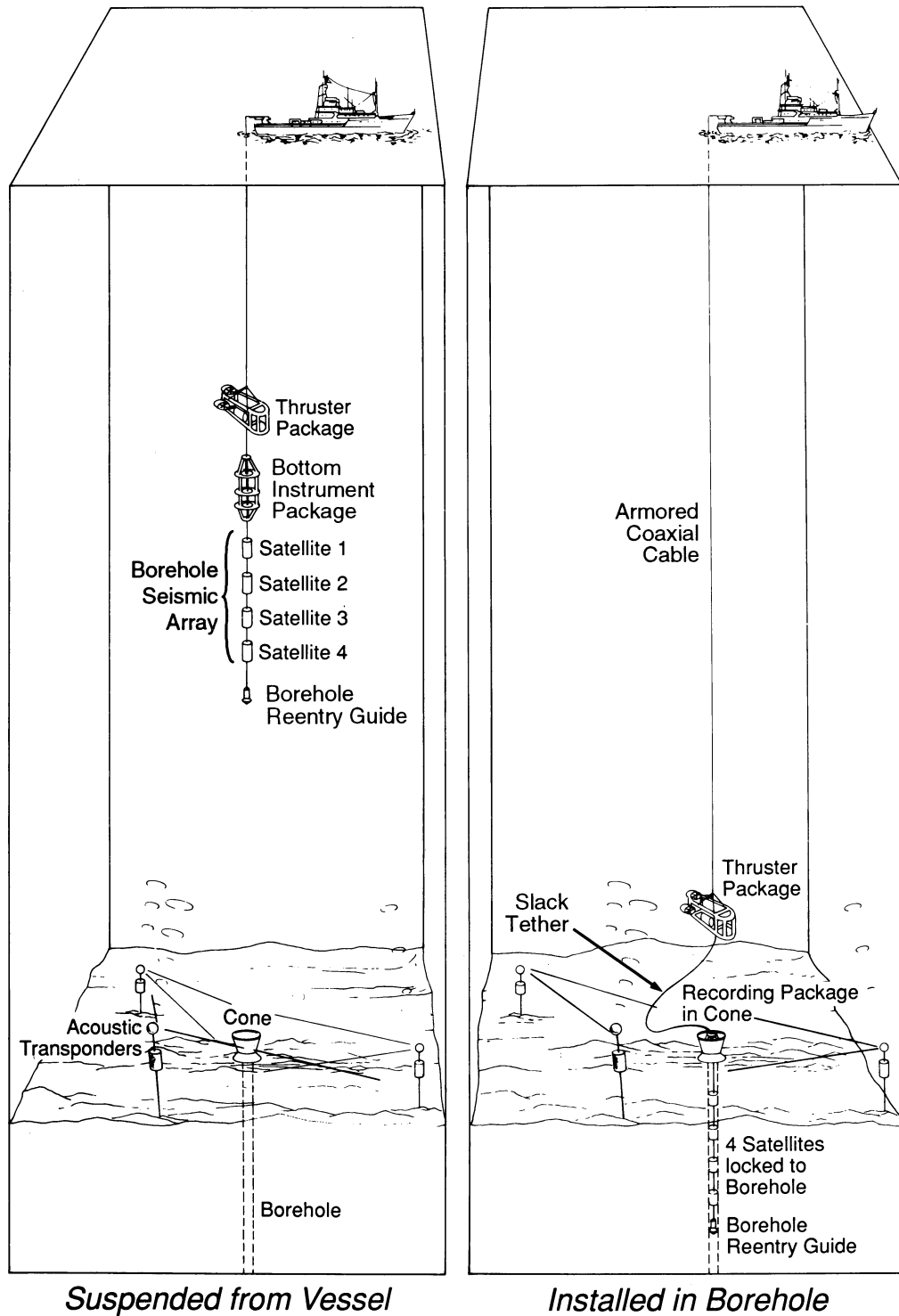


Fig. 1. SEABASS is deployed with a re-entry system like the one used on LFASE. SEABASS consists of the Bottom Instrument Package and the four node borehole array. The Borehole Re-entry Guide is used to locate and enter the borehole and the thruster is used along with dynamic positioning on the ship to position the system above the hole. The left frame shows the system deployed in the water column. The right frame shows the system installed in the borehole in 'tethered mode'. The tether can be disconnected to leave the system operating autonomously on the seafloor.

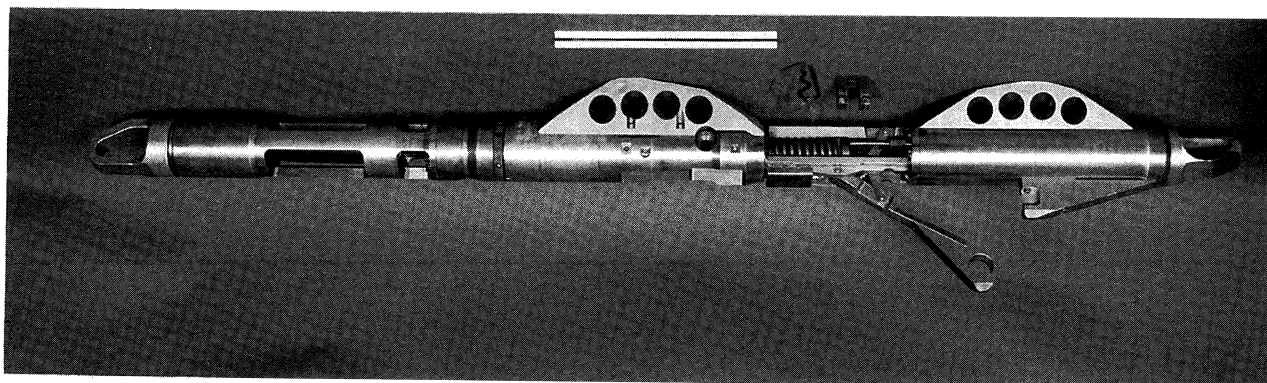


Fig. 2. Each node of the Multilock array on SEABASS consists of a three component seismometer with a clamping arm and pads. The optional borehole hydrophone is attached.

considered to be a valuable adjunct to surface multi-channel seismic profiles when a borehole is available. By using four sondes simultaneously, the Multilock system reduces the cost of acquiring VSP profiles.

Some of the modifications to the Multilock tool that were necessary for SEABASS were: i) The frequency response of the system was changed to 2.5–40 Hz using geophones with a natural frequency of 4.5 Hz; ii) an optional borehole hydrophone was provided for the top node; iii) telemetry and power supply functions were modified for operation over a short cable to other electronics packages and batteries on the BIP frame; and iv) since the modified unit was intended primarily for seafloor use, the temperature specification was reduced from 180 °C to 0–20 °C with the primary operating temperature at 0 °C.

The modified Multilock can be used in three configurations: i) It can be run as a normal four sonde VSP tool on seven conductor logging cable; ii) the system can be run as a fixed borehole array in a land or offshore borehole with the digitizing and acquisition electronics in a recording hut; or iii) the system can be deployed as a fixed array in the deep seafloor with self-contained recording capability as in SEABASS.

MECHANICAL SYSTEMS

Mechanically the borehole array component of SEABASS consists of four satellites (Figure 2) and a Data Telemetry Unit (DTU) housing (Ateliers Mécaniques de Saint-Gaudens, 1988a, 1988b). A selection of arms and removable back pads are available to provide for secure coupling of the satellites in boreholes ranging from 178 mm (7.0

inch) to 407 mm (16.0 in). The clamping arm and two pads are located 120° circumferentially from each other. The DTU is a separate borehole unit which does not have a clamping mechanism.

The cable connecting the four sondes and the DTU is 36 conductor (eighteen twisted pairs) double-armored logging cable with an outside diameter of 16 mm (0.65 in). Shear pins are built into the lower connector of each cable to provide weak links in case a sonde is stuck in the hole. These are designed so that the shear pins will separate before any of the components higher in the string mechanically fail. In the event of a shear pin separation, a clean, well-defined connection is left in the hole that can be 'fished' using a variety of tools on either a wireline or drill string.

ELECTRICAL SYSTEMS

The ground motion transducer in SEABASS is a Mark Products L-15-LBTWHT long-travel geophone with a natural frequency of 4.5 Hz, a coil resistance of 600 Ω and a moving mass of 23 g. Each geophone is damped to 60% of critical with a 2.87 K Ω resistor. Each of the three orthogonal components (one vertical axis and two horizontal axes) consists of two geophones in series. The 'long travel' version of the L-15 geophone operates to specifications with tilts up to 25° for the vertical sensors and up to 5° for the horizontal sensors.

The pressure transducer in SEABASS is a hydrophone built by Ocean and Atmospheric Science, Inc. (Model E-2SD). It has a sensitivity of –187 dB re:1 Volt/Pascal. Since the hydrophone is a capacitive device a hydrophone preamplifier is necessary before sending signals up the cable to the DTU. The hydrophone and its preamplifier are attached to the

top of the first node and the hydrophone signal is substituted for one of the horizontal components in the third node. To reduce confusion in this paper, 'preamplifier' refers only to the hydrophone preamplifier located in the hydrophone housing on the top satellite. There are also twelve 'DTU amplifiers', one for each channel, which are located with the filters in the DTU.

Each of the 12 transducer signals is transmitted analog on a twisted pair of wires to the Data Telemetry Unit (DTU; Géomécanique and Compagnie Générale de Géophysique, 1988b). The DTU contains amplifiers, filters, a 12-channel digitizer, state-of-health electronics and telemetry electronics. The modifications that were made to the DTU for SEABASS are described in Géomécanique (1988b, 1988d). The digitizer in the modified system samples the 12 channels at 2 ms intervals as in the original Multilock, even though the frequency response of the modified system is a factor of four lower. Subsampling for recording purposes is carried out either in the surface Interface Unit during VSPs, or in the Bottom Control Unit (BCU) during seafloor acquisition.

The DTU has a 'system test' function as described in Géomécanique and Compagnie Générale de Géophysique (1988a). It is applied in the DTU *in situ* and consists of a 'geophone test' (a pulse is applied on the geophone output), a 'filter test' (the geophone is disconnected and a pulse is applied on the output of a test resistor), and an 'electronic noise test' (data are acquired with the geophone replaced by the test resistor). A fourth useful test is the 'field noise test' where data are acquired with the geophone in place.

The data transmission amplifier can be switched for low power, short distance transmission (between the DTU and BCU on the seafloor) or high power transmission over a logging cable (for VSPs). The power supply unit in the DTU can also be switched between battery operation (as used for seafloor recording) and logging cable operation (as used in VSP operations with a surface power supply). In local battery operation the power consumption of the DTU is 9.1 watts.

SURFACE INTERFACE

The surface equipment for the Multilock system in VSP mode consists of a Control Box for the clamping arms and an Interface Unit (IU) to operate and process data from the downhole Data Telemetry Unit (DTU). The Control Box simply transmits the

necessary pulse to release the clamping arms. Once released the arms stay open and the tools are dragged up the hole. The Interface Unit has many functions (Géomécanique and Compagnie Générale de Géophysique, 1988a, 1988c). It triggers a test sequence in the DTU to carry out state-of-health checks and processes the results for quick-look display. It also demultiplexes the data stream and converts the 12 digital channels to analog outputs for display on an oscilloscope or ultraviolet paper recorder. The modifications that were made to the IU for SEABASS are described in Géomécanique (1988b, 1988c).

The Bottom Instrument Package

OVERVIEW

The Bottom Instrument Package (BIP) sits in the re-entry cone during seafloor operations and controls the borehole array functions (Figure 3). The BIP can be either tethered to the surface ship (via the soft tether, thruster and 0.68-in coaxial cable) or it can function autonomously on the seafloor.

In both tethered and autonomous seafloor operation the BIP has the following functions: i) In order to conserve power in the seafloor batteries, all electronics in the seafloor system are switched off between data acquisition intervals except for a low power 'Wake Up' circuit. ii) The BIP automatically subsamples the 2 ms data stream from the DTU to an 8 ms data stream and maintains the functionality of the auxiliary channels. (The anti-aliasing filters in the DTU conform to the lower sampling rate.) iii) An internal clock on the BIP provides accurate first sample times for each data record. iv) A scan count is tagged to each scan to check for integrity in the data telemetry and recording stages. v) State-of-health functions are monitored.

During tethered operation the BIP has the following functions: i) On surface command the BIP passes the signal to release the clamping arms in the four borehole sondes; ii) the BIP telemeters the digitized seismic data stream to the surface; iii) on either electrical command (via the tether) or acoustic command (via acoustic transponders on the BIP) the tether can be released to initiate 'sea floor recording' mode; iv) the BCU clock on the seafloor can be strobed to compare its time with the ship-board GOES clock. And clock drifts can be detected *in situ* and corrections can be applied in post processing.

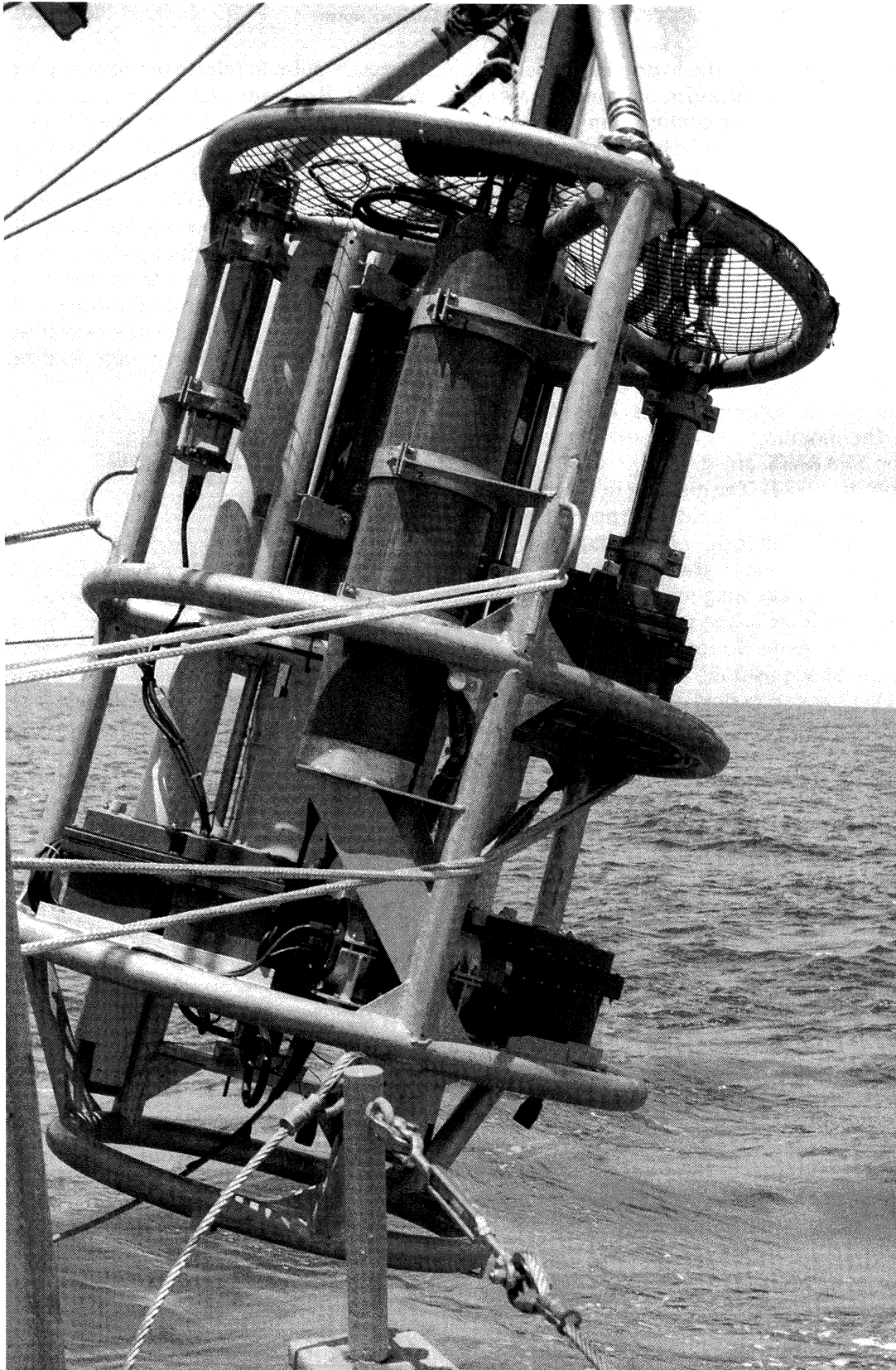


Fig. 3. The Bottom Instrument Package (BIP) is designed to sit in the re-entry cone on the seafloor. It contains command and control electronics, batteries and data recorders.

During autonomous seafloor operation the BIP has the following functions: i) The data stream is recorded on optical disks in the Data Recording Unit (DRU); records are acquired on a preprogrammed schedule or on acoustic command; ii) on acoustic command the DRU can be released to float to the surface; and iii) 'watchdog' circuitry checks to ensure that the microprocessor in the Bottom Control Unit (BCU) is functioning and, if not, reboots the microprocessor.

MECHANICAL SYSTEMS

The Bottom Instrument Package (BIP) frame contains all of the pressure housings for the seafloor equipment including the DRU (with release system), BCU, DTU, cable cutter, cable release, two acoustic releases, six batteries (five batteries for the BCU and one battery for the BRG), and the television for the re-entry operation (Bocconcelli *et al.*, 1991). The BIP fits in the re-entry cone on the seafloor (Figure 4; Deep Sea Drilling Project, 1983) and protrudes at least 1 m above the edge of the cone so that it can be recovered by grappling.

Since the DRU contains the experimental data, its recovery is imperative. If the bottom frame is stuck in the re-entry cone or the thruster is unable to grapple the frame, then the DRU can be released on acoustic command to float to the surface. For this purpose it is fabricated as a buoyant module which can be launched from the BIP on acoustic command (Figure 5).

The acoustic transponders provide communication with the BIP when the tether is disconnected or inactive. Acoustic commands can be used to disconnect the tether, release the DRU or initiate a data acquisition interval. Both transponders have the same functionality and two are used to provide redundancy.

On either electrical command over the tether or on acoustic command via one of the two transponders, the cable release device releases the tether from the top of the BIP. This action automatically places the BCU in autonomous seafloor operation mode.

CONTROL FUNCTIONS

The subsea computer in the BCU controls the sequence of events for all activities in SEABASS (Figure 6). The processor for the BCU is a low power CMOS version of a PC/XT using an 80C88 processor chip. The operating system is ROM-based MS-DOS.

To conserve power in the seafloor batteries during the autonomous portion of a deployment, all of the electronics in SEABASS are turned off between data acquisition intervals except for a low power 'Watchdog and Wake Up' circuit. Five events can trigger the circuit to turn on the SEABASS electronics: i) SEABASS is always turned on if power is being supplied from the surface ship either via the coaxial tether or a shipboard umbilical (MPL Power Detect). ii) In the event the shipboard power is not available, but the telemetry link is still active, SEABASS turns on when any signals are received on the telemetry link (Command Link Sense). iii) An acoustic command to one of two transponders mounted on the BIP activates SEABASS and initiates a data acquisition interval (Transponder). iv) An alarm signal from the main BCU clock wakes up the electronics. (For LFASE the main BCU clock was programmed to set off an alarm every 2 hours to trigger a 6-minute data acquisition interval.) v) A 'bark' from the 'watchdog' circuit wakes up the electronics. The 'watchdog' circuit attempts to correct any problems that occur if the system fails to respond, 'hangs-up', or misses a normal 'wake up'.

There are five ways to initiate a data acquisition interval: i) A background recording schedule is programmed directly into software to acquire a 6-minute record every 2 hours. ii) The user can specify up to 256 special 'wake up' times and durations which are stored in Electrically Erasable Programmable Read Only Memory (EEPROM). This schedule can be loaded or changed at any time prior to terminating the telemetry link. iii) An acoustic command initiates a 1-hour recording window. iv) During shipboard recording arbitrary start times and durations of an acquisition interval can be entered from the surface. v) Also during shipboard recording, a standard system test of the array can be activated.

CLOCKS AND TIMING

SEABASS, in seafloor recording mode, requires accurate timing in order to monitor events, such as earthquakes, and to acquire seismic refraction profiles. In earthquake monitoring, events are identified by the absolute time [in Universal Time (UTC) to an accuracy of one second] at which they occur. In seismic refraction profiles absolute time (to an accuracy of one second) is required to obtain ranges and bearings from the navigation data of the shooting ship and accurate relative times from the shot

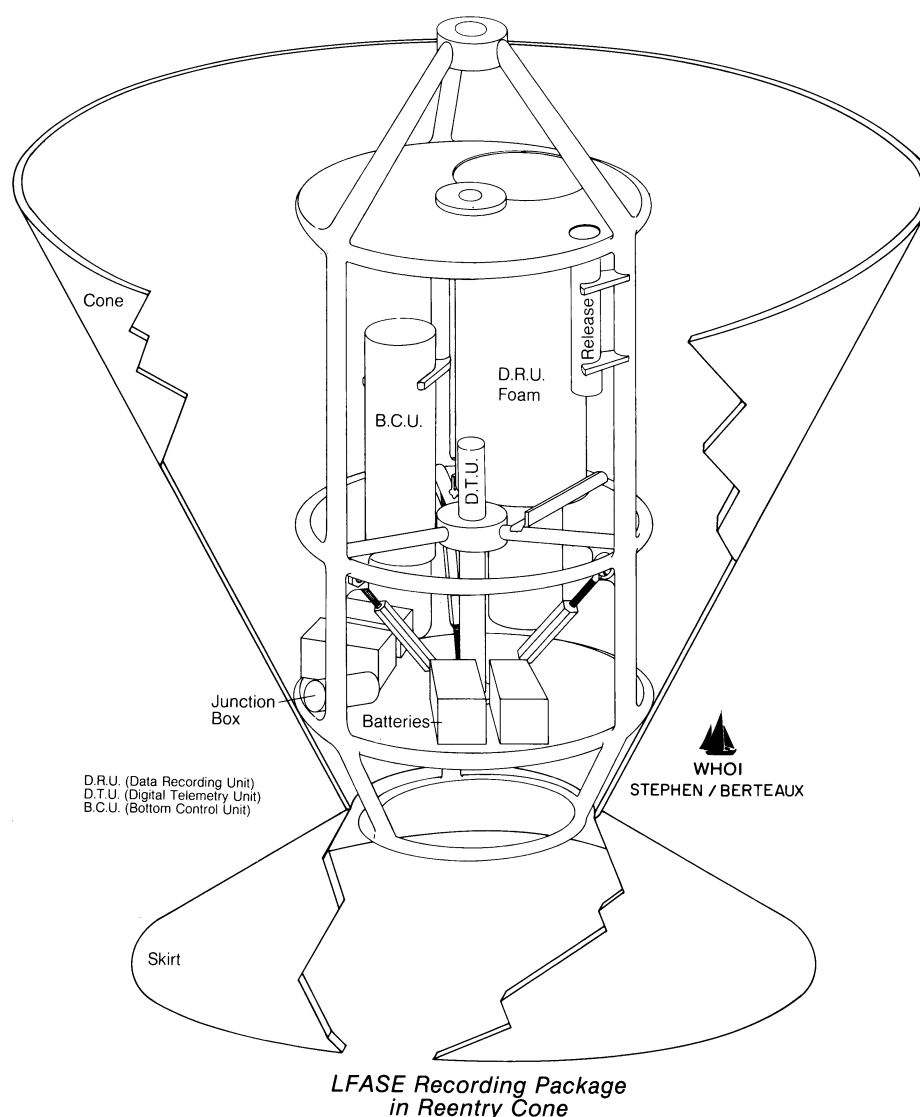


Fig. 4. This schematic diagram of the BIP in the re-entry cone shows the location of the principal mechanical components on the frame. For scale, the BIP is 3.66 m (12 ft) high and has a maximum diameter of 1.83 m (6 ft).

to the receivers (to within 20 ms) are required to measure meaningful velocities and depths for studying earth structure. In both applications, advanced array processing of the digital data requires extremely accurate (to within 50 μ s) relative times between samples on adjacent channels. This section discusses how timing to the required accuracy is carried out on SEABASS.

Three timing devices are used in a SEABASS deployment. i) An oscillator in the DTU controls the digitizing process of the 12 channels from the bore-hole array. Very accurate relative times are obtained. ii) Absolute 'instrument' time for the recorded data is provided by a high precision clock

mounted in the Bottom Control Unit. This is the time that is written on all seismic data records in the BCU and on-board ship. iii) Instrument time is referenced to Universal Time by calibrating the BCU clock with time from a GOES satellite. The calibration factor is applied during the data reduction stage so that all times in the laboratory (and data exchange) format are absolute GOES/UTC times.

If the aging and temperature drifts of the BCU clock and DTU sampling rate oscillators are taken into consideration, we can obtain GOES/UTC time of samples in the data stream to 1 ms. Since data is sampled every 8 ms we can obtain the time of a seismic event in the data to ± 5 ms.

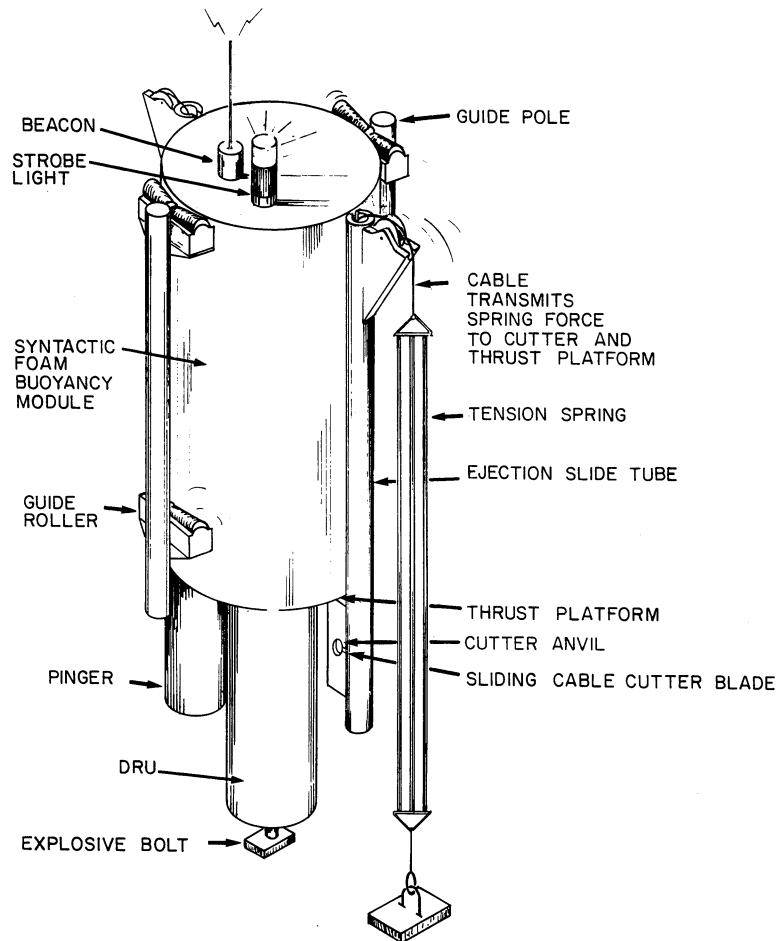


Fig. 5. The Data Recording Unit (DRU), which contains all data recorded on the seafloor, is installed in a buoyant package which can be released if necessary from the BIP by acoustic command. For scale the total length of the DRU is 1.85 m (73 in), the syntactic foam is 1.26 m (50 in) long and has an outside diameter of 0.61 m (2 ft).

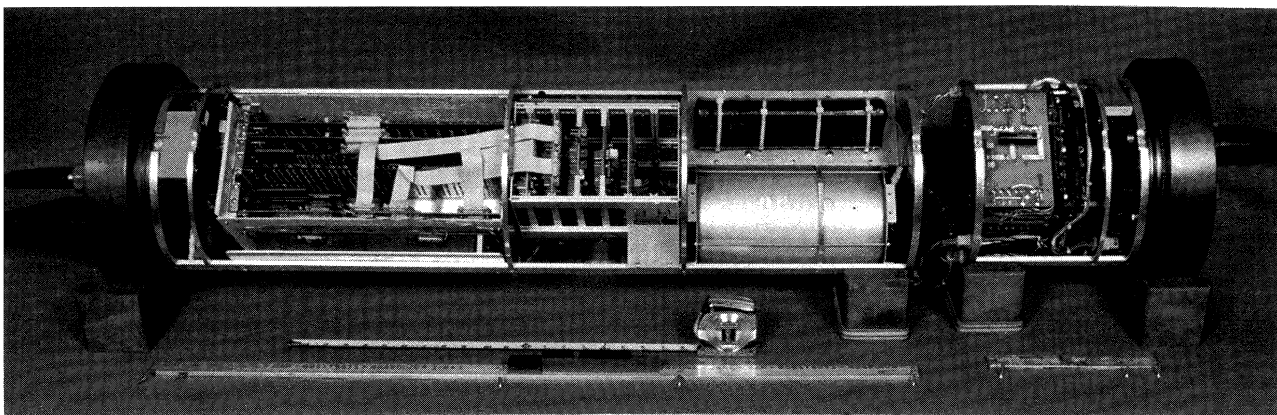


Fig. 6. This photograph shows the BCU electronics. The watchdog, wake-up and control logic, LOPACS computer, high precision clock, CGG interface, CGG data buffer and control logic and the telemetry unit are contained in the Bottom Control Unit housing.

(At-sea tests on LFASE indicated that the GOES satellite gives Universal Time, as received on WWV (the National Bureau of Standards Radio Station) and SATNAV (Satellite Navigation System), with an

accuracy of ± 1.6 ms. Peal (1991) has shown that these discrepancies are caused by diurnal variations in the satellite location and that appropriate corrections can be made to obtain accuracies of 100–200 μ s.)

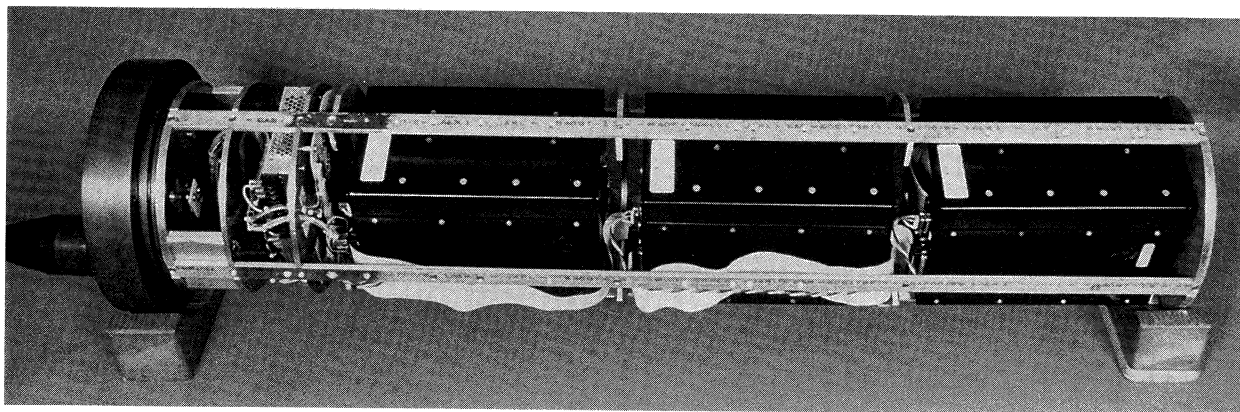


Fig. 7. This photograph shows the three optical disk recorders and the power supply and interface electronics in the DRU module.

(We did not use a temperature-controlled oscillator because these are insufficiently accurate and we did not use an oven-controlled oscillator because these consume too much power for long-term deployments.)

SEAFLOOR PROCESSING AND TELEMTRY

The BCU receives a 128 kbit s^{-1} serial bit stream from the DTU, corresponding to the 12 geophone (or 11 geophone plus hydrophone) channels sampled at 2 ms plus auxiliary channel data. Since the frequency band of the system (2–50 Hz) does not require such fine sampling, the data stream is sub-sampled every fourth sample, resulting in an acceptable transmission rate of 32 kbit s^{-1} and an acceptable data volume. At this rate each data channel is sampled 125 times per second.

The microcontroller (on the seafloor) also numbers each scan by placing a counter in one unused 16-bit data word. The data reduction system ashore reads this 'scan counter' to detect any data drop-outs that may have occurred in the telemetry, recording or data transcription stages.

The data are telemetered over a coaxial cable in the tether, through the thruster, and over the 0.68-in coaxial cable to the surface. A communication and interface electronic module (CIEM), designed and supplied by MPL/SIO, is mounted in the BCU housing. The CIEM supports: i) The video/power and engineering data channels to the BRG. These signals, which are necessary for the re-entry function, are carried on two twisted pairs from the BCU to the BRG, and totally by-pass all of the SEABASS electronics. ii) A full duplex 2400-baud telemetry link for BCU communications. ii) A high speed (32 kbit s^{-1}) one-way data link to transmit the seismic data to the

ship. iv) A 28-V power supply line that is also used to trigger the 'Arm Release' when the command is given.

SHIPBOARD RECORDING

A PC/AT desktop computer on-board the host vessel is used as a terminal to the BCU computer and as a recording system for the high bandwidth data telemetry channel. A data buffer, functionally similar to the one deployed in the BCU, is installed in the back plane of the PC/AT. A laboratory version of the optical disk drive records the seismic data on-board ship in the same format as the recorders in the DRU. Disks recorded on one system are interchangeable with the other system. Regardless of the acquisition interval the data stream is telemetered in real time to the surface and recorded continuously. The digital data stream is also passed in real time to the Multilock Interface Unit (IU) where state-of-health and quicklook functions are carried out.

SEAFLOOR RECORDING

Three optical drives are mounted in the DRU (Figure 7). The total capacity is 600 Mb (41 hrs of data). The drives are mounted in shock-resistant housings and operate in any orientation and at temperatures well below 0°C .

There are three ways that a data acquisition interval can be implemented. i) A fixed interval and duration is written into the control software prior to loading it on EPROM (Electrically Programmable Read Only Memory). This will ensure a minimum, background recording program whenever the BCU computer is operational. On LFASE

these 'hardwired' values were set to acquire a 6-min record every 2 hours. ii) In addition to this 'background' recording window, and overriding it if necessary, up to 256 special windows can be defined. These are stored on EEPROM as a start time and a duration. iii) Also, on acoustic command, via the acoustic transponders mounted on the BIP, a recording window can be initiated with a 1-hour duration. In the event that the tether is disconnected from the BIP prematurely this permits the receiving ship or the shooting ship to activate a large window in which to collect controlled source data.

For acquisition intervals of six minutes or less, the data are stored on RAM during the interval and dumped to optical disk after the data have been acquired. For intervals longer than six minutes the data are only buffered on RAM and are written continuously to optical disk throughout the recording window. (During seafloor recording on LFASE, mechanical noise from the optical disk recorder was observed on the borehole sensors. So acquisitions taken over intervals six minutes or less did not show the recorder noise and were of slightly better quality than the longer records.)

POWER CONSUMPTION

Power consumption of SEABASS can be considered in four parts. The clock and wake-up circuits, which are active when the BIP is 'asleep', only draw 3 mamps. The CPU computer in stand-by mode draws 380 mamps. The DTU, which runs during data acquisition intervals, draws 340 mamps. The DRU recorders, which run while data are being written to the optical disks, draw 1.07 amps. All systems run at 24 v.

There are two recording modes. In the first mode, data is acquired on RAM during the acquisition interval and written to disk after the acquisition. Total consumption in this mode is 1.06 kwh. In the second mode data are written to disk as it is being acquired. Total consumption in this mode allowing for two months on the seafloor is 1.88 kwh.

In an actual deployment such as LFASE the acquisition intervals vary between the two modes. Windows less than 6 min (the capacity of RAM) are scheduled to extend the total observation period. Longer windows, up to an hour, are acquired to get good statistics for the low frequency energy. Additional power is also required if the system malfunctions or if the BCU must search the recorders for available space prior to writing a file.

After the tether is disconnected, power is supplied from batteries mounted on the BIP. For the worst

case, where acquisition and recording occur simultaneously (1.88 kwh), SEABASS requires at least three batteries. On LFASE two additional batteries were used to allow for a safety factor in case a whole battery failed and to provide extra power in the case of subsystem malfunctions. The BCU clock and acoustic transponders have their own independent power supplies.

QUICKLOOK SHIPBOARD PROCESSING

The shipboard components of SEABASS provide three ways to check data quality in real time or near-real time while in tethered mode. i) In the Multilock Interface Unit (IU) the data are demultiplexed and passed through a digital-to-analog converter (DAC) which allows all 12 channels to be displayed on an oscillographic recorder or oscilloscope. (The analog output at this stage is used just to monitor events and the accuracy of the DAC is not an issue.) ii) The SEABASS data, which are demultiplexed in the IU, can be processed and displayed in the same fashion as data from the basic Multilock. iii) In order to check that data are being recorded correctly on the optical disk we have a separate Quicklook System (QLS) in the lab based on a third PC/AT. Software has been written to read data from the optical disk, to check the optical disk files for scan count and read errors and to display the data in a variety of formats. The Quicklook System is particularly convenient for generating figures for the Shipboard Report.

POST-DEPLOYMENT PROCESSING

Post-deployment processing of SEABASS data consists of six general tasks: i) Checking the data quality (for scan count errors, read errors, clipped or overloaded values, etc.); ii) converting all the data from field format to a convenient laboratory format, for storage and processing, and to an exchange format, for distribution to other labs participating in the experiment; iii) generating acquisition summaries in terms of RMS signal levels for the whole experiment; iv) computing spectra, coherence plots, and third octave band summaries of the ambient noise data and a limited amount of controlled source data; v) generating record sections of the controlled source data and maps of the shooting lines; and vi) computing the orientation of the horizontal sensors based on polarization analysis of the controlled source data. An overview of the post-deployment processing used on LFASE is given by Little *et al.* (1990a) and Bolmer *et al.* (1991).

A convenient format for in-house processing and data exchange is ROSE format which was developed for marine seismic experiments in which both ambient noise and controlled source files were acquired (Little *et al.*, 1990b). When SEABASS is used in VSP mode, as in the Michigan borehole test, the exchange format is SEG-Y (Barry *et al.*, 1975), which is widely used in the petroleum exploration industry.

A convenient way to summarize the data is to plot the root-mean-square (RMS) value in decibels (dB) for a given window length (for example, 10 secs) and interval (for example, 60 secs) for channel 1 (the vertical component of the top satellite) for all of the data acquired during the experiment as a function of time (Figure 8). On the same figure we show when the explosive and airgun sources were fired, when other seismometers in the experiment were recording and when earthquakes occurred that may have been detectable. This display is quite useful in assessing the amount of data acquired in each phase of an experiment, identifying interesting time intervals and in determining quiet ambient noise periods.

In order to reduce large quantities of ambient noise data to a manageable size we reduce whole spectra to six numbers representing the average power spectral density in third octave bands centered at 1, 2, 4, 8, 16, and 32 Hz and plot these, for various subsets of the 12 channels, as a function of time during the deployment (Figure 9). This type of plot contains frequency information which is not available in the RMS summaries and it is easy to compare noise levels between different sensors. Similar plots are generated to display the coherence (or cross correlation) between sensors.

Design Considerations and Specifications

FIELD VALUES OF PRESSURE AND GROUND VELOCITY

At the time we designed SEABASS we did not have simultaneous pressure and ground velocity values for signals and ambient noise in the frequency range of interest in boreholes on the seafloor or on land. The test procedures we carried out in Marolles, in Michigan and at sea have provided these values and they can be used for future designs.

Table II presents ambient noise and controlled source levels as one-third octave band averages for frequencies from 2.0 to 32 Hz. The data are based

on a vertical geophone co-located (within 1.5 m) with a borehole hydrophone. In the two land sites, Marolles and Michigan, the sensors are at 1540 and 50 m depth, respectively. At the seafloor (LFASE) site the sensors are at 10 m BSF. In all tests the results displayed are acquired in cased holes.

Table II shows clearly that the ratio of pressure in a borehole to the vertical motion of the borehole wall in field units varies by almost 60 dB (from -23 to -82 dB) depending on frequency, geographic location, depth in the well and signal type (ambient noise, airgun, land airgun, etc.). In fact even for ambient noise in land boreholes at the same frequency the ratio of geophone to hydrophone response varies by over 12 dB between holes. There is no simple relationship between the observed pressure and vertical particle velocity.

On the seafloor the ratio of geophone to hydrophone response has comparable levels over the band for ambient noise (-72 to -82 dB) and surface airgun shots (-65 and -72 dB). However in Michigan the geophone to hydrophone response ratio for ambient noise is about 20 dB greater (-44 to -64 dB) than on the seafloor and for the airgun source the ratio is 40-50 dB greater (-23 to -37 dB) than on the seafloor.

In designing systems to acquire both hydrophone and geophone data in boreholes it is necessary to consider the environment and objectives. Optimum gain strategies will differ for ambient noise studies, marine reflection/refraction studies or land source studies.

INSTRUMENT AND FIELD NOISE

One application of SEABASS is to measure the ambient seismic noise in the seafloor in the frequency band 2 to 50 Hz. Two questions immediately arise. Is the geophone used in SEABASS, the Mark Products L-15-LBTWHT, sensitive enough to measure true ambient noise levels? Is the electronic noise of the sensors and amplifiers (that is, of the modified CGG Multilock) less than the signal generated by seafloor ambient noise?

Melton (1976) and Riedesel *et al.*, (1990) give excellent reviews of the issues involved in the sensitivity of inertial seismometers and electronic noise of amplifiers. The sensitivity of the seismometer is limited by the Brownian motion of the air molecules which hit the seismometer mass. The Brownian noise level of the SEABASS sensors (two L-15-LBTWHTs in series per channel) at room temperature is $6.6 \times 10 \text{ (nm s}^{-2}\text{)}^2/\text{Hz}$. This is con-

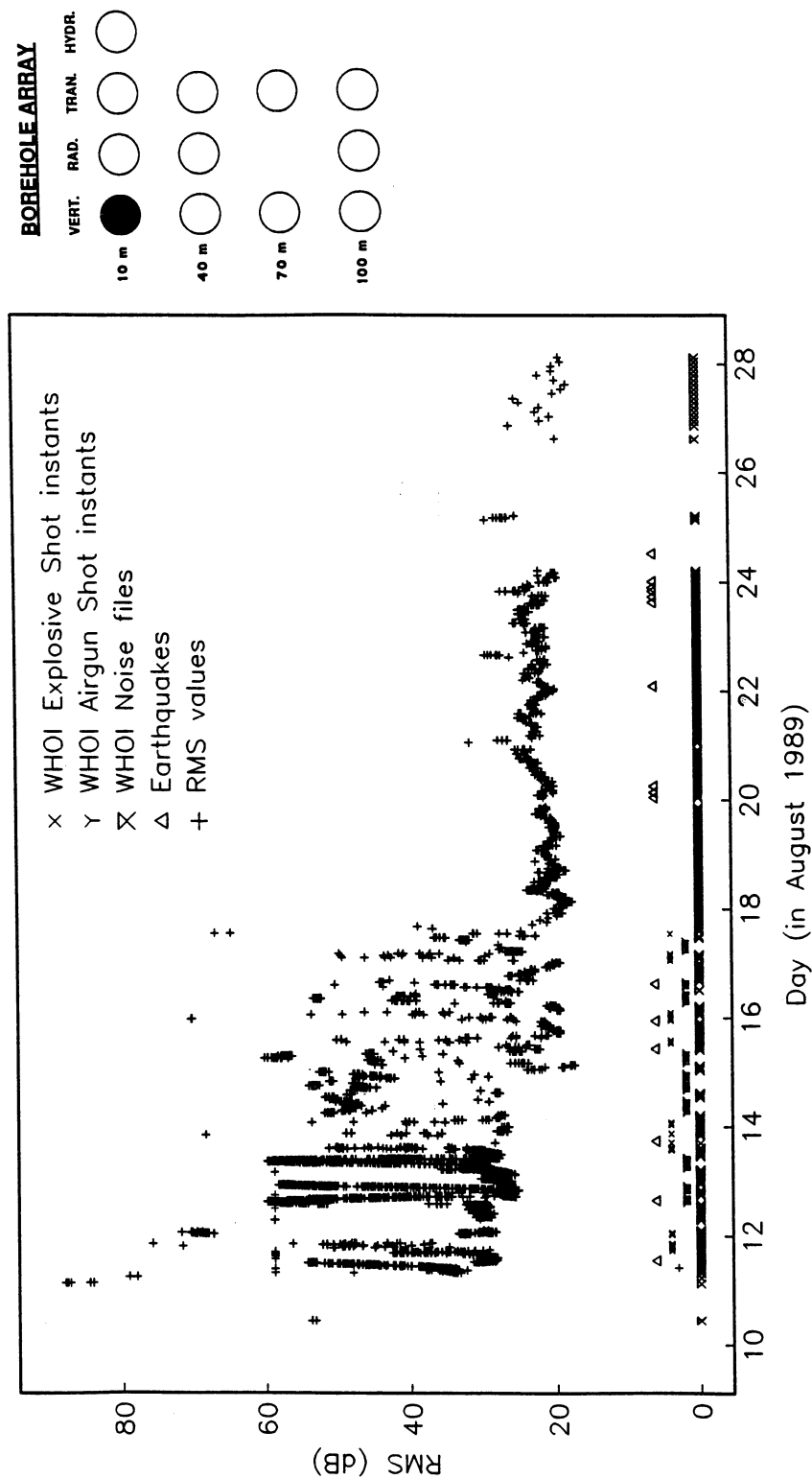


Fig. 8. RMS levels of the vertical channel in the top node for 10-sec windows every minute throughout the data set are a convenient way to summarize levels in the experiment. The peak levels (over 50 dB) on days 10–18 are due to the shooting program. In windows between shooting there is ship noise from the USNS *Lynch* and the R/V MELVILLE. After day 18 the two ships have left and the RMS levels show the variations in ambient noise. The peaks after day 18 are transient ships in the area. The symbols along the bottom of the figure show when explosive shots, airgun shots and earthquakes occurred during the experiment. No events associated with the earthquakes have been identified in the SEABASS data.

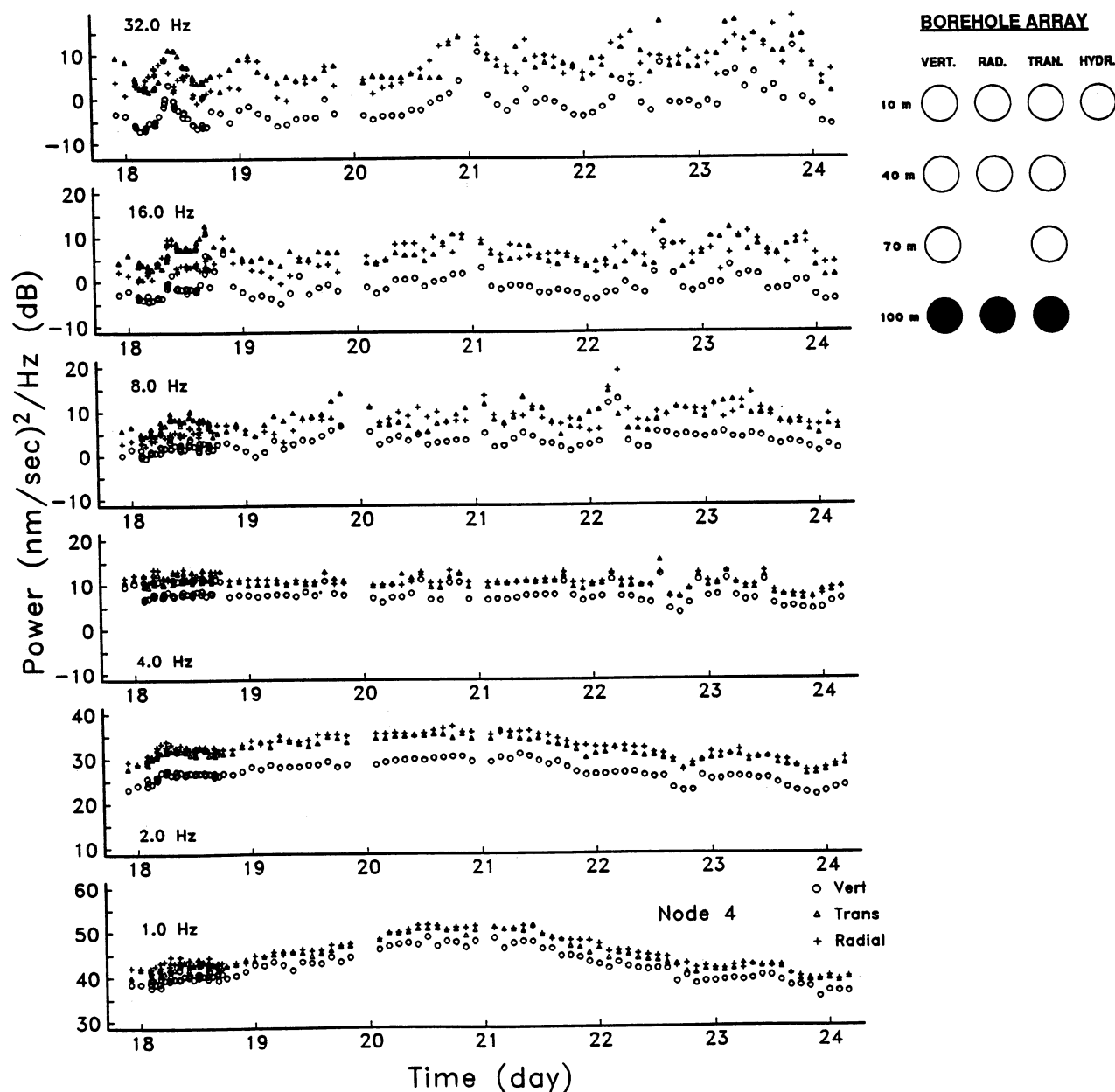


Fig. 9. A convenient way to look at frequency-dependent effects throughout time on a number of channels is to compute power levels in third octave bands. Spectra for this figure were computed for 5-minute contiguous windows. There is a broad rise and decline in noise levels at frequencies below 2.0 Hz at the bottom node which can be correlated with a passing storm. At higher frequencies significant noise level changes can occur on the vertical component without changes on the horizontal components. This has not been explained.

siderably noisier than the Brownian motion for the L22E or the L4C, about 6×10^0 and 1.5×10^{-1} $(\text{nm s}^{-2})^2/\text{Hz}$, respectively (Riedesel et al., 1990; their Figure 12), but the L-15-LBTWHT is a smaller geophone better suited to a portable borehole system.

The Brownian noise level alone is never observed in inertial seismometers since the resistance

of the seismometer coil and damping resistor contribute 'Johnson noise' and the operational amplifier in the first gain stage contributes voltage and current noise ($1/f$ noise) as well as additional Johnson noise from the resistive circuit elements. The contribution of these noise sources to the total electronic noise in SEABASS is shown in Figure 10 in units of nV^2/Hz on input to the amplifiers. The

TABLE II

Simultaneous hydrophone and geophone levels in boreholes in field units

	Geo- phone dB re: (nm s ⁻¹) ² /Hz	Hydro- phone dB re: μPa ² Hz ⁻¹	Geo/ Hydro dB re: (nm s ⁻¹) ² /μPa ²
<i>Ambient Noise</i>			
2 Hz			
Marolles	26	84	-58
Michigan	28	72	-44
LFASE	27	99	-72
4 Hz			
Marolles	22	84	-62
Michigan	23	75	-52
LFASE	7	84	-77
8 Hz			
Marolles	12	77	-65
Michigan	13	73	-60
LFASE	0	81	-81
16 Hz			
Marolles	8	76	-68
Michigan	9	73	-64
LFASE	1	80	-79
32 Hz			
Marolles	-3	75	-78
Michigan	5	69	-64
LFASE	2	84	-82
<i>Controlled Source</i>			
2 Hz			
Michigan	46	76	-30
LFASE	30	102	-72
4 Hz			
Michigan	54	77	-23
LFASE	21	97	-76
8 Hz			
Michigan	56	83	-27
LFASE	25	104	-80
16 Hz			
Michigan	52	83	-31
LFASE	31	96	-65
32 Hz			
Michigan	47	84	-37
LFASE	25	107	-82

total theoretical electronic noise level at 10 Hz is $3.41 \times 10 \text{ nV}^2/\text{Hz}$. For comparison the quietest electronic noise at 10 Hz for the configurations discussed by Riedesel *et al.* (1990; Figure 4) corresponds to $2.8 \times 10 \text{ nV}^2/\text{Hz}$ on input.

A bench test was carried out to check the electronic noise level of the amplifier (Géomécanique, 1988d). The input to the geophone channels was shorted with a $1 \text{ K}\Omega$ resistor (the effective resistance of the two seismometer coils and damping resistances) and spectra of the output noise were observed on a spectrum analyzer. At room temperature (20°C), the average of 32 spectra gave a flat curve between 2 and 40 Hz at a level of $3.72 \times 10 \text{ nV}^2/\text{Hz}$ at the amplifier input. This level is comparable to the theoretically predicted noise (Figure 10). The electronic noise of the modified CGG Multilock used in SEABASS is considered quite acceptable in relation to the theoretically achievable limits and in relation to other seismometer/amplifier configurations used for seafloor noise studies.

To confirm that the electronic noise specifications were being met on the seafloor under *in situ* conditions we acquired 'system test' records during the LFASE experiment. In this test, records were acquired while the geophones were replaced with 470Ω resistors in the DTU. The *in situ* system test spectrum compared favorably with the theoretical total electronic noise curve (Figure 11).

Figure 12 compares the ambient noise spectrum for a quiet interval on LFASE with the combined effect of Brownian noise and electronic noise levels of SEABASS. The observed subseafloor noise levels from LFASE are clearly well above the total theoretical noise level from 2.0 to 50 Hz. SEABASS is faithfully acquiring true ambient noise data from the seafloor.

For most of the nominal pass band of SEABASS (2–50 Hz) the total system noise is dominated by the Brownian noise (Figure 12). The Brownian noise is determined by the relatively small mass of the geophones and the low Q required to eliminate ringing. To lower the system noise level further requires going to either larger geophones or to more sophisticated sensor electronics (such as applying feedback to a high Q sensor or using a displacement sensor).

Figure 13 compares the SEABASS total theoretical noise level (Brownian geophone noise and electronic system noise) with the quietest land measurements acquired at Queen Creek (Fix, 1972) and La Jitas (Herrin, 1982; Li *et al.*, 1984). SEABASS would not be able to detect true ambient noise levels at these sites. However, typical quiet land stations are about 20 dB noisier than these levels (Figure 10.11 in Aki and Richards, 1980). SEABASS could be used to measure ambient noise at most land stations. Also shown for comparison is the quiet LFASE noise spectrum (from Figure 12)

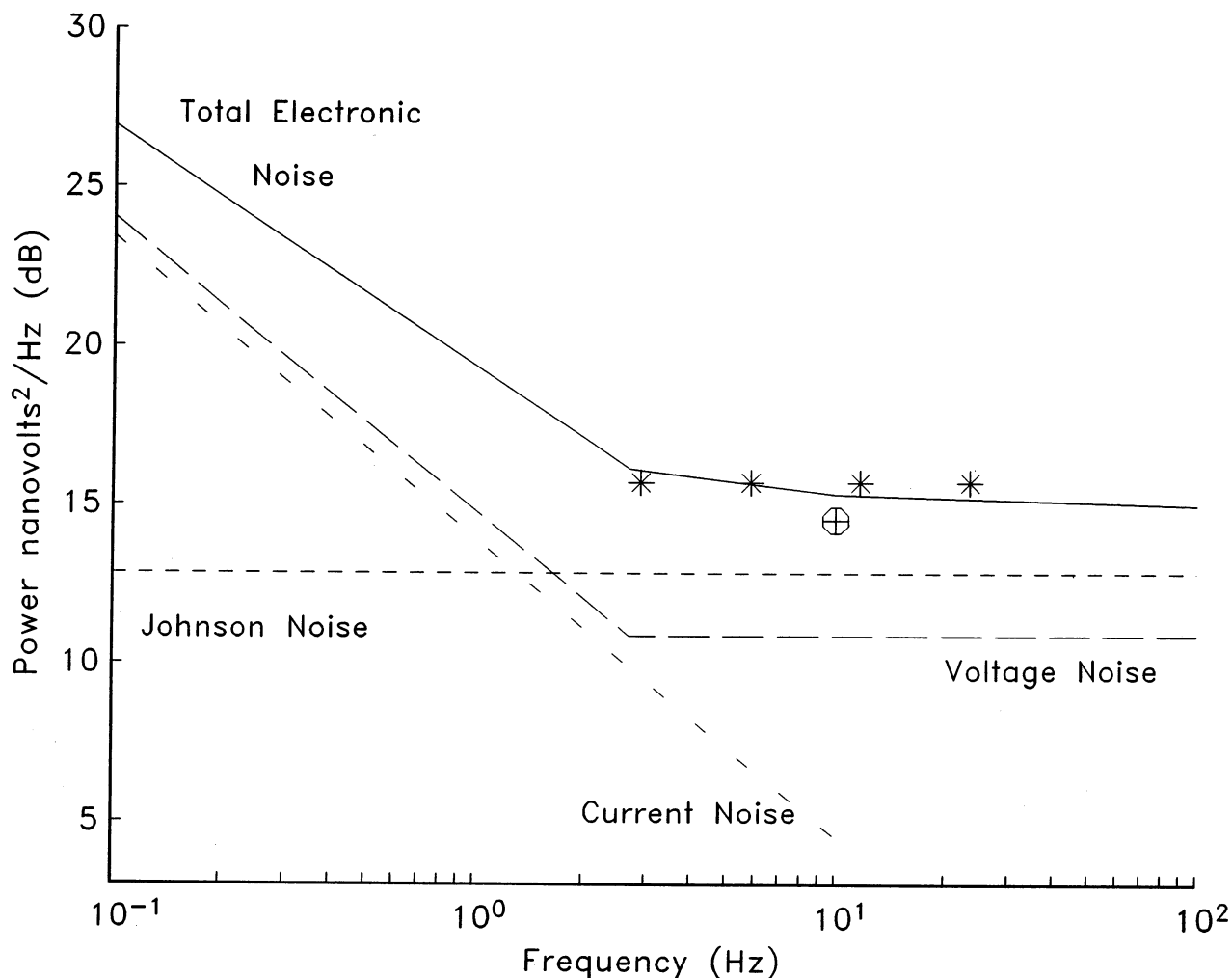


Fig. 10. The electrical system noise of the SEABASS amplifier consists of voltage noise, current noise and Johnson noise. The total electronic noise agrees favorably with the electronic noise levels (stars) measured in the laboratory with the geophones replaced by 1 K Ω resistors. The quietest electronic noise at 10 Hz for the configurations discussed by Riedesel *et al.* (1990; Figure 4) is shown as a cross inside an octagon. The observed noise level of the SEABASS amplifier is within 2 dB of the theoretically achievable limits and other 'state-of-the-art' systems. (The noise curves in this figure are computed for a 1 K Ω source resistance at 293°K. The results are presented as effective electronic noise levels at the input to the amplifier.)

which is also 20 dB or more higher than the quietest land stations.

Figure 14 compares vertical velocity spectra from the Paris basin (1540 m depth at Marolles), the Michigan basin (50 m depth), and the seafloor as acquired on LFASE (10 m depth). The seafloor noise is quietest between 2.0 and 20 Hz by as much as 20 dB but it is remarkable how similar the three spectra are below 2.0 Hz and above 20 Hz. The ambient noise sources and propagation mechanisms must differ considerably between these sites.

Figure 15 shows the electronic noise level on the hydrophone channel acquired in the laboratory and a quiet field noise record from LFASE. For the electronic noise level of the hydrophone we shorted

the input to the hydrophone preamplifier with a 0.015- μ farad capacitor. The electronic noise for the hydrophone channel is higher than for the geophone channels because of the -12 dB preamplifier used with the hydrophone element. We did not compute a theoretical noise level for the hydrophone and its preamplifier and we did not compute the effective 'Brownian' noise of the hydrophone element. However, the field noise level is at least 20 dB above the electronic noise level throughout the band. The extra sensitivity of the hydrophone to ambient noise and controlled sources compensates for the increased electrical noise.

Figure 16 compares ambient noise levels on a borehole hydrophone from the Paris basin, the

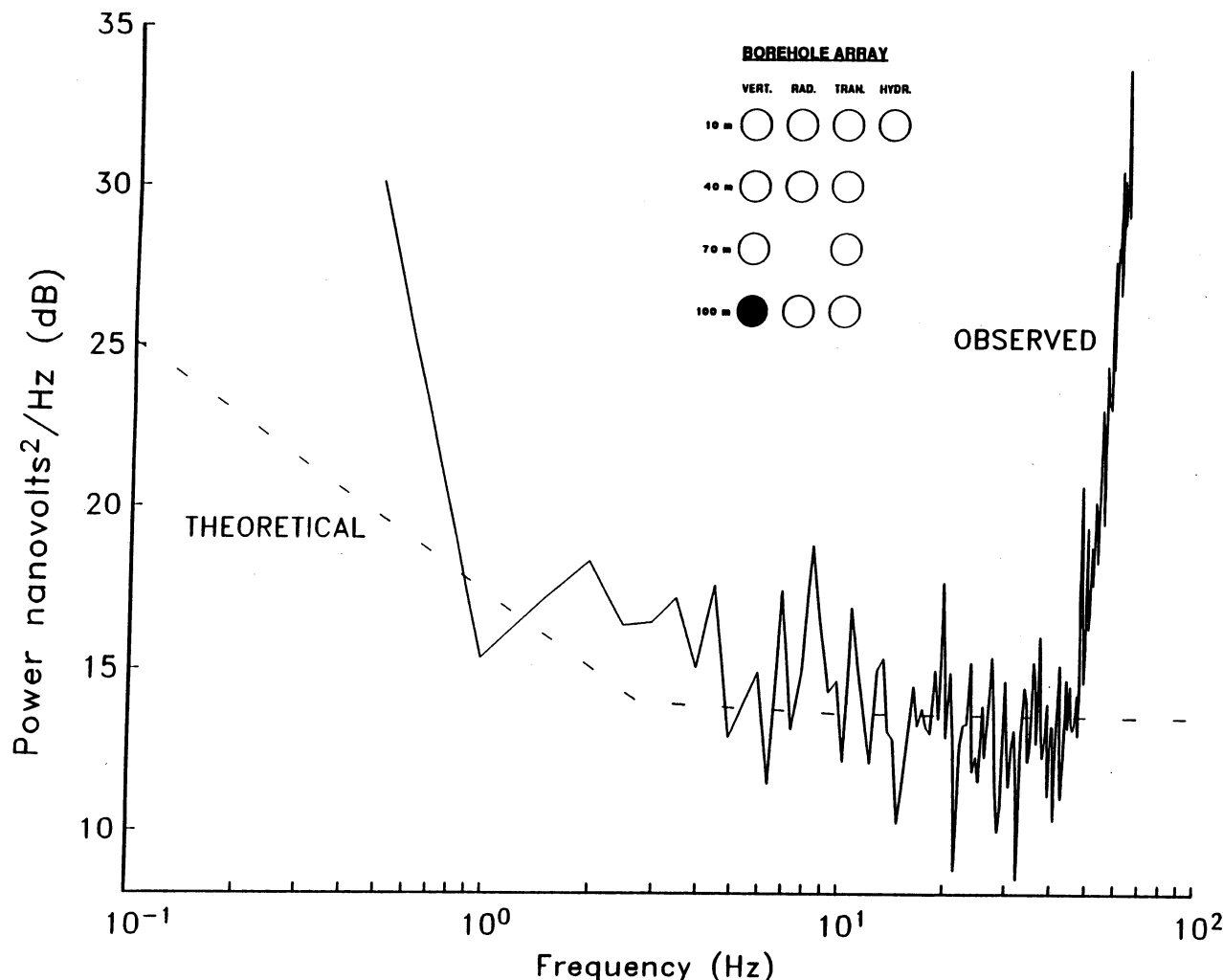


Fig. 11. The total theoretical electronic noise agrees well (within 6 dB) with the measured electronic noise spectrum from the seafloor in the band 2–50 Hz. These data were acquired during an *in situ* system test with the geophones replaced by 470 Ω resistors. The spectrum, which has been corrected for the system transfer function, rises sharply above 50 Hz because of aliased noise. (The electronic noise spectrum was computed over 1500 points (12 sec) using a 256-point averaging window. The theoretical noise curve is computed for a 470 Ω source resistance at 274°K. The results are presented as effective electronic noise levels at the input to the amplifier.)

Michigan basin and the seafloor for the same intervals as the geophone noise levels in Figure 14. The ambient pressure levels have a different behavior to the ambient velocity levels. The ambient pressure signal in the borehole is not simply related to the vertical ambient ground motion at the well. The similarity in ambient pressure levels at the three sites between 6 and 30 Hz is quite striking.

TRANSFER FUNCTIONS

The transfer function, from ground motion or borehole pressure to electrical signal on input to the digitizer, is comprised of four parts: the transducer, the DTU amplifier, the high cut filter and the low cut filter. For each seismometer channel there are

two geophones in series with a combined response given by:

$$G(s) = 65.4 \times \frac{s^2 T_9^2}{1 + 2s\zeta_3 T_9 + s^2 T_9^2} \text{ nV/nm/sec. (1)}$$

The values of T_i and z_i are summarized in Table III. The Laplace transform variable, s , corresponds to $i\omega$, where ω is angular frequency and i is the square root of -1 .

The borehole hydrophone consists of the transducer and a built-in -12 dB hydrophone preamplifier separate from the amplifiers in the Data Telemetry Unit. The combined response for the hydrophone and its preamplifier is:

$$H(s) = 0.112 \times \frac{sT_{11}}{sT_{11} + 1} \times \frac{sT_{12}}{sT_{12} + 1} \text{ nV / } \mu\text{Pa. (2)}$$

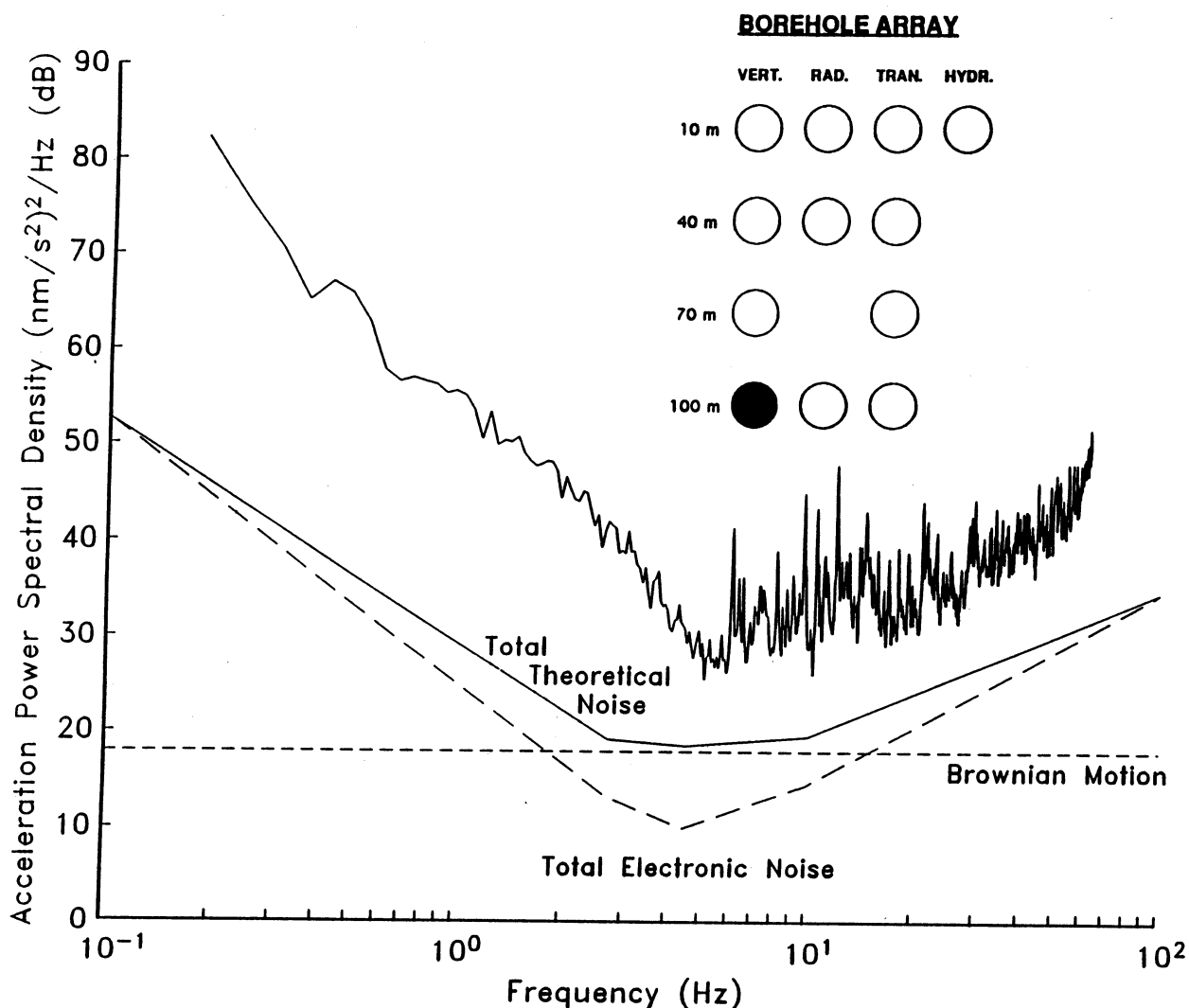


Fig. 12. The total system noise of SEABASS consists of Brownian noise in the geophones and electrical system noise from the amplifiers. Brownian noise is the major contributor to the total theoretical noise between 2.0 and 20 Hz. The theoretical noise is at least 10 dB less than the observed ambient noise in the seafloor for a quiet interval. This demonstrates that the LFASE results are not being contaminated by system noise. (The spectrum shown corresponds to the vertical channel of the bottom node. It is computed over 44,997 points (6 min) using a 2048-point averaging window. The total electronic noise in this figure is computed for a 1000 Ω effective geophone resistance at 274°K. The results are presented as effective ground acceleration at the geophone.)

The 12 channels in the Data Telemetry Unit each have an amplifier response given by:

$$A(s) = 2.00 \times 10^3 \times \frac{1}{sT_1 + 1} \times \frac{1}{sT_2 + 1} \quad (3)$$

The high cut filter consists of two 5-pole Butterworth filters with a combined response, for all 12 channels, of:

$$B(s) = \left(\frac{1}{sT_3 + 1} \times \frac{1}{1 + 2\zeta_1 sT_3 + s^2 T_3^2} \times \frac{1}{1 + 2\zeta_2 sT_3 + s^2 T_3^2} \right)^2 \quad (4)$$

There is one low cut filter in the amplifier/filter section and one in the digitizer. They are identical and their combined response is:

$$C(s) = \left(\frac{sT_8}{sT_8 + 1} \right)^2 \quad (5)$$

So the transfer function for the seismometer channels is the product $G(s)A(s)B(s)C(s)$ and the transfer function for the hydrophone channels is $H(s)A(s)B(s)C(s)$. The amplitude of these functions is plotted in Figure 17. Actual system gains as measured on the individual 'as built' amplifier/

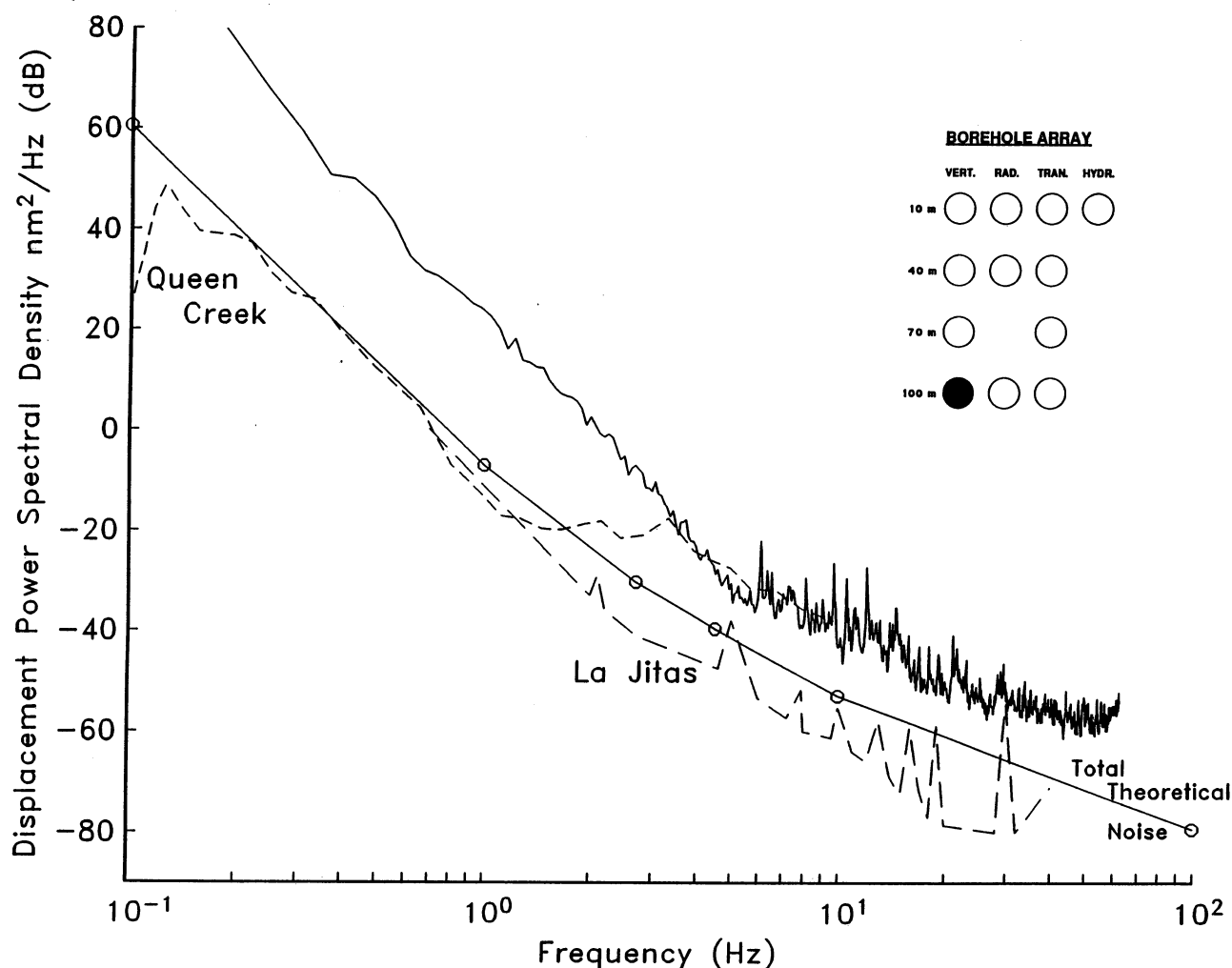


Fig. 13. The theoretical system noise of SEABASS is comparable to the ambient noise observed at the quietest land stations (Fix, 1972; Li *et al.*, 1984; Herrin, 1982) in the band 0.1 Hz to 40 Hz. SEABASS, as currently configured, would not be an appropriate system to measure ambient noise under these conditions. However these 'quietest' land stations have levels about 20 dB below typical 'quiet' stations and SEABASS would be a good, rugged, reliable sensor for most sites. (The LFASE spectrum shown is the same as in Figure 12. The results are presented as ground displacement at the geophone.)

filters are reported in Géomécannique (1988a) and are within 1 dB of nominal values.

The pass band for the geophone channels (as defined as the band between the 3 dB down points) is 4.7–40 Hz. The low end is determined by the response of the geophone and the high end is determined by the anti-aliasing filters. The pass band for the hydrophone channel is 3.9–40 Hz. The low end is determined by the low cut filters in the DTU and the high end is determined by the anti-aliasing filters which are the same as for the geophone channels. Both pass bands are smaller than the nominal bandwidth that was prescribed for SEABASS, 2.0–50 Hz.

Given a sampling rate of 125 samples s^{-1} , that is determined by program constraints, it is necessary

to obtain meaningful seismic data up to 50 Hz. For a Nyquist frequency of 62.5 Hz, a high cut frequency of 40 Hz and a roll-off of 60 dB/octave, the aliased noise level at 50 Hz is down 38.7 dB from its filtered value. So this configuration is acceptable for energy up to 50 Hz if one is willing to accept about 40 dB aliased noise rejection. The filtered values at 50 Hz are sufficiently high to ensure recovery of meaningful data by applying the inverse of the transfer function. This analysis applies to both the hydrophone and geophone channels.

At the low frequency end the response for the geophone channels is down 20 dB at 2.0 Hz and the response for the hydrophone channel is down 10 dB. However the ambient noise levels due to microseisms at 2.0 Hz are about 20 dB higher than

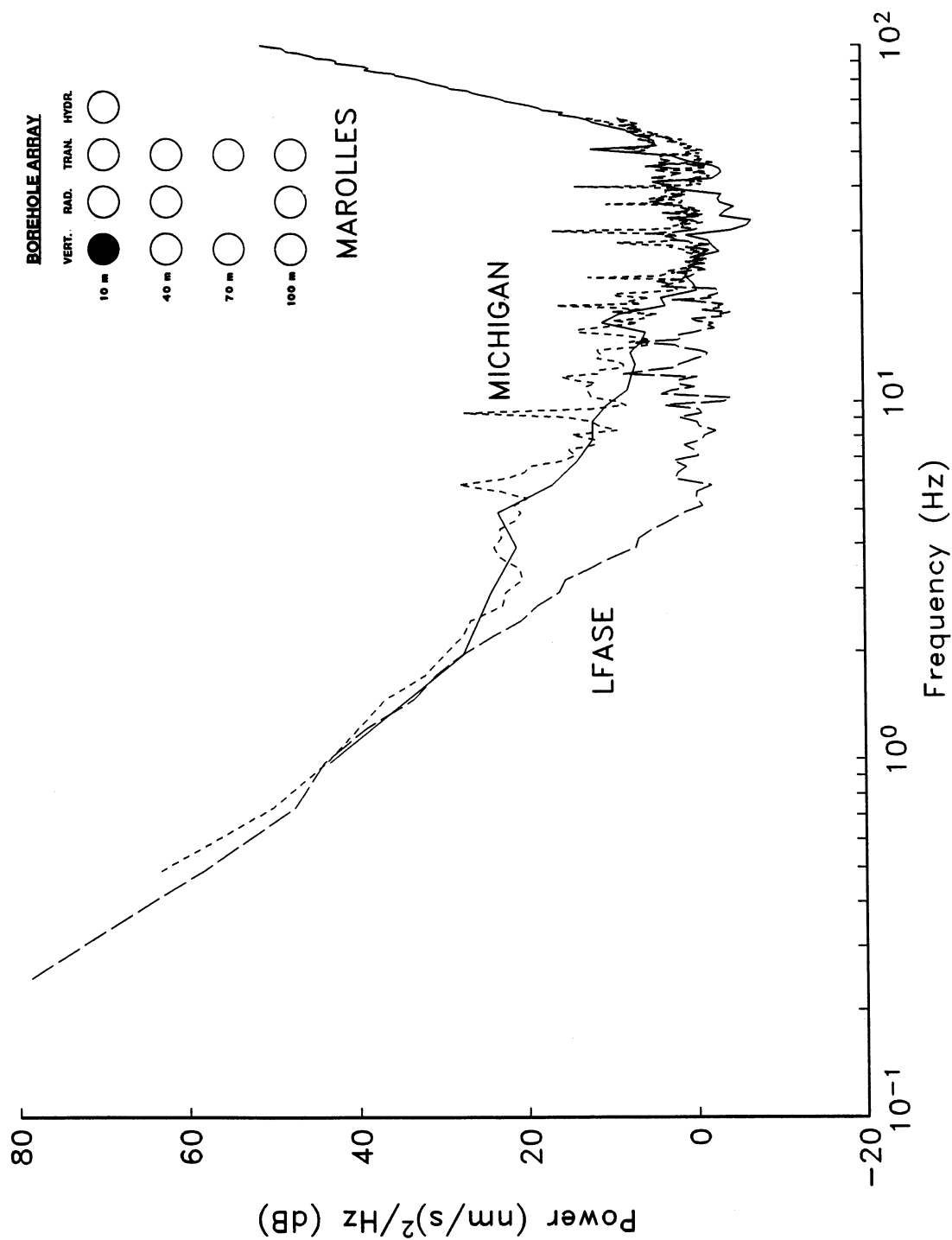


Fig. 14. The ambient vertical component noise is compared between Marolles (at 1,540 m depth during a fall day at a noisy land site in the Paris basin, solid line), Michigan (at 50 m depth during a quiet winter's night in a rural setting, short dashed line), and LFASE (10 m below the deep sea floor in the Blake-Bahama Basin, long dashed line). In the microseism band below 2.0 Hz the levels are remarkably similar. Between 3.0 and 20 Hz LFASE is up to 20 dB quieter than the land stations. The LFASE and Michigan levels are comparable above 20 Hz. There is a narrow band between 30 and 40 Hz for which the Marolles data are quieter than Michigan and the seafloor. The similarity of these noise levels is remarkable given the dramatic differences in environments. The ambient noise sources and propagation mechanisms must differ considerably between these sites. (For the Marolles, Michigan and LFASE spectra the window lengths are 8000 points (16 sec), 20,000 points (2.67 min) and 44,997 points (6 min), respectively. The averaging window for all three data sets is 512 points. The results are presented as ground velocity at the geophone.)

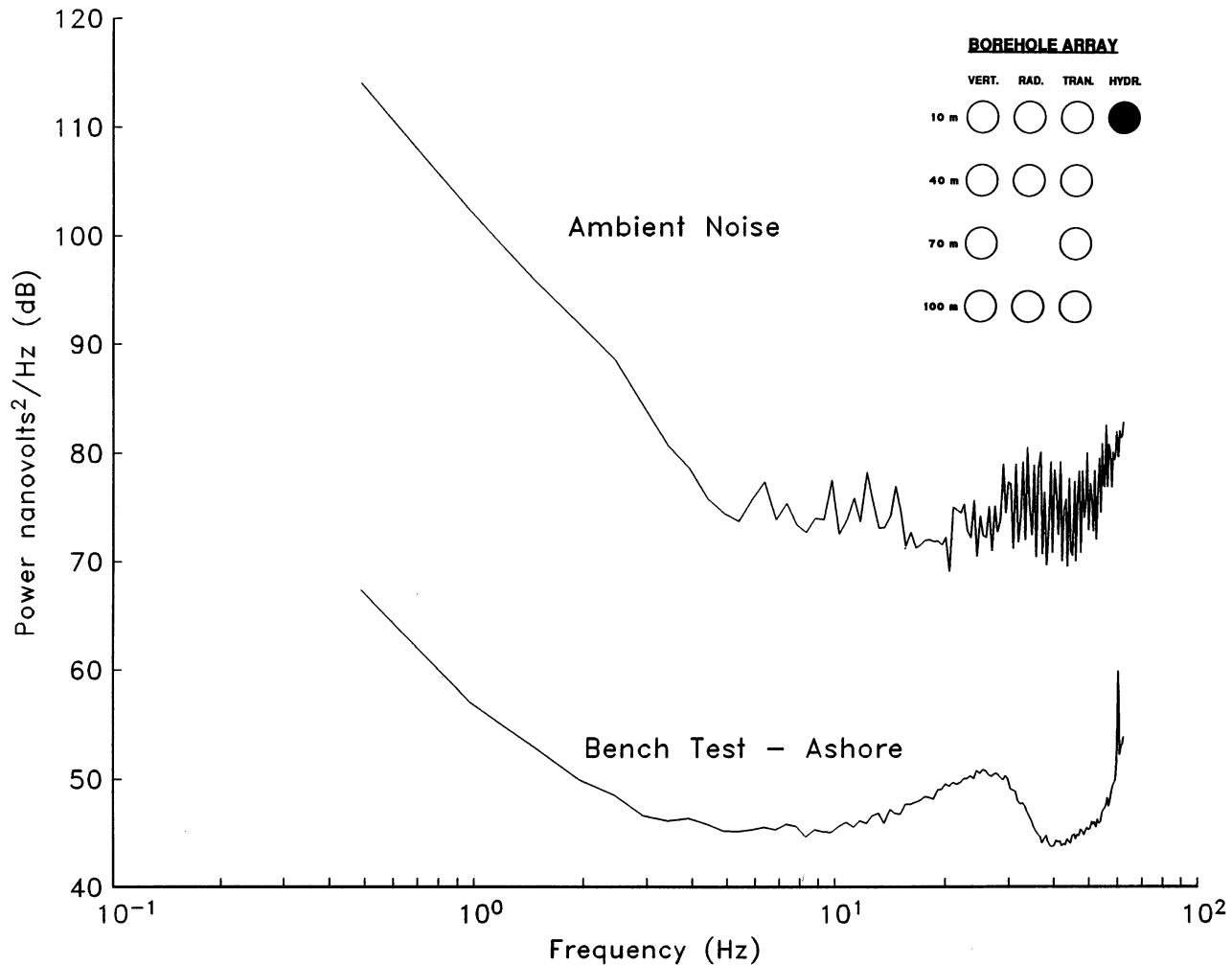


Fig. 15. The measured electronic noise spectrum on the hydrophone channel (with the hydrophone replaced by a capacitor) is compared with the observed hydrophone level from a quiet period on LFASE. The observed level is at least 20 dB greater throughout the band, confirming that the LFASE hydrophone results are not being contaminated by system noise. (For the LFASE and electronic noise spectra the window lengths are 44,997 points (6 min) and 44,000 points (5.87 min), respectively. The averaging window for both spectra is 256 points. The results are presented as effective electronic noise levels at the input to the hydrophone preamplifier.)

the levels at 10–40 Hz, which are due to shipping and weather. So the filter is just compensating for earth noise (and perhaps $1/f$ noise in the amplifiers) to keep the electrical signals flat.

THE DIGITIZER AND NUMBER REPRESENTATION

This section summarizes the way the voltage values on input to the digitizer are treated in the SEABASS system. Figure 18 shows schematically the data flow from ground motion or pressure at the transducers to the 32-bit computer (a Digital Equipment Corporation VAX 8800) used for data reduction and analysis.

Data values from the digitizer in the Data Telemetry Unit are represented by 16 bit binary words in A12G4 format as follows:

$$G_0G_1G_2G_3SM_0M_1M_2M_3M_4M_5M_6M_7M_8M_9M_{10}$$

The voltage on input to the digitizer (and gain ranging amplifiers) is given by (Géomécanique, 1988c):

$$V(mV) = 2.44 \times M / 2^G \quad (6)$$

where

$$G = \sum_{i=0}^3 (G_i \times 2^i)$$

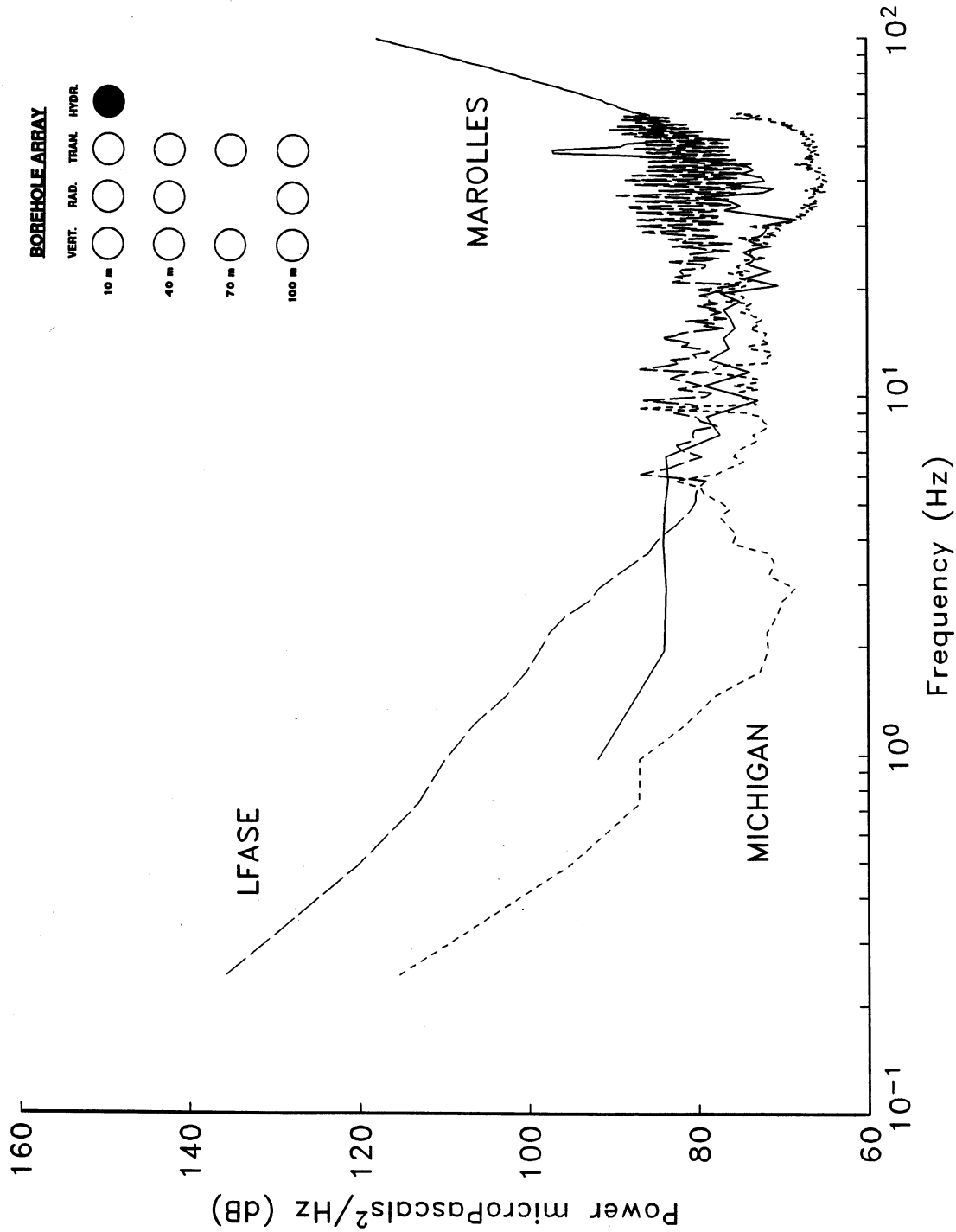


Fig. 16. The ambient pressure noise is compared between Marolles (solid line), Michigan (short dashed line) and LFASE (long dashed line). In contrast to the vertical motion (Figure 14), during the same time intervals at the same locations, the pressure field is quite different at the three sites below 5.0 Hz. Levels between 5.0 and 30 Hz are comparable at all three sites. Below 5.0 Hz and above 30 Hz the quietest ambient pressure noise was observed in Michigan. The physics of ambient noise for the velocity field and the pressure field must be dramatically different. Marolles, which was a daytime measurement in the Paris Basin and was subject to considerable cultural noise, has comparable levels to the deep sea floor. It is surprising that the Michigan levels, acquired in a rural land area during a quiet winter's night, are as much as 10 dB quieter than the deep sea levels at some frequencies. (The spectra were computed using the same values as Figure 14. The results are presented as pressure values at the hydrophone which was co-located (within 1.5 m) with the geophone in Figure 14.)

TABLE III

Transfer function parameters

The parameters are:

$T_1 = 1.8 \times 10^{**(-4)}$	$(f_{\text{hi-cut}} = 884 \text{ Hz})$
$T_2 = 2.4 \times 10^{**(-4)}$	$(f_{\text{hi-cut}} = 663 \text{ Hz})$
$T_3 = 3.658 \times 10^{**(-3)}$	$(f_{\text{hi-cut}} = 43.5 \text{ Hz})$
$T_8 = 7.234 \times 10^{**(-2)}$	$(f_{\text{low-cut}} = 2.20 \text{ Hz})$
$T_9 = 3.54 \times 10^{**(-2)}$	$(f_{\text{low-cut}} = 4.50 \text{ Hz})$
$T_{11} = 1.01 \times 10^{**(-1)}$	$(f_{\text{low-cut}} = 1.575 \text{ Hz})$
$T_{12} = 3.35 \times 10^{**(-1)}$	$(f_{\text{low-cut}} = 0.475 \text{ Hz})$

$$\zeta_1 = 0.304$$

$$\zeta_1 = 0.810$$

$$\zeta_3 = 0.600$$

(The Nyquist frequency of the digitizer is 62.5 Hz.)

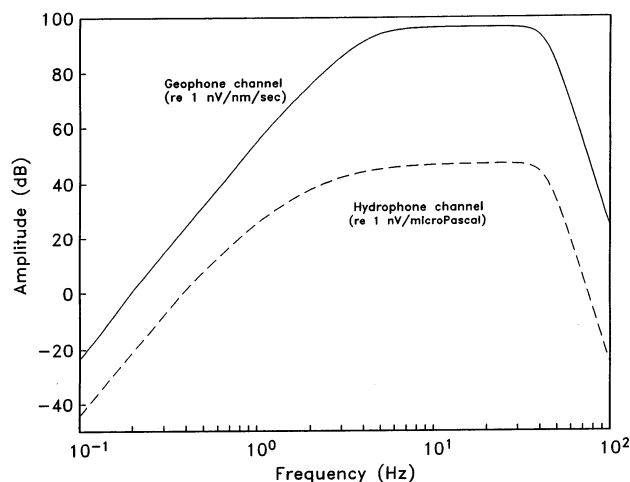


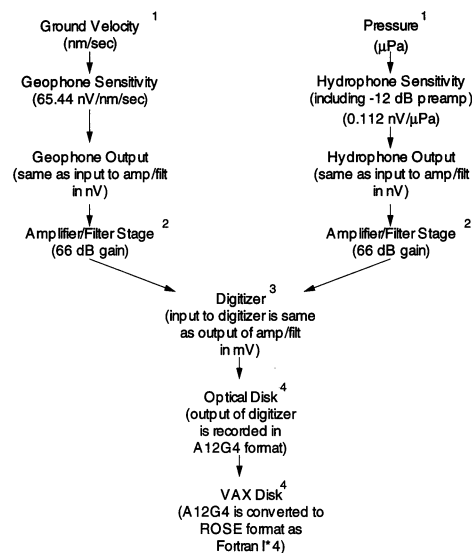
Fig. 17. The amplitude spectra of the SEABASS transfer function for geophone and hydrophone channels are flat within 3 dB between 4.7 to 40 Hz and 3.9 to 40 Hz, respectively.

$$M = \sum_{i=0}^{10} (M_i \times 2^i)$$

G has a maximum decimal value of 11, corresponding to 11 gain stages of 6 dB. S is the sign bit. A12G4 format, also referred to as 'field format' is used by SEABASS for all telemetry and storage on field media. (If accuracy greater than three significant digits is required, a more careful study of the analog to digital converter (ADC) is necessary.)

[The maximum dynamic range of this digitizing system (12 bits of mantissa and 4 bits of gain) is 132 dB. However this system does not have the precision of a full 22-bit ADC. For example we would be unable to faithfully record a 40 dB high frequency noise level within a 120 dB low frequency signal (in electronic units). This is not a

SEABASS Data Acquisition Flow Chart



- 1) Actual ground velocities and pressure are converted to voltage signals from the geophone and hydrophone sensitivities.
- 2) The output of the amplifier/filter section is quoted in mV and is obtained from the Geophone and Hydrophone Output by multiplying by $2.00 \times 10^{**(-3)}$.
- 3) The digitizer converts the analog levels in mV to an integer value by multiplying by $(2^{**11}) / 2.44141$.
- 4) The numbers on the optical and VAX disks are in different formats: A12G4 on optical disk and Fortran I*4 on VAX. The integer value is obtained by $M \times (2^{**(-G)}) \times (2^{**11})$.

Fig. 18. This figure summarizes the sensitivities and gains at the various levels of the SEABASS acquisition system.

serious limitation for the applications for which SEABASS is intended. To fully utilize a 22-bit ADC requires that the seismometer design and analog electronics, prior to the digitizer, meet the same specification in transfer functions, filters, harmonic distortion, power supply rejection, cross-talk, coupling, etc.]

The maximum field signal that can be recorded without clipping and the least significant bit (LSB) are summarized in Table IV. The maximum voltage on input to the digitizer and gain ranging section is 5.00×10^3 mV. The smallest detectable voltage on input to this section is 1.19×10^{-3} mV. The corresponding maximum and minimum ground velocity values are 3.83×10^4 nm s⁻¹ and 0.915×10^{-2} nm s⁻¹, respectively. The corresponding maximum and minimum pressure values are 22.3×10^6 μPa and 5.32 μPa, respectively.

The minimum (theoretical) values from the digitizer are never actually observed because they are much less than the electrical noise of the transducers and analog electronics. The dynamic range of the system can be defined as the ratio of the RMS

TABLE IV
SEABASS Numerology

Processing Stage	Formula	Largest Positive Number	Smallest Positive Number (LSB)
Field format	A12G4	0000 + 11111111111	1011 + 00000000001
Laboratory format	ROSE (INTEGERS) = $M \times 2^{-G} \times 2^{11}$	4,192,256*	1
Input to digitizer	$V(\text{mV}) =$ $\text{ROSE} \times 2.44141/(2^{11})$	5.00 V	1.19 μV
Input to amp/filters (geophone)	$V_g(\text{mV}) = V(\text{mV})/1,995.26^{**}$	2.50 mV	0.597 nV
Input to amp/filters (hydrophone)	$V_n(\text{mV}) = V(\text{mV})/501.18^{**}$	9.97 mV	2.38 nV
Ground Velocity	$\text{vel} (\text{nm s}^{-1}) =$ $V(\text{mV})/(1.3057 \times 10^{-1})$	$3.83 \times 10^4 \text{ nm s}^{-1}$	$0.915 \times 10^{-2} \text{ nm s}^{-1}$
Pressure	$p(\mu\text{Pa}) =$ $V(\text{mV})/(2.23871 \times 10^{-4})$	$22.3 \times 10^6 \mu\text{Pa}$	5.32 μPa

* The most negative number is -4,194,304 (0000100000000000 in A12G4 where 1 indicates a negative sign).

** In generating this table we have used the nominal values for the system gains in dB and maintained 5 to 6 significant figures. If the transfer function is required to better than three significant figures more care must be taken in the analysis. Actual system gains as measured on the 'as built' amplifier/filters are reported in Géomécanique (1988a) and are within 1 dB of nominal values.

value of the maximum undistorted signal to the RMS value of the noise (Melton, 1976). The RMS value of the maximum undistorted sinusoidal signal, which has a peak amplitude of 5.0 V on output, is 1.76×10^{-3} VRMS on input to the amplifier. The RMS value of the system noise referenced to the amplifier input, based on data acquired with the amplifier input shorted with 1000 Ω (the effective resistance of the two damped geophones), is 37.3 nVRMS (Géomécanique, 1988b). So the effective dynamic range of the geophone channels in the system is 94 dB. Since the theoretical dynamic range is 132 dB plus sign, we have 38 dB, or about 6 bits, in the noise. The effective dynamic range for the hydrophone channel is 73 dB. This is based on a measured RMS system noise level of 377.2 nVRMS on input to the DTU amplifier (the output of the -12 dB hydrophone preamplifier) when the hydrophone is replaced with a 0.015- μ farad capacitor.

On the LFASE project the data storage and exchange format was ROSE format (Latraille, 1983; Latraille and Dorman, 1983; Little *et al.*, 1990b). In ROSE format each number is represented by a 32-bit integer word. We convert from A12G4 format to ROSE format by simply multiplying by 2^{11} . So a ROSE format number is an integer value:

$$\text{ROSE} = M \times 2^{(11-G)}. \quad (7)$$

ROSE numbers will range from -4,194,304 to 4,192,256.

TOOL DIMENSIONS AND USE FROM ODP DRILL SHIPS

The inside diameter of the drill pipe presently being used from the D/V JOIDES Resolution is 104.8 mm (4-1/8 in). In borehole seismic experiments carried out from the drill ship and its predecessor the D/V GLOMAR CHALLENGER (for example, Stephen *et al.*, 1980), the borehole seismometers were small enough (92.1 mm, 3.62 in) to be lowered through the drill pipe. By using a special 'logging bit' the seismometers could be run out of the drill string into the open hole. The Multilock array used in SEABASS cannot be deployed in this fashion since the outside diameter of a satellite in its slimmest configuration is 112 mm (4.39 in). At the present time the Multilock string can only be deployed in deep sea boreholes using the wireline re-entry capability (Spiess *et al.*, 1989a, 1992) or submersible-assisted re-entry (Legrand *et al.*, 1989).

TEMPERATURE SPECIFICATIONS AND HYDROTHERMAL VENTS

The overall temperature specification of SEABASS is only 20 °C, however this applies primarily to the

DTU electronics. The cable and mechanical components, which actually go down the hole are rated to 180 °C. Borehole seismic monitoring of seafloor hydrothermal events could be extremely interesting scientifically. SEABASS could be used for these measurements if the maximum temperature in a borehole near the vents did not exceed 180 °C and if the BIP and DTU were offset from the well head in cold (less than 20 °C) water.

Test Procedures with Examples

OVERVIEW

A series of tests were carried out during the SEABASS development program. A preliminary sea test of mechanical components of the BIP was carried out from the R/V MELVILLE off the coast of California in the fall of 1988. At the same time the acceptance tests of the Multilock unit were being carried out in France. These consisted of the usual tests to confirm that the array met the mechanical and electrical specifications (Ateliers Mécaniques de Saint-Gaudens, 1988c; Géomécanique, 1988a, 1988b, 1988c) but also included shake table tests of the satellite clamping mechanism and a borehole test near the town of Marolles outside Paris (Compagnie Générale de Géophysique, 1988). In January, 1989, all of the SEABASS shipboard and seafloor electronics were tested with the Multilock unit in a land borehole in Michigan. In May, 1989, the SEABASS system was integrated with the wireline re-entry system (from MPL/SIO) in a wet test on the R/V MELVILLE off Martha's Vineyard. The development culminated in the LFASE experiment off Florida in which borehole data were acquired from the deep sea floor in both shipboard and seafloor recording modes.

SHAKE TABLE TESTS

Resonances of the clamping mechanism can cause ringing and poor quality data in borehole seismic measurements. In order to check for resonances in the sondes used for SEABASS we carried out a series of shake table tests at a vibration test facility near Paris (SOPEMEA, 1988) on 29 August and 26–27 September, 1988. A tank, about 2 m high, was mounted on a shake table and filled with water (Figure 19). A Multilock satellite, with or without the optional hydrophone, could be locked in the tank to simulate being clamped in the borehole.

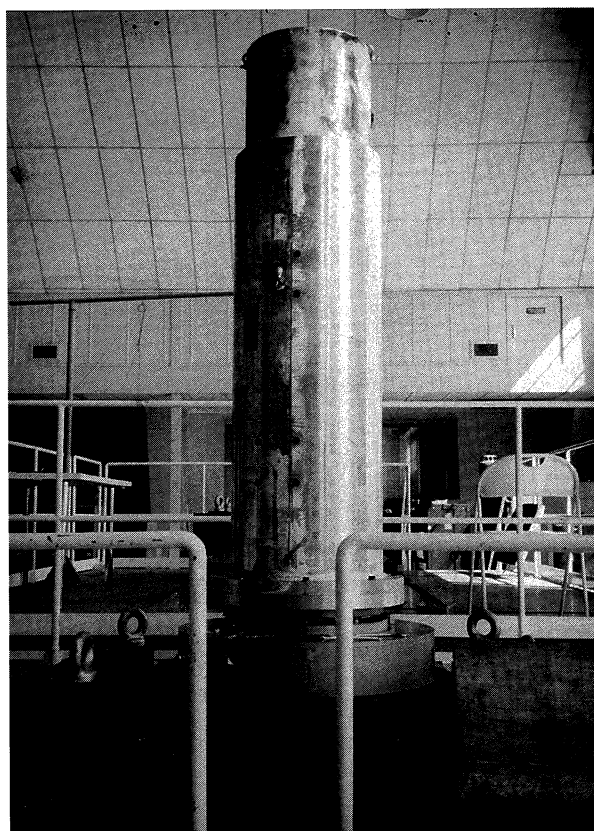


Fig. 19. In order to check for resonances of the clamping configurations used on SEABASS we carried out shake table tests with the sonde clamped in this test cylinder. The response of the tank is monitored by a three component accelerometer mounted on the side and a vertical component geophone mounted on the base of the tank. The forcing function of the vibrator is monitored by a three component accelerometer mounted on the shake table. All seven sensors could be compared with the response of the three component geophones in the sonde inside the tank.

Three component accelerometers were placed on the shake table and on the side of the tank in order to check that the tank was moving as a unit and was not itself resonating. The shake table could be vibrated either vertically or horizontally through a range of frequencies from 2.0–200 Hz.

The results of the vibration tests (Figures 20, 21 and 22) confirm that the clamping mechanism is ensuring good coupling to 9-in and 16-in boreholes within 3 dB in amplitude and 5° in phase across the pass band (2–50 Hz) on all three components for satellites with and without the optional hydrophone. Resonances of the system above 50 Hz are sufficiently small that they are adequately damped by the antialiasing filters.

Vibration Test – Vertical Component

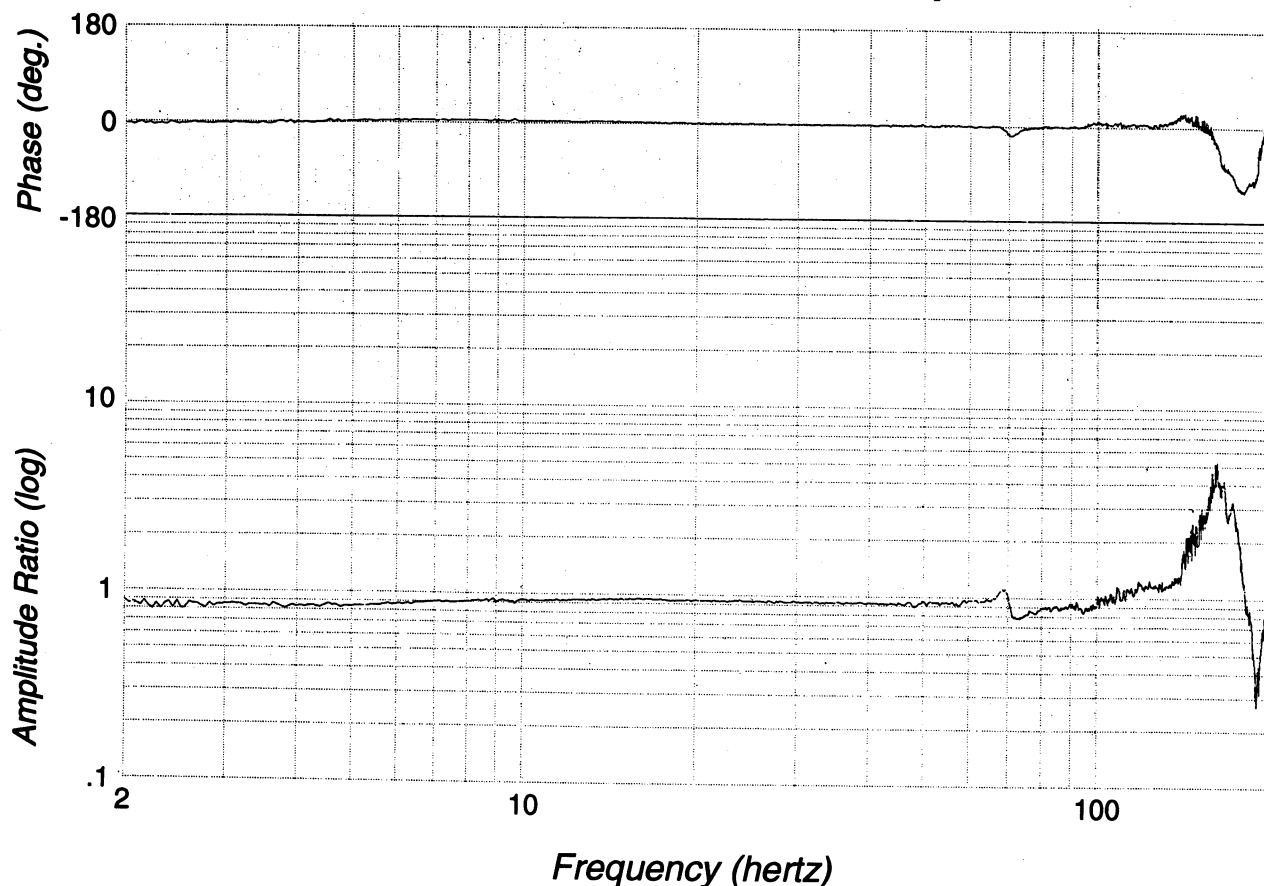


Fig. 20. The transfer function between the vertical accelerometer on the side of the test tank (corrected to velocity) and the vertical geophone in the sonde shows that the sonde is well coupled to the tank in the band from 2.0 Hz to over 65 Hz. For this test the tank is shaken vertically.

MICHIGAN BOREHOLE TEST

A land test of the complete SEABASS system was carried out at the MIT-Burch Site near Travers City, Michigan, between January 16 and 21, 1989. The site was selected because it was used often by the MIT VSP Consortium. Logistics were straightforward and a great deal was known about the hole from previous experiments (Turpening, 1990). The objectives of this test were: i) to mock up the seafloor configuration of SEABASS in a field situation and to run the system in both 'shipboard' and 'seafloor' recording modes; ii) to confirm the quality of data from the SEABASS system by running it in VSP mode and comparing the results with other VSPs acquired at the site; iii) to check the effect of casing on the received signals in the band 2–50 Hz; iv) to check the effect of tight and slack cables on the acquired signals and noise; and v) to carry out polarization studies of propagation at the site.

Figures 23 and 24 show the raw zero offset and 0.6 km offset VSPs from the MIT-Burch well. The source is a land airgun. Although further processing is required to enhance reflectors on these sections the data quality is quite good and there are no signs of ringing which would indicate poor coupling to the formation. The noisy trace at about 590 m depth is poor quality because the casing is poorly cemented. All VSP systems run at the site show poor results at this depth.

To confirm that all satellites are responding the same we show in Figure 25 traces from each satellite acquired at the same depth. Since all traces at the same depth are the same by inspection (to within the borehole noise level) we conclude that all sondes are responding in the same way. The top sonde has a hydrophone attached and has a slack cable above it; the middle two sondes are identical with taut cables above and below them; and the

Vibration Test – Radial Component

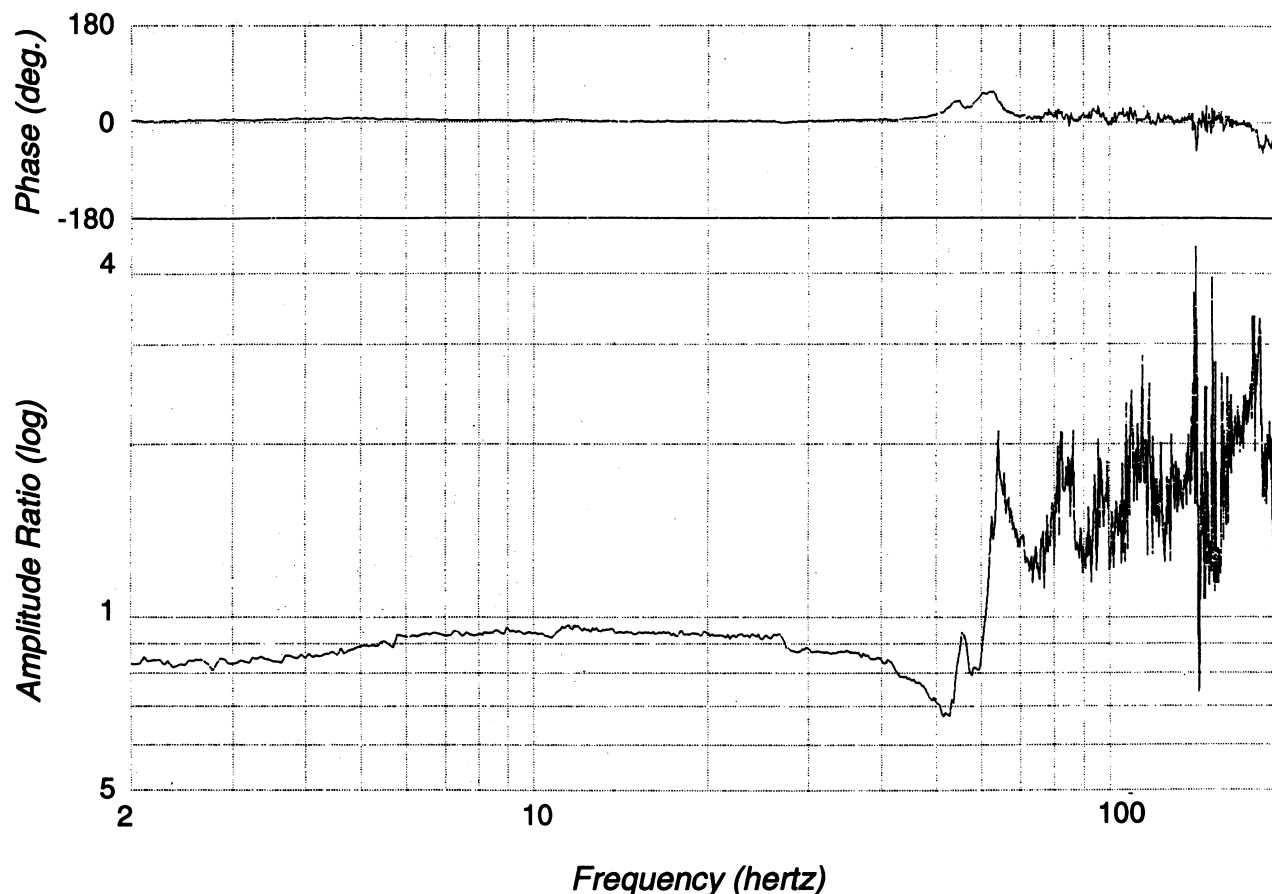


Fig. 21. The transfer function between the radial accelerometer on the side of the test tank (corrected to velocity) and the radial geophone in the sonde is flat with negligible phase shift from below 5.0 Hz to over 40 Hz. Significant resonances occur above 60 Hz, outside the pass band of the SEABASS system. At frequencies above 40 Hz the tank does not respond as a unit to the forcing function (the tank response depends on where the reference accelerometer is placed on the tank) so the discrepancies above 40 Hz could be artifacts of the test and are not necessarily due to the Multilock clamp. For this test the tank is shaken radially. Note that the vertical scale for amplitude differs from Figure 20.

bottom sonde just has a taut cable above it. We conclude that at these frequencies the effects of taut and slack cable and of adding the hydrophone to the top node are negligible. (This test was not done for the horizontal channels because we did not know their orientation. In the Michigan tests we only had the source at one location for each borehole run. Determining geophone orientation in heterogeneous media from a single shot is very unreliable.)

To check the effect of casing on the seismic signals we compare traces acquired just above and just below the casing shoe at 897 m (2944 feet) depth (Figure 26). The traces are essentially identical by inspection, confirming that the casing does not have a significant effect on the seismic signals at these frequencies.

THE FLORIDA DEPLOYMENT (LFASE)

SEABASS was built as one component of the Low Frequency Acoustic Seismic Experiment (LFASE). The principle objective of LFASE was to understand the physics of the excitation and propagation of low frequency signals and ambient noise (2 to 50 Hz) immediately above, at and below the seafloor. Since signals and noise can vary considerably over short distances away from an interface it was felt that measurements should be made simultaneously at a number of depths. LFASE was a multi-institutional effort with investigators from the Naval Ocean and Atmospheric Research Laboratory (NOARL), Science Applications International Corporation (SAIC), Scripps Institution of Oceanogra-

Vibration Test – Transverse Component

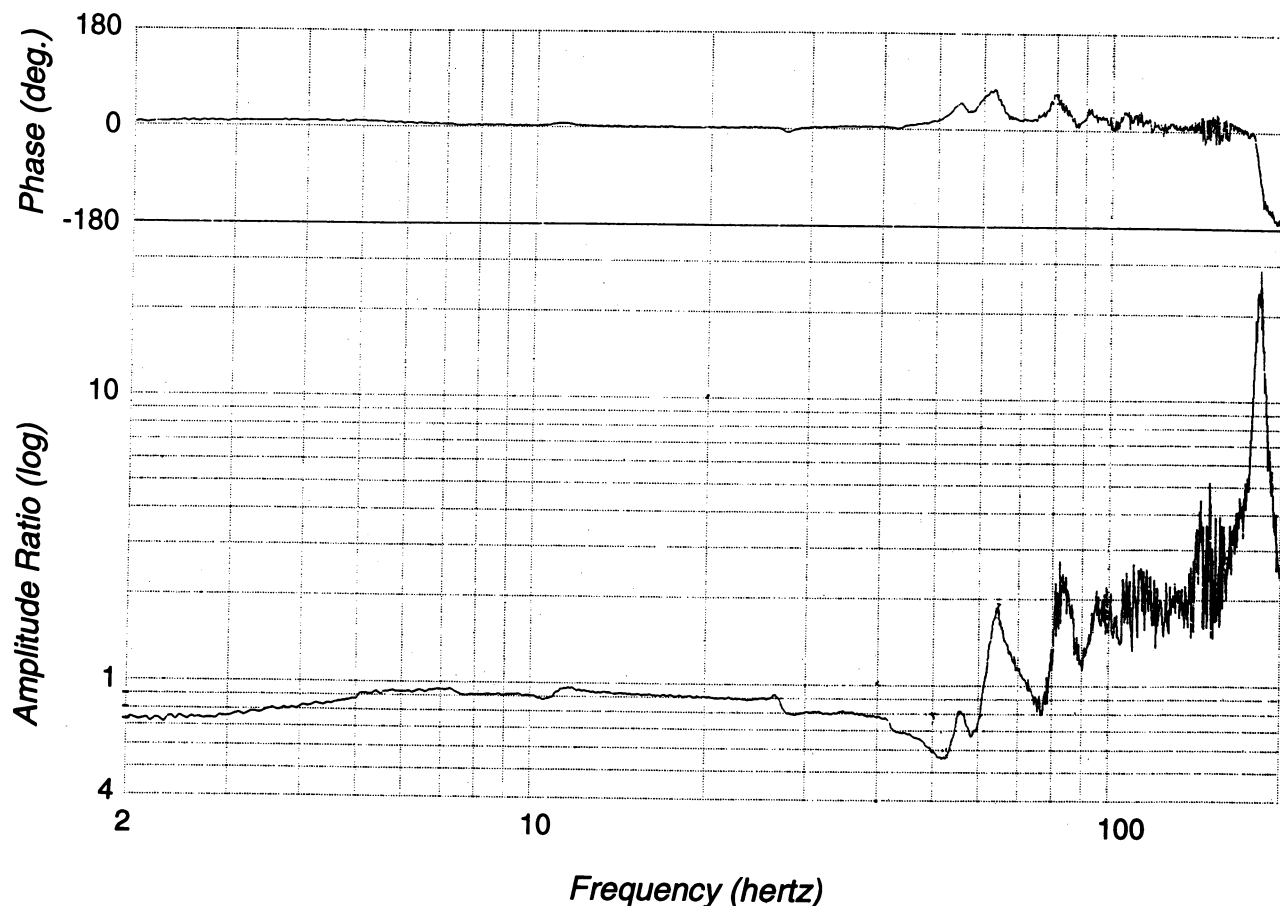


Fig. 22. The transfer function between the transverse accelerometer on the side of the test tank (corrected to velocity) and the transverse geophone in the sonde is flat with negligible phase shift from below 5.0 Hz to over 40 Hz. A major resonance of over 20 dB occurs at about 180 Hz, well outside the pass band of the SEABASS system. For this test the tank is shaken transversely. Note that the vertical scale for amplitude differs from Figures 20 and 21.

phy (SIO), and Woods Hole Oceanographic Institution (WHOI). The project was co-ordinated by Johns Hopkins University Applied Physics Laboratory.

SEABASS was deployed on LFASE using the wireline re-entry technique (Spiess *et al.*, 1989a, 1992) from the R/V MELVILLE in DSDP Hole 534A, about 250 miles E-NE of Miami, Florida (Sheridan, Gradstein *et al.*, 1983). Water depth at the site was 4971 m (Table V). Ocean Bottom Seismographs (OBSs) and a Vertical Hydrophone Array (VHA) above the seafloor were also deployed. While MELVILLE was on station, and connected to SEABASS via the coaxial tether, a shooting pattern of radial and circular lines was fired using airguns and explosive sources from the USNS *Lynch*. This phase of the experiment pro-

vided data on the propagation characteristics of the area as well as characterizing the geology of the sediments and crust surrounding the site. The soft tether was released and R/V MELVILLE returned to port, leaving SEABASS to acquire ambient noise records over a two-week period. SEABASS was recovered by grappling from R/V MELVILLE using the same thruster system that was used on deployment. A summary of the data acquired on SEABASS during LFASE was given by Bolmer *et al.* (1991).

SEABASS was configured with sondes at 10, 40, 70 and 100 m below the seafloor (BSF). The bore-hole hydrophone was located in the top sonde with a three component seismometer. In order to remain within the constraint of a 12-channel system, we sacrificed the data from the radial component of

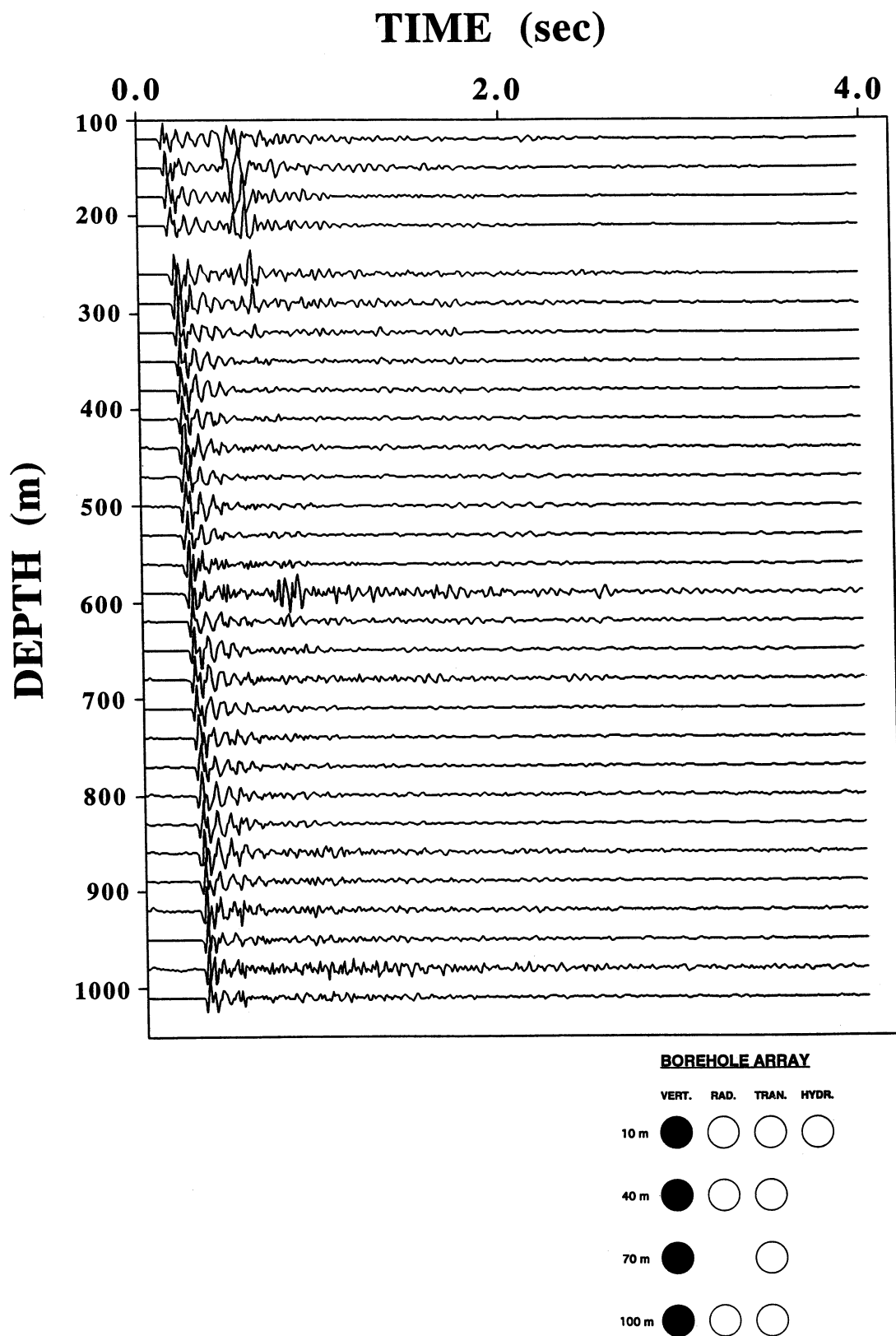


Fig. 23. The zero offset VSP (vertical component) from the Michigan test site shows excellent quality data comparable to other VSP tools run at the site for this bandwidth. The source is a Bolt land airgun.

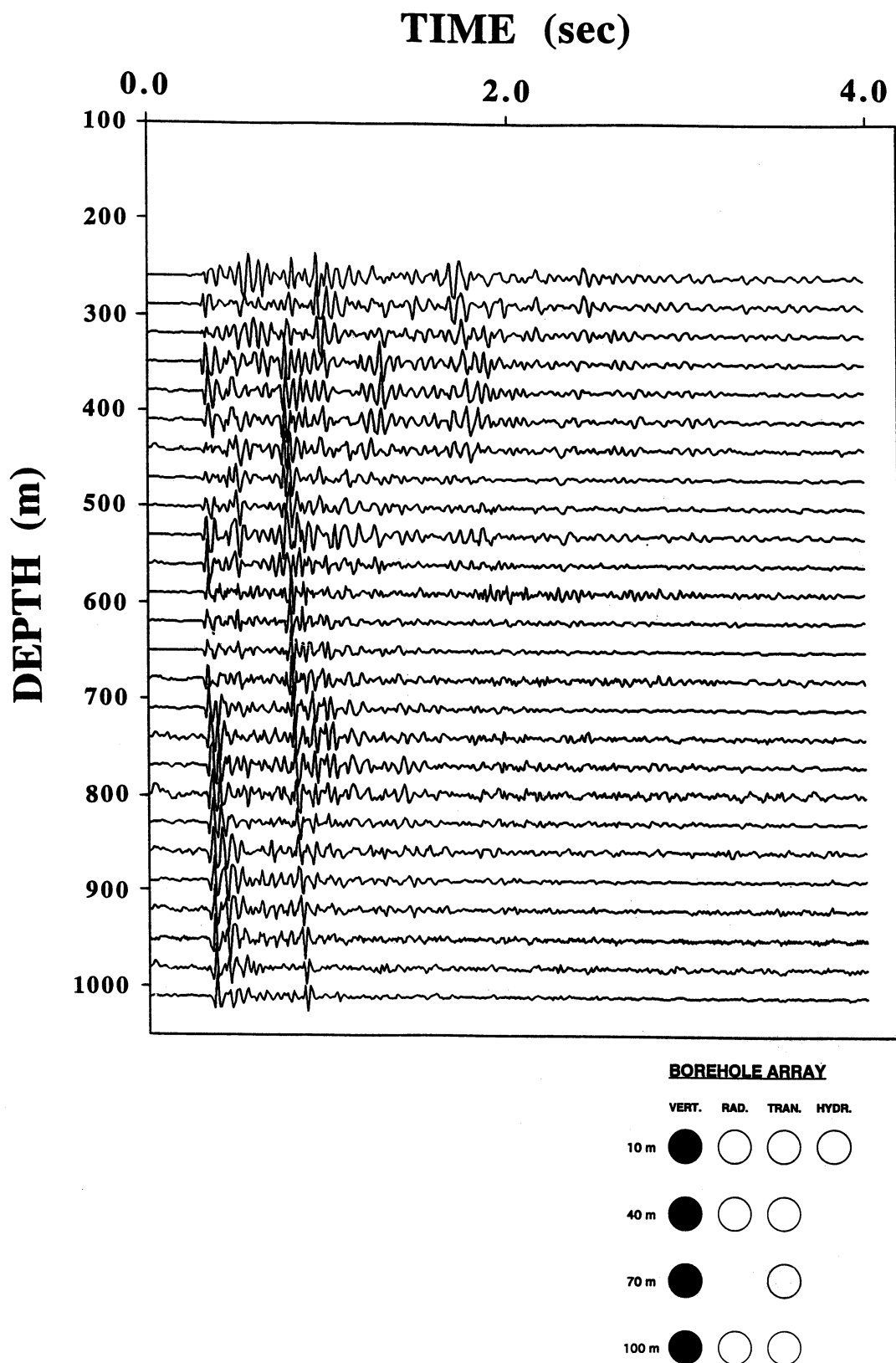


Fig. 24. The offset VSP (0.6 km) (vertical component) from the Michigan test site also has excellent quality data.

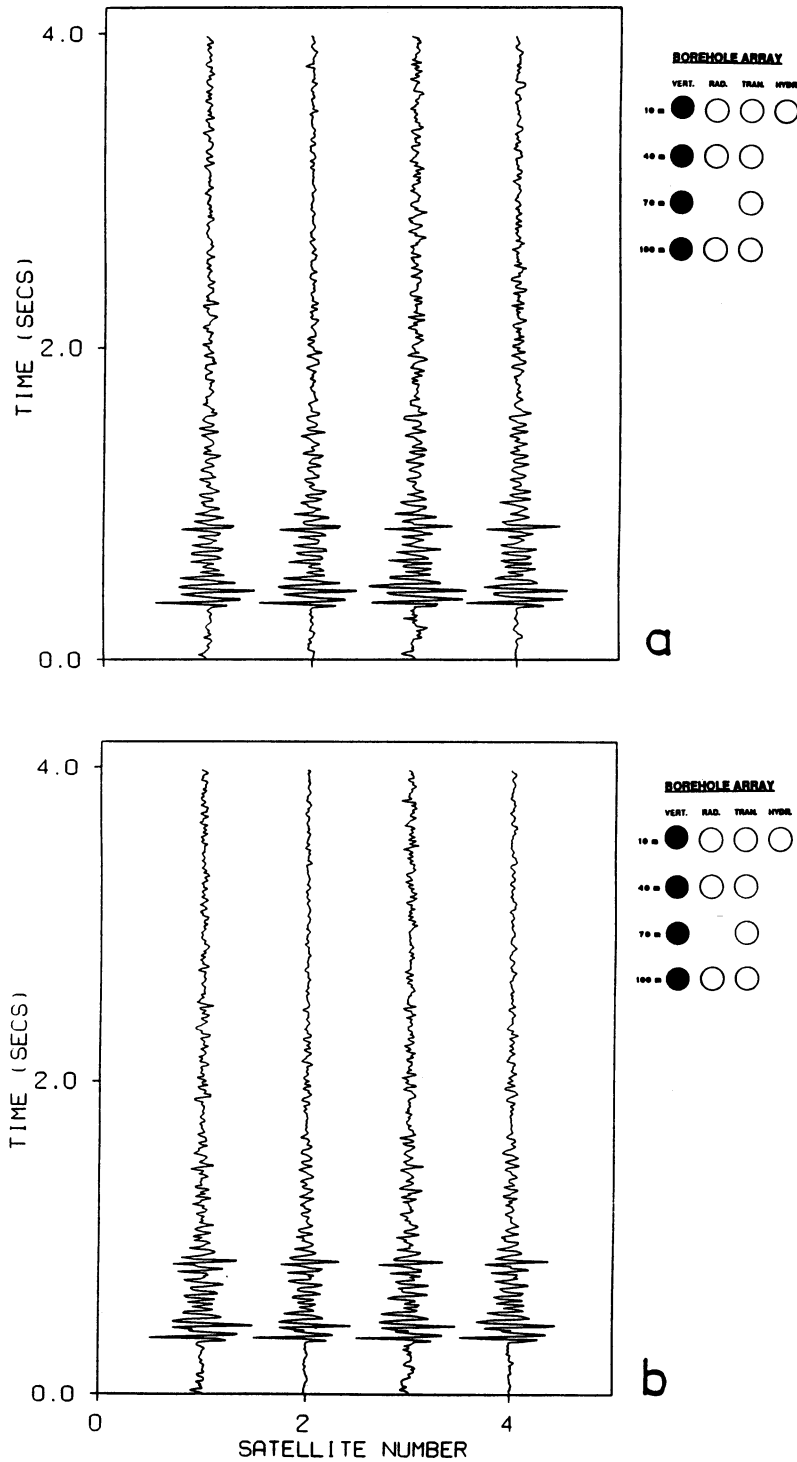


Fig. 25. The response of the four different satellites at the same borehole depth was checked in the Michigan test for a source offset at 0.6 km. a) shows the vertical component for all four satellites clamped at the same depth inside casing and b) shows the vertical component of all four satellites clamped at the same depth in open hole below the casing. There are no significant differences in the responses of the satellites.

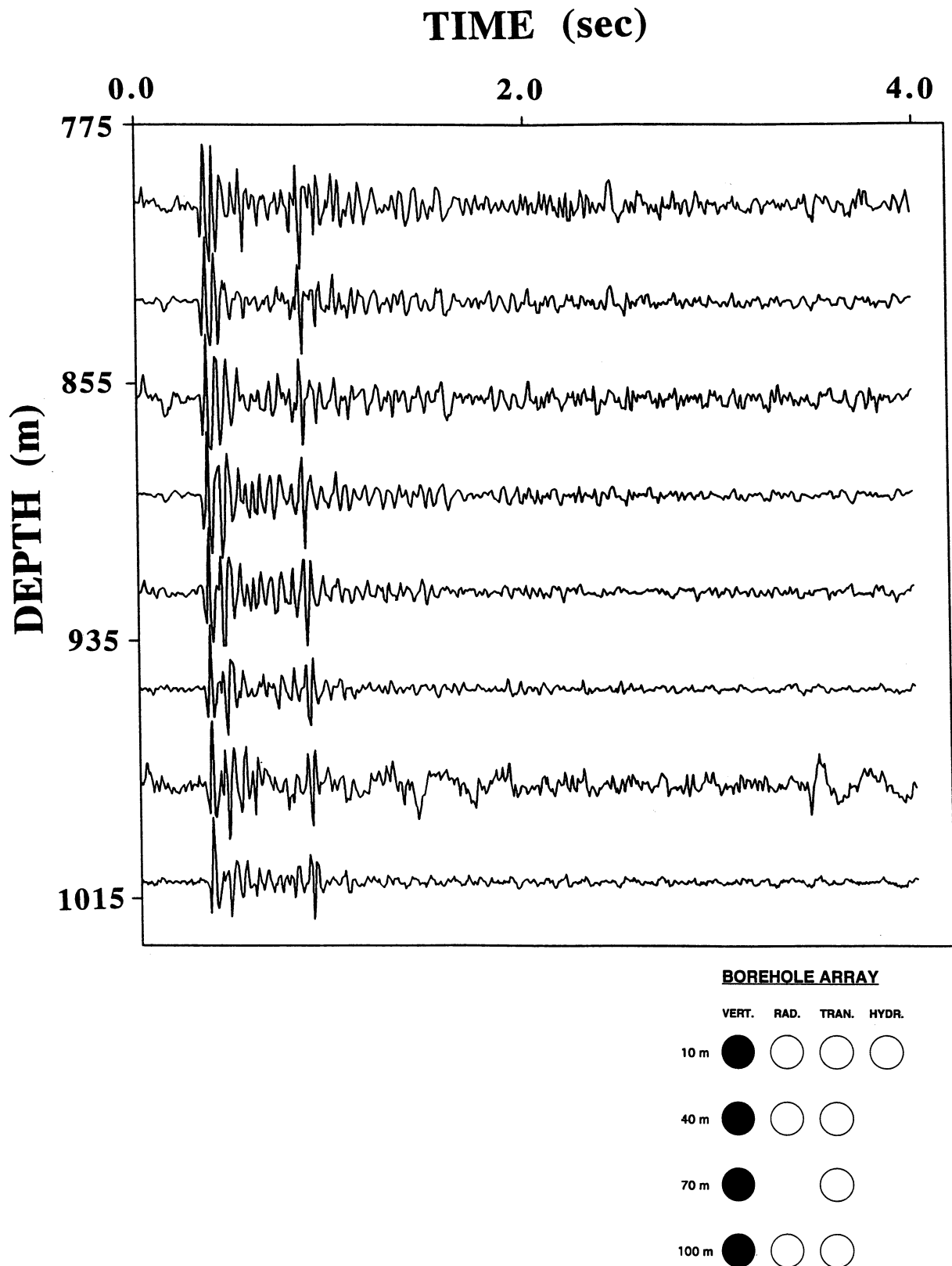


Fig. 26. The effect of casing is shown to be negligible on vertical traces which span the casing shoe at 900 m.

TABLE V
Summary of significant depths at DSDP Hole 534A

	Depth Below Rig Floor (m)	Depth Below Sea Level (m)	Depth Below Seafloor (m)
Top of Sediment	4976	4971	—
Bottom of 16" Casing	5062	5057	86
Bottom of 11-3/4" Casing	5507	5502	531
Top of Basaltic Basement	6611	6606	1635
Total Depth (9-7/8" open hole)	6642	6637	1666

the third node (70 m BSF). The second and fourth nodes had full three component seismometers. The first, third and fourth nodes were well coupled to the borehole. However the clamping arm on the second node (at 40 m BSF) did not release, resulting in poor quality data for this sonde.

Figure 27 shows all 12 time series for an 80-in airgun at normal incidence. Most of the energy is on the vertical components (channels 1, 4, 7 and 10). The vertical component of the second sonde (channel 4) has a resonance around 17 Hz due to the poor coupling. The hydrophone channel (9) has voltage levels about ten times greater than the geophone channels for both signals and noise. This is a consequence of the gain strategy used in the instrumentation and does not necessarily mean that the hydrophone is more sensitive. Only channels 4 and 9 saturate the system during airgun shooting. The hydrophone also shows a second arrival, which is not observed on the geophone channels, about one second after the first arrival. This is a reflection of the tube wave in the borehole which was generated when the direct wave hit the seafloor at the top of the well.

Figure 28 shows all 12 time series for the 80-in airgun at approximately 10 km offset. Larger relative signals can be seen on the horizontal components corresponding to larger angles of incidence. The resonance of the second sonde persists and the tube wave is still evident on the hydrophone channel.

Figure 29 shows a record section (time series of ground motion plotted for increasing range) of the vertical component of the top node for an airgun line. The first, large amplitude arrival out to ranges of about 12 km is the direct water wave. The largest amplitude arrival at ranges between 12 km and 30 km is the first water multiple. Beyond 30 km the largest amplitude arrival is the second water multi-

ple. A weak head wave from the ocean crust, with a phase velocity of about 6.0 km s^{-1} , is observed between 30 and 40 km at a time of about 12 sec.

Phase velocities across the SEABASS array give a clear indication of the direction of sound incident on the seafloor (Figure 30). Water waves are incident from above and have later arrival times with depth. Ground waves, turned in velocity gradients well below the seafloor, are incident from below and have earlier arrival times with depth.

Figure 31 shows polarization diagrams for the bottom node for the direct arrival. The distinct linearity in the polarizations indicates that the sonde is well clamped. The direct wave exhibits linear particle motions which are consistent with theory for body waves. Such linear particle motions are rarely observed in field data because seismometers are often poorly coupled to true ground motion and scattering from heterogeneities in the real earth often distorts 'ideal' observations. These plots are the best indicator of the high data quality obtained with SEABASS.

Figure 32 compares ambient noise levels between the vertical channels at 10 m and 100 m depth. The ambient noise decreases with depth by up to 12 dB between 15 and 50 Hz. Since electrical and Brownian noise levels are well below the observed ambient noise we are confident that we are measuring true earth noise.

The data acquired by SEABASS on the LFASE experiment are among the best quality seismic data ever obtained from the seafloor. Excellent coupling to the formation ensures faithful response to true ground motion. The coda observed in seafloor measurements, which is caused by a combination of poor coupling and strong interface wave scattering, is virtually eliminated on the borehole data. This is supported by the dramatically linear polarization diagrams (hodograms). System noise is at least 20 dB below the observed ambient noise, so that ambient noise studies can be carried out with confidence. Absolute times of seismic events are obtained to $\pm 5 \text{ ms}$ and relative times between data points on different channels are known to within $\pm 50 \mu\text{s}$.

Discussion and Summary

AMBIENT NOISE ISSUES

A number of previous studies address ambient noise and signal-to-noise issues for island, seafloor

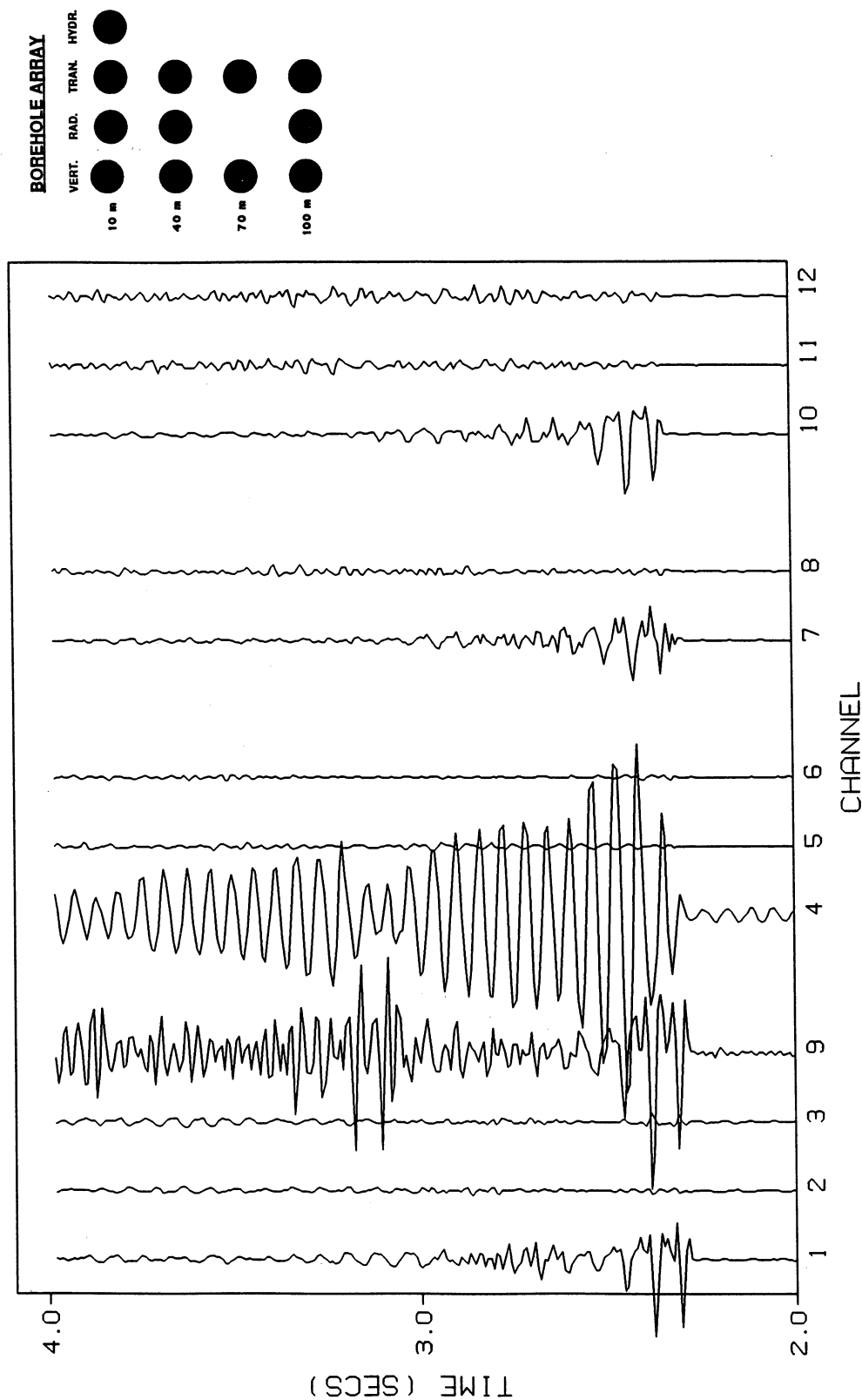


Fig. 27. All 12 SEABASS channels are shown for the seafloor installation on LFASE for an 80-in³ airgun at normal incidence. The strong resonance on channel 4 occurs because this sonde was not clamped. The tube wave can be seen on the hydrophone channel (9) just beyond 3.0 sec. Little energy is observed on the horizontal components because the sound is incident directly from above.

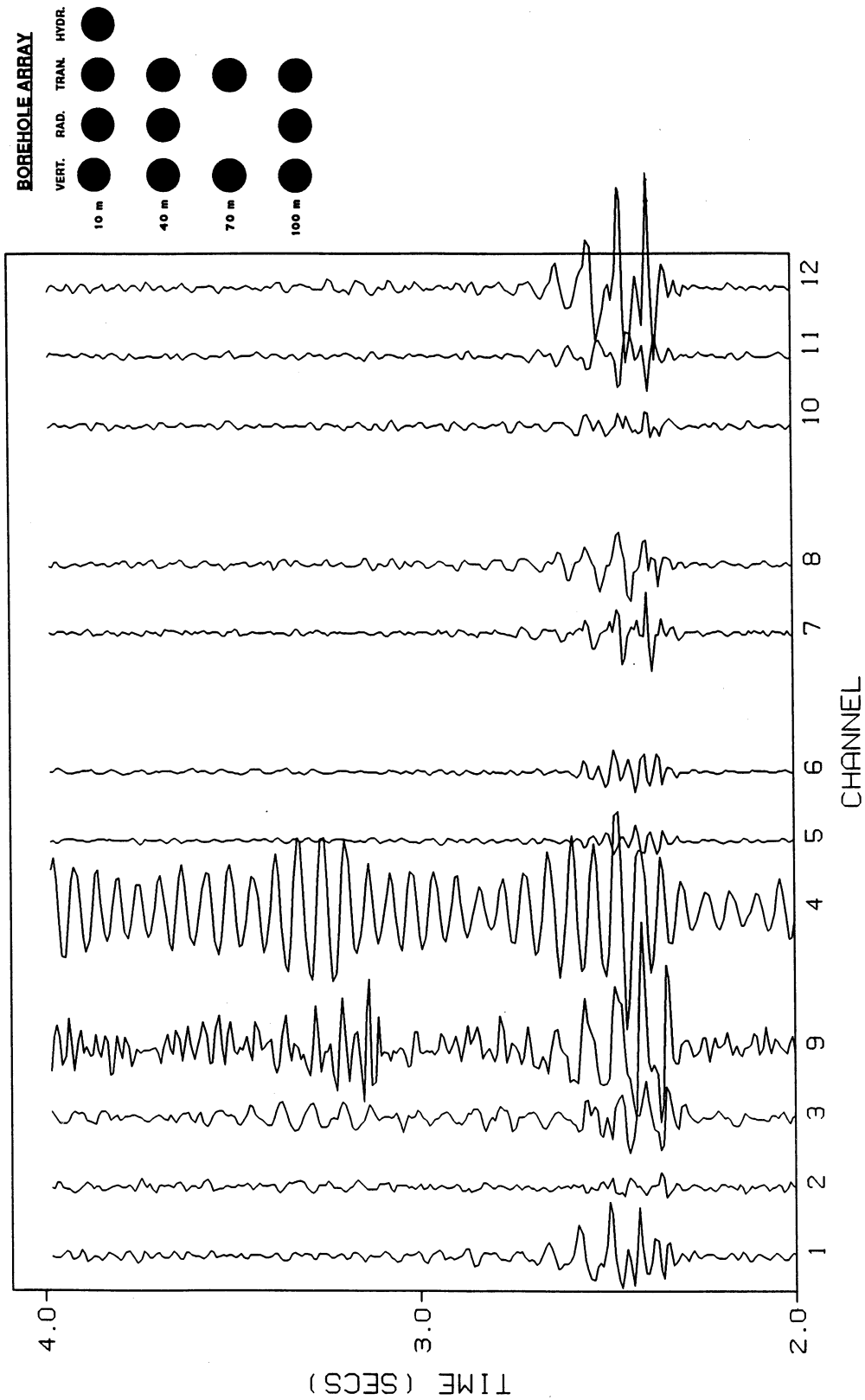


Fig. 28. All 12 SEABASS channels are shown for the seafloor installation on LFASE for an 80-in³ gun at 10 km range. The horizontal components show energy arriving from the side.

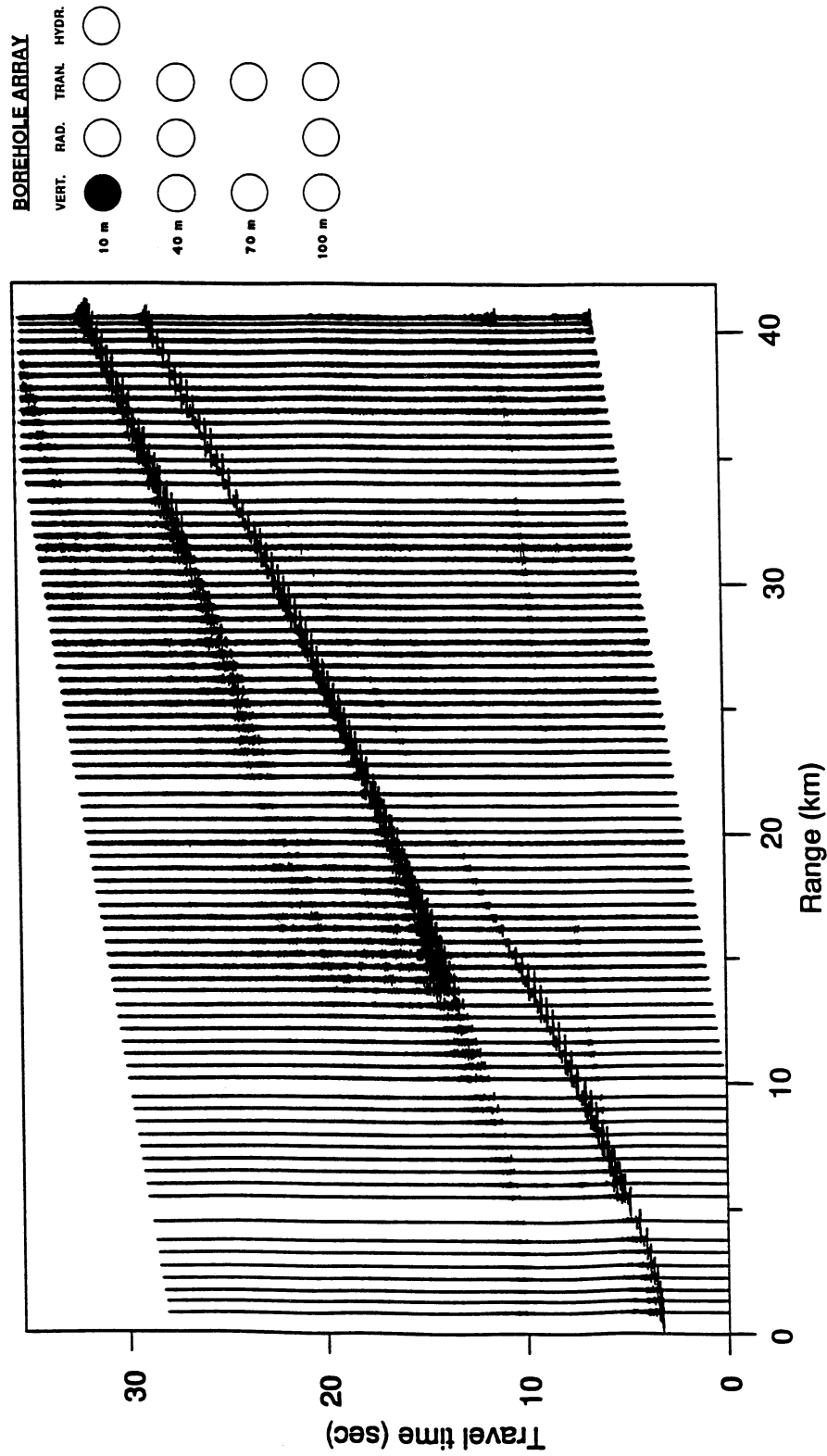


Fig. 29. An airgun refraction line from LFASE shows the distribution of energy with range. The direct (first) path decays beyond 20 km. The first water multiple has the dominant energy between about 12 and 25 km and the third water multiple is dominant from 25 to 40 km. A weak refraction arrival from the sub-bottom can be seen at ranges from 25 to 40 km at about 10 sec. The velocity of this arrival is 6.4 k s^{-1} indicating that it has penetrated to well within igneous basement.

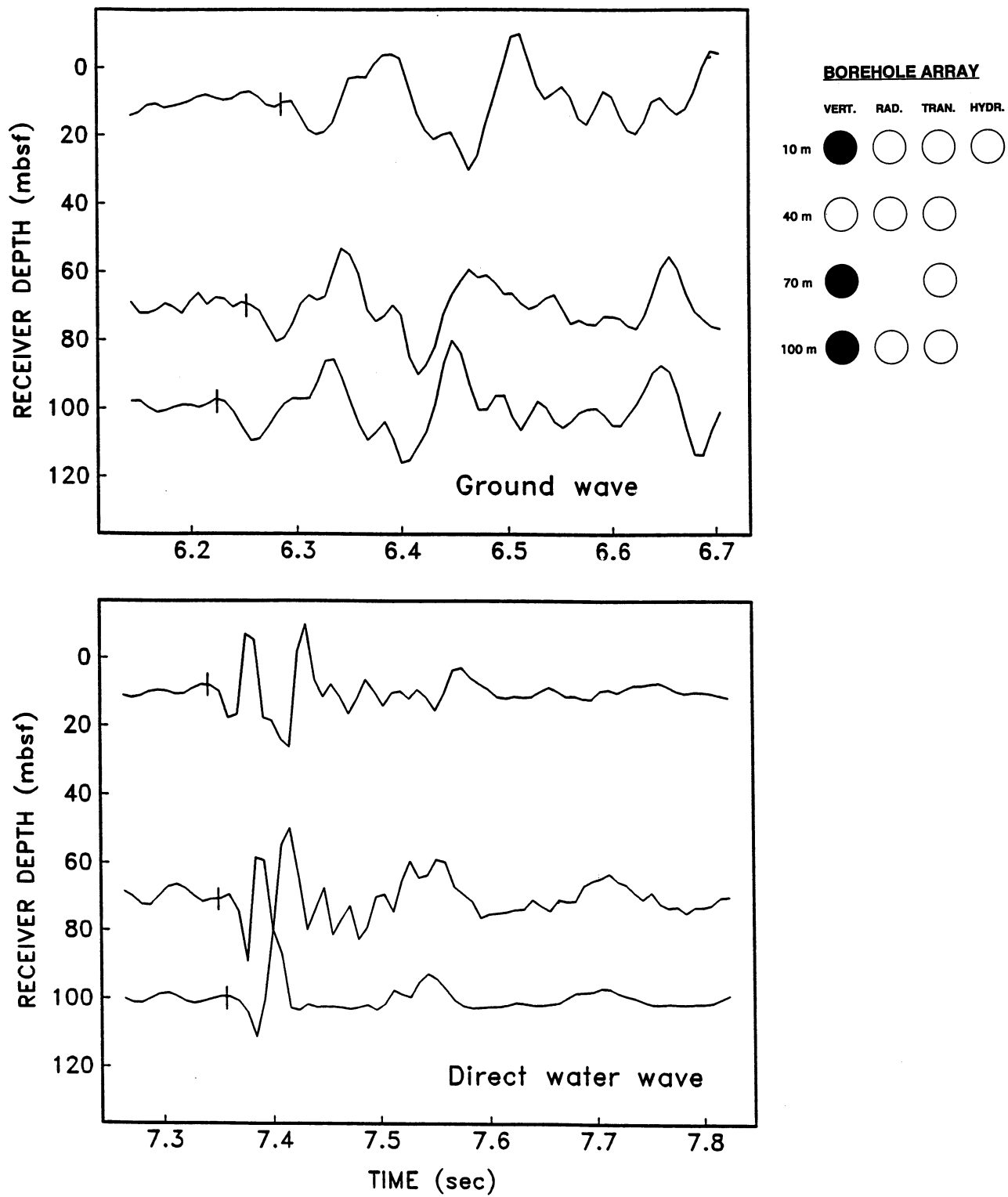


Fig. 30. The arrival times on the various traces across the array indicate that the water wave is coming from above and that the ground wave is coming from below. The shot for this figure is at 10 km range.

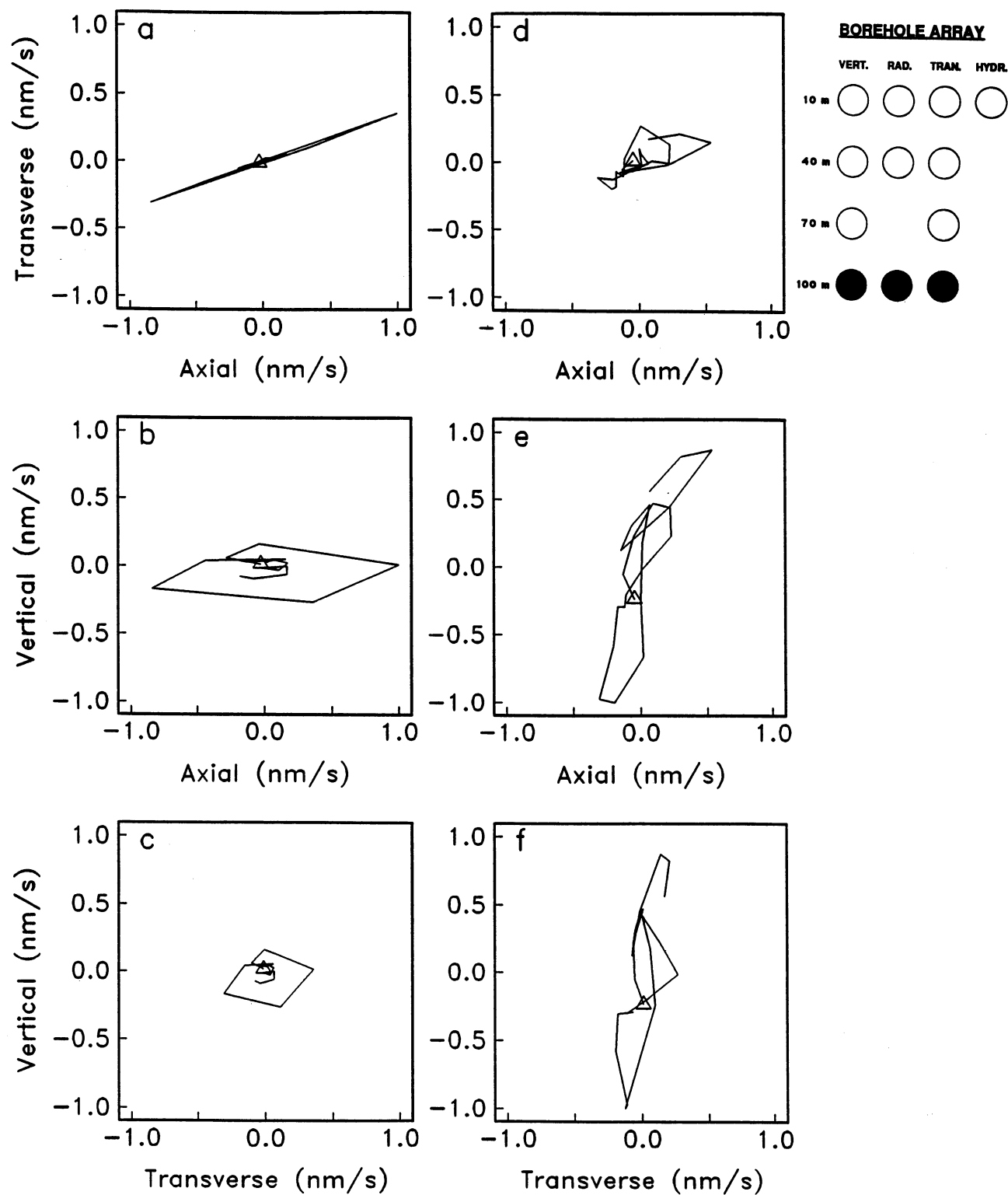


Fig. 31. The polarizations of the water wave (Figures a, b and c) are extremely linear in plan view (a) and point at the source with an azimuthal resolution of less than 5°. The polarizations of the ground wave arrival (Figures d, e and f) are consistent with a compressional wave incident from below. These polarizations correspond to the same shot as Figure 30.

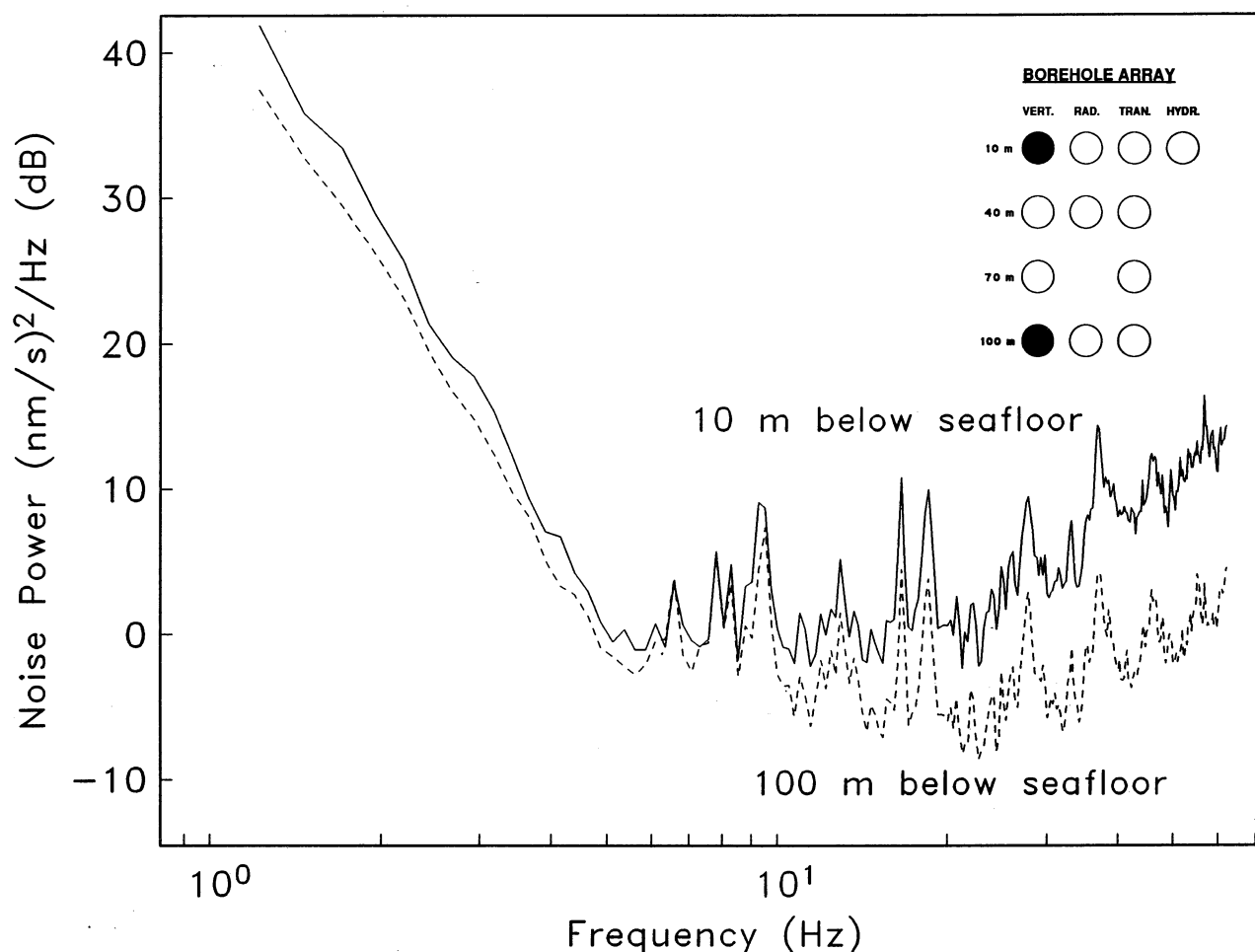


Fig. 32. The ambient noise spectra for the vertical component at 10 m and 100 m depth shows that noise levels decrease up to 12 dB in the upper 100 m of the seafloor in the band 15–50 Hz. Below 15 Hz the spectra are quite similar. (The spectra is based on an interval of 44,997 points (6 min) and the averaging window is 512 points.)

and sub-seafloor installations in the ULF and VLF bands (0.002–50 Hz) (for example, Adair *et al.*, 1986; Duennebie *et al.*, 1987; Hedlin and Orcutt, 1989; Sutton and Barstow, 1990). The goal of these studies is to determine the optimum sensor strategy for particular applications. Hedlin and Orcutt (1989), for example conclude that a borehole sensor (in their case the MSS) has 'significantly lower noise levels than seismometers on the ocean bottom or on islands' for frequencies above 0.2 Hz. The implication of their work is that the worldwide seismic net can be extended to the seafloor (to obtain better worldwide coverage for inversions for earth structure) without compromising data quality and signal-to-noise ratios. The LFASE experiment specifically addresses the issue of how ambient noise varies with depth below the seafloor in a sedimentary environment (Stephen *et al.*, 1991). SEABASS

provides the capability to simultaneously acquire ambient noise and controlled source data at a number of depths in a borehole on the seafloor without a ship present which may contaminate the results.

Figure 33 compares a sample of ambient noise from LFASE with results from the MSS (Adair *et al.*, 1986) and the OSS (Duennebie *et al.*, 1987). The LFASE data are from 100 m depth in sediments in the Blake-Bahama Basin. The MSS data are from a depth of 54 m within basaltic basement, in an area with 70 m of sediment cover, near the Tonga Trench. The OSS data are from a depth of 22 m in basement, in an area with 356 m of sediment cover, off Hokkaido, Japan. All sites are in water depths greater than 5000 m. Both the MSS and OSS data are from open, uncased holes and the LFASE data are from a cased hole. Below 4.0 Hz,

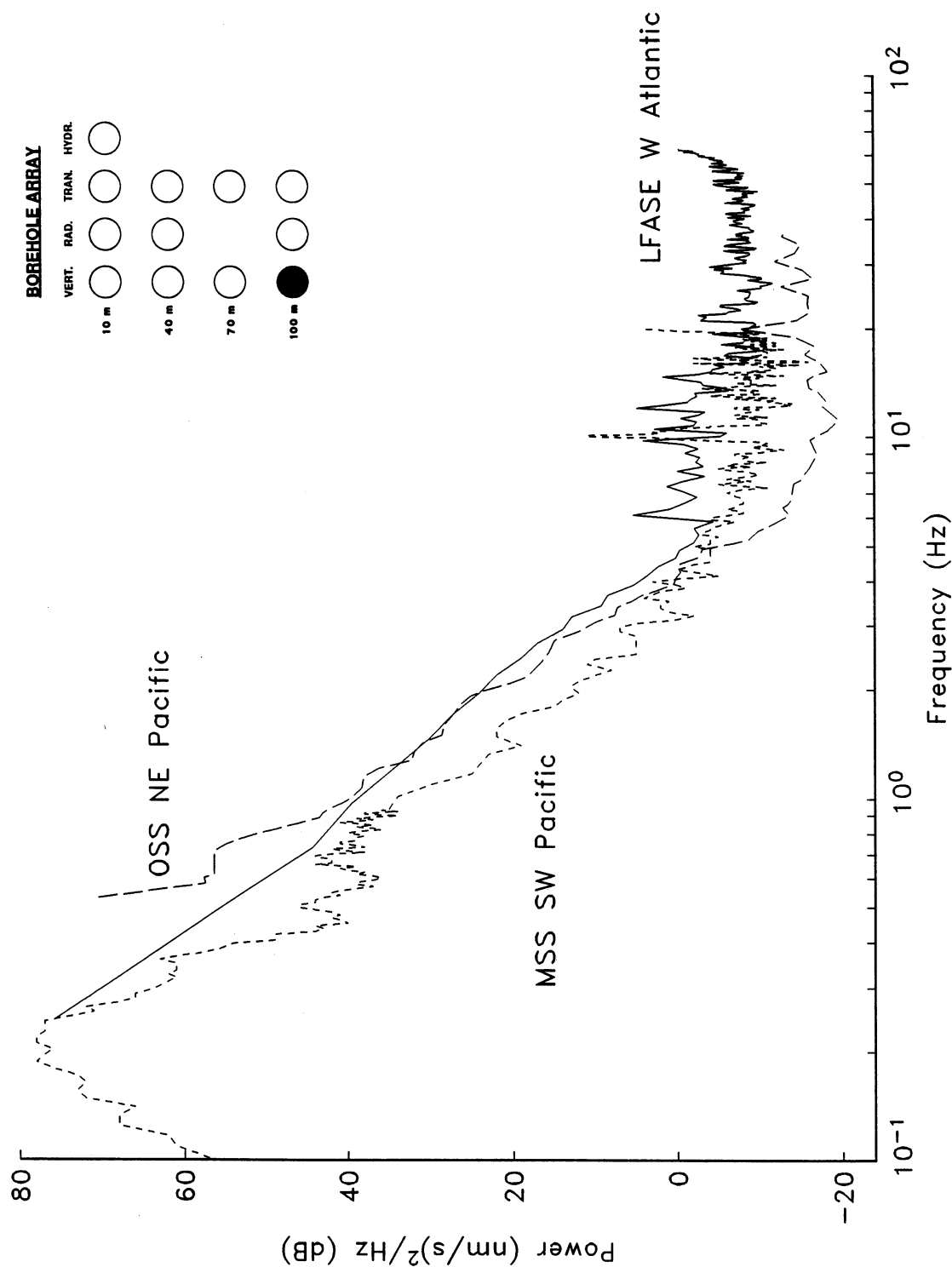


Fig. 33. The ambient noise from LFASE, at 100 m depth in sediments in the Blake-Bahama Basin, is comparable to other sub-seafloor observations acquired by the MSS (at 124 m BSF and 54 m within basaltic basement, near the Tonga Trench) and the OSS (at 378 m BSF and 22 m into basement off Hokkaido, Japan). Below 4.0 Hz, in the microseism band, the OSS and LFASE curves are similar and both are about 6 dB higher than the MSS data. In the shipping noise band, between 6.0 and 20 Hz, LFASE is about 6 dB noisier than MSS and about 12 dB noisier than OSS. MSS data are not available above 20 Hz, but in this band LFASE is about 6 dB noisier than OSS. [For the LFASE spectra the window length is 44,997 points (6 min) and the averaging window is 512 points. The OSS curve is from Duennebie *et al.* (1987) and the MSS curve is from Adair *et al.* (1986). The results are presented as ground velocity at the geophone.]

on the upper edge of the microseism band, the OSS and LFASE curves are similar and both are about 6 dB higher than the MSS data. These levels should correlate with ocean swell above each site. At the low end of the shipping noise band, between 6.0 and 20 Hz, LFASE is about 6 dB noisier than MSS and about 12 dB noisier than OSS. LFASE is expected to be noisier in this band because of its proximity to the sealanes along the U.S. East Coast. MSS is the furthest of the three sites from shipping traffic, and it is not clear why it is noisier than OSS in the shipping band. MSS data are not available above 20 Hz, but in this band LFASE is about 6 dB noisier than OSS, consistent with its proximity to shipping lanes. In general, all three sites appear to have the same ambient noise characteristics with discrepancies of less than 20 dB.

There is not a simple correspondence in the VLF band between the pressure level observed in boreholes (either on land or in the seafloor) and the ground motion measured by clamping to the borehole wall. This is particularly true for the tube waves generated by controlled sources. The signal-to-noise ratio for the tube wave is at least 40 dB greater for a borehole hydrophone than a co-located geophone. However even ambient noise levels do not correlate. The ratio of vertical velocity to borehole pressure for ambient noise varies by almost 40 dB depending on environment (geographic location, depth in the well, etc.). The physical mechanisms responsible for the ambient noise in the pressure field in boreholes are different than for ambient noise in the co-located velocity field. A lack of correspondence between pressure and ground motion for ocean bottom installations has been noted by Adair *et al.* (1988). However we expect that the physics governing the relationship between pressure and ground motion would be different for ocean bottom and borehole installations.

[The VLF ambient noise measurements discussed here should not be confused with ULF observations. At frequencies below 1 Hz, seafloor displacement and pressure are coherent in particular bands. For example, below 0.03 Hz the relationship between displacement and pressure can be used to infer crustal density and elasticity (Yamamoto *et al.*, 1989; Crawford *et al.*, 1991). In the VLF band, tube waves which do not exist for seafloor instruments, contribute significantly to the pressure field in the borehole.]

This paper has presented examples of ambient borehole pressure and three component ground velocity as acquired by SEABASS in two land boreholes and one seafloor borehole. Comparisons have been made with observations at the quietest land stations and at previous seafloor borehole installations. Many factors (such as wind, sea state, shipping, depth of sensor, rock type at sensor, presence of casing, fluid flow in the borehole, cultural noise, etc.) can affect the ambient noise in these environments in various frequency bands. Given these factors it is remarkable how similar the ambient noise fields are.

These rough quicklook comparisons based on a half dozen sites suggest that throughout the world 'baseline' ambient noise in the frequency band 2–50 Hz differs by less than 20 dB. ('Baseline' ambient noise means that we take the quietest spectrum in each data set before doing the comparisons.) There is almost as much variability in spectra between sensors at 10 and 100 m depth in the seafloor as there is between sensors in the seafloor and the Paris basin (compare Figure 14 with Figure 32).

McCreery *et al.* (in press) has proposed that seafloor ambient noise levels in the band 0.4–6 Hz (the 'holu spectrum') saturate because of a corresponding saturation in ocean wind wave amplitudes and that levels in this band on the seafloor are probably constant worldwide. Schreiner and Dorman (1990) suggest that noise in the holu band is scattered into a seafloor wave guide at short range lateral heterogeneities and that the noise propagates along the seafloor as fundamental and higher-mode interface waves (Rayleigh and Stoneley waves). The holu spectrum on LFASE has comparable spectral slope to McCreery's observations and is constant to within 2 dB between 10 and 100 m depth. The depth dependence of the holu spectrum will constrain the mode types contributing to the noise. However since the mode types will be sensitive to shallow seafloor structure a meaningful comparison of OBS and borehole data requires that they be obtained simultaneously at the same site. It is interesting to note that noise levels on land (in Michigan and the Paris Basin) follow the holu spectrum up to about 2 Hz but are about 20 dB louder at 6 Hz (Figure 14).

A more thorough study of the source and propagation mechanisms of VLF ambient noise in land and seafloor boreholes, considering the wide variety of contributing factors, is warranted and is beyond the scope of this paper.

TECHNICAL ISSUES

The SEABASS equipment is available for future experiments to study the ambient noise in the seafloor, the physics of sound propagation at and below the seafloor, and the geological structure of the sediments and crust in the deep sea. Future deployments of SEABASS in boreholes on the seafloor can use either wireline re-entry from a surface ship (Spiess *et al.*, 1989a, 1992) or submersible-assisted re-entry (Legrand *et al.*, 1989). However the array cannot be deployed through the drill pipe from the JOIDES Resolution since the outside diameter of the sondes exceeds the inside diameter of the pipe.

Although SEABASS has been designed for a VLF pass band of 2–50 Hz it obtains useful ULF ambient noise data down to 0.3 Hz (Bradley and Stephen, 1992). The polarization and depth dependence of the sound field down to these frequencies can be directly measured. As currently configured SEABASS can be used for ULF as well as VLF studies.

SEABASS can be modified for use with different borehole sensors such as a broadband seismometer (1000 s–10 Hz) for earthquake studies or a high frequency array (10–250 Hz) for conventional VSPs. SEABASS can also be used in land boreholes to carry out conventional VSPs or to acquire ambient noise levels at a number of depths simultaneously.

It is not necessary to have a borehole to use the seafloor control and recording package. The SEABASS BCU can be used with ocean bottom seismometers or shallowly buried seismometers. In this configuration it has advantages over conventional OBSs. Control over the seafloor package via the coaxial tether and cable to the ship gives considerable engineering flexibility to the bottom package. Equipment for implanting a shallow buried instrument (either 'washing-in' for sediments or using a remotely operated drilling device for hard rocks) can receive power and command signals over the coaxial cable. Television can be used to monitor the emplacement process. After installation the seismometer response can be checked on-board ship and post-emplacement procedures (such as leveling the seismometers and coupling tests) can be carried out prior to leaving the installation in autonomous mode.

SEABASS is a robust and calibrated system for acquiring, reducing and analyzing seismic data in the band 2–50 Hz below the seafloor. System noise

is sufficiently low that authentic ambient noise can be acquired in all but the quietest earth environments. The seismic sensors are well coupled to the formation in both cased and uncased holes. The Multilock clamping mechanism used on SEABASS has no resonances in the observation band. Considerable effort has been expended to anticipate potential problems and to build redundancy and safety procedures which will optimize the chances of recovering excellent quality data. As part of the acquisition system, SEABASS has a quicklook quality control capability. There is also extensive post-processing software for analyzing and displaying the scientific results and distributing and archiving the data.

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