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# UNDERWATER LOGARITHMIC IRRADIANCE METER FOR PRIMARY PRODUCTION AND ASSOCIATED STUDIES

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Summary:

An instrument for the measurement of underwater irradiance is described. Some experimental results are presented.

## 1. Introduction

The influence of irradiance upon primary production is of considerable interest and in 1973, the Institute of Oceanographic Sciences at Wormley in conjunction with the Plessey Radar Research Centre at Havant, produced a very compact battery powered underwater irradiance meter based upon the solid state Silicon photodiode sensor. The initial specifications for the biological requirements of the detectors, in that they should measure energy or quanta in the range 350-700nm, with a flat response within this spectral range, and sufficient accuracy to cover changes of several orders of magnitude, were those laid down in the recommendations of the SCOR Working Group 15 (ref. 1). The instruments were designed to be used in pairs, one monitoring the surface irradiance and the other the irradiance whilst submerged at some depth. The difference in readings would thus be an indication of the attenuation through the water.

A large dynamic range was required to accommodate irradiance levels ranging from that of direct sunlight down through several orders of magnitude. A logarithmic response enables a constant fractional resolution to be obtained over the range.

The instrument was designed to interface with the Bissett-Berman salinity, temperature and depth probe (STD) data collection and handling system (ref. 2). Figure 1 shows a diagram of a typical operating arrangement.

## 2. Constructional Details

Figure 2 shows a cross section of the instrument design. The main cylindrical housing is of a standard type used by I.O.S. Inside is another cylinder of diameter 2.8cm and a length of 10.5cm. This contains everything except the optical diffuser and the batteries (if used). Light from a solid-angular hemisphere is incident upon a Perspex diffusing element which makes a water-tight seal to the outer housing.

Two coloured glass filters (Schott 1mm F65 and 4mm KG3) amend the spectral distribution of the radiation such that, in conjunction with the spectral response of the photodiode, an overall nominally flat response results over the range 350-700nm. The light is finally

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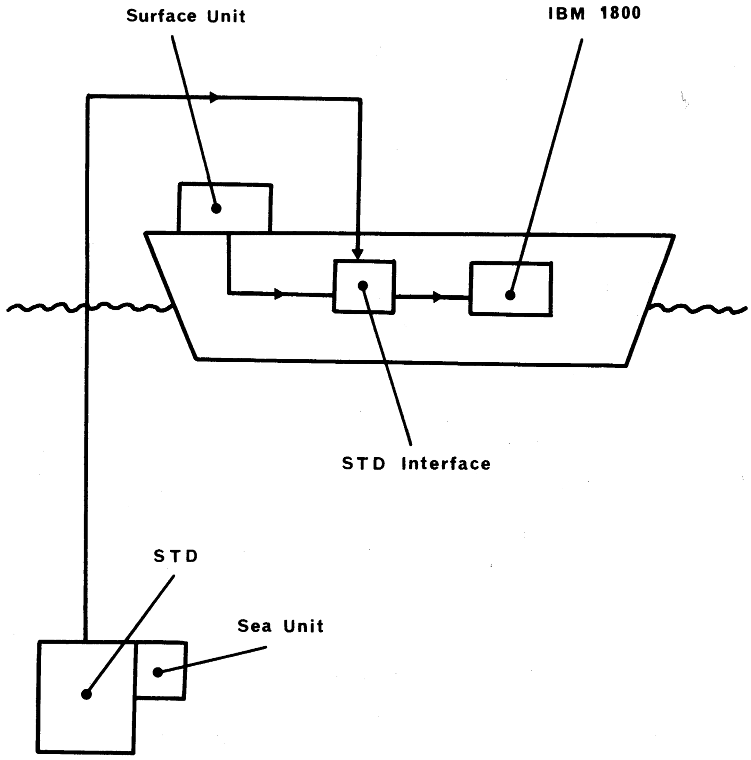


Fig.1 Operating Arrangement

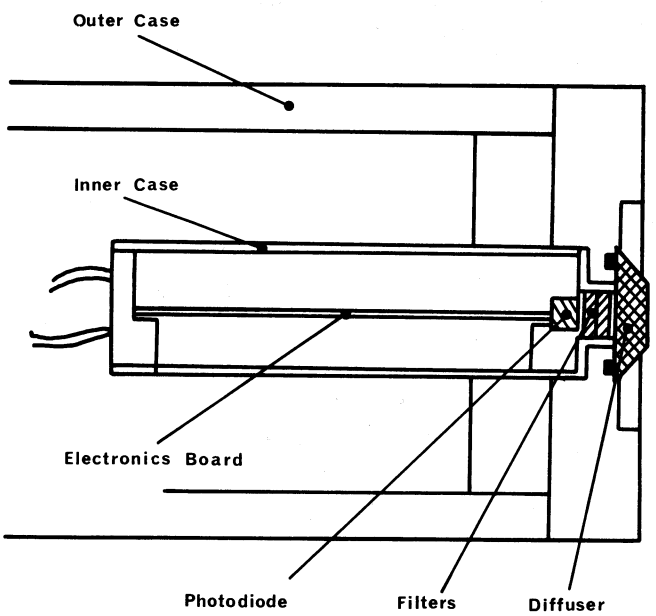


Fig. 2 Instrument Design

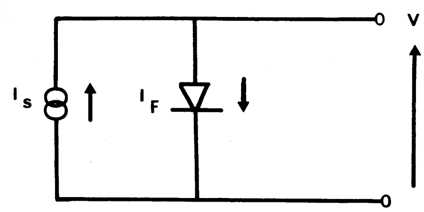


Fig.3 Photodiode Circuit Model

absorbed in the photodiode which is mounted in a TO5 can and protected by a glass window.

## 3. The Silicon Photodiode

The Silicon photodiode is a relatively simple and low cost device for the measurement of radiation in the visible and near infra-red portions of the spectrum. It is capable of operating over an extremely wide dynamic range and if suitably applied, is insensitive to temperature variations. It suffers no hysteresis and, as far as is known, is stable in that it will retain its response sensitivity over an indefinite period.

A simple equivalent circuit (figure 3) represents the device as a parallel combination of a current source $I_s$ and a semiconductor diode. The current is given by:

$$I_s = \int_\lambda \frac{\eta_\lambda e \lambda P_\lambda d\lambda}{hc} \quad \text{(amps)} \qquad (1)$$

where

| | |
|---|---|
| $e$ | is the electron charge |
| $h$ | is the Planck constant |
| $c$ | is the velocity of light |
| $\lambda$ | is the wavelength |
| $\eta_\lambda$ | the quantum efficiency at wavelength |
| $P_\lambda$ | the input power spectral density. |

Often, over a restricted spectral range, $\eta_\lambda$ remains fairly constant, and the response then varies directly with wavelength. In order to obtain a "flat energy" response, colour filters which attenuate in proportion to wavelength are therefore required.

The equation then simplifies to:

$$I_s = k \int_\lambda P_\lambda d\lambda = k P_s \qquad (2)$$

where k takes a value typically in the region of 0.1-0.2 amps/watt.

The semiconductor diode in parallel with the current source may be modelled thus:

$$I_F = I_D \left(\exp \frac{eV}{mkT} - 1\right) \qquad (3)$$

where

| | |
|---|---|
| $I_F$ | is the diode forward current |
| $I_D$ | the diffusion current |
| $V$ | the diode forward voltage |
| $k$ | the Boltzmann constant |
| $T$ | the absolute temperature |
| $m$ | is a dimensionless constant lying between 1 and 2. |

$I_F$ is essentially an error current that should be minimised or counteracted; it is highly temperature dependent. It is most effectively minimised by maintaining V at zero potential. The equivalent circuit then simplifies to a current source in parallel with a resistance $R_D$,

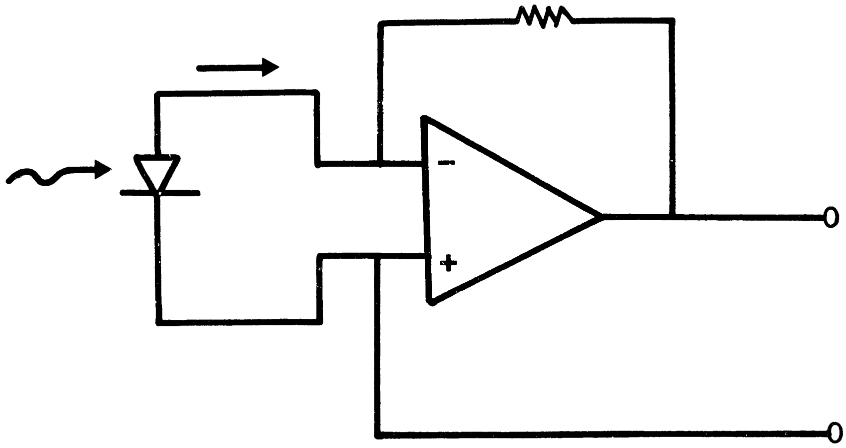

Fig.4 Photodiode Operation with Zero Bias

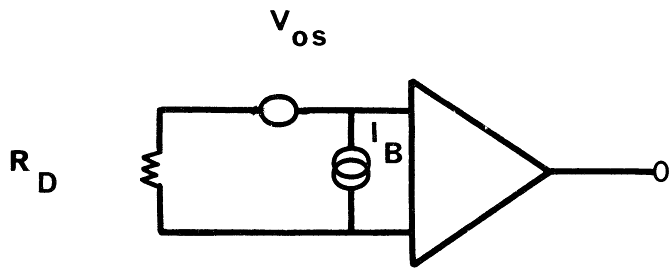


Fig.5 Error Equivalent Circuit

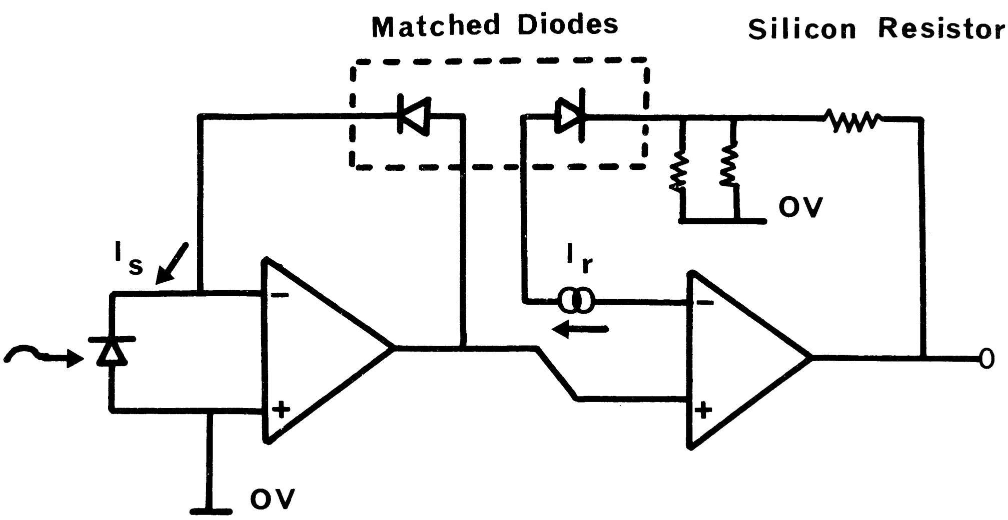


Fig.6 Log Converter

given by:

$$R_D = \frac{mKT}{eI_D} \tag{4}$$

A satisfactory arrangement to sustain zero bias is to connect the device across the input terminals of an operational amplifier to which shunt feedback is applied (figure 4).

## 4. Amplifier Considerations

Further errors in measurement can be introduced by the amplifier. In particular, with reference to figure 5, the error is given by:

$$I_E = I_B + \frac{V_{os}}{R_D} \tag{5}$$

where $I_B$ is the amplifier input bias current
$V_{os}$ is the amplifier offset voltage.

$I_B$ may be reduced to the order of $10^{-12}$A or less by the use of a FET input amplifier. $V_{os}$ should be nulled as far as is possible; this should be supplemented by choosing a photodiode with a large value of $R_D$. In this context, the Plessey SC100 photodiode appears to offer a higher resistance per unit area than any other device tested.

## 5. The Logarithmic Converter

The logarithmic conversion is carried out via a matched pair of semiconductor diodes sharing a common chip. These are of a very low leakage to maximise their current handling range and minimise errors at low levels. The first diode is strapped around the input amplifier as the shunt feedback element (figure 6). The output potential from this stage is given by:

$$V_0 = \frac{mKT}{e} \log_e \left[ 1 + \frac{I_S + I_E}{I_d} \right] \tag{6}$$

Through the second matched diode, a constant current $I_r$ is passed generating a potential

$$V_1 = \frac{mKT}{e} \log_e \left[ 1 + \frac{I_r}{CI_d} \right] \tag{7}$$

where C is the ratio (near unity) of the diode diffusion currents.
Upon subtraction;

$$V_0 - V_1 = \frac{mKT}{e} \log_e \left[ \frac{I_S + I_E + I_d}{\frac{I_r}{C} + I_d} \right] \tag{8}$$

By choosing $I_r \gg I_d$, then for $I_S \gg I_E + I_D$, (8) simplifies to

$$V_0 - V_1 = \frac{mKT}{e} \log_e \left[ \frac{CI_S}{I_r} \right] \tag{9}$$

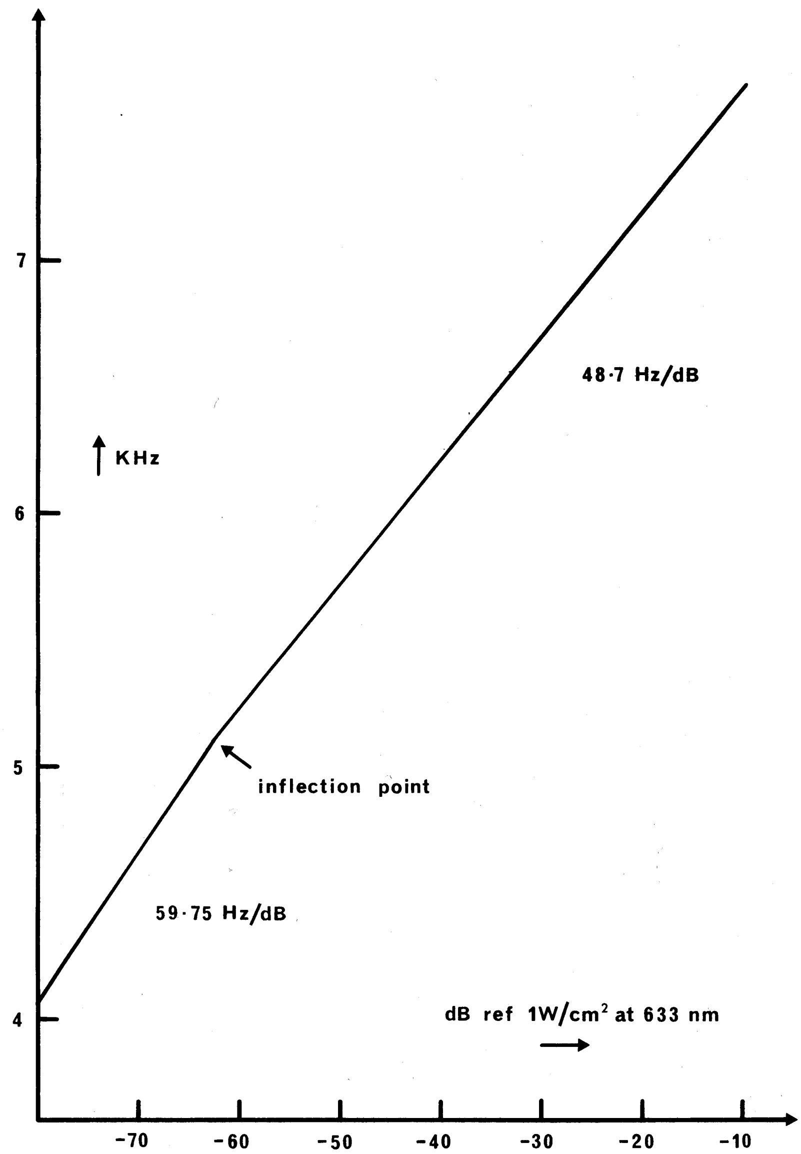


Fig. 7 Output Frequency v. Irradiance

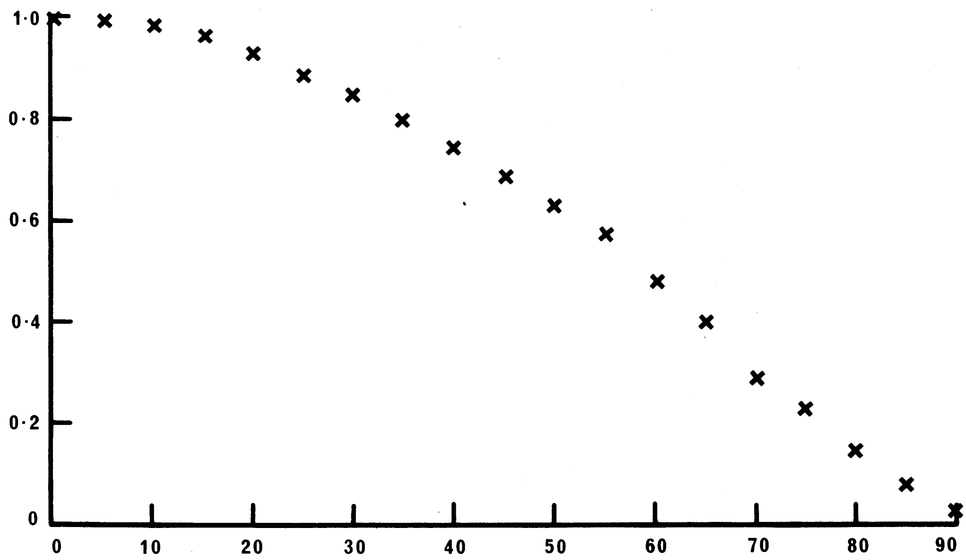


Fig. 8 Normalised Angular Response

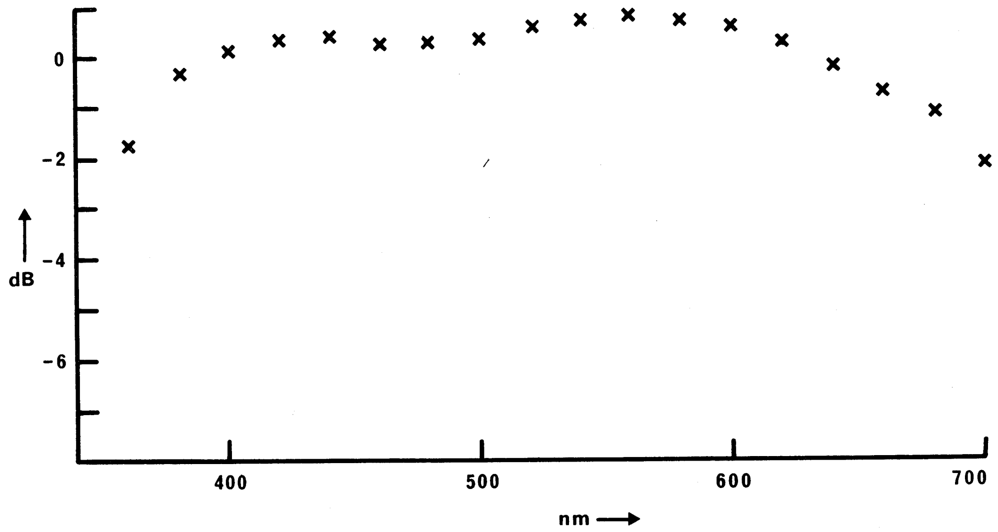


Fig. 9 **Spectral Response Normalised to 633 nm**

The remaining temperature dependence is removed by a resistor network which includes a temperature sensitive silicon resistor.

## 6. The Voltage to Frequency Converter

A COSMOS phase locked loop chip is used for the V.F. conversion. The makers claim a 1% linearity for this device. The exclusive OR phase detector is used as a simple inverter to provide complementary outputs to drive a transformer, thus easing the decoupling requirements. The transformer supplies a 5Vpkpk square wave to the cable up to the ship.

## 7. Power Supplies

Internal +5V and -5V rails are generated from a single voltage supply of nominally 18V. It operates satisfactorily from 12V to 30V. Total current consumption is about 10mA. A micropower version of the same configuration is feasible.

## 8. Performance

Figure 7, 8, 9, show the performance characteristics of the unit. Figure 7 shows the relationship between output frequency and input irradiance. An 80dB range is evident with a maximum in the region of 100mW/cm$^2$ corresponding to direct sunlight. This characteristic was measured with the aid of a He-Ne laser and a set of precision attenuators.

Figure 8 shows the angular response which is very close to cosinusoidal.

Figure 9 shows the spectral response as flat $\pm$ 1dB between 365nm and 700nm.

## 9. Computer Logging

The VCO was designed to give a frequency range similar to that used for salinity on the STD and the underwater meter was connected into the salinity channel of the STD interface and thence into the IBM 1800. The surface meter was connected to a standard Hewlett Packard frequency

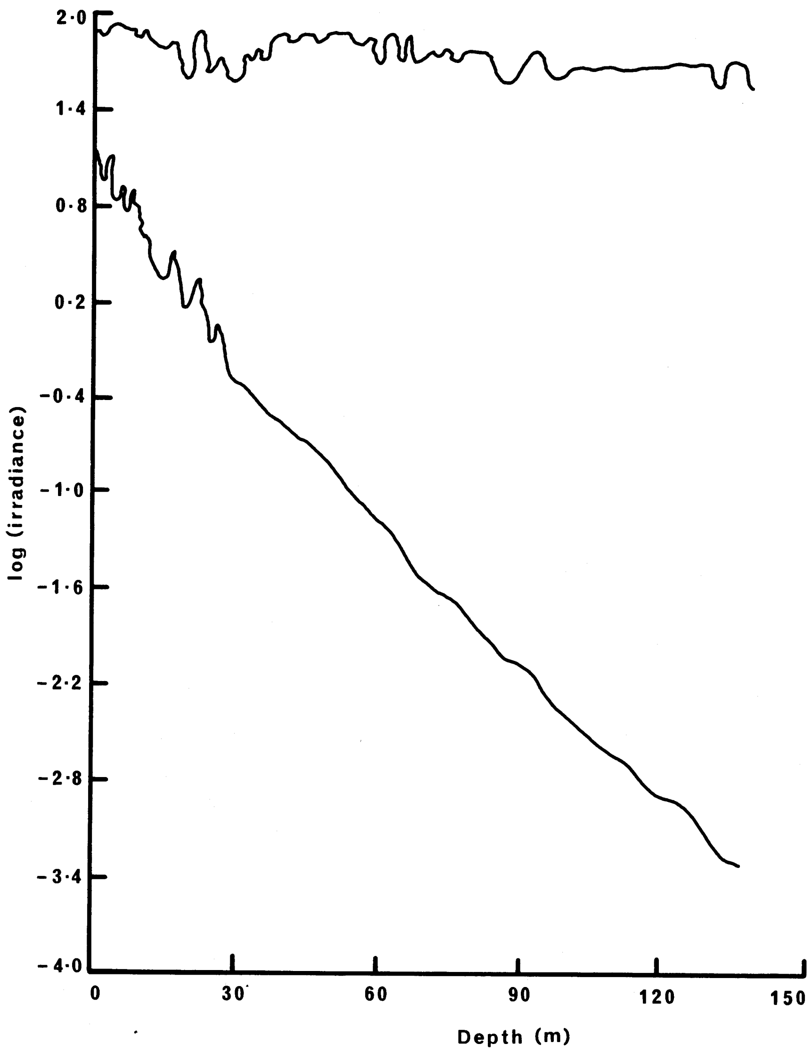


Fig. 10 Observation of underwater and surface irradiance

counter giving an analog voltage output which was also fed into the computer. The meters were usually sampled every second and the data stored on disk. A computer program was written to convert the frequencies to irradiance using the standard curves (figure 7) and to plot these values against depth (recorded by the STD) on either a Tektronix visual display unit or on a CALCOMP graph plotter.

## 10. Results

It was hoped to test the full system on Discovery Cruise 61 (April-May 1974) but unfortunately there was a manufacturer's delay in the delivery of the filters. However, a number of runs were carried out to test the system without filters and it was found to be very reliable. Since receiving the filters it has only been possible to carry out a few dips. Figure 10 shows the results obtained from a station at 10°38'N, 21°16'W in the Atlantic. The lower trace shows the change with depth of the logarithm of irradiance while the upper trace represents the logarithm of surface irradiance recorded at the same time. The graph shows well the problem of calculating attenuation under conditions of intermittent cloud cover. The changes in the surface light conditions are closely followed by the underwater irradiance down to depths of ca 30m. Below this the angular distribution of the underwater irradiance approaches the asymptotic state (ref. 3) and so this effect is reduced. Thus under these conditions the surface irradiance must be filtered using a low-pass filter where cut-off frequency is a decreasing function of the depth of the underwater meter. This aspect of the system is still in the process of development but it does illustrate the advantages of recording the two meters separately rather than building the attenuation calculation into the electronics.

Using the underwater irradiance graph, the irradiance is reduced to 1% of its surface value at 65m which is in good agreement with other observations in this area ref. 3, p. 122).

## 11. Conclusions

The present system was designed to work in connection with the STD and computer system available on board RRS Discovery. Subsequently it has been interfaced with a CTD system which is gradually replacing the STD. However, this latter system has not yet been tested. This is necessarily a fairly complex arrangement but does enable us to maximise the data which can be obtained, especially as additional modules, such as oxygen probes and fluorometers, can also be integrated into the system. The basic design is, however, simple and the form of the output from the sensors can be adjusted to the particular requirements. The present system can be modified for use on smaller ships without computer facilities, simply by taking spot readings of the frequency counter output at various depths. Thus with a knowledge of the necessary frequency (or voltage etc.) change, the depths at which the surface light intensity drops to a predetermined percentage level can be noted. Discrete samples can then be taken at these depths for primary production studies. Similarly from a series of values an attenuation curve can be drawn up.

It should be pointed out in this context that the light meters were deliberately designed to measure all the radiant energy available at any depth in the range of wavelengths, 350-700nm, being the range which phytoplankton can utilise for photosynthesis. The problem of measuring the actual energy utilised by phytoplankton in the open ocean was considered to be too complicated and also restrictive. However, by the use of suitable filters, it would be possible to calibrate the system for any desired range of wavelengths.

Initially the uses to which these light meters were to be put were twofold; firstly in connection with primary production studies, using incubators, where the water samples must be taken from depths corresponding to certain light intensities, and secondly, in connection with studies on the factors affecting the vertical distribution of phytoplankton and chlorophyll *a*. However, the photodiodes are more sensitive than is required for primary production studies (changes of 2-3 orders of magnitude), and, in fact, the present system has been calibrated at light intensities down to seven orders of magnitude less than the surface values. The deepest depth to which the sea unit light meter has been used is 150m, but with its integration into the CTD system much greater depths can be reached, and an instrument with even more sensitive photodiodes is at present being designed for use in connection with zooplankton studies.

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