A Multiple-Detector Irradiance Meter and Electronic Depth-Sensing Unit for Use in Biological Oceanography[1]

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ABSTRACT

The underwater irradiance meter or submarine photometer described here is designed to operate in the upper 100 to 150 m. It permits direct measurement of the downward blue-green irradiance (480 mμ) to a depth of 100–120 m on a clear day in water with an attenuation coefficient in the blue-green region of the spectrum of approximately 0.04/m. The meter can accommodate as many as five individual detector units as well as an associated depth-sensing element. The detectors are cosine flux collectors, equipped with a dry disk, self-generating, barrier layer cell. Any single detector unit may be readily oriented up, down, or horizontally. Selection among the detectors is made by energizing the switching mechanism with a push button. Their output is measured in the vessel's laboratory with a damped multirange microammeter of low internal resistance. The associated depth-sensing unit is transistorized and battery-powered and is capable of measuring depth down to 200 m with an accuracy of ± 2% in the 50–200 m range. The unit is stable, rugged, and relatively insensitive to temperature changes in the range between 2° and 25° C. The detector and depth signals are carried by a two-conductor electrical cable, which also supports the instrument. A sea return is utilized in the detector unit switching assembly.

Introduction. The need for a versatile irradiance meter for use in connection with studies of phytoplankton ecology has been plain for some time. Marine biologists and biological oceanographers studying phytoplankton and littoral alga photosynthesis are now frequently measuring attenuation coefficients and light levels; they require more complex and precise information as their studies become more elaborate.

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[2] The authors wish to acknowledge the information received from John Tyler, research physicist of the Visibility Laboratory of the University of California, Scripps Institution of Oceanography, La Jolla, concerning the design and characteristics of the flat plate collectors used in the detector unit.

The meter described here is the result of the authors' experience over seven years in measuring attenuation coefficients and developing instrumentation. This particular instrument has been in intermittent use and under modification for two years. The present design has proved to be reliable and of general applicability for high seas research in which the objective is to study, in the field, the role of light in photosynthesis.

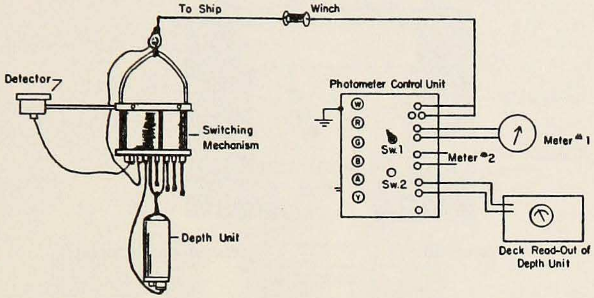

Figure 1. The irradiance meter and depth-sensing unit.

The meter (Fig. 1) is a single or multidetector unit capable of measuring the irradiance on a flat surface oriented at any desired angle. The individual flux collectors may be oriented in advance to measure the attenuation coefficient for downwelling or upwelling irradiance. By combining these two measurements it is possible to compute the reflectance at an imaginary horizontal plane in the sea, or to obtain the ratio of the irradiance on a plane facing the sun to that on a plane facing away from it. By proper selection of optical filters, the instrument can be set up to measure either the same optical property for a number of band widths nearly simultaneously or several optical properties for the same band width.

Irradiance is easily measured and by its use the results from different areas and regions can be standardized and compared. Furthermore, attenuation coefficients k calculated from the irradiance data using the following equation

$$k_\lambda = \frac{2.30}{L} (\log I_{\lambda,h} - \log I_{\lambda,h+L})$$

are useful in biological and physical oceanographic studies (Holmes, 1957 or Sverdrup, *et al.*, 1942).

The Detector Unit. Each detector unit (Fig. 2) consists of a photocell housing (i) and a threaded cap (c). The latter accommodates the Lambert or cosine collector (a), elevated about 1 mm above the cap and the lucite window (b). A watertight seal between these components is effected by rotating the threaded

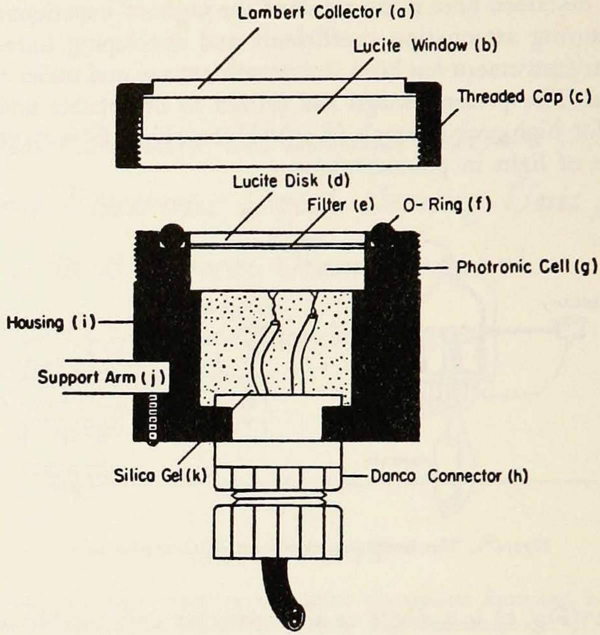

Figure 2. The detector unit.

cap until a seal is obtained between the O-ring (f) and the lucite window. The color and/or neutral filter (e) may be placed above the photocell (g); when gelatin filters are employed, they are held in contact with the photocell by a lucite disk (d). Silica gel (k) placed in the space below the photocell prevents window fogging and moisture damage to the gelatin filter. The electrical leads from the photocell are taken through the housing in a nylon stuffing tube (h) (Danco, Size 1, Danielson Mfg. Co., Danielson, Conn., packing assembly for the tube, Dorn Equip, Corp., Boston, Mass.); they terminate in a Joy plug (No. X8104–63, Joy Mfg. Co., Compton, Calif.).

The particular cosine collector used in this instrument is fabricated from milk-white translucent plastic (Rohm and Haas, Plexiglass 2333, Philadelphia, Pa.), the surface of which has been carefully abraded with carborundum (Grit No. 180) to give it cosine-collecting properties when submerged. There are of course other ways to build cosine collectors; the important thing to know is the properties of the flux collector.

Hermetically sealed barrier layer (dry disk) self-generating cells (Model 856RR), manufactured under the name Photronic Photoelectric Cell (Weston Electrical Instrument Corp., Newark, N.J.), have been employed in these detectors. These cells have proved stable and rugged enough for use in this type of work.

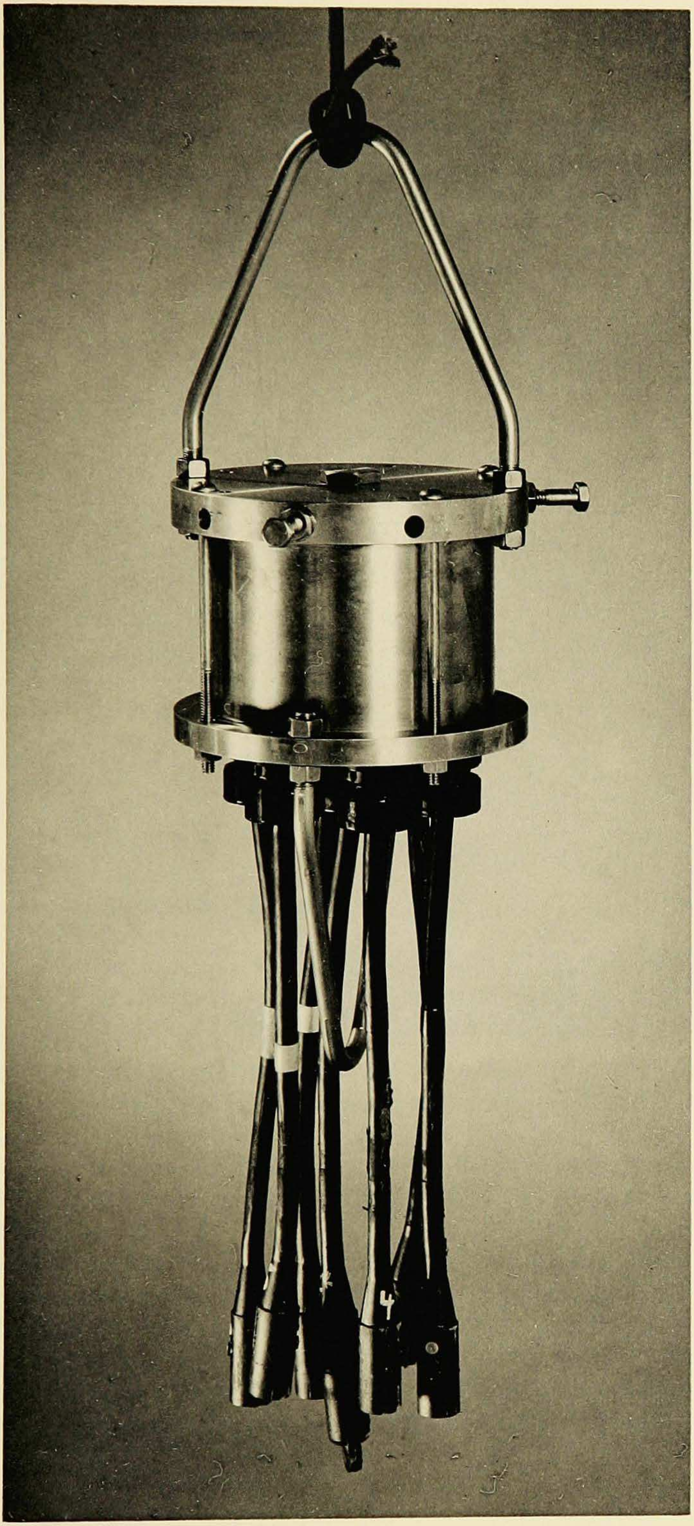

Figure 3. The underwater switching unit.

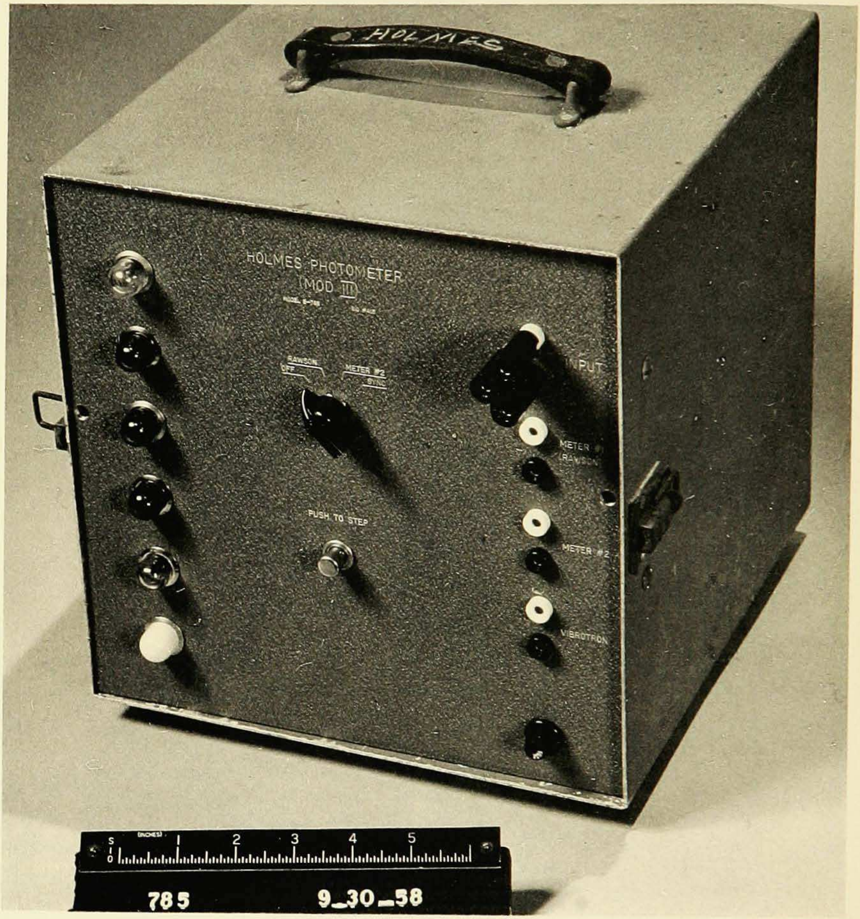

Figure 4. The deck control unit.

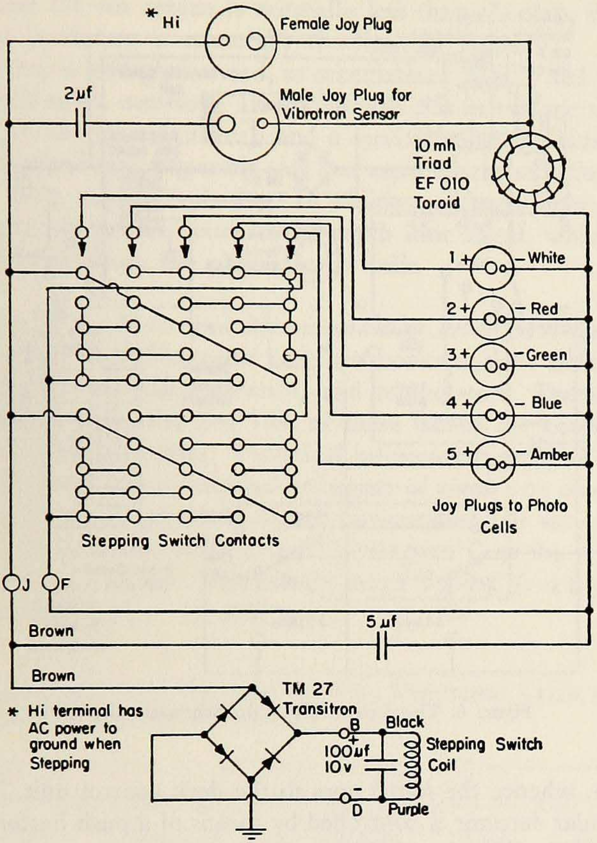

Figure 5. The underwater switching unit. Schematic diagram.

Switching Mechanism and Deck Control Unit. The detector units are mounted on stainless steel rods, approximately 40 cm long, which are inserted into holes provided on the top plate of the underwater switching unit (Figs. 1, 3). The orientation of the detectors may be adjusted and maintained by utilizing the Allen set-screws mounted in either the detector or the switching mechanism. Electrical continuity from the detectors is achieved by means of connecting the Joy connectors (Fig. 3).

The underwater component of the switching mechanism consists of an oilfilled brass housing which contains a rotary stepping switch (Type 44, Automatic Electric Sales Corp., North Lake) and associated equipment (Figs. 3, 5). Seven outlets pass through the bottom of the housing; five for use with detectors, one to connect with the depth element, and one to connect to the cable that supports the instrument and carries the signal to the photo-

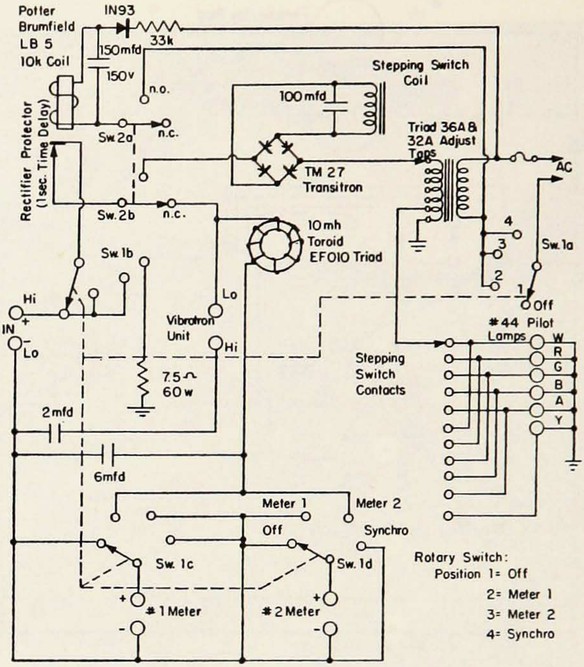

Figure 6. The deck control unit. Schematic diagram.

meter winch, whence the signal goes to the deck control unit. The selection of the particular detector is controlled by means of a push button on the deck control unit ("Push to Step", Sw. 2, Figs. 4, 6).

The deck control unit (Figs. 4, 6) is energized from 115-volt, 60-cycle, AC power. When the instrument is turned on, one of six panel lamps (the sixth has no detector associated with it) indicates which of the five detectors are connected to the meter or recorder jack located on the right-hand side of the instrument. Provision has been made for the use of two meters or of one meter and/or a meter-amplifier combination by the inclusion of a second outlet on the control unit. The selection of these outlets is controlled by a switch mounted in the middle of the control unit panel above the energizing (Push to Step) button.

There are several fundamental limitations to the mechanism as it is at present designed. First, a maximum of 4 ohms is all that can be tolerated per conductor between the deck and underwater units. If the resistance is increased above this limit, the photocell output becomes less linear at high light levels and effectively less sensitive. Further, since a sea return is used and is included in the 4-ohm limitation, the instrument is not designed to be used in fresh water. Because the sea return is normally less than 1/4 ohm, it is clear that the electrical conductor is essentially the limiting factor.

The circuitry is straightforward, as schematized Figs. 5 and 6 show. Two special features merit mention. The photocells not in use are shorted (as recommended by the manufacturer); and a specific control position is provided on the deck control unit to permit easy and rapid synchronization between the two units if they require rephasing. In addition, a simple filter system is used to prevent any interaction between the depth unit signal, which is AC, and the DC potentials from the photoelectric cells.

Performance of the Meter and Measurement of Attenuation Coefficients. The current generated by a Photronic cell in a constant light field is a function of cell sensitivity, external resistance, and temperature. During routine irradiance measurements, the first two of these factors are constant; only the temperature of the cell varies. Technical information supplied by the manufacturer shows that with an external resistance of about 105 ohms, the output of a cell in a constant light field of 200 foot-candles will vary from −2% to +3% in the temperature range 0–40°C, using 20°C as the reference point. The deviation is less in the temperature range 10–25° (*c* ±1.5%); the data are not corrected to allow for this error.

TABLE I. Linearity of Response of Two Photronic Cells as Determined from Optical Bench Measurements.

Log Flux (Theoretical)	μA Output at 105 ± 1 Ohms: Cell No. 8, 4 Feb.	10 Mar.	21 Oct.	29 Dec.	Cell No. 3, 3 Feb.	21 Oct.	26 Dec
0.0	1000	1000	1000	1000	1000	1000	1000
0.1	814	818	820	819	812	820	812
0.2	656	658	660	660	653	660	657
0.3	528	532	535	535	527	535	542
0.4	426	425	430	430	421	424	–
0.5	342	342	342	342	337	342	348
0.6	272	273	275	274	269	274	280
0.7	217	218	218	220	213	222	226
0.8	174	175	175	174	171	174	182
0.9	138	139	138	140	136	139	144
1.0	111	112	105	112	109	112	115
1.1	88.4	87.5	85	88	85.8	87.9	92
1.2	70.4	69.5	69.5	70.1	68.6	70.1	72.1
1.4	44.5	44.2	43	44.6	43	44.2	46.5
1.6	28.3	–	30	–	27.6	28.6	–
1.8	18.1	–	–	–	17.6	18.1	–
2.0	11.5	–	–	–	11.2	11.6	–
2.2	7.3	–	–	–	7.2	7.4	–
2.4	4.6	–	–	–	4.45	4.9	–

The type 856RR Photronic cells are stable in terms of linearity of response. However, since no two cells are identical, it is important if reliable measurements are to be made at high light levels to determine the linearity of response for each cell under the resistance load that will obtain during actual measurements. This may be done on an optical bench or with a series of neutral filters of known transmittance. In Table I, linearity-of-response data obtained at intervals over an 11-month period are given for two type 856RR cells. There is an indication of a slight increase in linearity over the time interval, but this may not be significant.

The flux sensitivity of one of these cells has remained virtually constant ($c \pm 5\%$) for two years.

During routine measurements at sea, the output of the detector unit(s) has been measured with a Rawson multimeter (Model 501, special slow response) possessing five scales (0–50, 100, 200, 500, and 1000 μA), each with an internal resistance of 100 ohms. The meter has been inductively damped so that its response time is on the order of 45 sec. It has been assumed that, under conditions of rapidly fluctuating light levels such as are frequently encountered in the upper 15 m, the damped meter gives an estimate of the average light levels.

Attenuation coefficients may be readily determined providing visible incident irradiance is measured simultaneously with the output of the detector(s) at a series of depths and providing the linearity of the detector element is known.

Under ideal field conditions this irradiance meter gives very reproducible

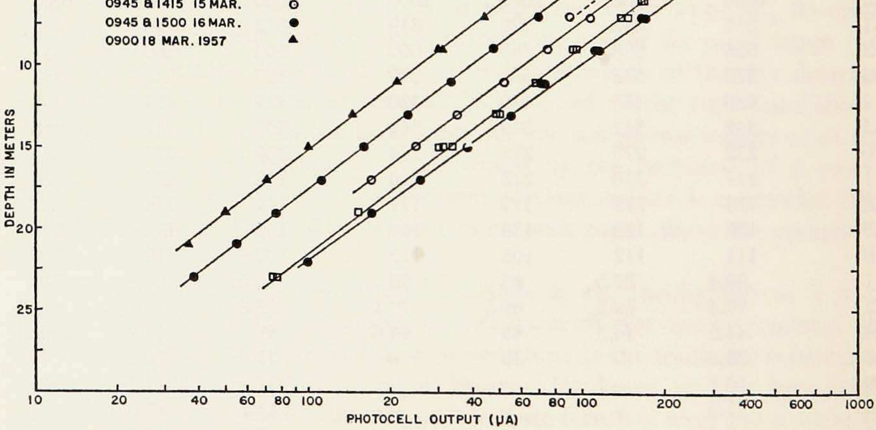

Figure 7. Relative irradiance at different depths. Lake Pend Oreille. Wratten No. 45 filter.

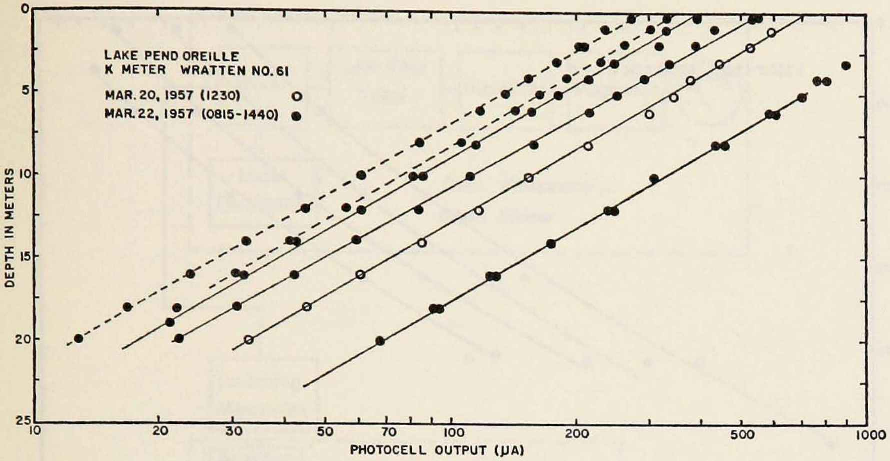

Figure 8. Relative irradiance at different depths. Lake Pend Oreille. Wratten No. 61 filter.

results, as the data presented in Figs. 7 and 8 demonstrate. These data were collected in Lake Pend Oreille, Idaho, in March 1957, with a different switching mechanism but with the same detector and galvanometer mentioned above. Correction for departure in linearity and for changes in incident solar radiation has been made. The corrections for incident radiation were made in such a way that the various curves are not superimposed. Thus the relatively minor departures in slope (the attenuation coefficient) between the eye-fitted curves may be readily seen. The Wratten No. 45 filter has its transmission peak at 480 mμ and the No. 61 at 520 mμ.

Comparable replicate measurement series obtained in the sea show that the *k* values are more variable than those obtained in Lake Pend Oreille. The vertical oscillations of the vessel and the high wire angles resulting from ship drift or subsurface currents make measurement more difficult and less certain. A typical series of measurements obtained on four separate lowerings of the irradiance meter in the Pacific Ocean about 20 miles west of La Jolla, California, on 1 May 1959 is illustrated in Fig. 9. Conditions were quite favorable during this set of observations: the sky was nearly uniformly overcast, sea and swell were moderate, and wire angles were less than 5 degrees. Corrections similar to those applied to the data in Figs. 7 and 8 were also made. The rather obvious differences in the slopes of these curves in the deeper layers probably are the result in part of inaccurate depth determinations. Had the depth element described in the next portion of this paper been employed, these curves might have become essentially parallel, as were the Pend Oreille profiles (Figs. 7, 8), where depth determinations had essentially no error.

While the sensitivity of the Photronic cell is not particularly high, measurements in the blue-green region (Wratten No. 45 filter) may be made to depths

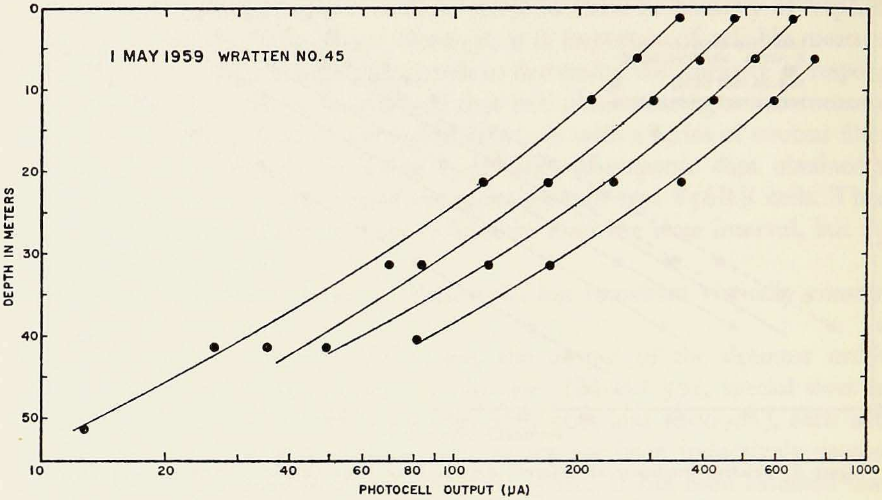

Figure 9. Relative irradiance at different depths. Pacific Ocean 20 miles west of La Jolla, California. Wratten No. 45 filter.

of approximately 100 to 120 m on clear days when the water possesses an attenuation coefficient (in this same spectral region) of approximately 0.04 per meter. Under these conditions about 1.8% of the blue-green light penetrating the sea surface will be found at 100 m depth. A considerable increase in sensitivity of the unit may be easily obtained by amplifying the photocell signal.

The Depth-sensing Unit. In order to measure attenuation coefficients with precision, instrument depth as well as light levels must be measured accurately. Experience gained from examining many irradiance-depth profiles has indicated that depths computed from wire length and wire angle measurements cease to be reliable with wire lengths exceeding 50–60 m if high wire angles (*i. e.*, 40–45°) are encountered. Thus if reliable light measurements deeper than approximately 60 m are desired, the photometer depth should be measured by some other technique. This requirement led to the development of the depth-sensing unit described below.

For convenience in describing it, the component parts of the depth unit are schematized in Fig. 10. The pressure-sensing element (Vibrotron Digital Pressure Gauge, Model 101-12-300, Borg-Warner Controlls Corp., Santa Ana, Calif.) consists of a vibrating wire maintained in a vacuum and driven by a transistorized, battery-powered amplifier. Pressure changes on the end of the wire that is attached to a pressure diaphragm alter the tension of the wire and hence its frequency.

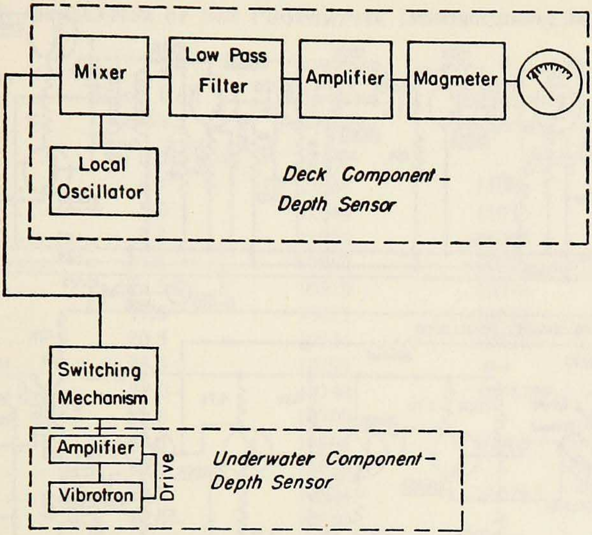

Figure 10. Principal components of the depth-sensing unit. Diagrammatic.

The deck component of the depth-sensing unit is connected to the meter control panel (Fig. 1). The amplified signal from the vibrating wire, coupled into the irradiance meter's switching mechanism, feeds into a mixer, where the local oscillator produces a frequency which corresponds to the Vibrotron zero psia frequency. The resultant difference frequency is fed through a low-pass filter to remove unwanted components and then amplified. The amplified signal passes through a Magmeter (No. F-5161, Airpax Products Co., Balti-

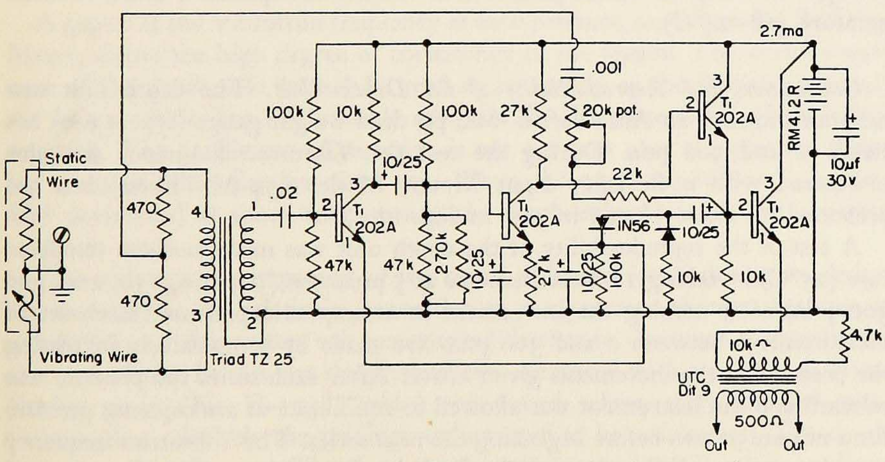

Figure 11. Depth-sensing unit. Wiring diagram of underwater unit.

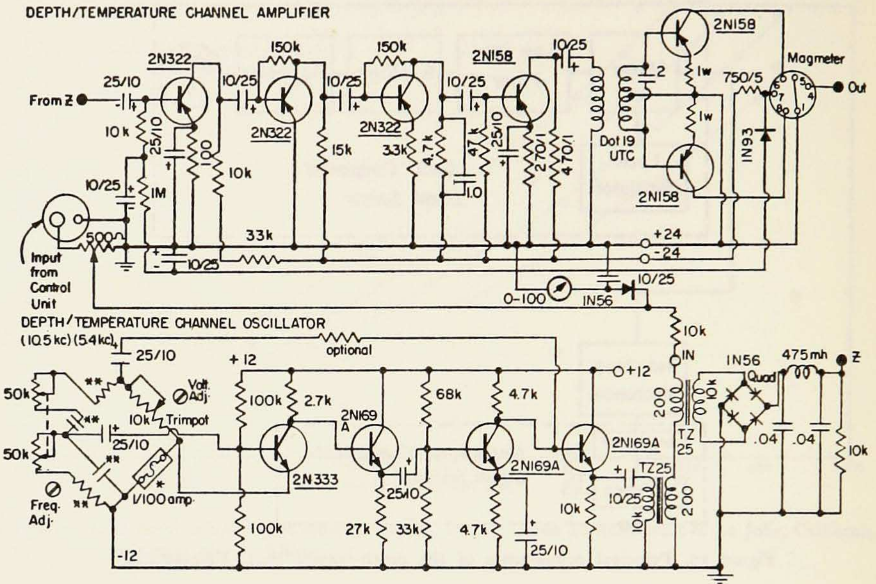

Figure 12. Depth-sensing unit. Wiring diagram of deck unit. * 8 AG Little fuse. ** Values depend on frequency. 904: Texas Instrument or 2N333 G.E. 2N169A; 2N322: G.E. 2N158 C.B.S.

more, Md.) and is then read on a 0–100 μA meter. Figs. 11 and 12 show the wiring diagrams of this circuitry.

Battery life in the deck component is of the order of several hundred hours. The depth component is somewhat underpowered, but battery life normally averages in excess of 10–11 hours with continuous operation at room temperature (18–24°C).

Calibration and Reproducibility of the Depth Unit. The depth unit was calibrated against an Aschcroft 0–600 psi dead weight gauge (type 1300) between 0 and 300 psia. During the test the Vibrotron frequency was also monitored with a Berkeley Eput Meter, Model 554-M. These data are presented in Table II and in part in Fig. 13.

A test of the reproducibility of the depth unit was made at room temperature (25°C) by taking 11 measurements at 5 pressures (50, 100, 150, 200, and 300 psia) after zeroing the instrument at atmospheric pressure. Each set of measurements between 0 and 300 psia was made by progressively increasing the pressure in the increments given above. After each series the pressure was released and the instrument was allowed to equilibrate at atmospheric pressure for a minute or two before beginning the next series. The Vibrotron frequency was also monitored directly with the Berkeley Eput Meter. The data obtained

TABLE II. Calibration of the Photometer Depth Unit (25°C).

	A		B	C
psia	Deck Unit Reading	Vibrotron Frequency	Vibrotron Frequency	Vibrotron Frequency
0	0.0	11108	–	11108
5	4.0	11067	11066	11066
10	5.0	11046	11045	11044
20	8.5	11004	11003	11002
30	11.5	10962	10961	10960
40	14.5	10919	10918	10918
50	17.5	10877	10876	10876
60	20.5	10834	10833	–
70	23.5	10791	–	–
80	27.0 –	10748	10747	10789(?)
90	30.0	10705	–	–
100	33.5	10661	10660	10659
110	36.5	10618	–	–
120	39.5	10574	10573	–
130	43.0 –	10530	–	–
140	46.5	10486	10484	–
150	50.5	10441	10440	10439
180	59.5	10306	10305	–
200	66.0+	10215	10214	10213
240	80.0	10031	10030	–
250	83.5	9984	–	9983
260	87.0 –	9937	–	–
280	93.5	9842	9842	–
300	100.5	9746	9746	9745

in this manner are given in Table III along with the mean value, standard deviation, and coefficient of variation for each pressure series.

A glance at the Vibrotron frequency at each pressure, as read on the Berkeley Meter, shows the high degree of consistency in the results. The deck component of the depth unit cannot be read as accurately as the frequency meter, nor is it as stable, but it is entirely adequate for the purpose for which it was designed. The coefficient of variation is not constant over the pressure range but averages somewhat less than 1%. Thus, for 95% confidence (±2 standard deviations) at room temperature, the depth estimate would be accurate to about ±2%.

The underwater component of the depth unit was found during its design and assembly to be relatively insensitive to temperature changes between 0 and 25°C; and this matter was investigated further in the laboratory with the unit as a whole. In this test the pressure was measured with a 0–300 psi Heise Burdon gauge (No. H-1731) which was found subsequently to need recalibration, but relatively the readings are assumed to be satisfactory. The depth unit was allowed to equilibrate at room temperature (25°C) when readings

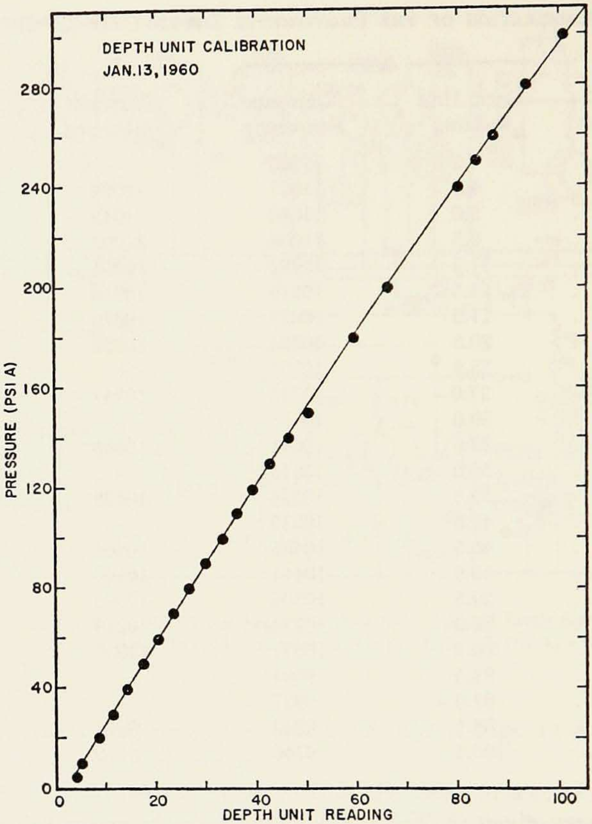

Figure 13. Depth unit calibration.

were taken, after which it was immersed in a water bath at 2–3°C for three hours before a second set of readings was taken. This procedure was repeated three times; the data are given in Table IV. The slight temperature effect observed should be taken into account if depth measurements are being made in arctic waters.

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TABLE III. Reproducibility of the Depth Unit (25°C).

	Atmospheric Pressure		50 psia		100 psia		150 psia		200 psia		300 psia	
	Vibrotron Frequency	Unit Reading	Vibrotron Frequency	Unit Reading	Vibrotron Frequency	Unit Reading	Vibrotron Frequency	Unit Reading	Vibrotron Frequency	Unit Reading	Vibrotron Frequency	Unit Reading
	11107	0.0	10876	16.5	10660	32.5	10440	50.0	10214	66.0	09746	101.0
	11107	0.0	10876	16.5	10661	32.0	10440	50.0	10217	66.0	09746	100.5
	11107	0.0	10877	16.5	10661	32.0	10441	50.0	10214	66.5	09746	100.5
	11108	0.0	10876	16.0	10661	33.0	10440	50.0	10214	66.5	09746	101.0
	11106	0.0	10876	16.0	10661	32.0	10440	49.0	10214	65.0	09746	99.5
	11107	0.0	10876	16.5	10660	32.0	10440	49.5	10215	65.5	09746	100.0
	11107	0.0	10877	16.5	10661	32.5	10441	50.0	10215	66.0	09746	100.0
	11108	0.0	10876	16.5	10661	32.0	10440	49.5	10215	66.5	09746	100.0
	11106	0.0	10876	16.5	10662	32.0	10441	49.0	10214	65.0	09746	100.0
	11107	0.0	10876	16.5	10661	32.0	10441	49.5	10214	65.5	09746	100.0
	11107	0.0	10877	17.0	10662	32.5	10441	50.0	10215	66.0	09746	100.0
	11107	0.0	10877	16.5	10662	32.0	10440	49.5	10215	65.0	09746	100.0
Mean value	11107	0.0	10876	16.4	10661	32.2	10440	49.7	10215	65.8	09746	100.2
Standard deviation	0.6030	–	0.5222	0.257	0.454	0.335	0.522	0.390	0.904	0.582	–	0.451
Coefficient of variation (percent)	0.0054	–	0.0048	1.57	0.0063	1.04	0.00500	0.784	0.00885	0.885	–	0.450

TABLE IV. TEMPERATURE EFFECT ON THE DEPTH ELEMENT AT VARIOUS PRESSURES*.

	18 January 1960			19 January 1960			19 January 1960	
	Room Temp.	Cold	Room Temp.	Room Temp.	Cold	Room Temp.	Cold	Room Temp.
Pressure*	25°C	2–3°C	25°C	21°C	2–3°C	25°C	2–3°C	25°C
psia	1300 PST	1530 PST	1645 PST	1022 PST	1155 PST	1335 PST	1605 PST	
0........	0	0	0	0	0	0	0	0
50........	15.5	15.0+	15.5	15.5	15.0+	15.0+	15.0	15.0
100........	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5
150........	48.0 –	48.0 –	48.0 –	48.0 –	47.5	48.0	47.5	47.5
200........	64.0	64.0 –	64.0+	64.5 –	64.0 –	64.0 –	63.5	63.0+
290........	95.0	94.0+	95.0	95.0	94.0+	94.0+	94.0	94.0+

* The pressure gauge employed in this series was found to require recalibration, hence the pressure values given are not accurate.