

# Spectral Irradiance Measurements Using a Novel Spectroradiometer

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## ABSTRACT

A novel design of a spectroradiometer has been implemented and tested in the sea to measure underwater optical and physical properties. The spectroradiometer has two high resolution diffraction-based spectrographs assembled back to back in an aluminium alloy casing. The spectrographs employ 512 element photodiode arrays to measure downward ( $E_d$ ) and upward ( $E_u$ ) spectral irradiance in the wavelength region 350-750 nm at a minimum practical resolution of 2 nm using 50 $\mu$  entrance slits. Apart from the optics, the radiometer measures temperature, depth and tilt of the instrument package. State-of-the-art electronics, software and some test results of the instrument are discussed.

## INTRODUCTION

The optical properties of ocean waters are to a large extent determined by the dissolved and suspended biological material which can be studied by measuring the distribution of light fluxes in the waters. The optical properties of the sea can be divided into two basic classes [4], i.e. the inherent optical properties (IOPs) and the apparent optical properties (AOPs). The IOPs include the volume scattering function, volume attenuation function and volume absorption function which are invariant under changes of the radiance distribution at that point. The AOPs, such as the diffuse attenuation coefficient for radiance, irradiance, and scalar irradiance and the irradiance reflectance at a given depth, are properties that vary under all changes of radiance distribution at that point and can be derived by defining equations from the *in situ* determination of irradiance (E) and radiance (L). The apparent optical properties depend, in a rather complicated way on the inherent optical properties.

Radiance is the basic radiometric quantity which has an angular dependence and is defined [5] as the radiant flux in a given direction ( $\theta$ ) per unit solid angle ( $dw$ ) per unit projected area ( $dA$ ):

$$L(\theta, \phi) = d^2\phi / dA \cdot \cos \theta \cdot dw \quad \dots(1)$$

Irradiance ( $E$ ) is the radiant flux  $d\phi$ , incident on an infinitesimal element of surface containing the point under consideration, divided by the area of that element:

$$E = d\phi/da \text{ (W/m}^2\text{/nm)} \quad \dots(2)$$

The two quantities  $E$  and  $L$  are related by the equation:

$$E = \int_{2\pi} L(\theta, \phi) \cdot \cos \theta \, d\omega \quad \dots(3)$$

The spectroradiometer measures irradiance using a collector with a cosine response such that it performs the integration in Eq. (3). The downwelling irradiance ( $E_d$ ) is measured by a horizontally oriented cosine collector facing upwards and the upwelling irradiance ( $E_u$ ) by a horizontally oriented cosine collector facing downwards. Some of the apparent optical properties that can be found from these measurements are: Irradiance attenuation coefficients  $K(z, \alpha)$  at depth  $z$ , and wavelength  $\lambda$  and is related to irradiance by the equation:

$$E(z, \alpha) = E(0, \lambda) \exp[-K(z, \lambda) \cdot z] \quad \dots(4)$$

where  $E(0, \lambda)$  is solar irradiance at the sea surface, and  $E(z, \lambda)$ , the irradiance at depth  $z$ .

The measurements of apparent optical properties are influenced to a great extent by external perturbations [1], thus placing very high demands on the spectroradiometer in terms of scanning speed, spectral resolution, accuracy and dynamic range.

The spectroradiometer described measures spectral irradiance in the wavelength region 350-750 nm with a resolution of 2 nm. Its minimum scanning speed is 12 ms and the operational scanning speed with real time averaging is 380 ms. High accuracy in measurements is obtained using a 16 bit analog to digital converter. With an r.m.s. noise count of 20, a dynamic range of around 3200 is obtained, thus enabling spectral measurements to levels below the euphotic zone.

## MATERIALS AND METHODS

The construction of the spectroradiometer is schematically shown in Fig.1. It consists of two symmetrical optical modules and a central electronics unit. The casing is constructed from 6061-T6 aluminium alloy. The different components involved in the design of the spectroradiometer are: optics, electronics and software. A brief description of each is given below:

**Radiometer optics** — The optics of the radiometer consists of two high resolution grating-based spectrographs assembled in an aluminium casing. Design details and operation of the spectrograph have been discussed in an earlier communication [2]. A cross-sectional view of the spectrograph is shown in Fig. 2. In operation, the in-water light flux falling on the cosine collector passes through a glass window ( $W$ ) mounted on the radiometer end cap. The diffuse flux from the back of the collector is brought to a focus by the symmetrical convex lens ( $CL$ )

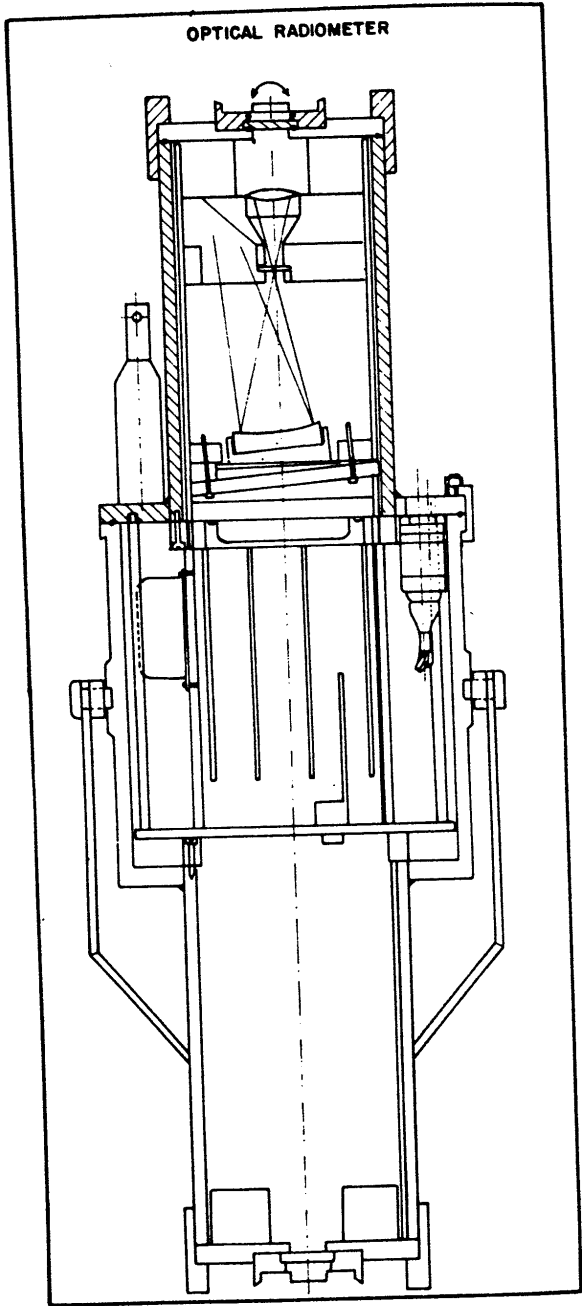


Fig.1 — Cross sectional view of spectroradiometer

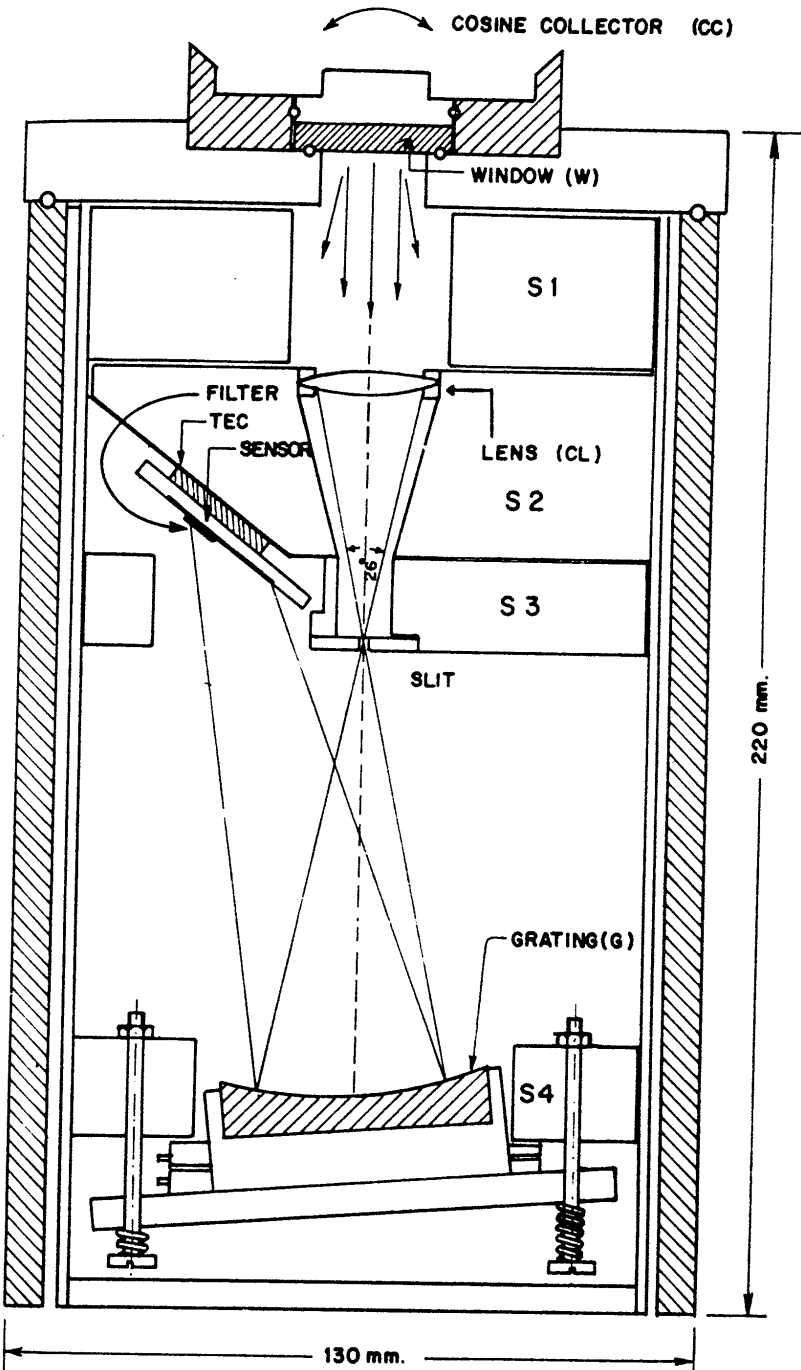


Fig.2 — Cross sectional view of spectrophotometer module

placed at a distance equal to its focal length from the entrance slits of the spectrograph. The concave grating (G) disperses, collimates and focuses the spectrum on a linear photodiode array located close to the entrance slits.

*Radiometer electronics* — The electronic design of the optical radiometer is based on a two-processor system to enable partition of system functions with one processor dedicated to spectral acquisition from upwelling and downwelling sensors and the other for control of system functions and data acquisition from ancillary sensors. The radiometer is a battery operated stand alone instrument that communicates through a serial port with a personal computer. The electronic system block diagram is shown in Fig.3. The two processors (Tattletale microcomputer and the 8031 microcontroller) communicate with each other and

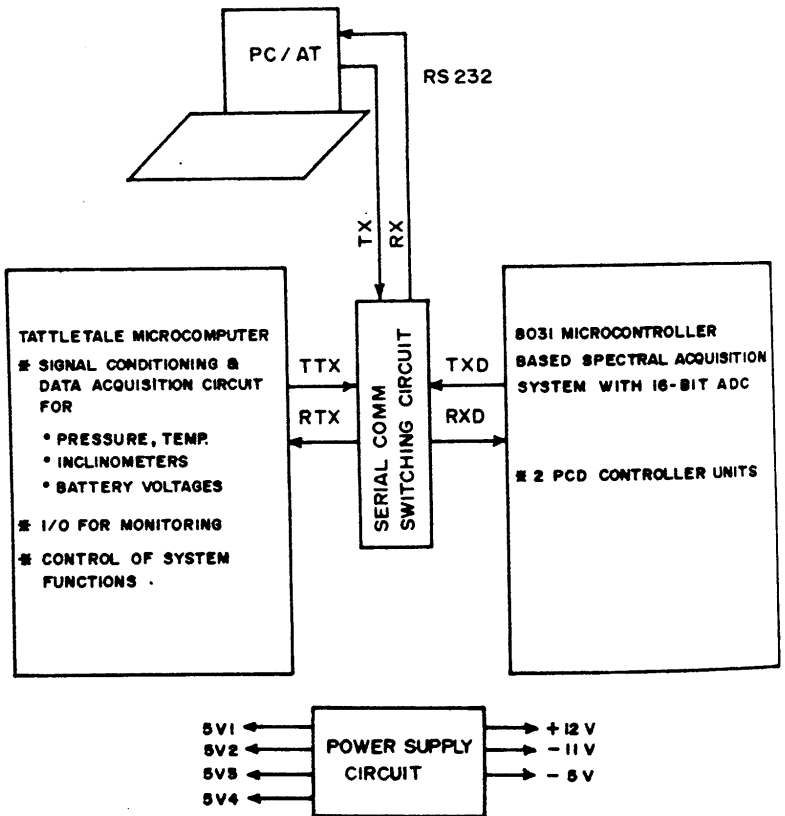


Fig.3 — Electronic system block diagram

with a PC through their serial port lines. The main function performed by the Tattletale processor is the control of system functions, such as time series or profiling mode of instrument operation, rate of spectral acquisition, communications control, system power supply control and acquisition of data from auxiliary sensors, of depth, temperature and inclinometers. The 8031 microcontroller operates at a high speed of 11 MHz and primarily performs the task of spectral data acquisition from two 512 pixel element photodiode arrays and stores this data on 256K bytes of random access memory.

*Radiometer control software* — The radiometer software consists of three separate programs executed on three different processors, namely, the Tattletale logger, the 80C31 microcontroller, and a desk top computer (PC). The Tattletale program was written in Tattletale Basic. The main function of the program is to pass commands from the PC to the 80C31 controller and *vice versa*. It also controls system functions, and acquires and stores data from the ancillary sensors. The software for the 80C31 controller is written in C. The processor receives instructions from the Tattletale logger to either perform in-water acquisition or to respond to PC commands when out of water. Some important program features include: multiple scans of diode arrays with averaging, programmable integration intervals and built-in debugging options. The PC software is essentially menu

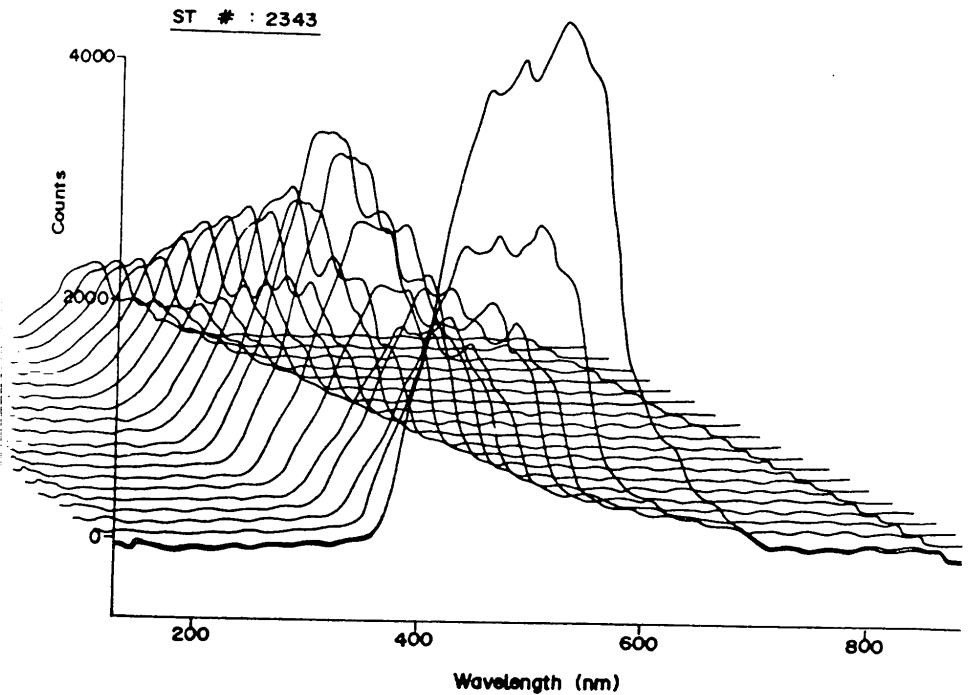


Fig.4 — Uncalibrated field data of downward irradiance spectra

driven and is used when initialising radiometer operation before an experiment, or to download stored data on hard disk, or for display purposes.

## RESULTS AND DISCUSSION

The spectral radiometer had its first uncalibrated field tests on a sea cruise of *FORV Sagar Sampada* during September 1991. The downward irradiance spectra recorded at 2 m depth intervals and scanned in 100 ms are shown in Fig. 4. At this scanning speed, light fluctuations produced by either surface waves or ship roll movement are recorded.

Calibrated downward irradiance ( $E_d$ ) spectra in Woods Hole waters are shown in Fig. 5. Real time averaging of spectral data is performed to avoid light fluctuations due to surface waves and ship roll. The units of the Y-axis have been converted from ADC counts to  $W/m^2/nm$ . Figure 5 shows a 4 h time series record of surface downward irradiance spectral changes on 20 June 1992. The collector face was at an approximate depth of 0.5 m and was positioned to look up to the sky. Sky conditions on that day were generally diffuse.

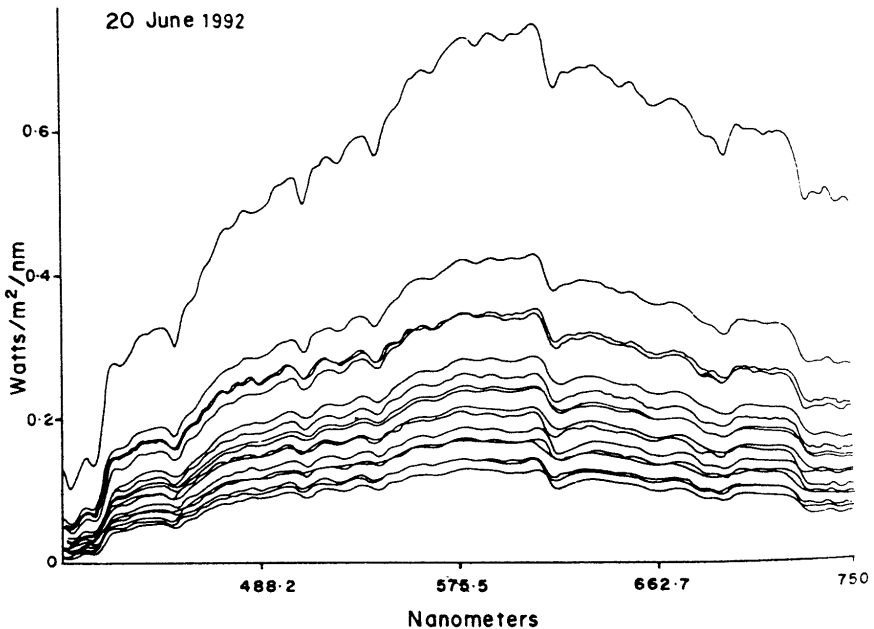


Fig. 5 — Surface  $E_d$  spectra with time (Woods Hole Pier)

The spectroradiometer described in this paper is the state of art development of an underwater optical instrument that gives very fine details on the structure of underwater light field. It will provide a more complete knowledge of the optical properties of natural wares and should increase our understanding of the processes of radiative transfer in the ocean.

### ACKNOWLEDGEMENT

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