DESIGN OF AN UNDERWATER RADIANCE PHOTOMETER

by

John E. Tyler

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SUMMARY

This report describes the design features of a radiance photometer capable of measuring the directional distribution of natural light underwater. This apparatus has evolved gradually over the past nine years in accordance with the needs of investigations of visibility by swimmers, experiments in underwater photography and television, and fundamental research in the principles of hydrologic optics. Several physicists, engineers, and technicians have contributed at different times to the design of the present equipment and its several earlier versions. The continuing development of this type of apparatus is probable because the data it secures is essential for calculations of visibility by swimmers, for the advancement of underwater photography and television, and for the guidance and testing of the steadily growing fundamental understanding of the propagation of light in the sea.

S Q Duntley

S. Q. Duntley
Contractor

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INTRODUCTION

In 1952 Dr. Duntley and associates had developed a complete theory of contrast transmission through water (applicable also to contrast transmission through the atmosphere) which designated the important water measurements and constants. The most important of these water measurements was the measurement of the natural luminance in all directions from a point within the hydrosol. From such data it is possible to:

(1) Compute the target and background luminance.

(2) Compute the ambient light level.

(3) Compute the scattering and absorption coefficients for the water.

(4) Obtain the basis for engineering computations and estimates on specific problems in underwater visibility, photography or television.

(5) Determine the limits of variation of light distribution for different types of lighting conditions and for for different types of water.

(6) Pave the way for the development of simple instrumentation for use in oceanographic survey work.

From a practical point of view it is therefore of the utmost importance to amass data on directional luminance in the underwater light field for a variety of sun altitudes and lighting conditions, and for different types of water.

This report describes the design features of an instrument for measuring directional luminance in the submarine environment.

OPTICAL DESIGN

Luminance is defined as the flux per unit solid angle per unit area arriving at the target from some point in the surrounding light field. It is usually measured with an instrument having a restricted solid angle of acceptance such as has been proposed by Gershun. In the present instrument three important considerations came into the optical design.

(1) The resolving power of the radiance tubes (i.e., their solid angle of acceptance). The solid angle of acceptance cannot be too large since this would have an undesirable averaging effect on the data with consequent loss of detail. Nor can the solid angle be too small since too great a reduction of the overall light signal would limit the depth of operation. A solid angle, having a cone angle of 6.6° was finally chosen and is believed to be a good compromise between these two opposing requirements.

(2) The optical coupling between the light collecting system and the multiplier phototube. It is well known that certain phototubes vary in sensitivity across their cathode surface. In any light measuring instrument it is necessary to prevent this spurious variation from appearing in the data. In order to accomplish this in the present instrument, a diffusing disc has been provided between the radiance tube and the detector. This disc spreads the light out evenly over the cathode surface.

(3) The Spectral quality of the light. For visibility calculations the spectral quality of the light measured must match the visibility function of the human eye. For photographic or television applications it may be necessary to consider some type of spectral quality for the measurements. In order to achieve flexibility in this parameter the instrument was provided with a filter drum as shown in figure 1. This drum will hold (6) pairs of filters, permitting measurements with different spectral qualities as required.

The only other optical component consists of a series of neutral filters mounted on a brass cylinder surrounding each multiplier phototube. These can be changed by remote control and serve to extend the range of the instrument.

MECHANICAL DESIGN

Mechanically the underwater photometer consists of three water tight boxes, interconnected by external cables: The photometer measuring head, a tilt box for controlling the tilt position of the photometer head, and an azimuth box containing equipment for maintaining the azimuth heading of the instrument. All three boxes are capable of withstanding the hydrostatic pressure encountered at a depth of 500 ft.

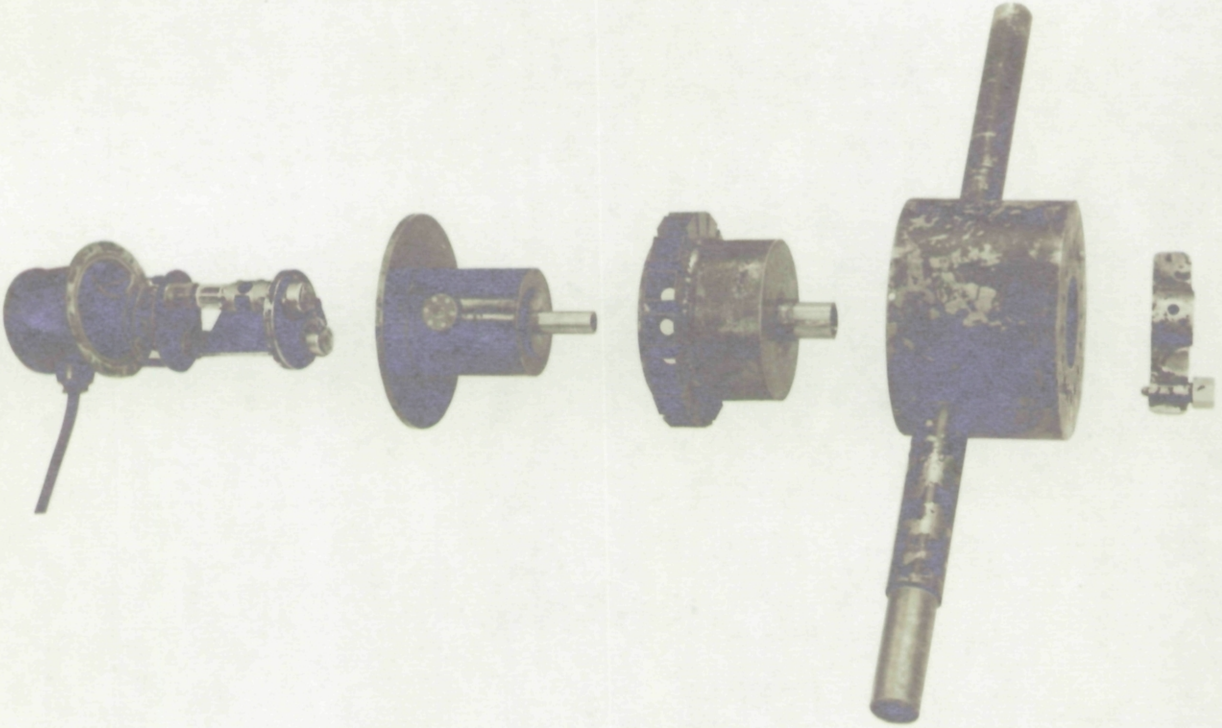

Figure 1

A. Photometer Head (See Figure 1)

1. Overall dimensions: (without radiance tubes)

   9 5/8 " long (without mounting hub)

   4 1/2 " dia. (6" dia. at flange)

2. This mechanism consists of a cylindrical container within which are mounted two 931A phototubes with their associated electronic components. Each phototube is surrounded by a cylindrical filter drum which can be rotated to any one of five positions by means of a Ledex rotary solenoid. The body cylinder is made of 1/4" brass tubing with 3/8th" brass plates inset into the ends and silver soldered in place. Approximately in the center of the photometer head are 6" diameter flanges provided with a standard "O" ring seal. These flanges are bolted together. It is at this point that the assembly separates giving access to the internal components. On opposite sides of the cylinder, on bosses silver soldered to the cylinder, are mounted the two radiance tubes. Each tube is 12 1/2" long and 1 3/4" in diameter and is provided with permanent internal baffles. In the boss at the base of these tubes is a diffuse Plexiglas window 1/4" thick and having 3/4" diameter clear aperature. Also external to the housing is a packing gland through which pass the signal leads from the phototubes and the leads for actuating the filter positioning solenoids. At one end on the center line is a keyed hub for mounting the photometer head onto a 1" diameter shaft from the tilt box. All housing and external parts are brass. Internal

parts are aluminum or brass and are keyed to insure proper orientation when assembled. Pressure sealing is obtained at the windows, as at the flange, by means of standard "O" rings. Plexiglas was used for the windows rather than glass since it is more resistant to thermal shock which may be encountered under severe environmental conditions.

B. Tilt Box

1. Overall Dimensions: 13" x 9 1/2" x 7"
2. Description

The tilt box is fabricated from 3/8" brass plates inset into each other and silver soldered. One side is removable to permit access to the interior and is sealed with a standard "O" ring. On one end are flanges for mounting the "azimuth positioning mechanism" and at the other end is a keyed 1" dia. shaft on which the "photometer head" mounts. This shaft is driven, through a spur gear reduction, by a reversible synchronous electric motor located within the box. Mounted on the tilt head shaft are two cams which actuate limit switches to restrict the tilt rotation to 220°. Also on this shaft is a spur gear which drives a selsyn to give a remote tilt angle indication on the control panel.

C. Positioning Mechanism

1. Overall dimensions:

13 3/16" x 12 5/16" x 12"

2. Description

This mechanism serves to position the underwater photometer about a vertical axis while it is suspended beneath the surface of the water on a cable. A stable reference is obtained by using a gyro which gives a signal to indicate the instrument's azimuth position about its vertical axis in the water. This position is displayed visually by a synchro repeater on deck. This position signal is also compared electronically with the desired position as indicated by a master synchro control transformer which is set manually. If the actual position and the desired position are not in agreement, a signal is generated and power is supplied to a propeller drive motor located within the positioning mechanism enclosure. This motor drives a propeller which rotates the entire underwater assembly, about the vertical axis, causing it to rotate toward the desired position. As the unit approaches the selected azimuth the applied power drops off reaching zero as it passes the set position and then reversing direction. The power applied varies from zero to maximum as the angular error goes from zero to approximately 10°. At maximum power the propeller applies about 1 ft. lb. of torque which results in an initial angular acceleration of $25^{\circ}/(\mathrm{sec})^{2}$ when the angular velocity and damping effect of the water are zero. To diminish the over-travel and "hunting" a damping fin of approximately 1 $\overline{\mathrm{FT}}^{2}$ area is mounted in the plane of the propeller. This damping fin limits the angular velocity to about $10^{\circ}/\mathrm{SEC}$. The unit has enough power to respond rapidly to small deviations from the desired heading, and is prevented from "running wild" or severly hunting by the damping fin already mentioned which also quickly disipates the momentum energy when the propeller ceases to drive. If left to its own devices the system will maintain the selected heading within $\pm 2^{\circ}$ in quiet water. A heading of better than $\pm 1^{\circ}$ can be maintained by manually operating the azimuth selector knob.

The azimuth indicating gyro and propeller motor are housed within a water-tight brass box which measures 13 3/16" x 12 5/16" x 12". The box has 3/8" walls which are inset into each other and silver soldered together. The propeller drive shaft and a set of miter gears are housed within a 2 1/4" brass tube which protrudes 4" beyond the main housing. The propeller is mounted at right angles to this 2 1/4" tube 3" out from the main housing. The propeller drive mechanism and propeller drive motor are mounted on a 3/8" plate which also serves as a cover to the main housing and allows access to the inside for checking purposes. A 1/4" x 1 1/4" diameter Plexiglas window allows the azimuth scale on the gyro to be read from outside the box. The positioning mechanism enclosure also serves as a junction box for the main electric cable from above water as well as the electrical cables going to the photometer head and the tilt box. Each cable enters the box through a separate packing gland. Sealing of the cover and the propeller drive mechanism is accomplished, as before, by using standard "O" rings. On the side of the box away from the propeller are flanges for mounting the assembly onto the end of the "tilt box."

ELECTRICAL DESIGN

The electrical system of the underwater photometer is shown in block diagram form in figure 2. Electrically the system includes two logarithmic photometers, circuitry for indicating the position of the photometer head in azimuth and elevation, and circuitry for the remote control of the head position in these two co-ordinates.

The logarithmic photometer circuits utilized in this equipment are a modification of the densitometer circuit described by Sweet[1]. This unit functions in such a fashion as to give output indication proportional to the logarithm of the flux incident on the phototube cathode. The high voltage required for the multiplier phototube dynodes and the output signal from the phototube are carried on shielded cables from the circuitry located on deck to the underwater unit. The signal circuit operates at a impedance level of about 200 megohms and it is, therefore, necessary to pay particular attention to the problem of insulation leakage and leakage paths at connectors. As this portion of the circuit is direct coupled any variation in leakage which is significant compared to 200 megohms will cause an error in the output indication.

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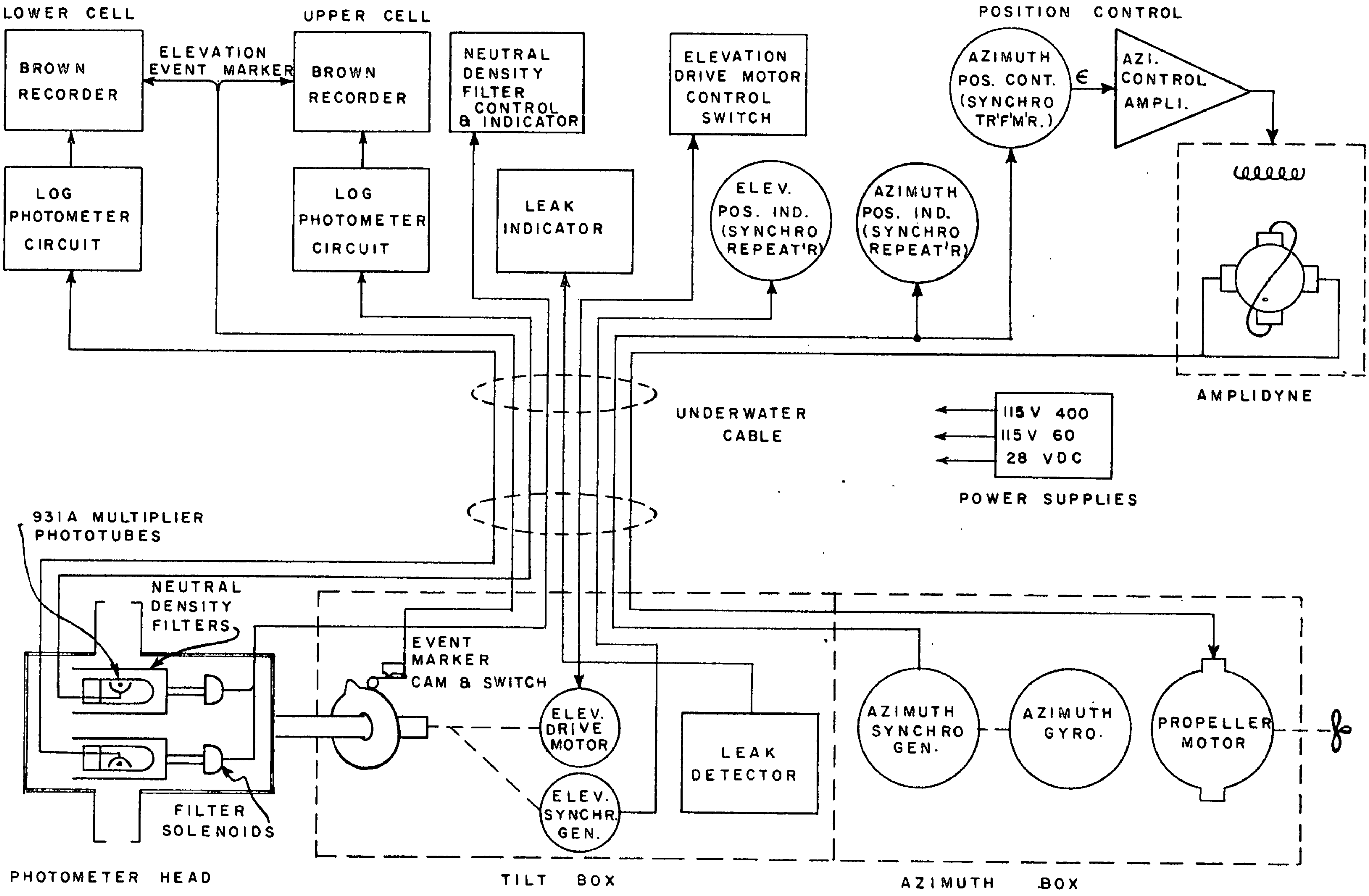
[1] For a more complete discussion of the operation of this circuit see Sweet, M. H., "An Improved Photomultiplier Tube Color Densitometer," J. of the SMPTE, Vol. 54, January 1950, p. 35.



BLOCK DIAGRAM – UNDERWATER PHOTOMETER

Figure 2

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The use of a clear acrylic spray on terminations of the leads in the underwater enclosure has proved generally useful in reducing the probability of leakage. The output from the logarithmic photometers is recorded continuously on Brown potentiometric recorders. To correlate the luminance data with the position of the photometer head a simple event marker scheme is used. This consists of a cam in the tilt box which trips a pulse-type Microswitch at the start of each elevation run applying a small voltage to the recorder signal channel thereby superimposing a small "pip" or event mark on the luminance record coincidental with the start of the run.

The remote control of the photometer head in elevation is accomplished by means of a Bodine 115 VAC reversible synchronous motor in the tilt box appropriately coupled by gears to the head. Because the speed of the synchronous motor is known and constant and because the time and position of the start of each elevation run is known, it is possible to linearly interpolate on the record to obtain the elevation position. In addition an elevation position synchro generator directly coupled to the photometer head is electrically connected to a synchro repeater on the control panel. This allows the operator to instantaneously know the elevation position of the radiance tubes while taking data.

The heart of the azimuth control system is a Sperry Gyrosyn Compass from a C4-A gyro compass system. This gyroscope is mounted in the gyro box assembly in the underwater portion of the equipment and provides an azimuth reference which is repeated on the surface by a synchro located in the control panel. The particular heading assumed by the gyro is arbitrary but is maintained constant during the data taking runs with a drift of less than 1° per hour. The gyro heading information is also fed to a syncro control transformer. The heading which the underwater equipment will assume is determined by the setting of the rotor of this control transformer. A lack of correspondence of position between the rotor in the synchro generator mounted on the gyro and the rotor in the control transformer will produce an error signal, E, whose phase is determined by the direction of unbalance and whose magnitude is proportional to the degree of unbalance for small errors. This error signal is applied to a phase sensitive amplifier, the output of which supplies the control field of a General Electric 5AM21JJD Amplidyne. The Amplidyne serves as a power amplifier to supply power to a Diehl 1/30 hp 27 v DC propeller motor mounted in the underwater equipment. Phases and polarities of the system are arranged in such a fashion that the propeller will rotate the entire underwater assembly about a vertical axis in such a direction as to reduce the error signal. An identical correction process occurs whether the error signal is caused by a twisting of the underwater unit or by the operator changing the setting of the control transformer. Hence both the arbitrary setting of the azimuth position and the maintenance of that position are controlled by the azimuth servo system. A schematic diagram of the servo system including error signal amplifier is shown in Figure 3. The operation of this amplifier may be briefly explained as follows: The 400 v error signal, E, from the control transformer, is applied to the grid of a 6C4 voltage amplifier tube. The polarity or phase of E depends on whether the error displacement is clockwise or counter-clockwise. After amplification by the 6C4 the error signal is applied to the primary of a transformer, is stepped up and applied from the center-tapped secondary of the transformer to the grids of a push-pull 12BH7 phase sensitive amplifier. This tube has approximately 350VAC, 400 cycles applied to its plates. The signal on one grid will be in phase with its plate voltage and a 400 v pulsating plate current will flow through this section of the 12BH7 and a control winding of the Amplidyne. This produces a pulsating d.c. output from the amplidyne which has sufficient magnitude and proper polarity to drive the propeller motor in the direction to eliminate the initial error signal E. The other section of the 12BH7 tube will conduct very little because its grid and plate voltages are 180° out of phase and also because the tube is biased at approximately cut-off.

If the initial displacement is in the opposite direction, an error signal of the opposite sense will be generated and the above process is repeated with the other section of the 12BH7 conducting. This causes the propeller motor to turn in the opposite direction and again forces the underwater unit to return to the desired azimuth.

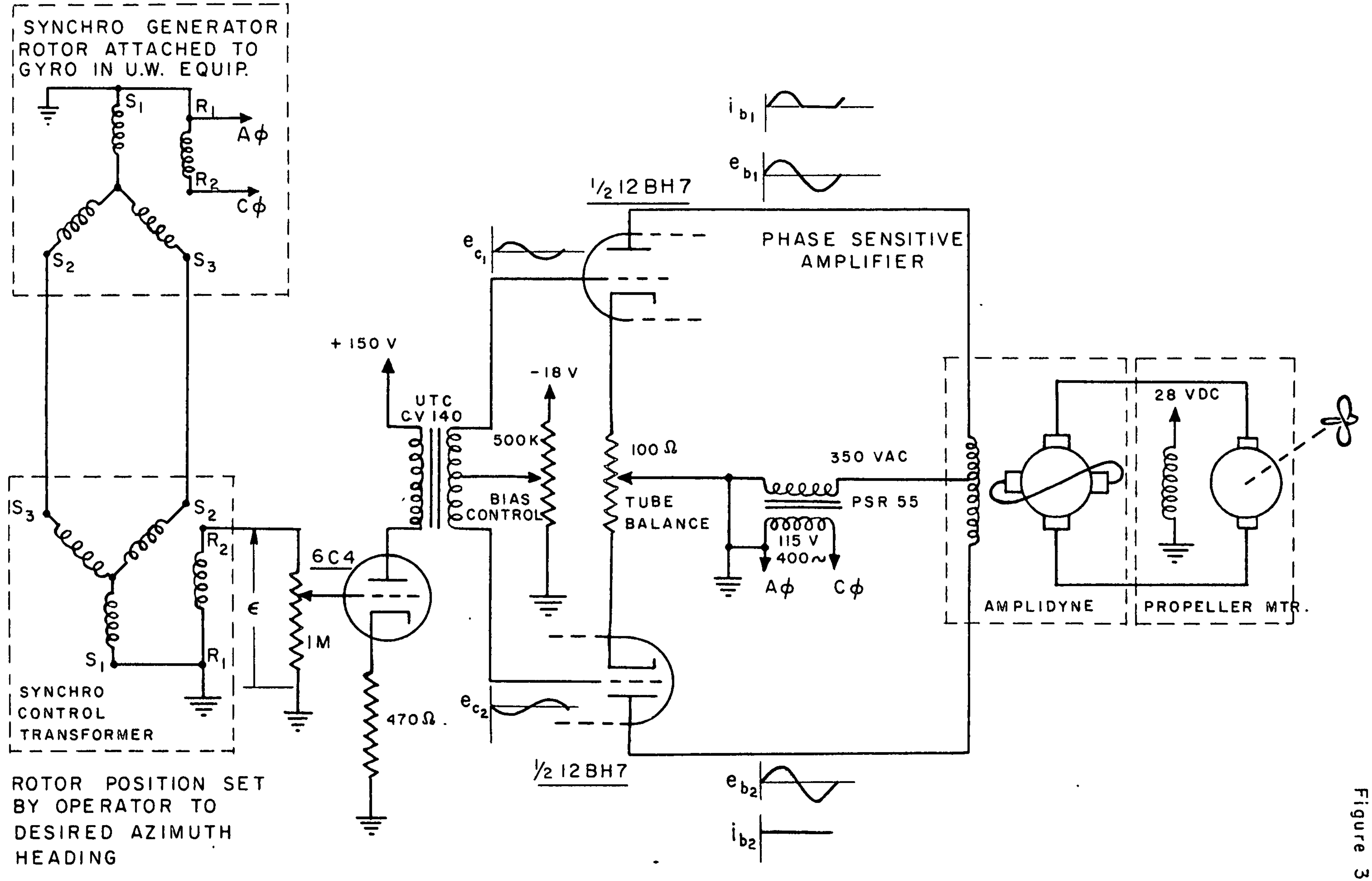

Figure 3

UNDERWATER PHOTOMETER
AZIMUTH POSITION SERVO

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To enable the operator to adjust the overall sensitivities of the two logarithmic photometers it is possible to interpose any one of five selected neutral density filters between the optical system and the multiplier phototubes in the underwater photometer head. To allow the operator to change filters during a data gathering run the filters are mounted on cylinders surrounding the phototubes. These cylinders can be rotated by means of Ledex rotary solenoids remotely actuated from the deck equipment. Closing a switch on the control panel operates two solenoid motors, the one driving the filter cylinder and the other driving an indicator on the control panel.

The electrical cable used between deck and underwater equipment is Belden #8280, a television camera cable. It has shielded coaxial conductors for the multiplier phototube high voltage and output signals, and also has a main overall shield which is grounded to minimize stray field effects. The vinyl plastic jacket of the cable is satisfactory for underwater use in water 300 feet deep.

Three power units are utilized to supply the circuits of the underwater photometer; a Sorensen 3000-S 60 cycle voltage regulator, a Holtzer-Cabot MG-153, 400 cycle inverter, and a 0 to 50 volt, 50 ampere D.C. power supply. The Sorensen supplies all 60 cycle requirements, i.e., the elevation synchros, the filter solenoids and indexes, the photometer circuits, the Brown recorder, and the

"Tilt Box" elevation motor. The 400 cycle inverter supplies the Gyrosyn compass, the azimuth repeater, the azimuth control transformer, and the error signal amplifier. The D. C. power supply supplies the primary D. C. power to the amplidyne, the 400 cycle inverter, and also supplies the shunt field of the propeller motor. This power supply, like the Sorensen, takes its primary power from a 115 V, 60 cycle A.C. line.

Under separate contract an instrument was built in accordance with the design considerations discussed herein. For the convenience of the reader photographs of this instrument are shown in figures 4 and 5.

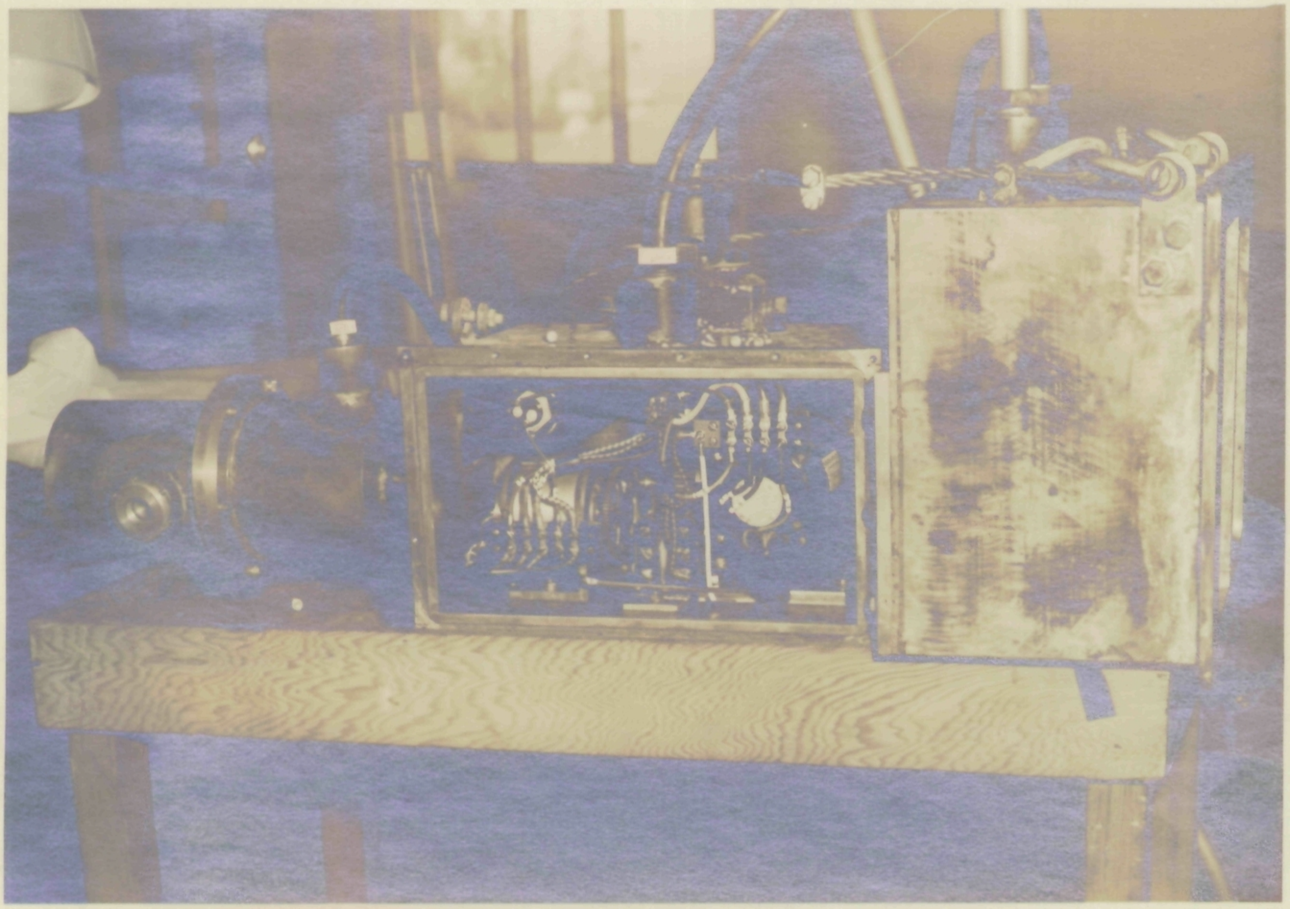

Figure 4

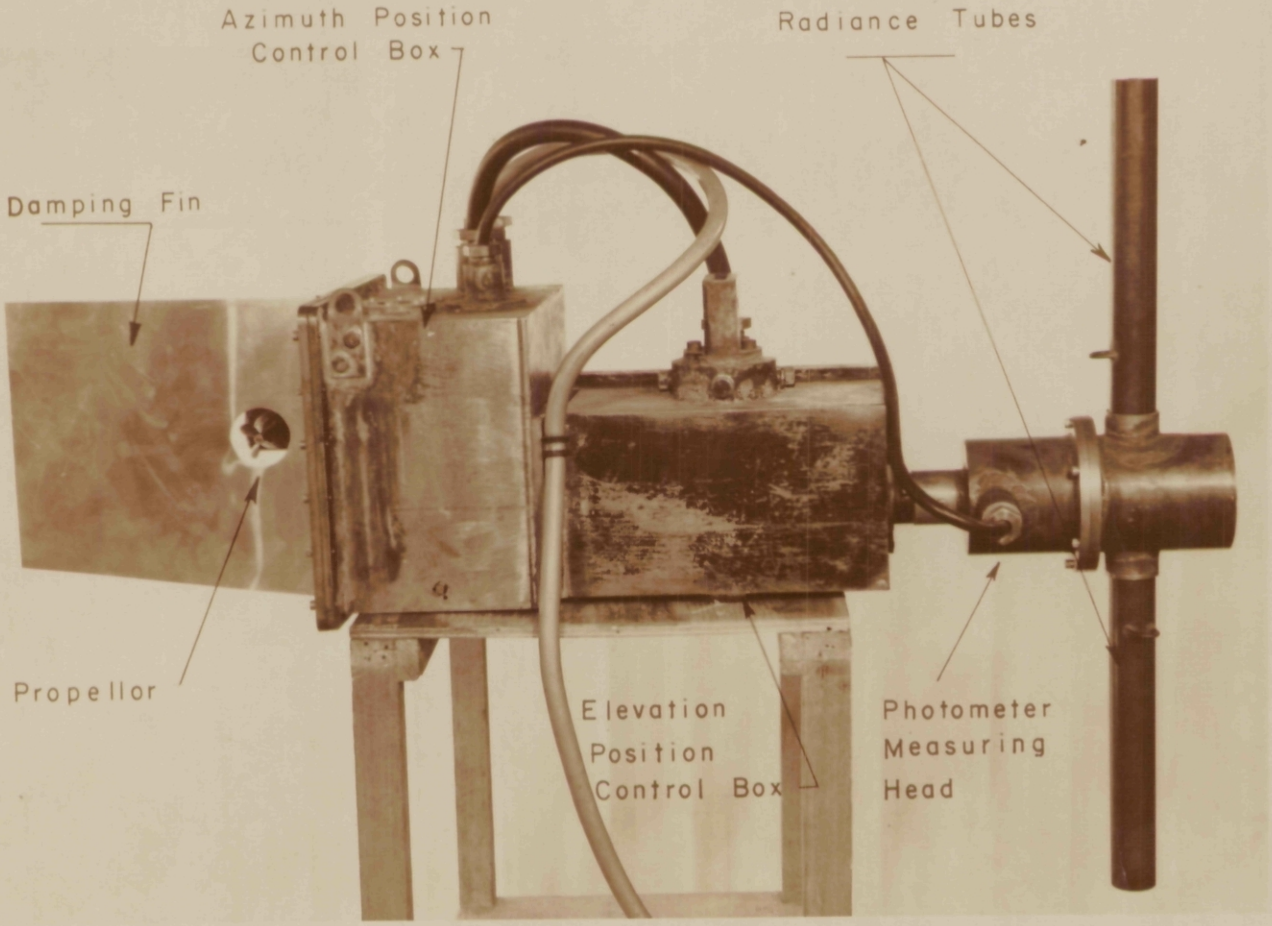

Figure 4a

Underwater Photometer

Measuring Head and Positioning Equipment

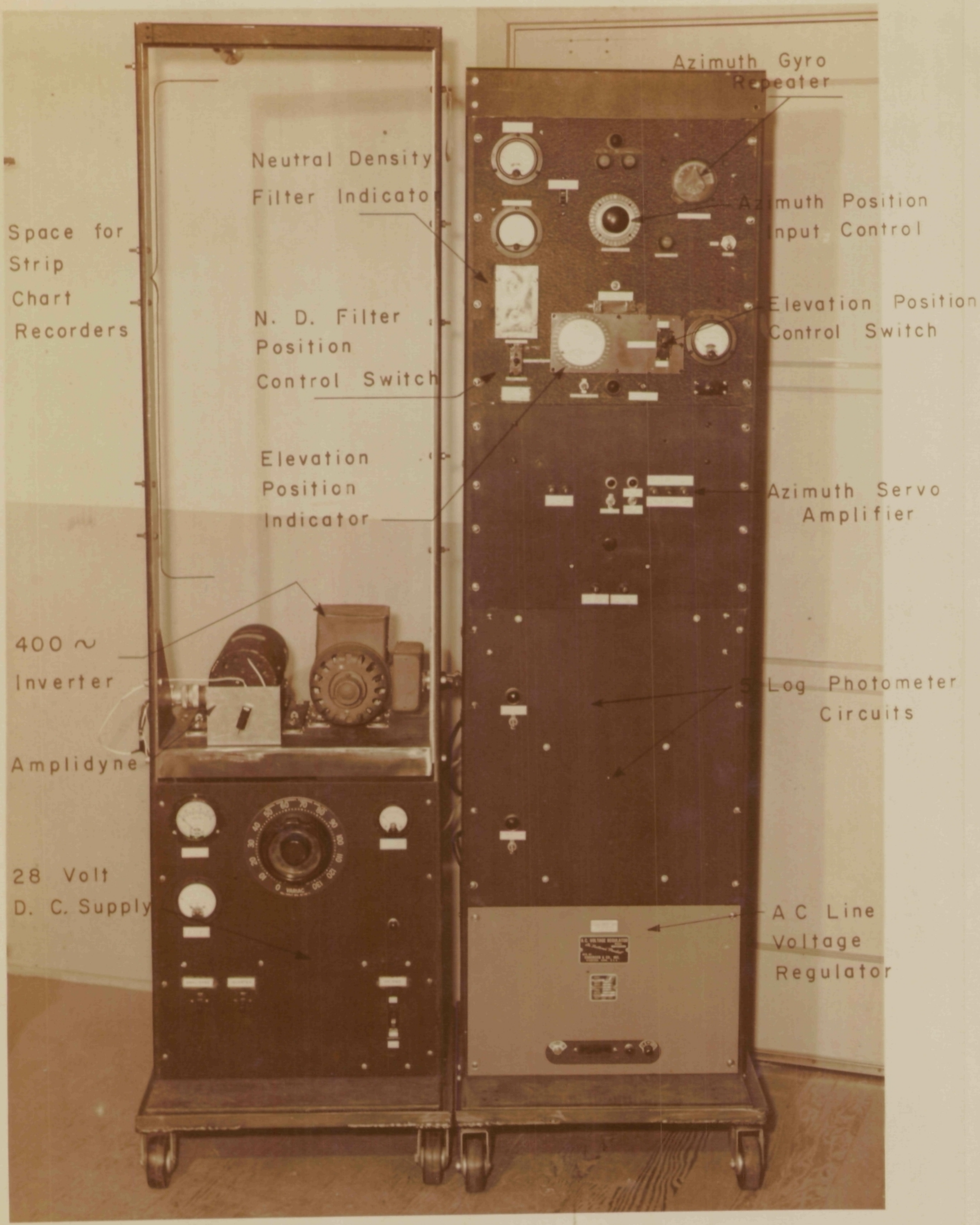

Figure 5

Underwater Photometer – Control and Recording Equipment