frequency f_c = 0.5 Mcy, and with n = 400,000 cycles, the sensitivity is 440 count/cm. Thus, the least count precision of 0.0023 cm of water pressure was obtained. With the measuring interval, Δt, set at 30 seconds, and an averaging time $n/\bar{f} \approx 27$ seconds, 2 seconds were available for display and data recording.

In a study of ordinary ocean waves, unfiltered Vibrotron gauges having a sensitivity of 1.63 cy/sec at a mean frequency of 13.8 kcy/sec were used. With f_c = 1 Mcy and n = 20,000, the sensitivity dR/dp = 105 count/cm provided a precision of approximately 0.1 mm of water pressure. With an averaging time of 20/13.8 ≈ 1.5 seconds, a measurement could be made and recorded every 2 seconds.

Digital Recording Equipment

The function diagram of the digital recording system is shown in Fig. 7. A one-megacycle crystal oscillator is divided by a six-stage decade divider to produce one pulse per second at the input to the program counter. Eight line coincidence gates connected to the eight most significant bits of the program counter operate various circuits to provide programming of the recorder. The first gate, G_1, actuates a pulse generator which resets the program counter every 300 seconds to establish the repetition rate of the equipment. Also, G_1 (i) actuates flip-flop A which resets the atmospheric and tide counters to zero, (ii) opens the input gates to the tide and atmospheric pressure counters, and (iii) increases the sample number counter by one count. Pulses from the tide and atmospheric pressure gauges accumulate in the tide and atmospheric binary counters for 296 seconds, at which time gate G_2 resets flip-flop A. The resetting of flip-flop A actuates the record sequence. Data in the counters for tide, atmosphere, and sample number are scanned six bits at a time and punched in paper tape. Simultaneously the nine least significant bits of each counter are decoded into octal characters and recorded by the paper tape printer.

A third gate, G_3, was provided to apply 110-volt power to the paper tape punch and printer only during the record cycle so that mechanical mechanisms would not have unnecessary wear during the remainder of the 5-minute interval. The tide recorder manufactured by the Applied Development Corporation, Maywood, California, has transistor logic throughout. Printed circuit logic cards mounted in the hinge chassis within a slide drawer, may be tipped to the position shown in Fig. 8 so that both the modules and subchassis wiring are accesible. The Tally paper tape perforator and Hewlett-Packard printers are also mounted on sliding supports so that they also can be conveniently maintained while in operation.

The equipment was enclosed in an airtight hardwood cabinet with a plexiglass door. Air was circulated through the equipment by blowers to maintain reasonable operating temperatures. Cooling of the air takes place through the stainless steel side which acts as a heat exchanger. Dehydrants installed inside the cabinet insure moisture-free operation of the equipment.

Vacuum tubes, mechanical relays, and high-voltage electrolytic condensers were avoided. Except for the printer and punch-drive motors and the air-conditioning blowers, the equipment was battery operated. Commercial 110-volt a-c power was used only to trickle-charge the batteries and drive the various motors. A battery operated inverter supplied 110-volt a-c power in case of power line failure.

References

1. G. H. Darwin, *Tides and Kindred Phenomena in the Solar System* (1898; Freeman, San Francisco, 1962).
2. G. W. Groves and F. Grivel, *Geofis. Intern.* **2**, 5 (1962).
3. F. E. Snodgrass, W. H. Munk, G. R. Miller, *J. Marine Res.* **20**, 3 (1962).
4. W. H. Munk and E. C. Bullard, *J. Geophys. Res.* **68**, 12 (1963).
5. R. W. Poindexter, in *Joint AIEE-IRE Conference on Telemetering and Remote Control, Long Beach, Calif., 26–27 Aug. 1952* (American Institute of Electrical Engineers, New York, 1953).
6. F. E. Snodgrass, W. Munk, M. J. Tucker, *Trans. Am. Geophys. Union* **39**, 1 (1958).

Seismic Measurements on the Ocean Bottom

New instruments are used to study earth's crustal structure and seismic background.

Hugh Bradner

For many years prospectors for oil have made seismic measurements in shallow water, but seismic recording in the remote environment of the deep ocean bottom is a far more difficult task, and only three successful records were published before 1961. Pioneering work was reported by Ewing and Vine in 1938 (*1*), but their measurements were interrupted by World War II. After the war Ewing's group at the Lamont Geological Observatory (*2*) resumed seismic recording from the deep ocean bottom. They were interested in monitoring small earthquakes and nuclear explosions and in studying the seismicity of the earth and the origin and propagation of the continual background quivering called microseism.

The concern with bomb test detection led, in 1960, to additional government support of related programs at Columbia (*3*) and by groups at the University of California's Institute of Geophysics and Planetary Physics (*4*) and at the Texas Instrument Company, Dallas, Texas (*5*). In 1961 the data on ocean-bottom seismic background was meager, and information on signal-to-noise ratios was essentially nonexistent. The prevailing view was that the ocean basins might provide a very quiet environment for monitoring explosion signals. An opposing view was that the ocean basins might be more noisy than land if the microseism back-

The author is professor at the University of California, Institute of Geophysics and Planetary Physics, and the department of aerospace science, at La Jolla.

ground is generated at sea, far from shore. The sources and propagation of microseisms have been investigated for half a century, but are still being actively debated. The group at the Institute of Geophysics and Planetary Physics undertook a study of microseism; the Texas Instruments Company group gave special attention to signals from earthquakes and explosions. Excellent unpublished reports of the work of all these groups are kept at a special VELA-UNIFORM seismic library at the University of Michigan.

Earlier Methods

In the early prospecting for petroleum the oil companies used geophones (insensitive, high-frequency seismometers) to make recordings in shallow water. The geophone was usually lowered on its cable from an anchored ship, and the seismic information was recorded on shipboard. Ewing and Vine, in their early recording on the deep ocean bottom in 1938, used a string of four geophones and four explosives, as shown in Fig. 1, to obtain a seismic refraction profile. In 1939 and 1940 they obtained a small amount of additional seismic refraction data from recording oscillographs and geophones that were free-dropped from the surface (*6*). Each geophone was buoyed by a 113-liter gasoline float and weighted down by iron ballast which had a time release. After the war Ewing and the other members of the Lamont group developed a system which would transmit seismic information acoustically from an instrument on the ocean bottom to a ship on the surface (*2*). In 1961 Monakhov, of the Soviet Union, reported his recording of microseisms from a small number of sites on the floor of the Black Sea, the Baltic, and the North Atlantic (*7*). This work was carried out with a single-component vertical seismometer and galvanometer recorder, gimbal-mounted in a heavy steel sphere of 54-centimeter inside diameter, which was lowered to the bottom on a steel cable. Monakhov's records were of 10 to 20 minutes' duration. Analysis of the data was limited to simple observations from the analog records of galvanometer deflection. Monakhov reached the tentative conclusion that microseisms are determined not only by the waves on the sea surface but also by features of the floor structure.

Today in the United States other

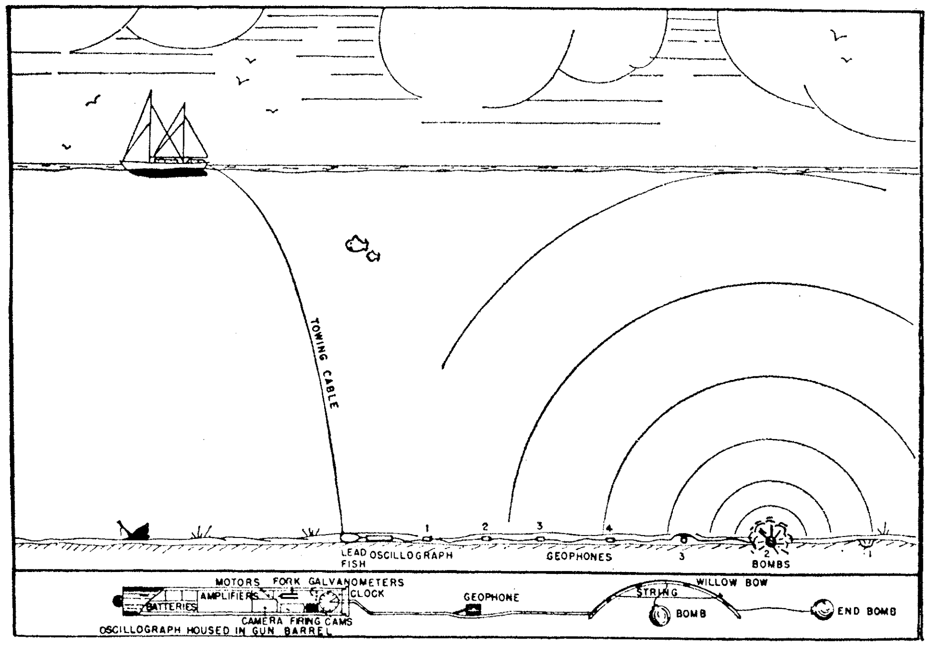

Fig. 1. First deep-ocean seismic measurements. [From Ewing and Vine (*1*)]

techniques and instruments are being developed and used by the Lamont, Texas Instruments, and University of California groups. In all, about 100 records have been made, despite the difficulties of recording from the deep ocean.

The Difficulties

In recording from the ocean bottom it is not economically feasible to try to control either the instrument coupling to the bottom or the angle at which the instrument reposes. Seismograph records must be examined critically for environmental effects, such as oscillation of the instrument by water currents. In ordinary land-based seismometry, the effects of a 10-kilometer-an-hour wind may shake the instrument and move it back and forth over a range of many millimicrons, even though it is mounted on a concrete pedestal and buried in an underground vault. In water, shaking of this amount would be produced by currents of a few tenths of a kilometer per hour. Unfortunately oceanographers cannot estimate even the order of magnitude of deep-ocean-bottom currents in most of the places of seismic interest.

The weight and volume of the instrument components that may be used are severely limited by the difficulties of handling equipment on shipboard. In turn, these limitations impose restrictions on power consumption and on the length of record that may be obtained. If the seismometer is connected to the surface by a recovery cable, it is likely to be dragged or jerked by the pitching and drifting of the ship, and seamanship, plus luck, may be required to avoid tangling and breaking of the cable. Even when the cable hangs vertically downward for 8 kilometers, the heaving and dragging at the upper end shake the seismometer by an intolerable amount, unless the cable can be decoupled from it. The usual method of decoupling is to terminate the cable in an anchor as heavy as the ship and cable can stand, and to separate the seismometer from the anchor by a few hundred meters of flexible line. Even so, there is some danger that the heaving on the anchor will transmit vibrations to the seismometer, or that the ship will drift far enough in a few minutes to drag the anchor and the instrument. If the instrument is to sink freely to the bottom without tether and to rise to the surface of its own accord after making a record, considerable ingenuity must be used in designing the apparatus and much care and good luck must attend the seagoing operation. The situation is bad if the instrument rises but fails to transmit a radio signal on reaching the surface. It is not easy to locate a small, drifting object on the vast surface of the ocean by visual means alone. The situation is worse if the instrument fails to rise, since recovery of a small object from the ocean bottom is beyond the capability of today's technology.

If a free-falling, untethered seismometer is to telemeter seismic information back to a ship on the surface, there are a number of problems, including those of signal strength, Doppler modulation of the signal when the receiving hydrophone rises and falls in the waves, and difficulty of operating in heavy weather.

All these problems may be circumvented by connecting the seismometer to the nearest land by electric cable, but extremely reliable apparatus is needed, and economic factors limit the distance that cables with repeater stations can be run from shore.

Columbia University Instruments and Measurements

The recent ocean-bottom seismometer work of the Lamont Geological Observatory is described in papers by Ewing and Ewing (*2*) and by Prentiss and Ewing (*8*). Most of their work was carried out with telemetering instruments, but Prentiss also mentions a 35-millimeter film-recording system. A block diagram of the telemetering ocean-bottom seismograph is shown in Fig. 2. Seismic motions are detected by a geophone with natural frequency of 2 cycles per second, operated at a critical damping ratio of about 0.5.

Representative calibrations of all the seismographs described in this article are shown in Fig. 3. The vertical scales have been multiplied by arbitrary factors for the different instruments, so that they can all be displayed conveniently on the same figure. All observers can extract meaningful data on microseisms at frequencies down to at least 0.2 cy/sec, in spite of the rapid decrease in instrument response, since the microseism background rises very rapidly in this region. However, high-resolution digital spectral analyses offer a great advantage over visual observation of wiggly-line analog displays in this region of opposing trends.

The amplified output from the geophone drives a variable inductance element which provides frequency modulation of an oscillator of about 1 watt power and center frequency of 12 kilocycles per second. The oscillator drives a small, free-flooding magnetostrictive acoustic radiator. The signal is detected, aboard a surface ship, by the transducer of a standard echo sounder. The signal is then amplified, recorded at lower carrier frequency on a tape recorder, and simultaneously displayed in demodulated form on a chart recorder. This method of operation allows the experimenter to monitor his equipment. That advantage is partially offset by the difficulties previously mentioned.

Implacement methods. Three different methods of telemetering seismometer implacement are described by Prentiss and Ewing (*8*). Initially, the bottom unit was considered expendable, and there was no mechanical link to the ship during recording. In later operations the instruments remained connected to the surface through a slack recovery cable. In the Atlantic near Bermuda, the seismometer package was connected to a 680-kilogram weight by 200 meters of manila line. The weight and line were lowered to the bottom on the end of a steel cable. Vibrations during lowering caused a characteristic "chirping" at the receiver. The chirping stopped when the seismometer reached bottom. Shortly thereafter, the impact of the weight was detected. Measurements were then obtained until the ship drifted far enough to drag the weight. By slacking the wire at the proper rate, the seismometer was decoupled from the ship for as long as 7 minutes. In the Arctic, measurements were made from an ice island which was drifting about 1.6 kilometers per day. In that environment the 680-kilogram weight was not used, and the seismograph remained quiet for periods of as long as an hour. The film-recording seismograph was lowered and recovered with polypropylene line of positive buoyancy, which was attached to a float at the surface and to a 230-kilogram weight on the bottom. The seismograph was attached to the weight by 180 meters of slack manila line. This method of implacement was used successfully for recording up to 24 hours of data. However, in the present stage of development the buoy technique requires a

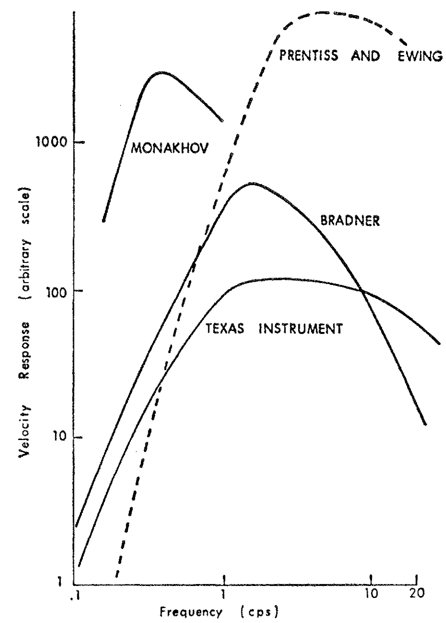

Fig. 3. Representative frequency calibrations of ocean-bottom seismographs.

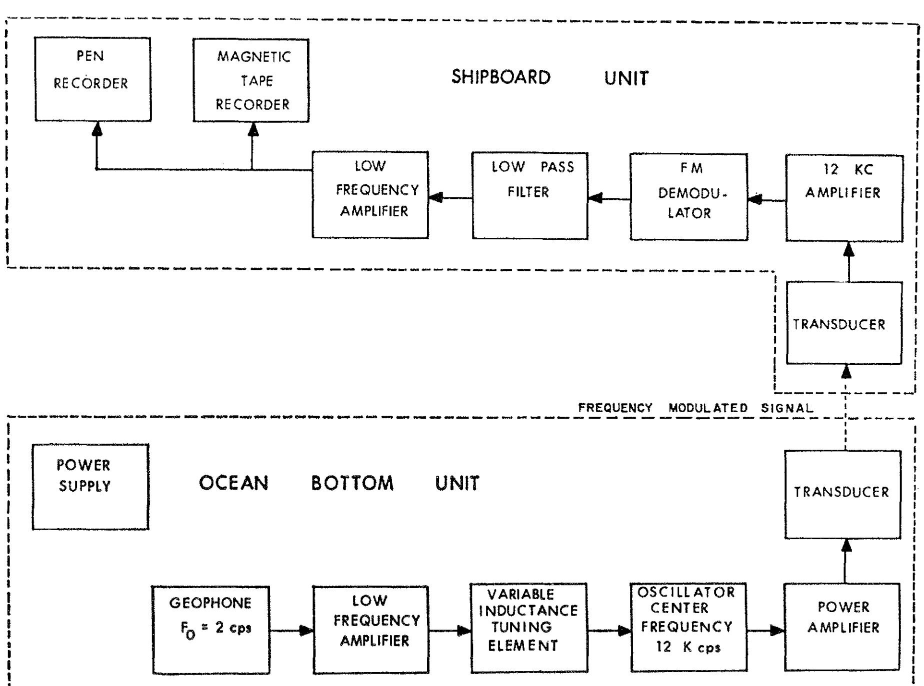

Fig. 2. Block diagram of Columbia University's telemetering ocean-bottom seismograph.

high level of judgment and seamanship on the part of the captain and crew. Furthermore, some oceanographers have observed that fish may sever plastic lines.

Shore-cabled seismometer. Recent unpublished work by the group at Columbia has been directed toward modifying a three-component lunar seismometer of 15-second period for ocean-bottom operation. This long-period seismometer, along with a short-period vertical seismometer and recorders of temperature, tide, and water current, will be installed about 145 kilometers off Point Reyes, along the coast of northern California. Data will be transmitted to shore by coaxial cable.

Data reduction. Two analog methods have been used by the Columbia group to obtain seismic spectra. In the first method, predominant periods and amplitudes are measured on broad-band visible recordings of the demodulated seismometer signals. A smooth line is then drawn through these data points. In the second method the demodulated seismograph records are passed through standard one-octave bandpass filters and then recorded on a chart. An envelope is drawn to include 90 percent of the peak-to-peak amplitude for the record of 5 minutes' duration. These methods of analysis are fast and easy, but they do not give the high spectral resolution or the quantitative results that can be obtained from numerical methods of time-series analysis with digital computers.

Seismic background in the Atlantic and Arctic oceans and in the Gulf of Mexico. Prentiss and Ewing (*8*) report five measurements in the Atlantic, three in the Arctic, and one in the Gulf of Mexico. Figure 4 shows these locations, along with all other deep-ocean-bottom seismic measurements that are reported in the literature and in the VELA-UNIFORM reports. On a global scale, the number of sample points is very small, even though the number of data have increased 50-fold in the past 5 years.

The Columbia workers have observed microseism background noise ranging from below the amplitude of background for a quiet continental site to well above the average for continental background. They conclude that the signal-to-noise ratios for seismic body waves, on at least some parts of the ocean floor, will be as good as those at average and quiet land stations. Measurements from a drifting ice island in the Arctic Ocean during the spring season indicated very low noise levels. The ice surface was found to be as quiet as the ocean bottom at that time.

The limited data from the Columbia investigations do not lead to final conclusions on the origin or mode of propagation of ambient seismic energy on the ocean floor. They suggest that the absolute amplitude of the ambient noise may be as much a function of local geology, bottom structure, and location in the ocean basin as a function of the meteorological conditions at the surface.

Texas Instruments Company Instruments and Measurements

Tethered seismometers. In the original Texas Instruments Company instrument, described by Thompson and Schneider (*9*), the multiplexed signal from three seismic transducers and one pressure transducer was digitally recorded. The dynamic range was 36 decibels. An improved instrument makes dual-level wide-band frequency-modulation recordings from the same transducers.

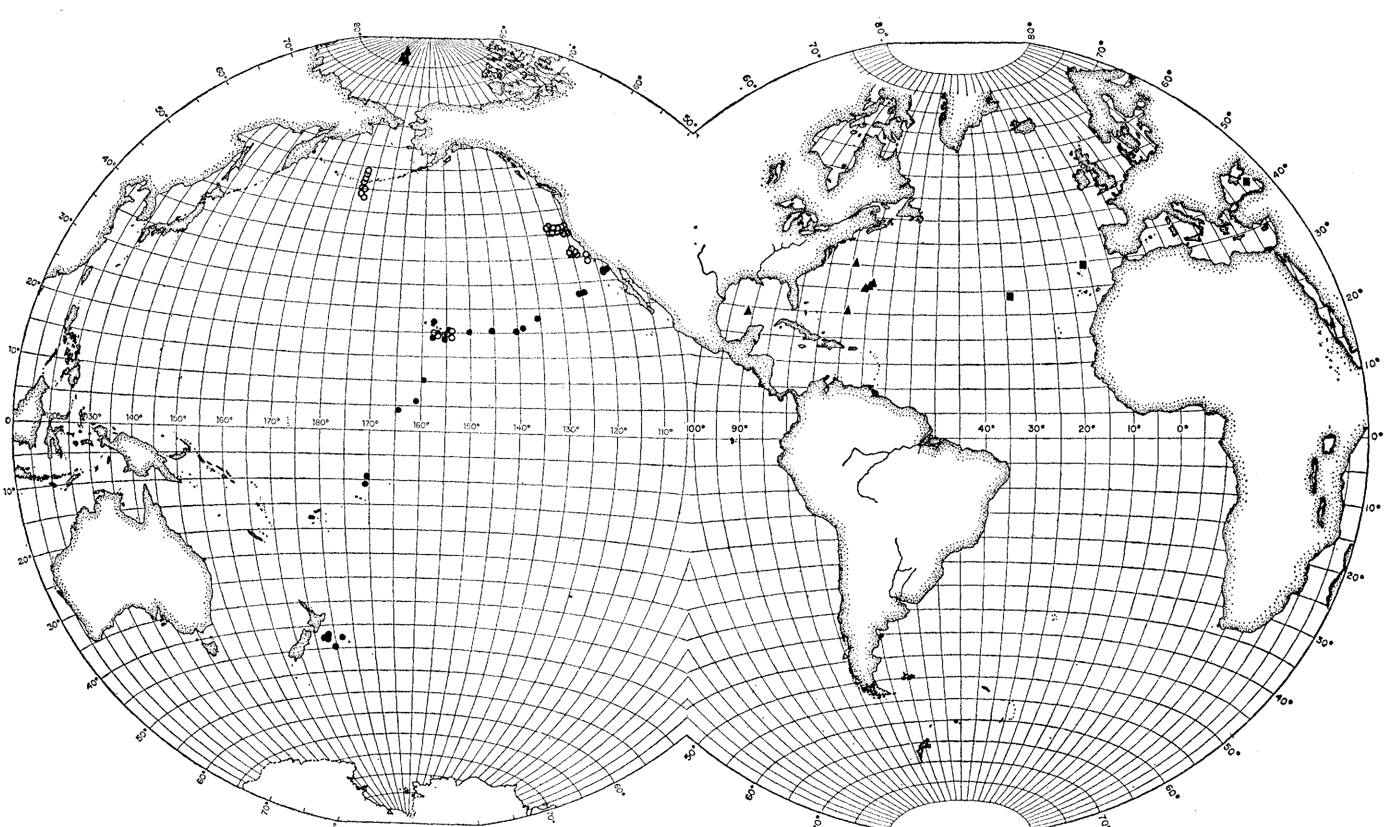

Fig. 4. Locations of deep-ocean seismic measurements: (triangles) Columbia University measurements; (squares) Monakhov measurements; (open circles) Texas Instruments Company measurements; (solid circles) University of California measurements.

Digital recording has the advantage of permitting measurement over a very large dynamic range. Values as high as 100 to 120 decibels are readily obtained. However, the recording time is limited, since the digital format does not make efficient use of the magnetic tape. With wide-band frequency-modulation recordings the dynamic range is normally limited to about 30 or 40 decibels. Such recordings make somewhat more efficient use of the magnetic tape. The highest packing density can be obtained by direct recording of the sub-audio signal at very low tape speeds. The dynamic range is again limited to about 30 to 40 decibels, and there are very severe requirements of amplifier stability and tape-speed uniformity.

A block diagram of the Texas Instruments dual-level frequency-modulation instrument is shown in Fig. 5. The three-component, gimbal-mounted seismometers have a sensitivity of better than 1 millimicron at frequency of 1 cy/sec. They are conventional moving-coil velocity sensors. Natural undamped frequency is 1 cy/sec, and the units have a critical damping ratio of 0.6 with a load of 12,500 ohms. Parametric reactance amplifiers with very low root mean square noise are used in the first stage. Equivalent input noise is less than 0.05 microvolt root mean square in the band between 0.8 to 10 cy/sec. The preamplified signals are split and further amplified into high-gain and low-gain signals, to provide a range of 72 decibels between maximum and minimum detectable signals.

The operation of the instrument is programmed by a preset clock driven by a precision tuning fork which runs continuously during a drop to the ocean bottom. Timing-clock signals are recorded on two channels of the tape. Data sampling is normally of 3 to 4 minutes' duration, at programmed times or when a sufficiently large seismic signal is received.

The pressure transducer is made from 16 PZT–4 lead zirconate titanate piezoelectric crystals, which have a sensitivity of 31.53 microvolts per microbar of pressure change. Filters in the amplifiers give a bandpass for seismometers and for the pressure transducer of 0.1 to 10 cy/sec. The entire package is powered by 16 Yardney LR–10 silver cells.

In designing a seismometer for studying seismic background signals in the deep ocean basins, the Texas Instruments Company decided to connect their instrument to the surface by cable. They used a tape recorder and self-contained batteries, instead of attempting to provide a down-the-cable power supply, since they thought that the expense and upkeep of a high-strength power line would be prohibitive in deep ocean work. The package, shown in Fig. 6, is attached to the lowering and recovery cable with a trip mechanism which allows it to fall freely through the last 6 meters of water, thus penetrating the bottom far enough to obtain good coupling. A 300-meter length of chain extends from the seismometer package to an anchor and the recovery cable, as shown in Fig. 7. The chain effectively eliminates problems of cable noise in most of the drops.

The completed instrument is more than 3 meters high and weighs 800 kilograms. The Danforth anchor weighs an additional 350 kilograms. In spite of the weight and awkwardness of this assembly, the Texas Instruments workers have recorded far more seismic data in the deep ocean than the other experimenters have. They have also made simultaneous land recordings in most cases.

The Texas Instruments Company is now completing construction of ten "pop-up" seismometers (instruments that come to the surface of their own accord) capable of direct recording for 30 days on low-speed magnetic tape. Five or more of these instruments will be used for an extensive set of measurements of natural signals, explosions, and background in the Aleutian area of the north Pacific Ocean.

Data reduction. The data from the Texas Instruments tethered seismometers are transcribed in analog strip-chart form for quick appraisal, then selected parts are analyzed digitally on

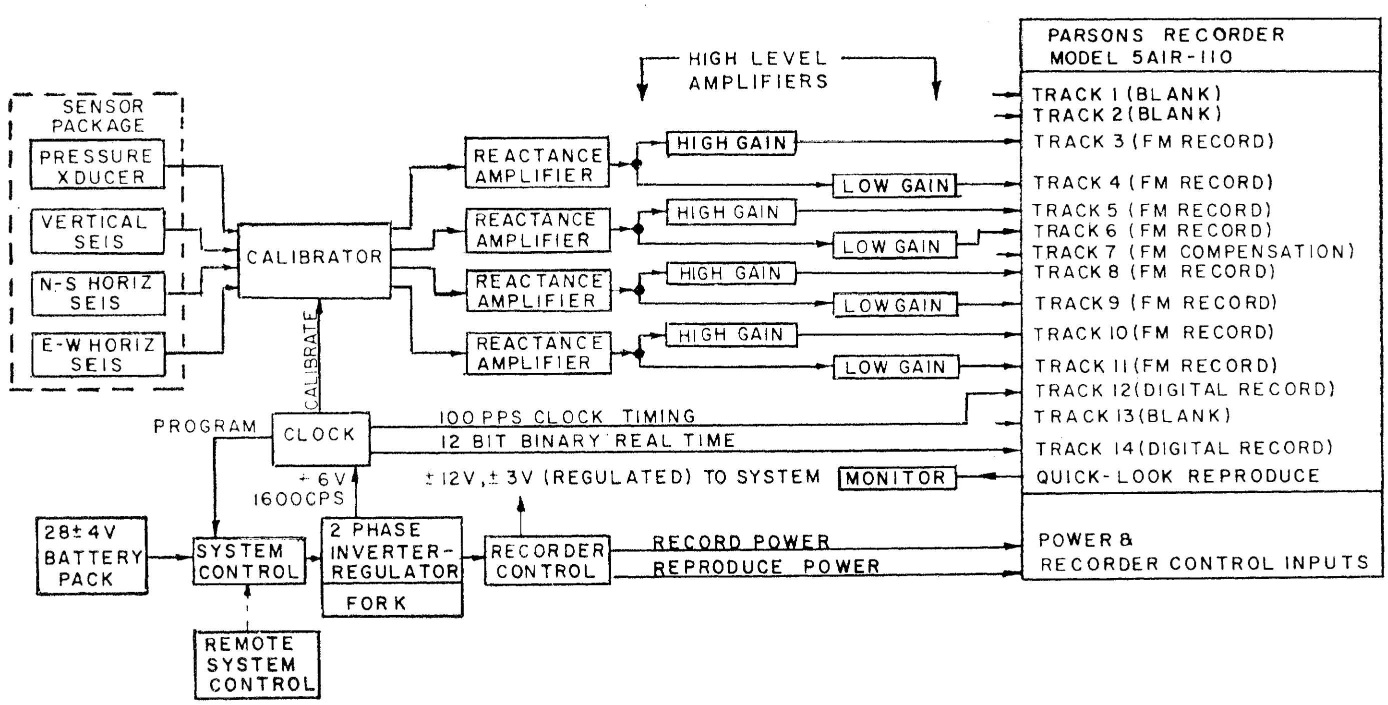

Fig. 5. Block diagram of Texas Instruments Company dual-level, frequency-modulation seismograph recorder.

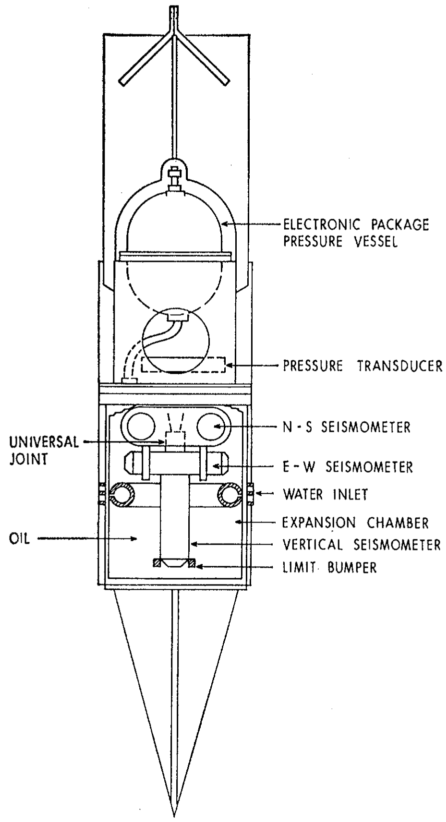

Fig. 6. Schematic diagram of Texas Instruments Company deep-ocean seismograph.

a special-purpose computer (see *10*).

Noise samples and events selected for analysis are transcribed from a frequency-modulation format to a digital format suitable for analysis by computer, with a 20-fold speed-up. Five hundred digital samples are taken per second. Hence the maximum permissible digital-analysis frequency is 250 cy/sec. Passband filters are used in the frequency-modulation digital transcription to suppress energy above the Nyquist frequency of 250 cy/sec (12.5 cy/sec real time).

Power spectra for seismic noise were obtained from the digital data by correlating noise samples approximately 3 minutes long. The correlations were computed to ± 5 seconds and transformed by Fourier analysis to give spectral estimates with resolution of 0.1 cy/sec. The spectral estimates were smoothed by "hanning" (*11*) to reduce the correlation truncation effects (*12*). The resolution, after smoothing, is approximately 0.2 cy/sec. This is in sharp contrast with the resolution of 1 octave that is normally obtained with analog filters.

Seismic background noise, and signals. The Texas Instruments group's observations on seismic noise in the deep oceans are in general agreement with the University of California results, discussed in the next section. The Texas Instruments data on signals include records of nuclear blasts, underwater explosions, and near and far earthquakes.

Schneider and Backus (*10*) report that the Texas Instruments group recorded five underground nuclear blasts and several small seismic events during the collection of data near Santa Catalina Island, off the coast of southern California. Technical progress reports in the VELA-UNIFORM library give additional information on a series of measurements made off the Mendocino coast of northern California, the Aleutian peninsula, and the Hawaiian Islands. They recorded only two seismic events during 90 hours of recording in the seismically active area of the Mendocino Scarp. This result probably represents a statistical fluctuation. They observed 30 seismic events during the Aleutian measurements. Schneider and Backus observed that the signal-to-noise ratios for the ocean-bottom and for land are comparable, although there is more high-frequency energy in the ocean-bottom spectrum. They point out that simultaneous measurements of water-pressure fluctuations and ground motion often indicate whether or not the source lies below the ocean bottom.

University of California Instruments and Measurements

Pop-up seismometer. At the University of California's Institute of Geophysics and Planetary Physics, in La Jolla, we were interested in studying the origin and propagation of microseisms. We planned to make measurements at a variety of locations throughout the central and south Pacific. For this purpose we thought that simultaneous seismic measurements of 1 hour's duration on the ocean bottom and on land would be sufficient. The instruments must be small enough to be handled by boats 20 meters long with a minimum of special rigging. These considerations led us to put a tape-recording seismometer into a hollow, buoyant aluminum sphere which could be rigidly attached to a 70-kilogram lead spike anchor, lifted over the ship's rail, and allowed to sink freely to the bottom. With this equipment there is no link between the instrument and the surface during the recording. When the hour-long record is completed, the lead anchor becomes detached from the instrument, which then floats to the surface. (The anchor is normally detached by a dissolving magnesium link, or by a clock. Recently we have begun to use a clock which accelerates the electrolytic solution of the magnesium link at a predetermined time.) To facilitate retrie-

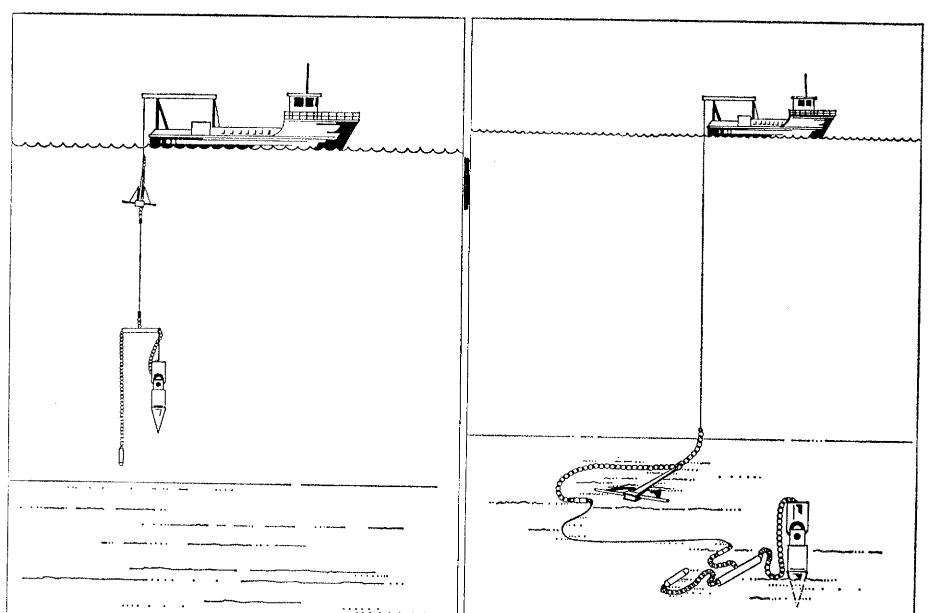

Fig. 7. Making ocean-bottom measurements with the Texas Instruments Company seismograph, 1963.

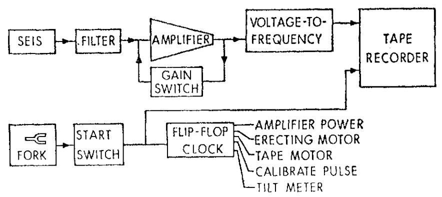

Fig. 8. Block diagram of the University of California seismograph and frequency-modulation recorder.

val, a citizen's band radio transmitter turns on when the sphere reaches the surface.

The first ocean-bottom instrument and the land instrument contained single-component, vertical seismometers; the second ocean-bottom instrument contained a three-component, triaxial seismometer. All the seismometers are interchangeable. The single-component instrument is described by Bradner and Dodds (*13*); the three-component instrument is like it in all significant respects. Seismic signals from the electromagnetic transducer are amplified, passed through a voltage-to-frequency modulator, and recorded on 1.27-centimeter magnetic tape. Timing circuits turn on the amplifier and tape recorder after a preset delay, and turn it off after 1 hour of recording. A block diagram of the system is shown in Fig. 8. The transducer is a modified version of the seismometer developed for lunar recording by the California Institute of Technology's Jet Propulsion Laboratory. It has a 1.6-kilogram moving magnet mass and a 2000-ohm coil, giving 0.7 microvolt per millimicron motion of the seismometer at 1 cy/sec at 0.7 critical damping. The resonant frequency of the instrument is 1 cy/sec. Therefore, its sensitivity at frequencies between 1 and 1/7 cy/sec falls off at approximately the rate at which the microseism noise motion increases. The amplifier is a standard United Electrodynamics solid-state seismic amplifier, with adjustable gain up to 10^5. It has a high-frequency, two-stage cut-off filter at 10 cy/sec, and a low-frequency cut-off filter at 0.1 cy/sec. The converter gives ± 40 percent modulation for swing of ± 2.36 volts, in accordance with IRIG (Inter-Range Instrumentation Group) standards. Center frequency is 1.688 kcy/sec. The over-all dynamic range of the instrument, including playback, is 40 decibels. The modified PI Type 100 recorder operates at 4¾ cm/sec. All instrument timing functions are performed by a precision fork with frequency of 582 cy/sec. The fork frequency is also recorded on one tape track, so that compensation can be made for variations in tape speed.

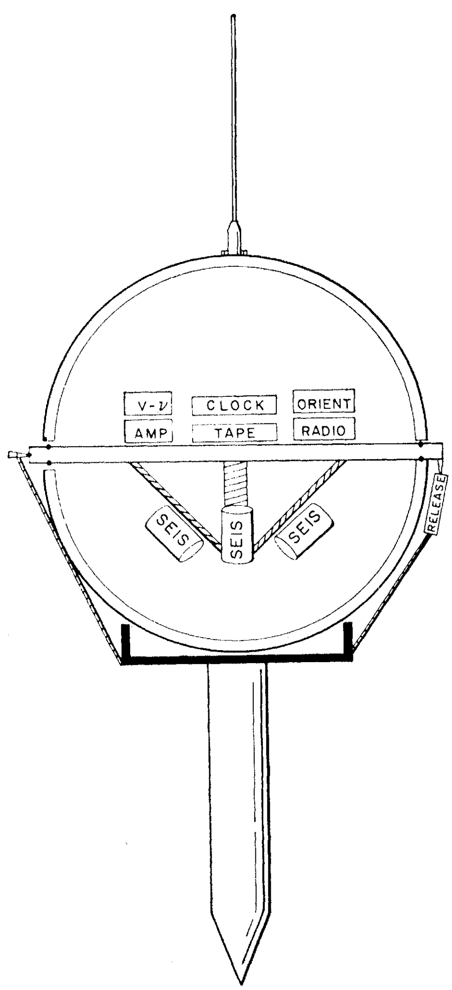

Fig. 9. Schematic view of the University of California's three-component frequency-modulation tape-recording seismograph.

The seismometer can function from the vertical to within 10 degrees of the horizontal by virtue of a motor-driven screw which adjusts spring tension to center the mass at the start of the recording cycle. The tilt angle and compass orientation of the instrument on the ocean bottom are recorded by a tiltmeter mounted inside the pressure sphere. The tilt indicator is a flashbulb in a pendulum, with a fiducial aperture for exposing Eastman photo-resist coating when the bulb fires. At the same time the orientation is photographically recorded by means of the light that enters through a small slit in the compass card.

The tuning-fork clock controls the functions of centering the seismometer mass, activating the tilt recorder, turning on the amplifier, initiating the recording cycle, and terminating the recording cycle. The clock is activated on the surface immediately before launching. The record starts 3 hours later, after the instrument has come to rest on the ocean bottom. The instrument is powered by low-temperature mercury batteries.

The pressure vessel that contains the seismographic equipment is made from two deep-drawn hemispheres, of 56-centimeter diameter, made of 7178 T-6 aluminum. The spheres are assembled by clamping, with six angle brackets, onto an O-ringed aluminum center plate which carries all the instruments in the sphere. Electrical leads can be brought out through the center plate or through the surface of the sphere by means of Mecca plugs or by similar high-pressure bulkhead connectors. A Mecca plug mounted through the top of the hemisphere serves as antenna feedthrough for the citizen's band radio recovery beacon. Figure 9 is a schematic diagram of the assembled three-component package.

The anchor is a lead spike, 10 centimeters in diameter and 50 centimeters long, with a 30-degree conical top. The top of the spike terminates in a dish-shaped flange, which carries three cable eyes for attachment to the buoyant seismometer sphere. These dimensions were chosen as those which would allow the spike to penetrate 40 to 50 centimeters into mud-clay sediment of the rigidity thought to be characteristic of the broad, flat Pacific Ocean basin. If the anchor strikes soft mud, the flange will keep the package from penetrating so far that the Van Dorn magnesium release (*14*) will be obstructed.

The package returns to the surface in about 6 hours after launching, and the radio begins to transmit as soon as the antenna is above water. The radio-beacon signal is detected on shipboard by an ordinary citizen's band receiver. A commercial three-element yagi antenna, mounted at a high point on the ship, serves for homing on the floating sphere. The sphere is picked up by a short length of floating polypropylene tag line and easily lifted back on board the ship (Fig. 10). We have made more than 40 successful drops and recoveries with untethered pop-up seismometers.

Data Reduction

Data from the Texas Instruments seismometer and our magnetic tapes are examined in similar ways. The records can be played back for visual observation in analog display, and they can be fed into a computer for detailed analysis. The frequency-modulation signals are fed directly from the tape to an electronic counter whose sampling rate is controlled by the 582-cy/sec reference track on the tape. The output of this counter is processed in a CDC-1604 computer with a general-purpose time series analysis program, "BOMM" (*15*).

Normally, each spectrum represents a time series 8 minutes long. The Tukey method of spectral analysis is used, with 200 lags (*12*). The sampling rate is 18 per second, resulting in 90 degrees of freedom.

Representative seismic-background spectra for land and for the ocean bottom are shown in Fig. 11. The calibrations of the instruments were taken into account during the analysis; therefore, the computed spectra represent actual earth noise. Instrument noise is below the minimum signal level for the spectra. The land instrument was a vertical seismometer mounted on bedrock in a cave on the island of Oahu, Hawaii. The ocean-bottom instrument was a three-component equiaxial seismometer located 800 kilometers to the east of Oahu, at a water depth of 5.2 kilometers. Only one component is shown in Fig. 11. The other two components were similar. The relatively smooth monotonic decrease in power density of the land spectrum at frequencies above the microseism peak is characteristic of all our island records. Spectra from the continental United States usually show more peaked structure, presumably due to the large amount of manmade noise and the large area for meteorological effects. Evenly spaced peaks such as appear in the ocean-bottom record are quite common. Their frequencies are compatible with a regular set of "organ-pipe" modes in the water. In Fig. 11 every fourth mode appears to be strongly excited. These modes, with amplitude nodes at the bottom and amplitude antinodes at the top of the water, will have frequencies $\nu_n = (8n + 1)\, C/4D$, where D is water depth and C is velocity of sound in water. The uppermost scale at the top of Fig. 11 shows the frequencies that correspond to the water depth of 5300 meters. The second scale at the top of Fig. 11 shows the frequencies that correspond to 5300 meters of water plus 100 meters of mud, with the same compressional velocity.

The energy of the sea-bottom noise is higher by one or more orders of magnitude than the energy of noise measured on land in the lower frequencies, and higher by three or more orders of magnitude in the upper frequencies. This indicates that a great deal of the microseismic energy may be generated at sea and that the higher frequencies are not transmitted to land.

In their experiments the Texas Instruments workers were concerned primarily with seismic signals, and therefore their amplifier gains were usually set at too low a level to give good background spectra, except in the high energy regions below about 2 or 3 cy/sec. A few unpublished spectra recorded by them at higher amplifier gain are in qualitative agreement with our results at frequencies between 0.3 and 10 cy/sec, except that their spectra show a general downward trend at the higher frequencies. This disagreement must be investigated further, since the shape of the noise spectrum is related to the location of the noise sources, and to the way the energy propagates along the ocean bottom or across the continental borders. The microseism spectrum is nearly constant during a 1-hour record. Day-to-day changes may be large, however.

On land, a significant part of the microseism energy is carried in surface waves of two types—retrograde vertically polarized waves, called Rayleigh waves, and horizontally polarized shear waves, called Love waves. A three-component seismometer can distinguish

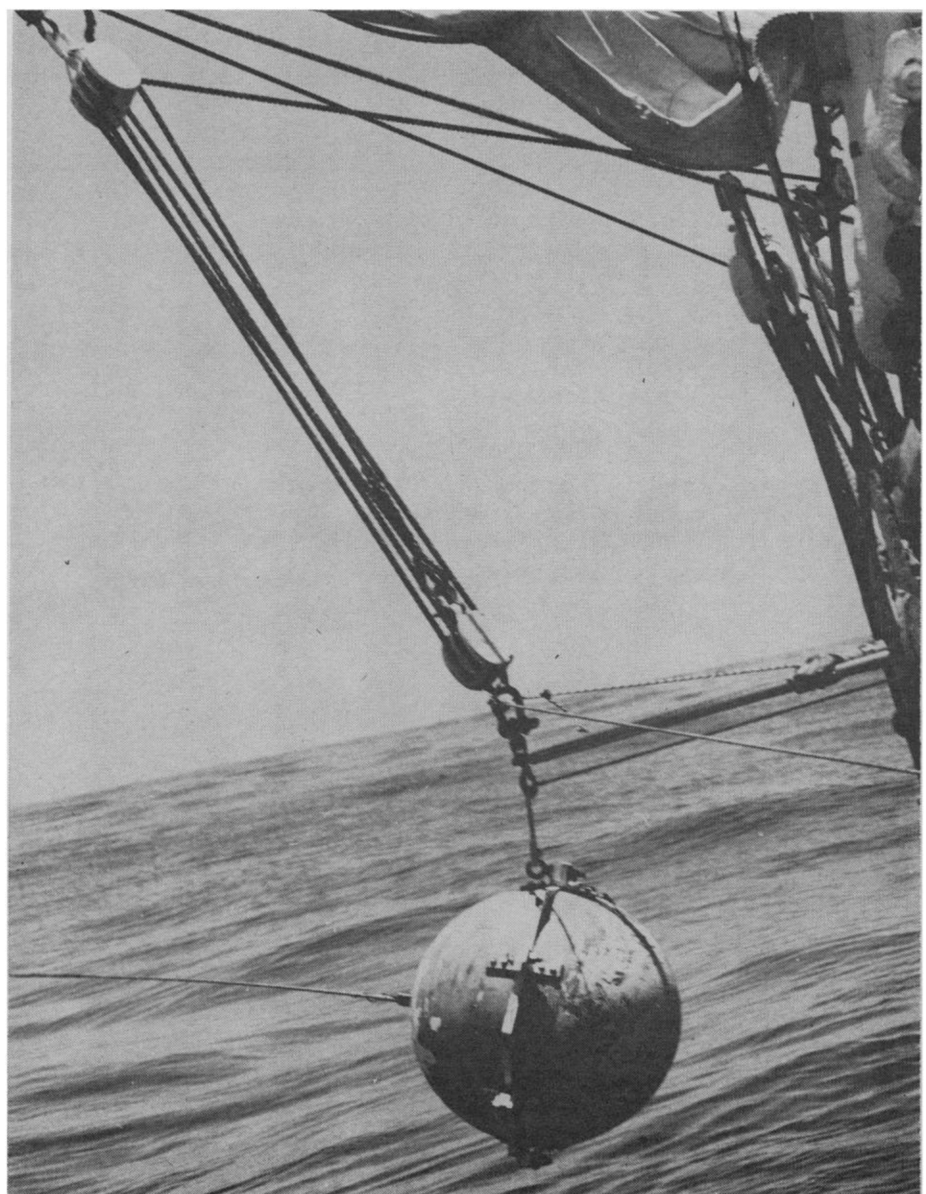

Fig. 10. Recovering the University of California seismograph package.

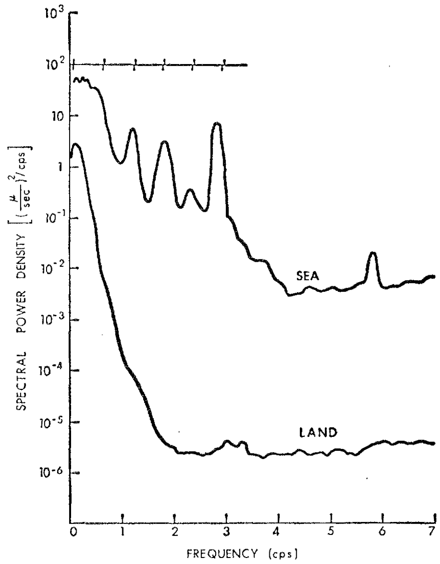

Fig. 11. Typical microseism noise spectra for the ocean bottom and for Oahu, Hawaii, 8 February 1963.

these waves in spectral peaks if the energy comes from a localized source. Pure Love waves, for example, would have no vertical component and would have a zero-degree or 180-degree phase difference between the two coherent, horizontal components. Pure Rayleigh or Love waves are rarely found, since modes are converted by scattering in the inhomogeneous earth, and more than one source may be active at any time. We are unable to regularly associate the energy in the microseism peak with either the vertical or the horizontal polarized surface waves that are commonly recognized at land stations, although either form of wave may contribute much of the energy on a given day. We find that near-vertical compressional waves in the water, which we call "organ-pipe" waves, can be responsible for some marked peaks in the low-frequency region.

The shape of the spectrum does not change markedly as we travel to mid-ocean, far from storms or shore lines. From that observation we conclude that high-frequency seismic background noise is generated locally, throughout the area of our stations in the Pacific Ocean. The most likely mechanism for generation of high-frequency energy is a statistical superposition of oppositely traveling surface-water waves. These standing waves will exert forces on the bottom, at half the wave frequency (*16*).

We have found good examples of all the currently accepted mechanisms of microseism generation. There is evidence for generation near shore, and in storms far from shore. We suggest that the normal, continual microseism background is a superposition of energy from many sources. The peak at a period of 6 to 8 seconds may be accentuated by the resonance of the 5-kilometer thick ocean wave guide, as well as by the predominant frequency of the surface waves.

Conclusion

With apparatus developed for ocean-bottom seismic recording, earthquakes have been observed, propagation velocities have been measured, microseism noise has been studied, and it has been determined that signal-to-noise ratios may allow the monitoring of bomb tests. But many more measurements will be needed before definitive remarks can be made about any of the phenomena.

References and Notes

1. M. Ewing and A. Vine, *Trans. Am. Geophys. Union* (1938), pt. 1, p. 248.
2. J. Ewing and M. Ewing, *J. Geophys. Res.* **66**, 3863 (1963).
3. Chief members of the Lamont Geological Observatory group are J. Ewing, M. Ewing, and D. D. Prentiss. The work was reported under contract AF19(604)8357.
4. Chief members of the Institute of Geophysics and Planetary Physics group at the University of California are H. Bradner, J. G. Dodds, and R. Foulks. This work is reported under contract AF49(638)-905.
5. Chief members of the Texas Instruments Company group are W. A. Schneider, M. M. Backus, P. D. Davis, Jr., Buford Baker, and P. J. Farrell. This work is reported under contract AF19(604)8368.
6. M. Ewing, G. P. Woollard, A. C. Vine, J. L. Worzel, *Bull. Geol. Soc. Am.* **57**, 909 (1946).
7. F. I. Monakhov, *Bull. Acad. Sci. U.S.S.R. Geophys. Ser.* (*English Transl.*) **1961**, No. 5, 461 (1961); *ibid.* **1962**, No. 7, 573 (1962).
8. D. D. Prentiss and J. I. Ewing, *Bull. Seism. Soc. Am.* **53**, 765 (July 1963).
9. J. T. Thompson and W. Schneider, *Proc. I.R.E.* (*Inst. Radio Engrs.*) **50**, 2209 (1962).
10. W. A. Schneider and M. M. Backus, *J. Geophys. Res.* **69**, 1135 (1964).
11. "Hanning" refers to the operation of smoothing with weights 0.25, 0.50, and 0.25, after Julius von Hann.
12. R. B. Blackman and J. W. Tukey, *The Measurement of Power Spectra* (Dover, New York, 1959).
13. H. Bradner and J. G. Dodds, *J. Geophys. Res.*, in press.
14. W. G. Van Dorn, *Scripps Inst. Oceanog. Rept. 53-23* (1953).
15. E. Bullard, F. E. Oglebay, W. H. Munk, G. R. Miller, "A User's Guide to BOMM," *Univ. Calif. (La Jolla) Publ.* (1964).
16. M. S. Longuet-Higgins, *Phil. Trans. Roy. Soc. London* **A243**, 1 (1950); K. Hasselmann, *Rev. Geophys.* **1**, 177 (1963).

17. This research was supported by the Advanced Research Projects Agency and was monitored by the Air Force Office of Scientific Research, under contract AF49(638)-1388. I thank the Air Force Office of Scientific Research, Columbia University, and the Texas Instruments Company for permission to use information and figures from their reports.

High-Speed Automatic Analysis of Biomedical Pictures

Robert S. Ledley

The biological and medical scientist has developed highly specialized and precise techniques for photographing structures, forms, and phenomena that occur in almost every field of biomedical research. Huge masses of material are accumulating at an ever-increasing rate, such as photomicrographs of chromosomes that relate to genetic diseases; photomicrograph sequences showing the dendritic structure of nerve cells; electron micrographs of muscle fiber structure and of DNA with bases containing radioactive heavy atoms; and films of x-ray diffraction patterns of biologically important molecules. Individual pictures hold a great wealth of precise numerical information, such as morphological and structural characteristics of lengths, areas, volumes, densities; from sequences of pictures quantitative results can be derived, such as kinematic and dynamic characteristics of trajectories, velocities, and accelerations.

The large-scale quantitative analysis of these pictures cannot be achieved by manual methods, because of the tedium, manual precision, and extensive time that is necessarily involved. Hence we have embarked on a program designed to enable such pictures to be analyzed

The author is president of the National Biomedical Research Foundation and instructor in pediatrics at the Johns Hopkins Medical School.