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An Expendable Bathythermograph[1]

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ABSTRACT

An inexpensive bathythermograph comprising an expendable, radio-telemetering buoy and the associated shipboard apparatus is described, and some of the problems to be encountered in its development are considered briefly. Estimates of attainable specifications of an operational buoy, based on experience gained in the development of a crude laboratory model, are also presented.

Introduction. An expendable bathythermograph is one of several new instruments being considered by oceanographers in their search for more rapid and widespread data-gathering techniques. The desirable features of such an instrument are at once apparent: It must be inexpensive, reliable, and simple to operate, and it must provide an accuracy comparable to that of existing bathythermographs. It should also be capable of being placed in operation from any surface vessel or from aircraft. The instrument proposed here represents an approach to the simultaneous attainment of these features.

A rather crude laboratory model has been constructed in order to evaluate some of the major difficulties to be encountered in the development of such an instrument. It is to be emphasized that the laboratory model is merely representative of the proposed instrument, not a prototype.

General Description and Principles of Operation. Fig. 1 shows a block diagram of the proposed instrument. The expendable part is contained in a radio-telemetering buoy which may be catapulted from vessels or aircraft moving at high speed. After a suitable time delay (10 to 15 seconds), a diving weight containing the temperature-sensing thermistor is released from the base of the buoy. The weight is suspended from a miniature, single-conductor cable that terminates at one thermistor lead, the sea serving to complete the circuit comprising the thermistor and its constant current source.
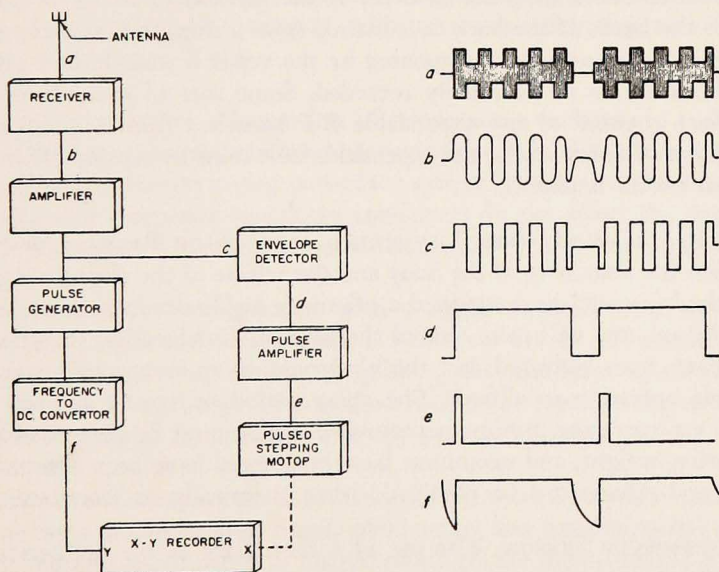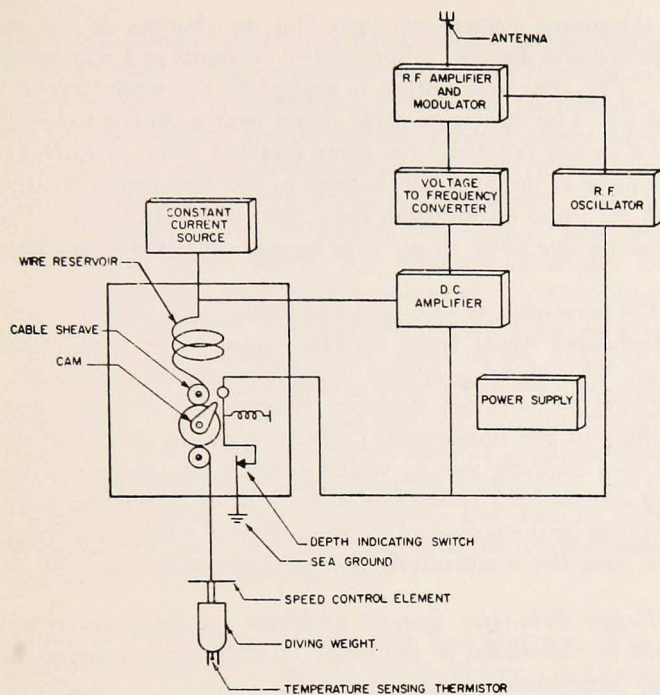
Figure 1. Block diagram of the proposed system.

Changes in the thermistor voltage corresponding to changes in the sea temperature are amplified and directed to the control elements of a voltage-to-frequency converter. The converter output is applied to the modulator of a telemetering transmitter. The miniature cable passes over a sheave to which is attached a cam and switch assembly. For every foot (30.5 cm) of cable extended, an electrical pulse is initiated and applied to the transmitter in such manner as to quench the radio transmission for a brief interval of time. The radio signal can thus be described as an interrupted, amplitude-modulated wave train.

At the receiver, the waveform is amplified and demodulated by the usual techniques, the demodulated signal being an interrupted wave train at the modulation frequency. This signal is applied simultaneously to a frequency-to-voltage converter and an envelope detector. Short-duration pulses (corresponding to quenching of the transmission) appearing in the output of the detector are applied to a stepping motor, which controls the motion of the recorder stylus along one of two coordinate axes. Motion along the other coordinate axis is governed by the output of the frequency-to-voltage converter. Ideally, the recorder plots the temperature as a function of depth.

Consideration of Design Principles. Several problems are immediately apparent, and these will be considered in the order in which they arise in the preceding operational description.

Buoy Launching. First in order is the method or methods employed to launch the buoy. If the buoy is launched from a ship, the buoy certainly must be clear of the turbulence generated by the vessel if near-surface temperature variations are to be accurately recorded. Some sort of catapulting system is therefore essential to any expendable BT launched from a vessel moving at high speed. Consequently, the expendable unit must be capable of withstanding a considerable impact.

Time Delay between Launching and Sensor Release. A time delay between the launching of the buoy and the release of the diving weight assures that the buoy will have attained a relatively stable orientation in the surface, i. e. the antenna will have cleared the surface. Incidentally, the power supply will have been activated and the electronic components will have achieved a stable operating condition. The delay period of 10–15 seconds is only a rough estimate; the minimum permissible delay must be determined after the geometry, weight, and maximum launching speed have been ascertained. The delay and release can be obtained either chemically or electromechanically.

Thermistor Sensor. The use of a thermistor as the temperature sensor is highly desirable for several reasons. Compared with other sensors, thermistors are inexpensive and very sentitive to temperature variations, hence the amount

of amplification required and the attendant power dissipation are minimized, as is the cost of the expendable buoy. While greater sensitivities can be obtained by operating thermistors at constant temperature, the instrumentation is more complicated and necessitates a larger power supply capacity. Constant current operation is therefore to be preferred. (For an account of the properties of thermistors in moving fluids, see Rasmussen, 1962.)

On the other hand, thermistors are noted for their relatively slow response time, and it would appear that temperature sensors having response times much shorter than those usually associated with thermistors would be necessary to achieve the high diving speeds required for accurate depth indications. However, time constants in sea water of the order of 10^{-2} seconds can be achieved with readily available bead thermistors by mounting them properly and heating them with suitable currents. Diving rates of the order of 10 feet/sec (3 m/sec) in even the steepest thermal gradients can be utilized to obtain variational temperature measurements accurate to $\pm 0.1\,°C$.

Faster response times are desirable and may be obtained with improved thermistor construction. The effect of aging on thermistor characteristics must also be more carefully examined.

SINGLE CONDUCTOR CABLE AND SEA RETURN. The use of a single conductor cable and sea return in the thermistor circuit would reduce buoy size and cost, and the high-level signals together with available high-resistance thermistors make this scheme practical. Cable packaging presents no serious difficulty. Readily available, compact cable reservoirs providing tension-free payout are in widespread use.

SIGNAL MULTIPLEXING. Conversion of temperature variation to a variable frequency signal must be made to insure accuracy and reliability of the measurement. Since gain variations in that part of the system lying between the voltage-to-frequency and frequency-to-voltage converters do not affect the data, the first conversion should preferably occur immediately in the output of the thermistor.

By interrupting the transmission with a signal controlled by the cable extension, both depth and temperature information can be efficiently transmitted via a single carrier, thereby simplifying the multiplexing circuit and reducing the cost of the buoy. The method is effective provided the switching and modulating signal frequencies differ by several octaves.

TEMPERATURE CALIBRATION. Calibration of the recorder temperature scale for any one buoy would be most simply obtained by first linearizing the output voltage vs. thermistor-temperature characteristic of the buoy-receiver system. Since there is a one-to-one correspondence between the thermistor-temperature and the modulation frequency, the linearization could be effected through

proper design of the frequency-to-voltage conversion circuit. A two-point temperature calibration would then be sufficient to establish the temperature scale of the recorder or of other data-processing equipment. The two temperatures could be checked by successively replacing the thermistor with two precision resistors having resistance values corresponding to those of the thermistor at the desired temperature, e. g. $5°$ and $15°C$. These resistors could be built into the buoy and inserted into the thermistor circuit during calibration by means of an externally accessible switch.

To examine the feasibility of this calibration method when applied to a large number of buoys having slightly different frequency vs. thermistor-temperature characteristics, the frequency appearing in the output of the voltage-to-frequency converter is expressed as

$$f(T) = f(T_0) + i[R(T) - R(T_0)]A, \qquad (1)$$

where $R(T)$ is the thermistor resistance at the temperature T, i is the constant thermistor current, and A is the conversion ratio of the converter in cps/volt. The converter is assumed to be linear so that A is a constant. The thermistor resistance (Becker *et al.*, 1946) can be written as

$$R(T) = R(T_0) e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)}, \qquad (2)$$

where B is a constant determined by the semiconducting material from which the thermistor is manufactured. Then

$$f(T) - f(T_0) = iR(T_0) A\left[e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)} - 1\right]. \qquad (3)$$

Suppose that the response of the frequency-to-voltage converter in the receiving apparatus is adjusted to linearize its output voltage with respect to temperature variations measured with a particular buoy. The desired converter output voltage may be expressed as

$$G[(f(T)] \propto \frac{1}{\frac{B}{T_0} + \ln\left[\frac{f(T) - f_1(T_0)}{A_1 i_1 R_1(T_0)} + 1\right]}. \qquad (4)$$

The subscript $_1$ denotes parameters associated with the reference buoy. That this expression reduces to a linear function of temperature may be seen by substituting the expression for $f(T)$ in eq. (3) with the subscript $_1$ added to each of the parameters. The variation in output voltage obtained with this buoy is then

$$e_{01} \propto [T - T_0]\left[\frac{dG(f_1)}{dT}\right]_{T_0} = \frac{T - T_0}{B}. \qquad (5)$$

For a second buoy having a slightly different frequency vs. thermistor-temperature characteristic,

$$e_{02} \propto [T - T_0] \left[\frac{dG(f_2)}{dT}\right]_{T_0} + \frac{1}{2} [T - T_0]^2 \left[\frac{d^2 G(f_2)}{dT^2}\right]_{T_0} + \cdots, \quad (6)$$

where now

$$G[f_2(T)] \propto \frac{1}{\frac{B}{T_0} + ln\left\{\frac{f_2(T) - f_1(T_0) + A_2 i_2 R_2(T_0)\left[e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)} - 1\right]}{A_1 i_1 R_1(T_0)} + 1\right\}}. \quad (7)$$

Assuming (i) a typical value of 3000°K for B, (ii) a difference of 5 % between the products $A_1 i_1 R_1(T_0)$ and $A_2 i_2 R_2(T_0)$, and (iii) a frequency difference, $f_2(T_0) - f_1(T_0)$, of less than the frequency change resulting from a 0.5°K temperature variation, the deviation of e_{02} from linearity would be less than 1 % over a 10° temperature range in the neighborhood of 300°K. The range of linearity could be extended by reducing the variability among the products $A_n i_n R_n(T_0)$; this reduction would be achieved through proper adjustment of the thermistor current and the converter bias. Hence, it appears that an accurate, two-point temperature calibration is practical.

EFFECTS OF BUOY DRIFT, DIVING SPEED, AND SEA STATE. The measurement accuracy is affected by the buoy drift speed and sensor diving speed as well as by the response time of the sensor and the thermal gradient. Studies of buoy drift must be conducted before a minimum diving speed can be associated with a given measurement accuracy; however, it can be stated that a depth accuracy of 1 % requires a diving speed approaching ten times the buoy drift speed. If, for example, the buoy drift speed were one knot, a diving speed of almost 16 feet/sec (4.9 m/sec) would be required for a depth measurement accuracy of 1 %. Now an error in depth can be converted to an error in temperature only if the relation between the two variables is known. However, an estimate of the maximum variational temperature error to be expected for a given depth error can be obtained by assuming a constant gradient having the maximum value to be encountered. Let g and y represent the gradient and depth, respectively. Then the error in temperature variation, E_T, due to an error in depth, E_Y, is gE_Y degrees. Thus, if a constant error in depth of 1 % results from a buoy drift of one knot, the temperature error at any depth is 0.01 gy. For a 100-foot (30.5-m) depth in a constant gradient of 0.1 °C/foot (0.33°C/m) the temperature error would amount to 0.1 °C. If no additional error is to result from the inability of the sensor to follow the temperature variations, the sensor response time must approach 10 milliseconds, and this response time is representative of the lowest value obtainable with thermistors heated by constant currents. Although gradients as high as, or

higher than, 0.1°/foot (0.33°/m) can be anticipated, they do not extend over very great depths. Hence, the ratio of diving speed to drift can be reduced.

In view of the above estimates, it appears that measurement accuracies approaching 1 % can be obtained with thermistor diving speeds of the order of 10 feet/sec (3 m/sec) with buoy drift speeds of from one to two knots.

High seas will produce two undesirable effects. First, the buoy antenna will be shielded by the waves for periods of time dependent on the wave period and height, by the height of the receiving antenna, and by the distance separating the two antennae. Attendant interruptions of the received signals will, of course, produce cumulative errors in the depth indication. Effective use of the proposed instrument will therefore be restricted by sea state to a degree dependent upon the type of vessel from which it is launched. Second, vertical motion of the buoy will give rise to an uncertainty in the depth indication. Assuming extremely low cable tension, the indicated depth will be the instantaneous depth measured from the sea surface rather than from mean water level.

Laboratory Model. To investigate further the feasibility of the proposed system, a laboratory model has been developed. In constructing this model, emphasis was placed on accuracy and simplicity of instrumentation. Circuits and components of known reliability were utilized wherever possible. Transistors were not used because it was believed that the circuit development would require an unwarranted amount of time. There is little doubt, however, that transistorization would afford a reduction in the cost of the instrument. Problems concerning the mechanical strength, buoyancy, and stability of the buoy as well as problems pertaining to antenna design, radio range, and power supply specifications were not examined extensively, since it was known that these problems had been successfully attacked in other areas of undersea instrumentation. In fact, the identical problems were investigated during the early sonobuoy phases of Project Jezebel.

BUOY INSTRUMENTATION. A schematic diagram of the buoy circuitry is shown in Fig. 2. A constant thermistor current is provided by the battery, B, and the resistor, R, in series with the thermistor and the cable. The thermistor is a medium-sized bead having a resistance of 30.000 Ω at 25 °C and a time constant of 70 milliseconds in sea water. Smaller beads providing a time constant of the order of 10 milliseconds could have been employed, but repeated use of the laboratory model in nearshore areas demanded the more ruggedly mounted sensor obtainable with larger thermistors.

The thermistor voltage is amplified by the differential circuit utilizing the twin triode, V_1, and the amplified signal is applied to the grids of a free-running multivibrator comprising two pentodes, V_2 and V_3. A frequency range of
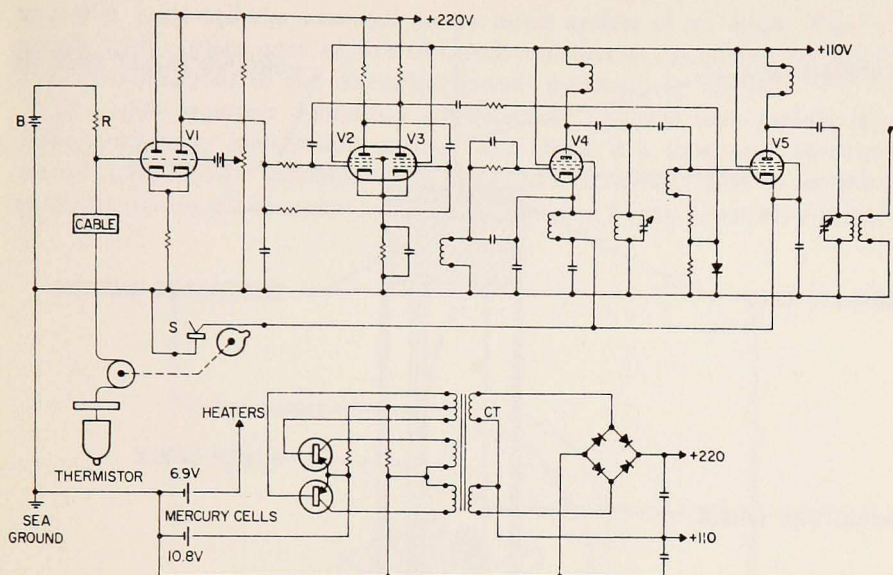
Figure 2. Buoy instrumentation.

from 6 to 9 kc corresponds to a variation in temperature of from 10° to 20°C. The square-wave voltage appearing in the multivibrator output is employed to gate the power amplifier, V_5. Since the r. f. signal appearing in the plate circuit of the oscillator, V_4, is also coupled to this amplifier, the radio transmission is interrupted at a rate equal to the modulation frequency. The cathodes of V_4 and V_5 are returned to ground through the switch, S, which opens briefly once per revolution of the cam, the switching rate being equal to the number of feet of cable extended per second. The waveform appearing in the transmitter output is similar to that labeled "a" in Fig. 1; however, the minimum peak-to-peak carrier power is zero.

In an expendable buoy, the power supply would consist of relatively low-quality batteries. However, an inverter power supply employing mercury batteries provides the higher degree of stability required for the experimental model.

Fig. 3 shows the arrangement of the components comprising the expendable unit. The buoy is a 3-foot (91-cm) length of plexiglass tubing having a diameter of 5.0 inches (12.7 cm) and a wall thickness of 0.125 inches (0.318 cm). A fitting at the base of the quarter-wavelength antenna permits the attachment of four horizontal rods, which serve as a ground plane. The electronic chassis is located near the top of the buoy and is approximately 1.5 feet (46 cm) above the power supply. The lead from the thermistor cable to the electronic chassis passes through a fitting in a plexiglass sealing disc. The electrical system is grounded to the sea via another lead passing through the disc and terminating
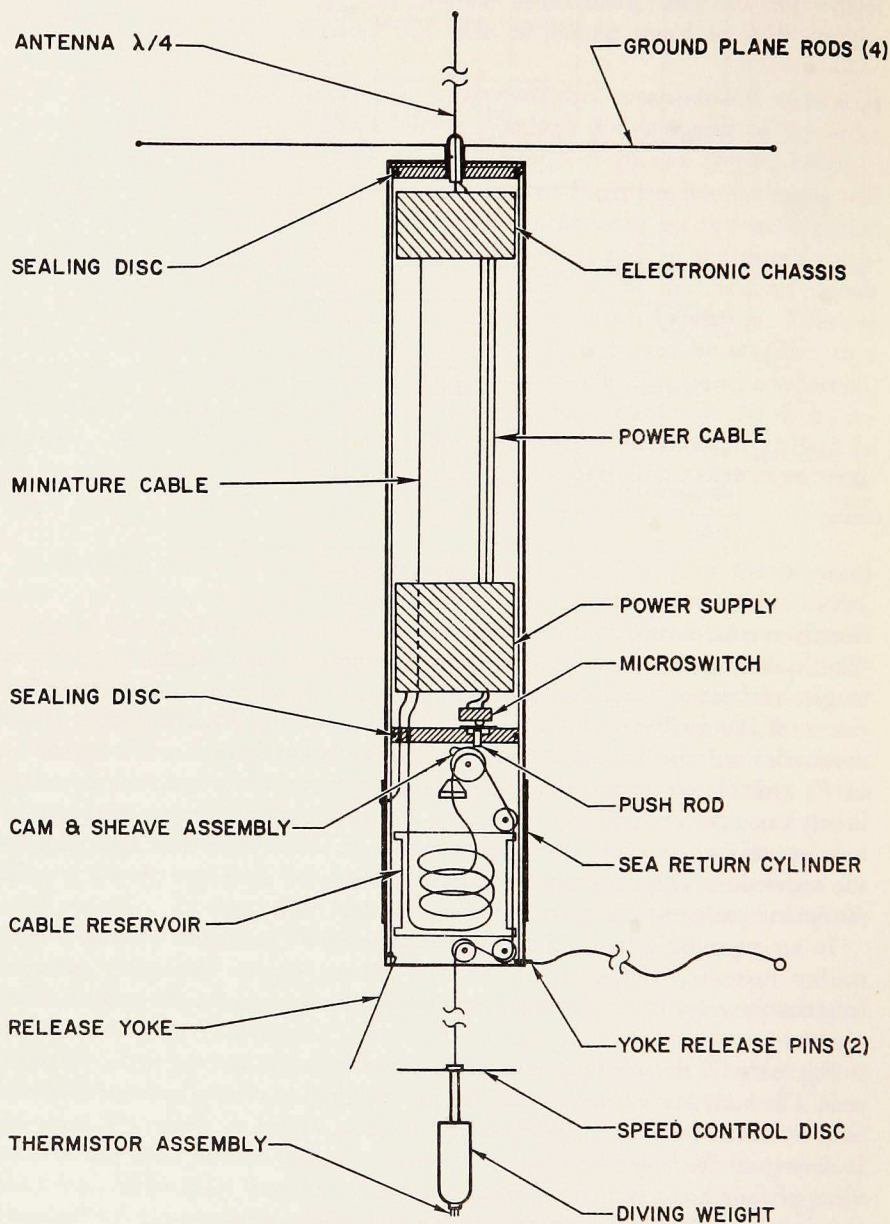
Figure 3. Components of expendable bathythermograph.

at a thin brass cylinder mounted on the outer surface of the buoy. The relatively large surface area of this electrode and that of the diving weight reduce the resistance in the thermistor circuit presented by the sea.

The cable reservoir contains a commercially available wire package providing extremely low-tension payout. The cable is a 24-gauge, 19-strand, tinned copper wire insulated by a 1/64-inch (0.04-cm) wall of polyvinyl chloride, its over-all diameter being 0.063 inch (0.16 cm). From the reservoir,
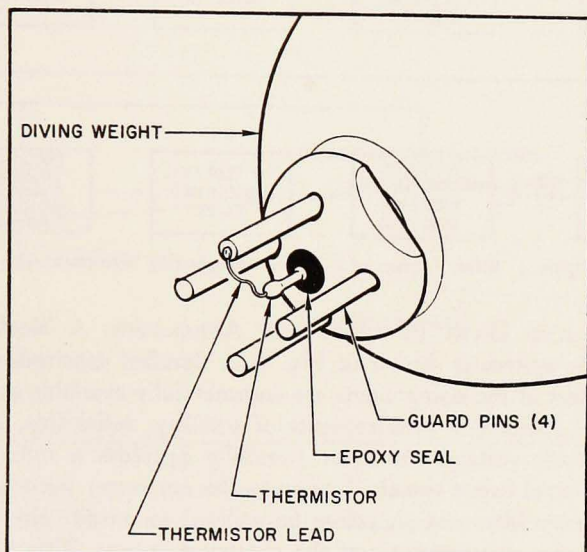

Figure 4. Detail of thermistor assembly.

the cable passes over a 1.9-inch (4.9-cm) diameter sheave that is coupled to the cam via a 2:1 gear assembly. The cable then passes over a system of pulleys and terminates in a fitting in the shaft of the diving weight assembly. The microswitch is mounted on the upper side of the sealing disc and is actuated by a push-rod whose vertical throw is controlled by the cam. A rubber membrane separates the upper surface of the push-rod and the switch lever. The diving weight is a streamlined bronze cylinder having a diameter of 1.5 inches (3.8 cm) and a length of 4.25 inches (10.8 cm). A small hole bored along the axis of the diving weight serves as a conduit for the cable, which terminates at the thermistor assembly. Speed control and stability of the diving weight are provided by a 5-inch (12.7-cm) diameter aluminum disc, rigidly coupled to the upper end of the weight via a 3.25-inch (8.25-cm) length of 0.375-inch (0.952-cm) o. D. bronze tubing. Fig. 4 shows the thermistor assembly in more detail.
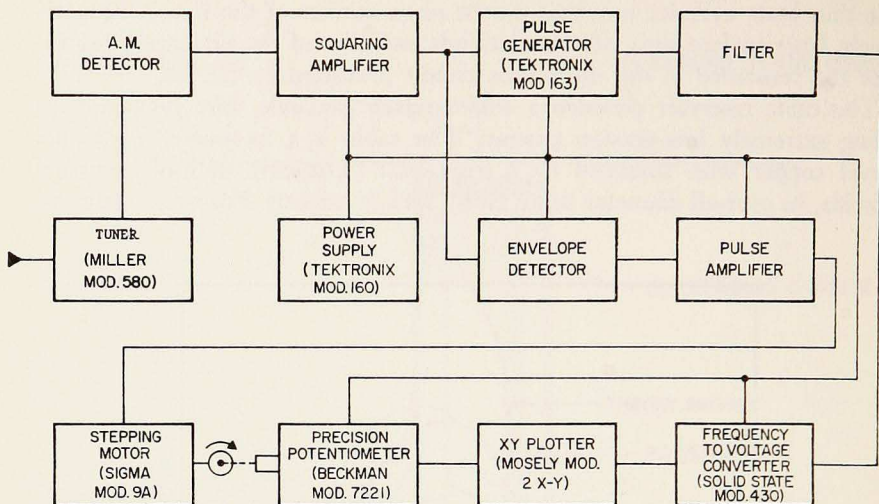
Figure 5. Block diagram of receiving and plotting instrumentation.

RECEIVING AND DATA PRESENTATION APPARATUS. A block diagram of this part of the system is shown in Fig. 5. A detailed description will not be given, since most of the components are commercially available and are capable of meeting all reasonable requirements of stability, reliability, and accuracy. The frequency-to-voltage converter normally provides a linear conversion. For very low-level input signals, however, the converter becomes amplitude-sensitive. A wave filter can therefore be utilized to modify the frequency-to-voltage conversion characteristic of the receiving system. The filter employed in the experimental instrument was adjusted to yield a linear variation of voltage with temperature in the range of from 10° to 17°C.

Results of Preliminary Investigatons

DIVING RATE. The diving rate achieves a steady value within a few seconds following release of the weight. No error in depth results from the varying diving rate, since only the length of extended cable is measured. Neither the time constant nor the temperature sensitivity are significantly affected by small changes in the diving rate provided that the diving rate exceeds 2 feet/sec (60 cm/sec) and that the thermistor power is sufficiently low to prevent heating to a temperature of more than a few tenths of a degree above ambient. In the model, a diving rate of 3 feet/sec (90 cm/sec) is employed, and the thermistor temperature exceeds the water temperature by less than 0.1°C.

SEA RESISTANCE. The resistance in the thermistor circuit presented by the sea return varies from approximately 4 ohms at a thermistor depth of 10 feet

(3 m) to approximately 7.5 ohms at 1000 feet (300 m). The effective cumulative temperature error attributable to the varying sea return resistance is less than 0.015°C. It should be remembered, however, that at greater depths, the temperature will usually be lower than at the surface, and the sea return resistance would therefore be a smaller fraction of the thermistor resistance.

STABILITY WITH REGARD TO POWER SUPPLY VARIATIONS. The error in temperature as a function of power supply variations is shown in Fig. 6. The
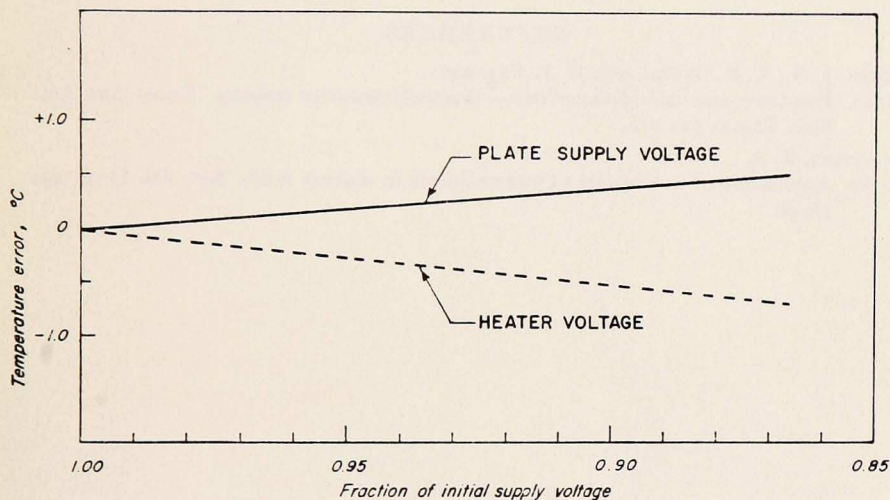

Figure 6. Error in temperature as a function of power supply variations.

error is less than −0.5°C for a decrease in heater voltage of 10% and less than +0.5°C for a decrease in $B+$ voltage of 10%. However, the rates of supply voltage variation are very nearly the same, and the net temperature error is of the order of 0.1°C for a 10% decrease in supply voltage. If the inverter power supply were replaced by a 6-volt battery having a capacity of 0.5 ampere-hour and two 100-volt batteries of 0.03 ampere-hour capacity, the cumulative temperature error at a depth of 1000 feet (300 m) would be approximately 0.1°C. For the faster diving rates anticipated, the battery capacity could be reduced still further.

Although the laboratory model is a rather crude and inefficient instrument, it serves to demonstrate the combined attributes of simplicity, accuracy, and low cost obtainable with the proposed system. Considerable engineering research and development would be required to firmly establish the specifications and cost of an operational instrument; however, experience gained in the development and construction of the laboratory model permits reasonable estimates of some attainable specifications and the cost of the expendable buoy:

1. Buoy Size and Weight
   a. Diameter: 3.5 inches (9 cm).
   b. Length: 3 feet (1 m) excluding antenna.
   c. Weight: 10 pounds (3.7 kg).
2. Temperature Sensor Diving Speed: 10 ft/sec (3 m/sec).
3. Accuracy: 1.0% for drift speeds of less than 2 knots.
4. Power Dissipation: 3 watts (maximum).
5. Buoy Cost: Less than $100 per unit, mass produced.

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Page 31, the first of four equations immediately above equation 34a —

"$\varrho = (\Delta\varrho), \ldots$" should read "$\varrho = (\Delta\varrho)\lambda, \ldots$"