

THE DESIGN OF AN IN-WATER OPTICAL RADIOMETER

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ABSTRACT

Despite the power of satellite remote sensing methods in estimating chlorophyll and other important physical parameters; baseline optical data using in-situ radiometers is needed for the validation of remotely sensed optical data. In-water radiometers which measure the spectral composition of the sub-surface light field can be used to correctly classify water types through an estimation of biogenous and non-biogenous matter present in the ocean, and more importantly to gain insights into the role played by absorption and scattering processes in the optical properties of water masses.

In this paper, we shall describe our design approach to a current development effort on a profiling optical radiometer that will measure upwelling and downwelling spectral irradiance over an effective dynamic range greater than six decades, and with a spectral resolution of 2nm. The emergence of a new generation of radiometers is now practically possible with the advent of scientific grade CCD (charged couple device) area array detectors having wide dynamic ranges, high quantum efficiencies in the range 350nm to 800nm, and very low noise features. The presentation discusses efficient methods of light collection using fast optics. The use of state of art electronics for signal processing, acquisition and data storage and sophisticated control software, are novel features of this development.

INTRODUCTION

Remote sensing by satellites offers the means of obtaining synoptic data over large tracts of the ocean, and a way to understand physical processes in the ocean on a global scale. Applying suitable algorithms on the data from the Coastal Zone Colour Scanner (CZCS) can result in useful information and insight on the dynamics of the distribution of chlorophyll bearing phytoplankton in the upper attenuation length, and therefore reliable estimates of primary production per unit area (Jerlov, 1976). Apart from this, and several other diverse applications of remote sensing, baseline optical measurements using in-situ radiometers is needed not only for the validation of satellite derived imageries, but for a basic understanding of absorption and scattering processes in sea water.

There exist several different optical measurements that are commonly carried out in studies of the optical properties of the ocean. Of these, the measurement of spectral upwelling and downwelling irradiance as a function of depth, provides the best way to extract or derive a large set of meaningful optical parameters. We shall consider here, the optical and electronic design criteria adopted in the development of a profiling radiometer. Our aim in this development, is the measurement of the complete irradiance (upwelling & downwelling) spectrum in the photosynthetic waveband 350nm to 700nm with an effective resolution of 2nm. The paper

will also consider briefly, the electronics to be used in the radiometer, and the software required in deriving optical parameters from irradiance data.

IRRADIANCE MEASUREMENTS

Irradiance (E), by definition, is the radiant flux $d\phi$ (or the time rate of flow of radiant energy) incident on an infinitesimal element of surface containing a point, divided by the area of that element: unit are $W/m^2/nm$

$$E = d\phi/dA \quad (1)$$

Radiance (L), in contrast has an angular dependence, and is defined as the radiant flux in given direction (θ), per unit solid angle ($d\omega$) per unit projected area (dA): (Tyler et al., 1970).

$$L(\theta, \phi) = d^2\phi/dA \cos\theta d\omega \quad (2)$$

The two quantities E and L are related (in spherical coordinates) by:

$$E = \int_0^{2\pi} \int_0^{\pi/2} L(\theta, \phi) \cos\theta \sin\theta d\theta d\phi \quad (3)$$

In the design of an irradiance spectrometer, it is necessary to use a collector with a cosine response, such that it performs the integration in equation (Baker et al., 1984). A true cosine collector will collect underwater light flux independent of the angle of incidence on its face. The design of cosine collectors corrected for the immersion effect in water is well understood (Tyler et al. 1970), and there is little need to discuss the details here.

Irradiance, is an apparent optical property of the sea (Jerlov, 1976), because it is depended on changes of the radiance distribution, $L(\theta, \phi)$. In a simple description, it obeys the law:

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

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

$E(z, \lambda)$ is the irradiance at depth z

$K(z, \lambda)$ is the vertical attenuation coefficient.

Irradiance E, and K are functions of the wavelength of light λ , and the depth z below the sea surface.

ESTIMATES OF IRRADIANCE LEVELS

In the measurement of irradiance, it is necessary to estimate its changes across the spectrum (350nm to 700nm) at depth z , and also the change in E with z at a particular wavelength (e.g. 550nm).

a. Change in E across the spectrum

Assume that the surface irradiance $E(0, \lambda) = 1W/m^2/nm$, $z=50m$, and consider wavelengths $\lambda_1 = 440nm$, $\lambda_2 = 640nm$. Using K values for pure seawater (Baker et al., 1982) we get:

For $\lambda_1 = 440 nm$: $K_1 = .017 m^{-1}$; $z = 50 m$

$E(z, \lambda_1) = 4.2 \times 10^{-1} W/m^2/nm$

For $\lambda_2 = 640 nm$: $K_2 = .35 m^{-1}$; $z = 50 m$

$E(z, \lambda_2) = 2.5 \times 10^{-8} W/m^2/nm$

We expect, that for a depth $z = 50$ m, the irradiance will vary by typically 7 decades in signal level from the blue to the red end of the spectrum. This dynamic range will increase with z , and also in waters with large chlorophyll concentrations, where the K coefficient is larger than for pure sea water alone.

b. Change in E with depth at fixed wavelength

Assume as before that $E(0,\lambda) = 1\text{W/m}^2/\text{nm}$, $z = 180\text{m}$ and choose the wavelength at the peak of the irradiance distribution $\lambda = 550$ nm.

For $\lambda = 550\text{nm}$: $K = .065\text{ m}^{-1}$: $z = 180\text{m}$

$E(z,\lambda) = 8.3 \times 10^{-6}\text{ W/m}^2/\text{nm}$.

As before, irradiance will vary by at least 6 to 7 decades in signal level from the surface $z = 0\text{m}$ to $z = 180\text{m}$. At the blue and red wavelengths, the changes in E will be similar to each other, but greater than 6 decades.

The calculations for irradiance levels provide important guidelines for designing a radiometer. These are:

1) It is clear that the collecting optics for the irradiance spectrometer must be optimised for collection efficiency because of the extremely low light levels. Scattered flux in the spectrometer must be minimised.

2) A low light level detector with a dynamic range $> 10^7$ is needed in this measurement.

We shall consider these points in a later section. Before we do this, we need to look at other possible sources of errors that are present when measuring spectral irradiance.

PERTURBATIONS ON SPECTRAL IRRADIANCE MEASUREMENTS

Irradiance, because of its status as an apparent optical property is influenced by various external perturbations. Such perturbations are caused by surface wave noise, changing sky conditions resulting from cloud movement, and changing sun zenith angle, ship's roll, drift from ocean currents, and the effect of ship's shadow produced above water (Smith et al., 1984).

Surface wave noise produces high frequency quasi-periodic fluctuations on irradiance data taken from the upper attenuation length (0-50m); fluctuations being damped out gradually at larger depths. The use of present day optical detectors e.g. PDAs (photo diode arrays) or CCDs (charge coupled devices) having scan times of the order of milliseconds, coupled with variable exposure timing, and arithmetic averaging of spectral scans can minimise fluctuations from surface wave noise.

The effect of ship's roll and current drifts could cause a variable tilt angle to be imposed on the radiometer sea unit. The face of the irradiance collector would be tilted off the vertical, and it would be necessary to measure a 'tilt vector' during a complete cast, for the purpose of applying corrections to irradiance data.

The effect due to rapidly changing sky conditions (Smith et al., 1984) (e.g. fast moving cumulus clouds on a clear sky background, or uniformly overcast skies)

can be subtracted by doing simultaneous measurements of sky irradiance above water. A separate skylight sensor would be a necessary addition to any radiometer system.

Shipshadow effects can be avoided by taking measurements from the sunny side of the ship, and with the sea unit lowered from a point clear off the side of the ship (Smith *et al.*, 1984). Work done on shipshadow effects indicate that the maximum perturbation occurs near the sea surface with negligible effects from one attenuation length. Above water irradiance data is needed for a first order correction due to this effect.

Irradiance is also a function of the sun's zenith angle, time of day, and the latitude/longitude of the experiment site. Therefore these extra parameters need to be included in any experiment where irradiance measurements are made.

DESIGN CRITERIA FOR IRRADIANCE SPECTROMETER

In this section we shall enumerate the general points of a good spectrometer, discuss the magnification and throughput of the meter and lastly the choice of a detector.

The large relative changes in irradiance (section 3) across the spectrum 10^{-7} $W/m^2/nm$, and the exponential attenuation of the signal to levels of 10^{-8} $W/m^2/nm$ at a depth of 180m, points to the necessity of:

- * Good light collector and collection optics
- * Optimising the throughput of the spectrometer
- * Reducing scattered flux in the design
- * Large dynamic range detector ($> 10^7$) e.g. CCD or PDA.

Cosine collectors based on a design by Smith (1969) are used widely in several radiometers (Smith *et al.*, 1978 and Tyler *et al.*, 1966). The underwater response of the collector is very nearly cosine, and agrees with the definition of irradiance. The material used in these collectors is translucent plexiglass, acrylic or a diffusing plastic. These materials tend to backscatter incident radiant flux more strongly in water than in air, producing a loss in signal reaching the detector. Coupled with this 'immersion effect', is the fact that diffusing plastics absorb typically 30% to 40% of the light flux at all wavelengths across the range 400-700nm (Tyler *et al.*, 1970). It appears that more design work needs to be done on cosine collectors using materials (solid or liquid) having an index of refraction close to that of seawater, so that the transfer of flux to the spectrometer is more efficient.

Magnification of the spectrometer

Consider the general optical system in Fig. 1, drawn with the hypothetical Principal surfaces for the object and image side of the system.

The numerical aperture for the object side is:

$$\sin \theta = \phi / 2s \tag{5}$$

The numerical aperture for the image side is:

$$\sin \theta'' = \phi / 2s'' \tag{6}$$

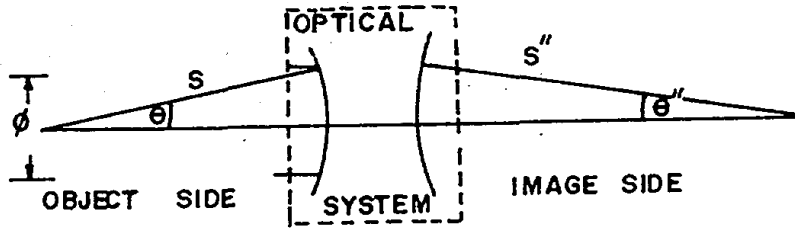


Fig. 1. General optical system.

Eliminating ϕ from 5 and 6, we get:

$$s''/s = \sin(\theta) / \sin(\theta'') = m$$

Thus the magnification of the system is the ratio of the numerical apertures of the object and image sides of the system. Specializing this general concept to a slit and grating based irradiance spectrometer, it would be desirable in the design to collect light over as wide an angle as possible, hence the collimator for the spectrometer must have low f-number optics, i.e.:

$$\sin(\theta) > \sin(\theta'')$$

$$\text{or } m > 1$$

This is a necessary condition for good light collection. The condition $m < 1$ would give $(\theta) < (\theta'')$, implying a relative increase in the collimator f-number, a smaller throughput, and a lowering of the signal to noise ratio at the detector. The condition $m > 1$, would ensure that the image of the slit, after dispersion by the grating, will be magnified width-wise relative to a pixel on a CCD detector.

Throughput of the spectrometer

The throughput T , is measured at the entrance slits (object side) of the spectrometer, where it is equal to the product of the area of the entrance aperture, and the solid angle subtended there by the grating or collimator:

$$T = (\pi/4) \cdot w.h. (D/f)^2 \cdot t \quad (7)$$

where $F\#$ (collimator) = f/D

and $w.h$ = area of the slit aperture

D = diameter of the collimator

f = focal length of collimator

t = optical efficiency factor after transmission & reflection losses.

Using wider slit widths can increase T , but at the cost of lower resolution. Another way is to use a large aperture grating with a high number of rulings/mm. This will then require shorter focal length for the imaging optics, and hence larger T .

Choice of detector

The nature of irradiance measurements, and the associated perturbations on it demands that we use a large dynamic range optical detector. This boils down to a choice between CCD and PDA image sensors as the detector for our radiometer. Having made a careful analysis of the noise figures, we conclude in favour of 2-D CCD arrays for the following reasons:

a) The signal/noise ratio (SNR) of CCD arrays increases parabolically as a function of exposure time. In contrast, PDA detectors are plagued by the build-up of dark currents (and other noise contributions i.e. fixed pattern and reset noise) competing with signal.

b) Read noise in a CCD is substantially lower (- 10 to 15 electrons) than in a PDA (- 1000 electrons).

c) The use of the BINNING readout mode in a CCD can increase the SNR of the device. No such analogous capability exists for PDA devices.

d) The possibility of using arithmetic averaging of BINNED spectra in a frame transfer CCD will be especially useful if the radiometer is to be used at larger depths where signal levels are poor.

e) In this application, the complete width and height of the entrance slits of the irradiance spectrometer could be imaged on to superpixel of the 2-D CCD array. This imaging method will utilize all the signal collected by the collimator optics.

Apart from the above differences, CCD and PDA detectors both have the capability of doing fast scans of the photosynthetic waveband i.e. within tens of milliseconds. Use of this feature will significantly minimise surface wave noise, and will result in high resolution (< 2nm) irradiance spectra at all depths.

The principal drawbacks in using a CCD detector are:

a) Necessity of cooling CCD's to reduce dark noise and its fluctuations. A reasonable approach is to use air convection thermoelectric coolers with closed loop thermostating.

b) The aspect ratio of the imaged slit on the CCD has to conform to CCD array geometry. This requires precise imaging optics for the spectrometer.

COMPONENTS OF THE RADIOMETER

In this section, we shall assemble all the elements required for the design of a high resolution profiling radiometer. The main task of the system is to measure upwelling and downwelling spectra at constant depth intervals (2m). A real time display of irradiance spectra transmitted by cable from the sea unit to the screen of the ship's computer would enable one to get a visual feel of the in-water light field during the descent of the radiometer. This approach, although attractive is costly, and has been abandoned in our design because of the problem of large amounts of data generated, and the need to suppress ship's noise. Instead, all data from a cast, will be recorded on high density solid state memories, Data inspection will be done after a cast, by connecting the radiometer to a personal computer.

The in-water unit of the radiometer system will carry the following:

1) High efficiency cosine collectors for downwelling and upwelling irradiance (E_d and E_u).

2) Two high resolution grating based spectrometers of similar design for measuring E_u and E_d .

3) Two CCD area arrays mounted on the spectrometers.

- 4) Temperature, depth, chlorophyll fluorosensor and tilt sensors.
- 5) Real time clock sensors and battery backup circuits for the retention of spectral data on memories.

The above water components of the system will be:

- 1) A skylight sensor with a cosine collector and battery based electronics to record above water downwelling irradiance needed to correct in-water measurements.
- 2) A fast personal computer for the transfer, and analysis of spectral data after the cast.

HARDWARE AND SOFTWARE FOR THE RADIOMETER

In this section we shall describe the essential blocks of the electronic circuitry and the outlines of the software presently being developed.

Hardware (mechanical)

The optics of the in-water unit will be ceramic or epoxy encased in an aluminium alloy pressure housing. It will be filled with inert gas and evacuated to circumvent moisture effects and thermal conduction to the sea, and will also lower the thermal mass to be cooled. The electronics and battery circuitry will remain physically isolated from the optical sections to prevent deterioration of the optics from any out-gassing that may occur from the sealed batteries, and also to allow easy exchange with spare electronics/optics sections at sea. The instrument will be weighted at one end to provide a static bias maintaining verticality and ribs on the upper outer portion for dynamic bias during descent. Lightweight kevlar rope will lower and haul the instrument.

Hardware (electronics)

The system block diagram is presented in Fig. 2. It is controlled by a Tattletale datalogger. The datalogger performs housekeeping chores, system checks and interfaces to a PC on deck. It also interfaces to all oceanographic sensors except the downwelling and upwelling CCDs, which task is looked after by an Intel 80C51 microcontroller.

The Tattletale logger is a high chip density microcomputer circuit of low power consumption $30\mu\text{a}$, large memory 1Mbyte, 11 channel A to D converter and with several other features that are highlighted later.

Prior to deployment, the data acquisition parameters are fed into the system via the optical RS 232 link. This link allows communications with an on-board PC at upto 9600 baud without opening the in-water connectors which sometimes tend to cause problems. In a similar technique, the in-house batteries are charged, at low trickle charge rates, via an inductive charger, thus ensuring that O rings seals do not have to be unmade and made every time one communicates with the system or charges the batteries. The realtime clock of the in-water unit is set by the PC as also the acquisition details. Any desired channel can be circumvented, acquisition can be independently configured. CCD controls are passed to the Intel 80C51 and

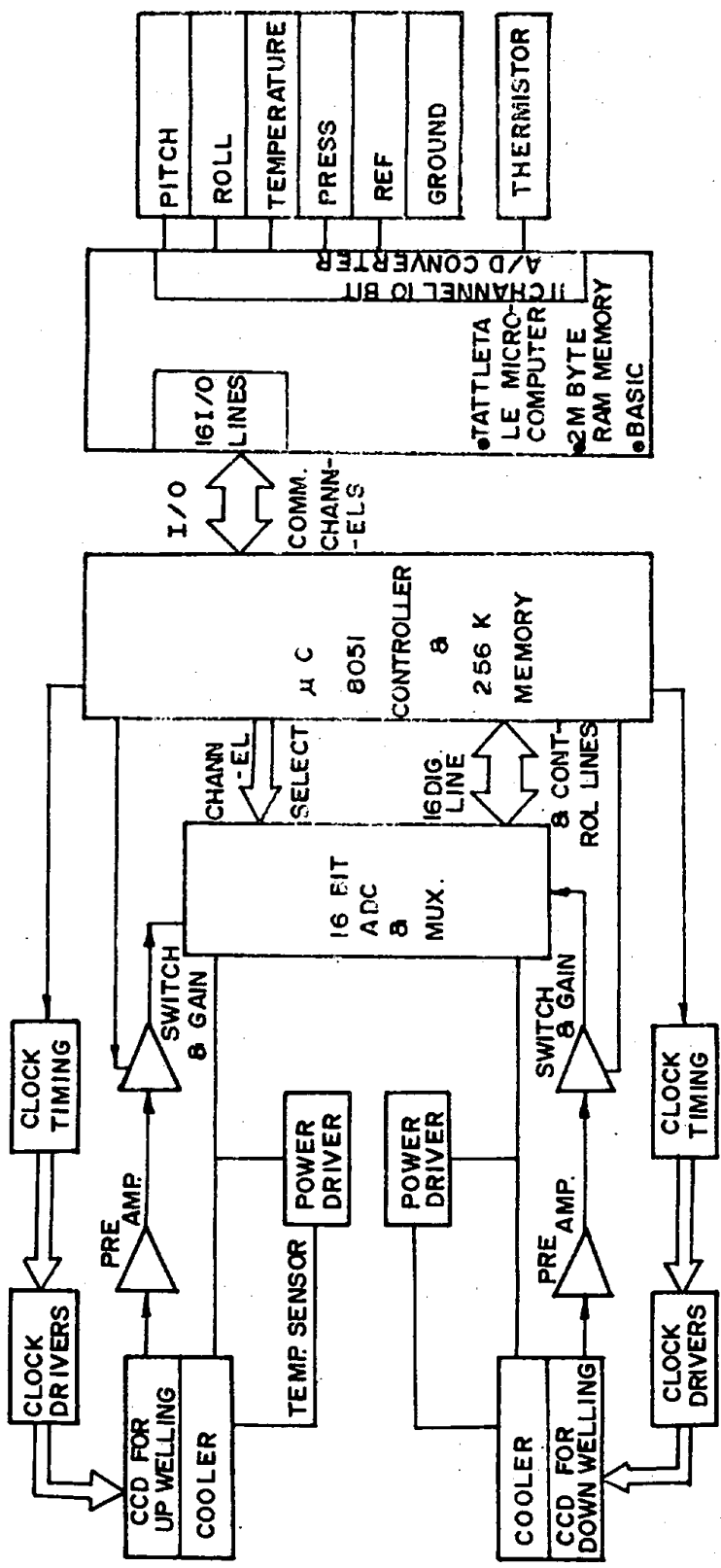


Fig. 2. Electronic block diagram for the radiometer.

schemes such as binning, on-chip integration, aperture timings and dark current estimation can be set up from the external PC.

Nine analog channels also feed directly to the Tattletale. They are pitch and roll to determine the projected area of the CCD array to the vertical; water temperature and pressure to determine the external environment of the probe; an on-board thermistor for house keeping information, fluorescence data, and a voltage reference and ground as checks for the analog to digital converter. The Tattletale is programmed in Basic and manages data memory. Thus every depth/time interval data that is successfully collected by the Intel 80C51, is passed to the Tattletale for storage.

The computer also controls the running parameters of the Intel 80C51. Since supply power is a prime and scarce commodity in this instrument, the in-water computer was primarily chosen for its frugal consumption. It is switched on by a non-polarising sea-switch mechanism. This sea-switch mechanism is used in the instrument to ensure fool-proof power up only when the unit touches the water. The largest consumer of power are the cooler drivers for the arrays. Thus even though the arrays will be working at elevated temperatures at the surface since the coolers would not have sufficient time, it is also the area of highest signal strength. The resident software is also set to switch the system off when it detects that end of cast is reached. This ensures further savings in the power consumption.

The Intel 80C51 together with the 16 bit ADC, the CCD array with signal conditioning and control circuitry, and the solid state coolers for the CCD arrays, form the kernel of the data acquisition package.

On initial power up the controller configures its I/O lines for input. The computer transfers relevant acquisition details to it. These include amongst other details, the limits to be set on signal-to-noise ratio, aperture times, binning widths in pixels, number of scans per data acquired and dynamic range of amplifier gain. Registers in memory maintain the status of deployment either as initial start up, cast, end of cast or data dump to PC.

During a cast, the computer which maintains real time and monitors depth, signals the controller to commence acquisition. The controller does several iterative passes to ensure that no pixel saturates and aperture timings are met, and adequate signal is attained with/without binning. When these adaptive factors have been determined at a depth, the controller acquires a set of CCD data averages and stores it. This is repeated for the other irradiance sensor. Data on the upwelling and downwelling irradiances, temperature of the arrays during measurement, value of amplifier gain, dark current noise, binning width or integration, and analog reference and ground are transferred via the I/O lines to the computer.

The irradiance field data together with a time stamp and the oceanographic parameters mentioned earlier are logged onto computer memory which is played back on recovery. "C" is the programming language for the microcontroller.

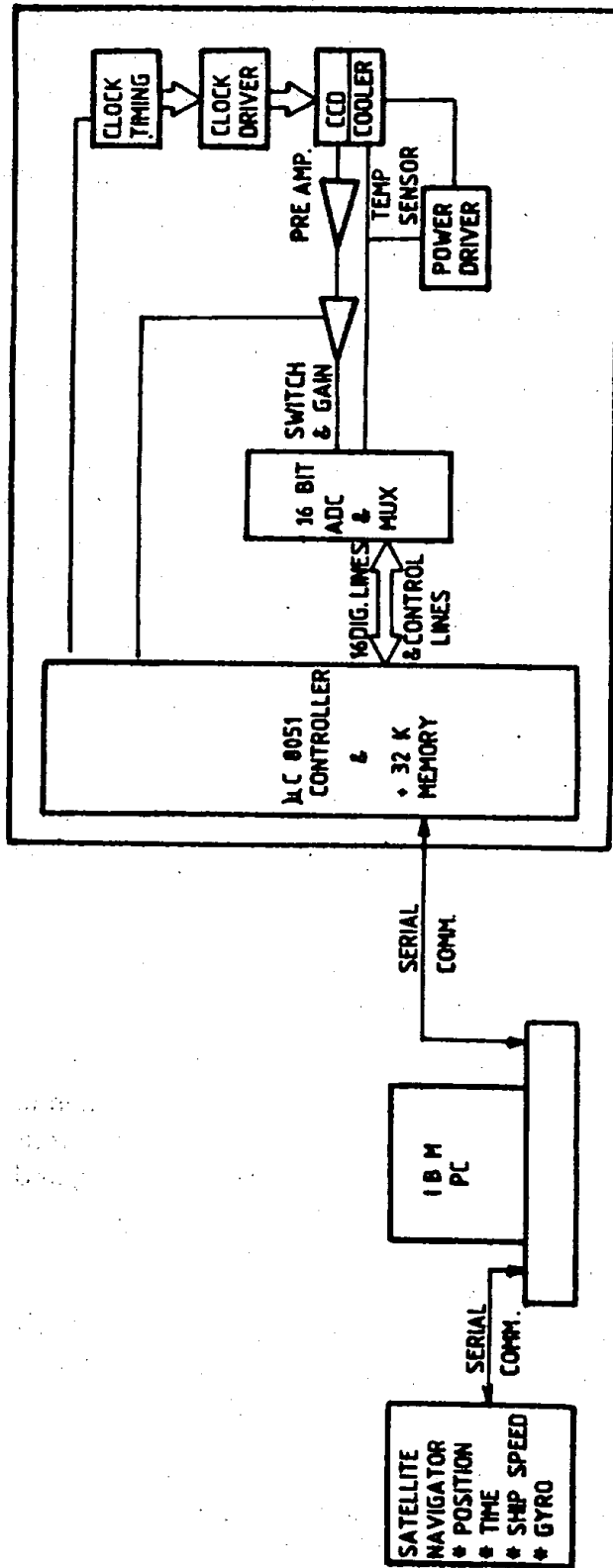


Fig. 3. Skylight sensor.

On recovery from the cast, the acquired data is transferred to a personal computer via an optical link. Raw data is stored on one file. A menu based program allows large amounts of data processing to be carried out before analysis is begun. These are:

- 1) The irradiance field data is corrected for CCD thermal noise using temperature data of the coolers.
- 2) Instruments tilt in 2 axes are used to compensate for orientation away from the vertical.
- 3) Drift due to currents and surface winds are corrected by using data from the ship's satellite navigator.
- 4) Changes in skylight conditions are corrected for by using a separate sky light sensor, shown in Fig. 3, and designed to float just below the surface. Skylight data is controlled by the lab PC which time stamps the data and also acquires positional information from the satellite navigator. Latitude, longitude, time of year, time of day and heading of the ship is used to compute any ship shadow effects.

CONCLUSIONS

The objective of this paper has been to discuss in broad outline, design criteria used in the development of a profiling radiometer. With the advent of PDA, CCD, CID array detectors, high quality optical components, micro-controllers, and the ease of developing sophisticated control software, one can begin to develop a range of high performance instruments for studying the optical properties of the oceans.

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