cost of the analog-to-digital magnetic-tape converter is comparable to the cost of a small computer. However, a number of commercial installations can provide the conversion service at rates considerably lower than those for computer time.

Summary and Forecast

The use of digital techniques in the biological laboratory is relatively recent (*22*). At present, computer equipment is extremely expensive by contrast with conventional electronic equipment. However, the costs are decreasing, and these techniques are rapidly becoming more accessible as well as more powerful. Improvement in the fabrication, size, and compactness of solid-state devices promises rapid progress in computer technology of interest to the biologist. Through the use of integrated circuits it will be possible to make general-purpose computers no larger than a laboratory oscilloscope, as compared with the present desk-size console with auxiliary cabinets. Within a decade the speed of computation will increase by an order of magnitude, and the costs will decrease significantly. Moreover, it seems likely that the parts of a computer and the laboratory "interface" will become available as modular units. An experimenter will then be able to assemble the components necessary for a particular application and change them as required. At present, one has to modify commercial equipment for the nonstandard, biological uses. However, with modular building blocks of relatively small size and more reasonable cost the digital computer may become as familiar a laboratory tool tomorrow as the cathode-ray oscilloscope or the spectrophotometer is today.

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23. We thank L. Eisenberg and P. Rosen of the Rockefeller Institute for helpful criticism and S. Benerofe of Adcom Corporation, J. Hahn of Columbia University, W. Helmreich of International Business Machines Corporation, and J. B. Krauss of Technical Measurements Corporation for helpful information.

Precision Digital Tide Gauge

Vibrating wire pressure transducers provide sea level measurements to the nearest one-tenth millimeter.

Frank E. Snodgrass

Tides were explained by an ancient Chinese writer who wrote, "Water is the blood of the earth and the tides are the beating of its pulse," but long before Newton's theory of gravity, men knew that "the movement of the ocean observes a regular series like a heavenly body, there being a daily, monthly, and yearly movement according to the influence of the moon" (*1*). Following Newton's theory of gravity such great men as Bernoulli, Euler, Laplace, Airy, Kelvin, and George Darwin were prominent in the study of the tides. A detailed theory based on the gravitational attraction of the moon and sun was developed not only for the ocean tides but also the solid earth tides as well. Harmonic analyses of tide data provided a rational method of ocean tide predictions.

For a half century after the work of Darwin, tide gauges were maintained and tide prediction tables were routinely produced, but little was done to further the understanding of the tides. High-speed computers and new electronic instruments have broken this lull. Solution of the tide equations from reasonable approximations of the real ocean basin shapes are being found. Measurement of tides and tide currents are now being made in the deep sea. Tidal charts for an entire ocean basin may soon be produced to tie together the measurements along the coasts. The puzzling problems of tidal dissipation may be solved with greater detail.

The tide gauge described in this paper is one of many new instruments made possible by the reliability of transistors and the precision of digital techniques. The purpose of the recorder is to obtain precise data of sea level fluctuations near shore to accurately describe the tides. Just as a prism and photo cell can determine light's energy spectrum, digital computers can compute the energy at the various frequencies present in the sea level record to determine the sea level spectrum. Sharp lines of energy are found at the various frequencies corresponding to the driving force of the moon and sun to describe the tides. We find, however, that the line spectrum of the ocean tides is superimposed on a continuum of energy due to low-frequency sea level fluctuations. These limit the

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accuracy of tide measurement; thus, we think of them as "noise."

The noise signals are due primarily to variations of atmospheric pressure, traveling storm centers, nonlinear reflection of ocean waves (surf beat) from the coasts, and wind stress on the sea surface. At frequencies below 1 cycle per day, the sea surface responds roughly as an inverted barometer, and the spectral energy density increases sharply with decreasing frequency (*2*). At frequencies above 6 cy/day, the energy density decreases gradually with increasing frequency (*3*). The gauge described in this article was designed primarily to measure the noise continuum between these two sets of measurements.

Sea-level noise near the tidal frequencies is approximately 10^{-4} of that of the tides for stations along the California coast. The measurement of the noise therefore requires an instrument with a resolution of 1 mm and a dynamic range sufficient not to be driven off scale by the 3-m tides.

Vibrotron pressure transducers manufactured by the Borg-Warner Corporation measuring subsurface absolute pressure (rather than surface elevation) provided the necessary resolution and dynamic range. Unfortunately, by measuring absolute pressure, atmospheric pressure is included in the readings. A second recorder channel is therefore included in the system to record atmospheric pressure simultaneously. By subtracting the atmospheric-pressure record from the subsurface-pressure record, a measure of sea level is obtained. Vibrotron transducers having an absolute pressure range of 0 to 1 bar provide precision of 0.2 μbar, more than adequate for the atmospheric pressure correction.

The Problem

In the design of the tide recorder, as in that of any digital system, two considerations are paramount. (i) The instrumental noise spectrum must be small compared to the true spectrum at all frequencies of interest; (ii) If Δt is the sampling interval, and $f_N = 1/2\Delta t$ the Nyquist frequency, then the recorded spectrum above f_N must be small compared to the recorded spectrum below f_N.

Figure 1 summarizes the situation for measurement of tides. The noise spectrum as obtained from capped (zero input) transducers under actual

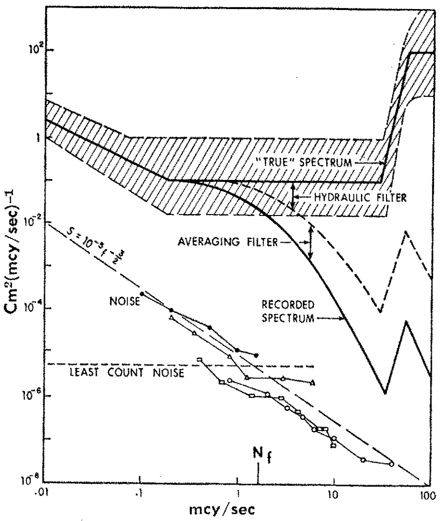

Fig. 1. The sea-level spectrum is compared to the noise spectra of the instrument as an indication of the quality of the measurements. Reduction of high-frequency energy by the hydraulic filter and the averaging filter to minimize sampling errors is indicated. The least-count noise level shown applies to the noise measurements indicated by closed circles and triangles and to the tide spectrum measurements.

field conditions is 20 to 30 db below the true spectrum. Toward the low frequencies the noise spectrum rises as $f^{-3/2}$ and is apparently due to the temperature fluctuation. To obtain a tolerable level of temperature noise the transducer was buried in the sea floor. At the high-frequency end the noise spectrum approaches a constant density determined by the "least count." If each value is recorded to the nearest least count unit, C, and differs from the true value by an amount which lies between $\pm \frac{1}{2}C$ and has a uniform probability in this interval, the resulting error then is $C^2/12$. This error is equally distributed among all frequencies from zero to the Nyquist frequency. For readings taken to the nearest 0.006 cm of water pressure at a sampling interval, Δt, of 5 minutes, $N_f = \frac{1}{2}\Delta t = 1/600(\text{cy/sec}) = 1.66$ mcy/sec, and the energy density of the least count error is $(C^2/12)/N_f = 2 \times 10^{-6}$ cm^2 per mcy/sec. Except at the high frequencies, this energy density is negligible compared to instrument noise. Thus, further reduction of the least-count error would not improve overall resolution unless the instrument noise also could be reduced.

Regarding condition (ii), Fig. 1 indicates that, in the true spectrum, energy above the Nyquist frequency is not small compared to the energy below the Nyquist frequency. A two-stage low-pass hydraulic filter made with capillary tubes and metal bellows prevented high-frequency pressure fluctuations from acting on the transducer. An attenuation of 12 db per octave is obtained at frequencies above 3 mcy/sec. Additional filtering of the data is obtained by the averaging process of measuring the Vibrotron frequency. The response, r, to a frequency, f, by averaging over a time, t, is $r = \sin x/x$ where $x = 2\pi tf/2$. The filter has strong side bands whose peaks lie along a line $2f_t/f$ where $f_t = 1/2\pi t$. With this line as the minimum attenuation, the energy at the high frequencies is reduced as f^{-2}. Attenuation of the high frequencies for an averaging time of 300 seconds is as indicated. The recorded spectrum, which then satisfied condition ii, was corrected for the effects of both the hydraulic and time-averaging filters.

With these difficulties of digital recording fully met, we could then take advantage of the 60-db dynamic range of the transducer. Over a period of 6 months, readings having a least-count precision of 0.1 mm of water pressure were obtained every 5 minutes with the pressure gauge installed on the bottom, 1000 m off shore in 20 m of water depth near the Scripps Institution of Oceanography, La Jolla, California. Spectrum analysis of the data with a frequency resolution of 0.1 cy/day (*4*) provided the desired information about the ocean-wave noise continuum behind the line spectrum of the tides.

Vibrotron Transducer

The Vibrotron pressure transducer was originally developed by the Southwest Research Institute and is now being manufactured by the Borg-Warner Corporation, Santa Ana, California. The transducer has been described in the literature (*5, 6*), and I shall review only the essential features.

The gauge is constructed so that pressure signals vary the frequency of a wire vibrating in a magnetic field. The a-c voltage induced in the vibrating wire can be amplified, transmitted, and recorded with all the advantages normally attributed to frequency modulation systems. The vibrating wire, which is a tungsten filament a few thousandths of a centimeter in diameter and about 1 cm in length, is stretched between a rigid support and a small diaphragm exposed to the pressure. The wire, magnets, and support structure are encased in an evacuated cylinder 2 cm in diameter and approximately 10 cm in length, with electrical connections at one end and the diaphragm and pressure port at the other. As the pressure increases, the diaphragm is deflected inward, diminishing the tension in the wire and decreasing its natural frequency.

The vibrating wire and a second nonvibrating wire are connected in a bridge which is roughly balanced to d-c voltages. The output of the bridge, being essentially the a-c voltage induced in the vibrating wire, is amplified and fed back to the bridge in a sense required to maintain the wire in oscillation. A transistorized amplifier with a gain of 5000 and an output of 2 volts a-c provided the required feedback and sufficient power for output circuits. With proper impedance-matching transformers, the output signal can be transmitted over several kilometers of cable. Power (24 volts d-c, 4 ma) is fed to the Vibrotron gauge through the same two conductors that are used for the return signal.

The frequency of vibration of the wire depends slightly on the amplitude of its vibration. A constant amplitude of vibration is achieved by allowing the amplifier to overdrive in its last stage. The resulting distortion in output waveform is not troublesome. Harmonics do not cause transmission problems since multiplexing is not used. Measuring the signal frequency depends only upon the number of cycles (zero crossings), and this is unaffected by waveform distortion except in extreme cases. Extreme distortion is satisfactorily corrected with simple filters.

Pressure Sensitivity

Laboratory calibration of the Vibrotron gauge indicates that the frequency, f, varies with the absolute pressure, p, according to the characteristic equation

$$f^2 = Ap + B.$$

Variations in frequency associated with waves and tides amount to less than 1 percent of the mean frequency; accordingly, with good approximation the gauge sensitivity

$$\frac{df}{dp} = \frac{A}{2f} \approx \frac{A}{2\bar{f}}$$

has been taken as constant in our measurements.

Our tide Vibrotron gauge had a range of about 150 m of sea water with a frequency range of 18 kcy at zero pressure and 10 kcy at full pressure; therefore,

$$A = (18^2 - 10^2)/(0 - 150) \approx - 1.5 \text{ kcy}^2/\text{m},$$
$$B = 18^2 \text{ kcy}^2.$$

At the installation depth the mean frequency was about 15 kcy and

$$\frac{df}{dp} = -0.5 (\text{cy/sec}) \text{cm}^{-1}.$$

If the oscillations are counted over 1-second intervals, a least-count precision of

$$\frac{dp}{df} = \frac{2\bar{f}}{A} = \frac{1}{-0.5} = -2 \text{ cm}$$

of water pressure is obtained. The low precision is the result of dealing only with an integral number of cycles during a short time interval. One remedy is to count over intervals of time longer than 1 second. Low frequency ocean waves and tides were measured by counting for 5 minutes; the least count was then $2/300 = 0.006$ cm of water.

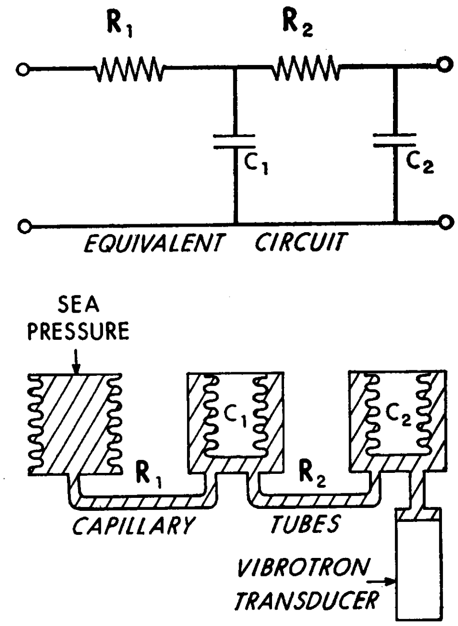

Fig. 3. The hydraulic and equivalent electrical circuits for the pressure head shown in Fig. 2. The bellows between the sea pressure and the capillary tube serves only to isolate the unit from the sea water.

Temperature Sensitivity

The Vibrotron transducer is designed to minimize differential thermal expansion between the vibrating wire and the support structure for the wire. The manufacturer guarantees the temperature sensitivity not to exceed 0.1 percent of the bandwidth per degree Celsius. For a transducer with a frequency bandwidth of 8000 cy/sec the temperature sensitivity would be 8 cy/sec per deg C. With a pressure sensitivity of 0.5 (cy/sec) cm^{-1} this temperature sensitivity is equivalent to 16 cm/deg C.

Temperature-pressure calibrations indicate that the Vibrotron gauge can be better described by including a temperature term in the characteristic equation so that

$$f^2 = Ap + B + CT.$$

The pressure and temperature sensitivities become $\delta f/\delta p = A/2f$ and $\delta f/\delta T = C/2f$. If the temperature sensitivity is expressed as an equivalent pressure sensitivity $\delta p/\delta T = C/A$

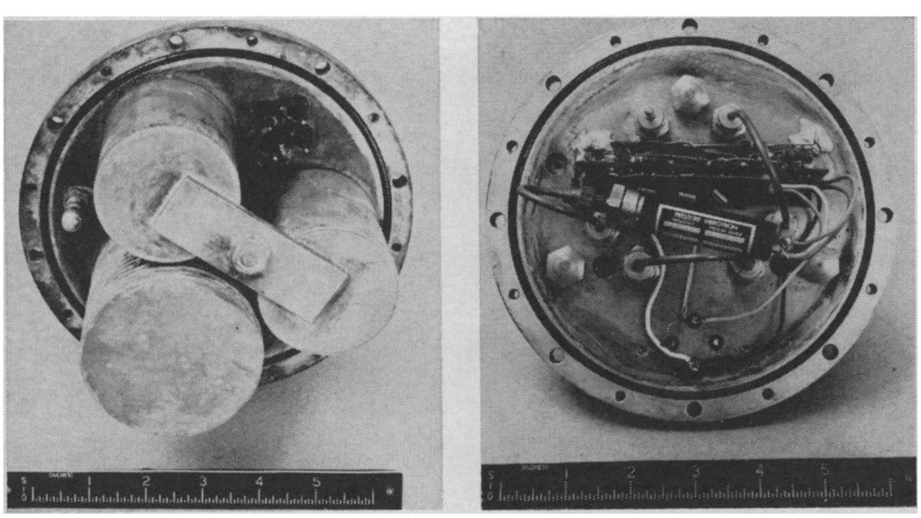

Fig. 2. The tide gauge pressure head. The unit contains a two-stage, low-pass hydraulic filter connected to the Vibrotron transducer. The filter consists of brass capillary tubes connected to oil filled metal bellows.

which is independent of frequency. The value 16 cm/deg C is therefore applicable to all installation depths and temperatures.

Shielding of the Vibrotron transducer from temperature fluctuations was achieved by burying the instrument in the sea bottom to a depth of 2 m. A plastic snorkel was provided to transmit the pressure signals to the gauge.

Noise

A change of one in the least significant digit of the digital recording, that is, 1 least count, represents a change of sea level of 0.006 cm. With a gauge having a range of 160 m the least count represents only 4×10^{-7} of full scale. To determine whether this precision was meaningful several instrumental noise tests were performed.

The Vibrotron gauge, sea cables, and recording equipment were installed exactly as they were to be used in the study of ocean tides. The pressure port of the Vibrotron gauge was then capped, and recordings were made of the Vibrotron frequency. The instability of the Vibrotron frequency represented the system noise. Spectral analysis of this data (closed circles, Fig 1) provided a noise level that could be compared to the energy level of ocean waves and tides to determine the quality of the data.

By modifying the recording equipment as described in the section "Noise Measurements," the sampling interval was reduced while maintaining the same least count. The recording of the capped Vibrotron signal consisted of 3000 numbers, and these diminished smoothly from 5,397,394 to 5,397,285 with only the last digit varying by a unit value or by one least count. For example, the last two digits of the first ten numbers are 94, 93, 93, 94, 93, 94, 94, 94, 93, 94. Only in two instances did the last digit vary by 2 in two successive numbers, and never by 3. The drift was removed by the computer; the resulting spectrum (triangles, Fig. 1) at the high frequencies was nearly white, corresponding to a root mean squared (rms) value of about 0.5 least counts. The low-frequency energy density was about as measured in the first test. By further increasing the recorder sensitivity to about 3000 count/cm of water pressure and by reducing Δt to 10 seconds, random variation of the capped Vibrotron frequency could be observed at even higher frequencies. Analyses of output of the Vibrotron gauge provided the two noise spectra, open circles and squares, shown in Fig. 1.

Approximating all data as indicated by the dashed line, the noise spectrum, $S_n = 10^{-5} f_n^{-3/2}$ cm^2 (mcy/sec)$^{-1}$ where the noise frequency, f_n, is expressed in mcy/sec. Over a frequency band of 10^{-1} to 10^{2} mcy/sec, the total energy would be 0.6×10^{-4} cm^2 or equivalent to an rms pressure signal of 0.8×10^{-2} cm.

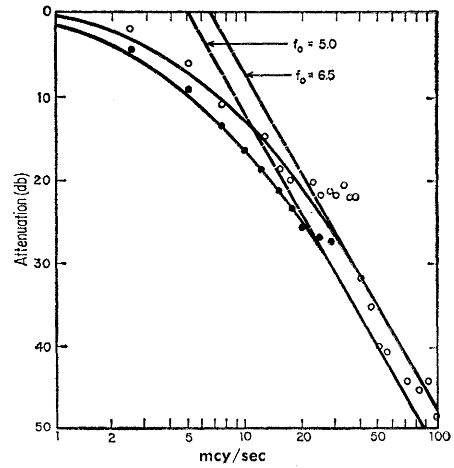

Fig. 5. The frequency response of the hydraulic filter determined from the ocean wave spectra of Fig. 4 is compared to the calculated frequency response shown as solid lines.

Since the data represent the stability of the entire system, several factors might be responsible for the instability. If the entire blame is laid to temperature fluctuations at the Vibrotron gauge, we can estimate the temperature fluctuations in the sea floor. The particular gauge used for the tests had a temperature sensitivity such that one degree of temperature signal was equivalent to 5.0 cm of pressure signal. At this sensitivity, an rms temperature fluctuation of 3×10^{-4} deg C could produce the total energy of the noise spectrum from 0.1 to 100 mcy/sec.

Fig. 4. The energy spectra of ocean waves measured simultaneously with filtered and unfiltered gauges. The ratio of energies is a measure of the hydraulic-filter frequency response.

Filtering of Data

Energy above the Nyquist frequency, f_N, introduces sampling errors into the digital data. These errors result from a heterodyning of the input signal with the sampling frequency, and cause, in turn, the introduction of spurious signals into the data at the difference frequency. The spectrum of the signals being recorded must have low energy at and above the Nyquist frequency compared to the energy at frequencies below the Nyquist frequency. Conversely, the sampling rate must be so adjusted that at least two data samples

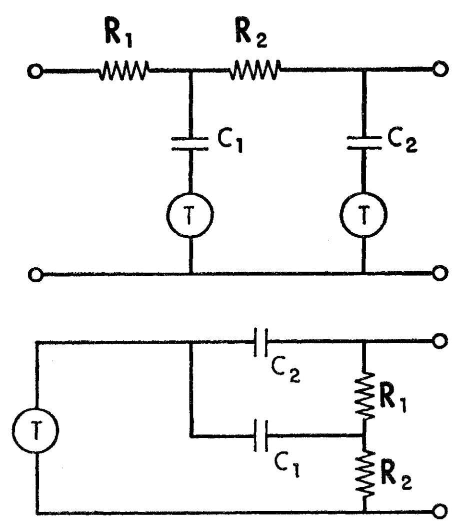

Fig. 6. The equivalent electrical circuit of the pressure head temperature response. Temperature signals are assumed to be simultaneously generated in the two metal bellows chambers. The hydraulic filter, designed to pass low frequency pressure signals, acts as a high-pass filter to temperature signals.

per cycle are obtained for the highest frequency component with appreciable energy found in the input signals.

The desired sampling rate, however, is determined by the highest frequency of interest in the data. Thus, if we wish to study the ocean wave continuum at frequencies of 6 cy/hr or less as in the case of our tide study, a sampling rate of 12 readings per hour is sufficient. Unfortunately, the spectrum between 4 and 10 cy/min (ordinary gravity waves) has an energy density 30 db greater than that of frequencies of 6 cy/hr or less. To avoid excessive sampling errors, the data would therefore need to be sampled every 3 seconds, 100 times more often than desired. Removal of unwanted high frequencies by analog filters before digitization would overcome this problem. With the Vibrotron transducer, which converts pressure to frequency, the filtering must be accomplished before the transducer if the dynamic range of the device is to be preserved. A unit containing a two-stage low-pass hydraulic filter preceding the transducer is shown in Fig. 2.

Two capillary tubes connected to oil-filled metal bellows, as indicated schematically in Fig. 3, provide the necessary low-pass filter. If identical stages ($R_1 = R_2$, $C_1 = C_2$) are assumed, the amplitude response, A, and phase response, ϕ, of the filter to sinusoidal input signal of frequency, f, are

$$A = (k^4 + 7k^2 + 1)^{-\frac{1}{2}}, \phi = 3k/(1 - k^2),$$

where

$$k = 2\pi RCf = f/f_0.$$

The filter is equivalent to a two-stage RC filter, each stage with a time constant, $t_0 = RC$, of 32 seconds. The cutoff frequency, $f_0 = (2\pi \times 32)^{-1} = 0.005$ cy/sec $= 18$ cy/hr. At higher frequencies the energy is reduced by f^{-4} or 12 db per octave. Energy at the Nyquist frequency 6 cy/hr is reduced only by a factor of 1.3. At the frequency of sea and swell, the reduction is by 10^5. The high attenuation assures a negligible error from sampling.

To describe the response of the filter only the time constant, t_0, needs to be determined. Usually poor knowledge of the dimensions of the capillary tubes, end effects, fluid viscosity, and bellows characteristics limits the accuracy of calculating the time constant from physical dimensions. Further, because of the low frequencies, a direct measure of the response of the gauge to applied sinusoidal pressure signals is impractical.

Experimental determination of t_0 is readily accomplished by making use of the transient response of the filter. The time constant can be found simply by measuring the time required for the transducer to indicate 21.2 percent of an applied step pressure.

Energy spectra of ocean waves measured simultaneously with a filtered gauge and an unfiltered gauge are shown in Fig. 4. The ratio of the energy at each frequency is a measure of the amplitude-squared of the hydraulic filter. At frequencies above 50 mcy/sec, the spectrum of the filtered gauge becomes white at a level corresponding to $\pm$ 0.5 least count, indicating that the filter has so reduced the signal that it cannot be read. In Fig. 5, the response of the filter determined from the ocean-wave spectra (circles) is compared to the response calculated from the measured time constant (solid lines) for two hydraulic filters.

Filter Temperature Effects

The principal temperature effect in the hydraulic filter results from the linear dependence of the filter time constants on the viscosity of the oil. Calibration data indicated that within the range of temperatures to which the instrument might be subjected, the log of the time constant decreases linearly with the log of the temperature in agreement with viscosity data furnished by the oil manufacturer. In our work it was necessary to allow for dependence of the frequency response on temperature in the interpretation of the instrument output at the high frequencies.

Differential expansion between the metal parts of the compliant chamber and the oil contained within the

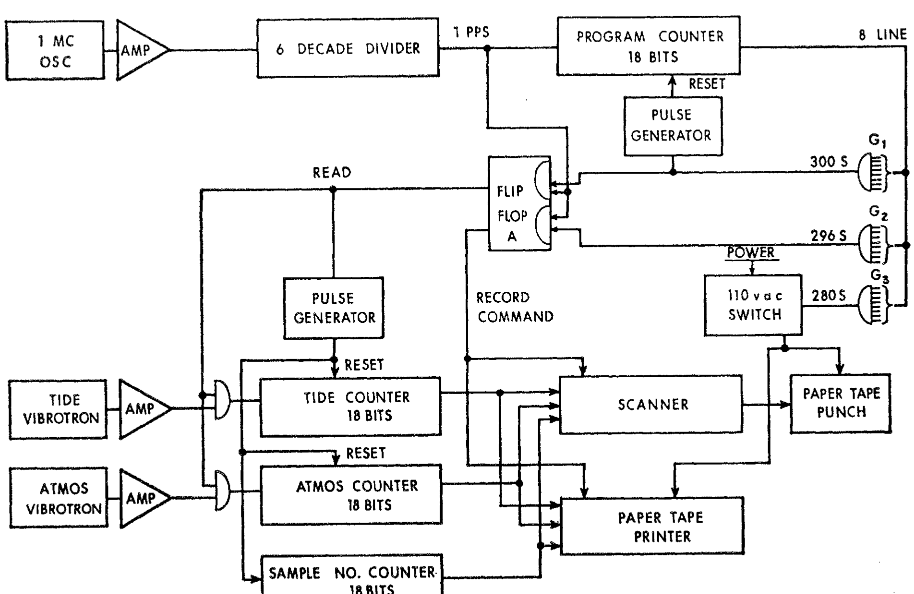

Fig. 7. Block diagram of the tide gauge recorder. Readings of the frequencies of two Vibrotron gauges in cycles per 296 seconds and the data sample number are recorded by a paper tape punch and a paper tape printer.

chambers produces pressure signals that are sensed by the transducer and cannot be distinguished from sea pressure signals. An estimate of the pressure change in the compliant chamber, Δp, due to a temperature change ΔT is $\Delta p = (\alpha_1 - \alpha_2) V \Delta T / \beta$, where α_1 is the coefficient of expansion of the oil, α_2 is the coefficient of expansion of the metal parts, V the oil volume, and β the bellows spring constant. If α_2 is neglected and $V = 100$ cm^3, $\alpha_1 = 1.2 \times 10^{-3}$ per degree C, and $\beta = 0.036$ cm^3, per cm of water pressure, then $\Delta p / \Delta T = 3.3$ cm of water pressure per degree C. Laboratory tests indicate that the effect is somewhat smaller.

If temperature signals affect equally and simultaneously both compliant chambers, an estimate of the frequency response of the gauge to temperature-generated pressure signals can be made. As seen in equivalent electrical circuits of Fig. 6, the hydraulic filter now has a high-pass response. Thus the filter, designed to pass low-frequency sea pressure signals, acts as a high-pass filter to temperature signals. Tide frequency temperature signals are attenuated to 2 percent.

If as before $k = f/f_0$, where $f_0 = (2\pi RC)^{-1}$, but f is now the frequency of the temperature fluctuations, the response of the temperature filter is

$$R_t = \frac{1}{1 - (k^2 - 3jk)^{-\frac{1}{2}}}$$

which has an amplitude response

$$A_t = [(k^4 + 9k^2)/(k^4 + 7k^2 + 1)]^{\frac{1}{2}}$$

The response of the filter as shown in Fig. 6 can be approximated by a single-stage filter with a time constant, $t'_0 = 3t_0$.

Noise Measurements

The required resolution for the tide measurements was obtained by counting the number of integral cycles of the Vibrotron signal over an interval of time long compared to 1 second. At higher frequencies the time available for measurement is reduced with a proportional loss in resolution. Therefore, to measure pressure fluctuations at higher frequencies, a modification of the tide-gauge equipment is necessary.

High resolution also can be provided by measuring the Vibrotron frequency with greater precision than integral cycles. We obtained the needed precision by measuring the average period rather than the average frequency of the Vibrotron signal. The average period was determined by counting crystal oscillator pulses dring an interval of time, $t = n/f$, where n is a predetermined number of cycles and f is the Vibrotron frequency. If f_c is the frequency of the crystal pulses, the reading, R, of the crystal pulse counter is

$$R = nf/f_c = n/f_c\,(Ap + B)^{\frac{1}{2}}$$

and the recording sensitivity is

$$\frac{dR}{dp} = \frac{Af_c n}{2f^3} \approx \frac{A}{2\bar{f}} \times \frac{f_c}{\bar{f}} \times \frac{n}{\bar{f}}$$

The transducer sensitivity, $A/2\bar{f}$, is increased by the ratio of the crystal frequency to the Vibrotron frequency, $f_c/\bar{f}$, and by the length of the measurement interval, $n/\bar{f}$, in seconds.

With this technique, noise signals with frequencies of 1 cy/min were studied with essentially the same Vibrotron and filter that was used in the tide study. With a transducer sensitivity of 0.5 cy/sec cm^{-1} at a mean frequency, $\bar{f} = 15$ kcy, a crystal oscillator

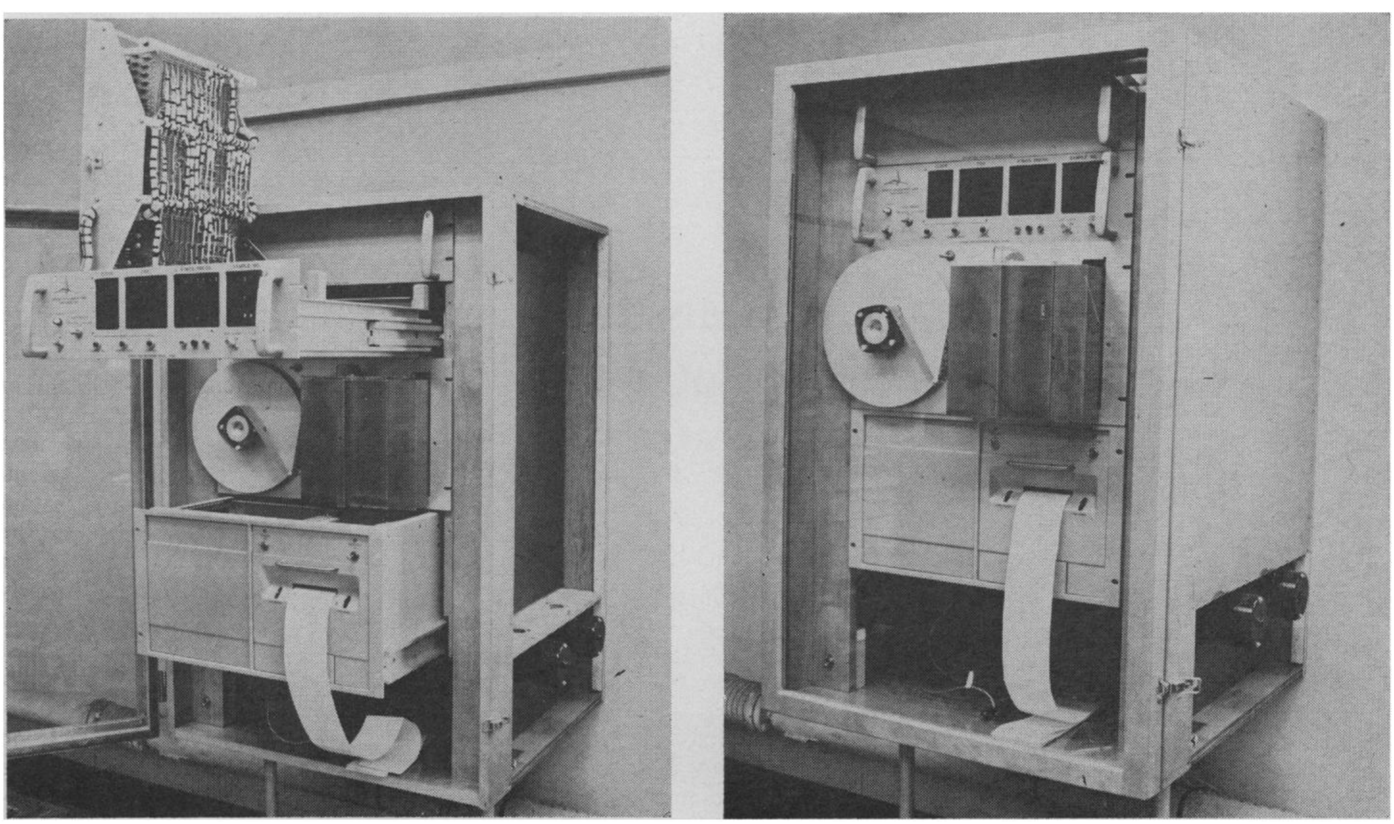

Fig. 8. The tide gauge recorder. Printed circuit logic cards installed in hinged chassis provide accessibility. Cooling of the electronic equipment enclosed in the air-tight cabinet is accomplished by forced-air circulation and metal sides. Dehydrant inside the cabinets insures moisture-free operation. Equipment operates from automobile batteries which are trickle-charged from commercial power lines.

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 $20/13.8 \approx 1.5$ 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.

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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-

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