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MEASUREMENT OF THE REFLECTANCE RATIO OF NATURAL LIGHT IN THE SEA

BY
B. BOOTY

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ABSTRACT

Theoretical and instrumental aspects of the measurement of reflectance ratios in the sea have been considered. Problems have been identified and an instrument, designed to avoid fundamental difficulties inherent in this type of measurement, has been built. Pre-design experiments and experience at sea with the prototype instrument have provided supporting evidence for hypotheses.

This paper outlines the thinking and summarises the main conclusions reached regarding the measurement of sub-surface reflectance ratios. It contains also a brief description of the instrument which has been designed and constructed for use as a tool for the further development of optical methods for the identification and quantification of materials suspended or dissolved in the sea.

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INTRODUCTION

The role of reflectance ratio measurements in the sea as analytical data is generally accepted. Values of R, or more specifically $R(\lambda)$, the reflectance ratio at a wavelength λ, are seen to have a potential to provide a measure of ocean colour and hence provide sea-truth for use in the interpretation of remotely sensed ocean colour data.

The basis of this is the well established principle that, to a first order at least, $R(\lambda)$ is related to the backscattering and absorption coefficients of the water column, b_b and a respectively, by a relationship of the form:

$$R(\lambda) = f - \frac{b_b(\lambda)}{a(\lambda)}$$

(Duntley 1942, Gordon et al 1975, Morel and Prieur 1977, Kirk 1981).

Values of b_b and a are greatly influenced by materials dissolved or suspended in the water column so, in principle, measurements of $R(\lambda)$, themselves related to observed colour, are potentially a key to the identification and quantification of materials in the water.

In practice, efforts to correlate absolute reflectance measurements and quantitative analyses of water quality have not been particularly successful. Very much more successful though, have been algorithms based on comparisons of two or more reflectance ratios at different wavelengths. Clarke et al (1979) proposed that chlorophyll concentrations in water could be estimated using the ratio of surface radiances at different wavelengths, and the concept was developed, notably by Morel and Prieur (1977) who showed that chlorophyll concentrations could be related to the ratio of reflectances at 440nm and 560nm. The principle has since been explored by a number of workers, and algorithms have been developed which are valid within limits. Even so, uncertainties of 30% or more are common. Taking a slightly different approach, Grew (1980) found that it was possible to overcome variations in surface radiances, brought about by variations in surface illumination, through the use of inflection ratios, defined as $S(i)^2/S(i-m)\,S(i+n)$, where m and n are selected wavelength differences on a central wavelength i. This technique has been developed by Campbell and Esaias (1983) to relate reflectance ratios to chlorophyll concentrations. Thus, within limits, the measurement of relative, rather than absolute, reflectance ratios appears to be what is required to develop a quantitative analytical capability.

A major limitation of this approach is that it can be applied only to Case 1 waters, that is waters where optical properties are dominated by a phytoplankton population. Attempts to correlate reflectance ratios and suspended inorganic sediment loads in the so called Case 2 waters, that is waters which contain an appreciable amount of inorganic material or dissolved organics not derived from local primary production, have been less successful. Indeed there is evidence to suggest that, above a low threshold, R is independent of inorganic sediment concentration. Theoretical studies by Llewellyn (1987) and laboratory measurements of scatter and absorption in turbidified water (Booty 1974) point strongly to this conclusion.

There are, of course, two sides to this problem, and it is important to bear in mind also that any lack of correlation between reflectance measurements and water quality measurements by conventional methods may be due as much to uncertainties in the latter as in the former. However, the work summarised here has been solely concerned with one side; the purely practical difficulties of obtaining meaningful near surface reflectance data, which will be relevant to the quantitative analysis of material dissolved or suspended in sea water.

THE MEASUREMENT PROBLEM

The simple concept of two light sensors, one pointing upward to measure downwelling irradiance, Ed, and another, in the same plane, pointing downwards to measure upwelling irradiance, Eu, is sound in principle but, in practice, is fraught with inherent problems.

A major uncertainty is the sub-surface radiance distribution. A typical near surface radiance distribution pattern (see for example Smith 1974) will be asymmetric in the vertical plane and, in most cases, in the horizontal plane also. The effects of solar angle, refraction at the surface and diffusion in the water column will combine to form a quite complex shape. In the downward direction there will be noticeable cut offs at the critical angle (the manhole effect) on either side of a diffusing beam with its peak in the direction of the sun. Upwelling light, on the other hand will be entirely diffuse with a regular distribution across the lower hemisphere weighted only slightly by the angle of the sun. If then we define an apparent reflectance ratio, R^* say, as the ratio of a reading from a downward looking sensor to a reading from an identical upward looking sensor, the value of R^* will be, to a very large extent, a measure of the interaction between the asymmetric (and usually constantly changing) light field, and the angular response curve of the sensor units. It is, for example, quite likely that the ratio of scaler irradiance, that is irradiance measured with a sensor with a uniform hemispherical response, will differ from that measured with an ideal cosine collector by more than 50%. The difference between results with cosine collectors and moderately collimated sensors is less marked, but it is perhaps worth noting too that the more collimated the sensor pair, the more critical it becomes for instrument trim to be maintained. However, the main conclusion here is that a combination of uncertainty regarding the optical characteristics of the sensors, unavoidable variations in trim and a constantly changing radiance distribution, has the potential to introduce uncertainty into the measurement.

A second category of difficulty is interference with the light field by the instrument itself; self shielding. The problem lies in the difficulty of making measurements of upwelling light, Eu which is due to backscattering of illumination from above. Any sensor looking down into the water is in danger of looking directly into its own shadow and hence the small section of the water column it observed is not typical of the whole.

Realising that the magnitude of the self shielding effect will vary with both the size of the shielding area and the turbidity of the water, an effort was made to quantify it using two identical sensor pairs mounted, one pair at each end of a horizontal bar, and suspended in the sea. Having established that each pair indicated a similar value of R*, collars were added to one to increase its shielding area in steps, while maintaining the unshielded pair for comparison. The expectation was that the degree of self shielding might be seen to vary with effective sensor unit area and with water turbidity, and the hope was that, by interpolation, a correction factor might be arrived at. However, this expectation was not realised. The self shielding effect was clearly visible, altering the apparent reflectance ratio by more than 25% in some cases, but it seemed not to be related to collar area. It became clear from this that an overriding factor was the nature of the surface illumination and consequent sub-surface radiance distribution. With cloud cover, the diffuse surface illumination cast a shadow below and into the field of view of the downward looking sensor. In brighter interludes, without the cloud cover, direct sunlight provided a strong horizontal component which moved the sensor's shadow to one side of its field of view and the self shielding effect was reduced to practically zero.

This rather perfunctory test highlighted the following important and hitherto not fully appreciated point. The magnitude of the self shielding effect, which can be considerable in some circumstances, depends to some extent upon instrument dimensions but to a very much greater extent upon circumstantial variables such as cloud cover, solar angle and, bearing in mind considerations of the effects of surface slope on sub-surface radiance distribution, possibly even wave action. This is a disturbing conclusion for someone intent upon measuring absolute values of R in a real ocean situation, and certainly appears not to have been taken into consideration in the design of some instruments.

Total elimination of the effect would be difficult. One approach would seem to be the minimisation of the problem by minimising the shadowing potential of the instrument. In a multi-sensor unit this means, not only keeping the size of sensor housings to a minimum in relation to sensing area, but also separating housings to avoid mutual shielding. Even so, there are practical limits to this approach and it is hard to see how it would be possible to reduce uncertainties due to self shielding to an acceptable level.

It was concluded that a more practical approach would be to aim at measurements which are meaningful in the context of the objective but are independent of the circumstances of the illumination. Bearing in mind that, as has already been pointed out, the measurement of comparative, rather than absolute, reflectances is a worthwhile objective, this can be achieved using a multi-spectral, multi-sensor instrument provided that the design allows the ratio $R^*(\lambda)/R(\lambda)$ to be constant for all values of λ, ie for all sensor pairs, in any particular circumstances of deployment and surface illumination. This, in effect, means ensuring that each detector pair is, as far as possible, optically isolated from the rest of the instrument. An instrument with a cluster of detectors in a single, relatively large housing, for example, represents perhaps the worst possible design. Such an instrument will not only yield results which are unacceptably dependent upon variations in circumstances, but will make inter-wavelength comparisons invalid, as position of any particular sensor within the cluster, relative to the orientation of the instrument to the sun, will have a major effect on the result.

A third difficulty concerns the dynamic character of the system under observation. In any real ocean situation, there will be frequent and substantial changes in the natural sub-surface light intensity; commonly several orders of magnitude (see, for example, Goldberg et al 1984). Added to this there are the effects of a continuously changing surface shape, with waves creating radiance distribution patterns. Measurements have been made in Southampton Water using a rotating, collimated sensor and continuous recording. Results show the expected asymmetric radiance distribution but at the same time show clearly an effect due to wave action (Boxall, personal communication). How much this is due to absorption in a varying path length (in principle not a factor affecting measurement of R) and how much is due to changes in surface angle modifying downwelling radiance distribution cannot be determined directly with the results available, but they do support the proposition that both short and long term variations in light level and radiance distribution have to be taken into account in sub-surface light measurements. Clearly, simultaneous sampling of related upward and downward looking detectors is essential.

To summarise, initial thoughts and some experiments have led to the following basic conclusions:-

(a) While the theory of the behaviour of light in water is very well established, constraints, uncertainties and variations in sub surface light levels and distributions, combine to make the accurate determination of absolute values of R a difficult, not to say impracticable, objective in the case of a field instrument operating in a real ocean situation.

(b) Comparison of two or more apparent ratios at different wavelengths is a realistic objective but care is needed in the design of the instrument, to ensure that changing circumstances affect all sensor pairs equally. i.e. the design of the instrument must be such that the relationship between the true and the measured (apparent) reflectance, $R^*(\lambda)/R(\lambda)$, is the same for every wavelength, whatever the circumstances of the surface illumination or instrument deployment.

(c) There are two essential criteria which have to be met in an optimum instrument for the in-situ determination of relative reflectance data. These are:-

(i) It is desirable that there should be minimum shadowing of the field of view of the downward looking sensors. Much more important though, is to keep in mind the fact that, while a potential for self shielding error is designed into an instrument, the magnitude of the effect on any particular occasion depends upon a number of circumstantial variables not in the control of the operator. It follows that, where a multi-sensor instrument is used to compare reflectance ratios at different wavelengths (a common circumstance), the self shielding characteristics of all downward looking sensors must be identical, regardless of surface illumination conditions and consequent sub-surface radiance distributions. Outputs from sensors in a downward looking array, contained in a relatively large opaque housing or structure, cannot be compared one with another.

(ii) Simultaneous interrogation of related sensors is absolutely essential in a real ocean situation. While averaging may go some way towards removing high frequency variations in overall light levels and distributions, medium or lower frequency variations, of the type brought about by waves or shadowing by clouds for example, are ever present. As such, any ratios obtained by comparing sequential measurements, even measurements taken at intervals of only a few seconds, must be regarded as suspect. It follows that a single sided instrument, that is one capable of measuring only one direction at a time is not suitable for this purpose.

Any relaxation in (i) or (ii) above will almost certainly result in an instrument which produces results which are as much, or probably more, dependent upon conditions of sea surface, sky and deployment, than upon water quality.

A PROTOTYPE INSTRUMENT

There was a requirement for a simple instrument, capable of making meaningful reflectance measurements from small boats in sheltered waters. Cost was a major consideration and hence the use of familiar technology and equipment already to hand influenced the design to a very large extent, dictating a multi-sensor instrument rather than the potentially more satisfactory solution of a single-sensor, spectrum analysing instrument. Thus a prototype instrument was built to a design which takes account of the considerations discussed. In particular the very difficult problem of determining $R^*(\lambda)/R(\lambda)$ and the still more difficult problem of how to maintain or monitor it in the rapidly and widely varying circumstances in which the instrument will be required to operate, has been sidestepped by designing specifically with the measurement of comparative ratios as an objective.

Four minimum sized sensor housings, each containing an upward looking and a downward looking sensor, complete with a pair of matched amplifiers and colour filters, are supported on a spider like frame (see Fig. 1). The frame holds the sensor pairs apart so that each is operating in, as near as is possible, a similar light field, undisturbed by the shadow of its neighbour. The whole hangs, semi-gimballed, in a weighted harness, which is suspended at any desired depth from a surface float. It is towed from just above the pivot point so that the sensor array, which is maintained flat and level by a 1m long tail, swims ahead of the surface disturbance (see Figs. 2). Amplified outputs from the sensors are fed via a multicore cable to the surface for processing and recording.

A deck unit containing a similar set of sensors, amplifiers and colour filters, monitors surface illumination at the same four wavelengths, and data from this is processed and recorded together with the sub-surface data.

The sensors are OSD 100 silicon diffused photodiodes, each with an active area of 1cm^2. They have a quantum efficiency which is reasonably constant at about 70% between 500nm and 900nm and remain useful down to 400nm. The chief characteristics which make this diode particularly suitable for the task in hand are its wide dynamic range and its consistent logarithmic response. In practice, the useful dynamic range of the instrument is governed by the input requirements of the data processing equipment, but even so it is of the order of 10^6.

Interference filters are used, giving detection wavelengths of 435, 550 and 650nm, with half height bandwidths of 7.4, 9.2 and 11.4nm respectively (see Fig. 4). The fourth sensor pair is used full spectrum.

The non-dimensional nature of the measurement eliminates the need for any absolute calibration. All that is required is to check that the upward and downward characteristics and sensitivity of each sensor in any sensor pair are identical and remain so. This is achieved by simply inverting the instrument and establishing that this produces no change in the measured value of R* at each wavelength. Any inequality in sensitivity could be allowed for in subsequent calculation, or alternatively sensitivities can be adjusted. In practice, to date, the detectors, which were selected in matched pairs in the first place, have shown no tendency to change, and no allowances or adjustments have been necessary.

Particular attention has been given to two aspects of the design:-

(i) Sensor housings have been kept to the minimum practical dimensions in relation to detection area in an effort to minimise self shielding. For the reasons already stressed, the housings are as near as possible identical and are mounted well away from each other, in an effort to ensure that $R^*(\lambda)/R(\lambda)$ will be the same for all four selected wavelengths whatever the circumstances of deployment or surface illumination.

(ii) Simultaneous interrogation of all channels is achieved using a readout and recording system (see Fig. 5) developed from equipment, originally designed for use with an acoustic Doppler current profiler, but later modified for use in a number of other applications. (Pascal and Perret 1988).

The inadequacy of sequential measurements has been amply demonstrated in using the prototype instrument. In normal use all channels are sampled simultaneously 128 times in an 18 sec period, the results digitised and mean values recorded every 30 secs. Using this routine, values of $R(\lambda_1)/R(\lambda_2)$ measured in an open sea situation, where well mixed conditions may be expected to exist, are found to be consistently within one or two percent of one another. In similar circumstances, but with the instrument used manually, that is interrogating each sensor in sequence and recording its output, repeated measurements of the above ratio are generally found to vary by twenty or thirty percent.

The data processing equipment can be programmed to follow any required sampling, processing and readout routine. The presently used sequence was chosen somewhat arbitrarily to sample at a rate which is high compared with the highest likely significant wave frequency and to average and print out at intervals which were thought to give a manageable data repetition rate. At the instrument's maximum towing speed, 4 knots, the present routine produces a print-out every 60m (through the water) which is made up of an average of 128 interrogations of each channel taken over a distance of 36m.

OPERATIONAL EXPERIENCE

The instrument has been deployed on a number of occasions and in a variety of sea conditions, mainly in the Solent and in the Channel to the South of the Isle of Wight, and has proved to be remarkably seaworthy and stable under tow. The safe towing speed limit, 4 knots, is set by the supporting float rather than by the underwater unit.

A large quantity of data has been collected, mainly in the form of printed paper. The original concept was of an instrument for use in small boats in sheltered water, so it was designed to be self contained and dependent entirely upon internal batteries. In these circumstances a small paper tape printer proved ideal for data recording. Later the instrument was upgraded in a number of detailed ways to make it suitable for use from a small ship. When operating from a ship it is convenient to read directly into an IBM compatible computer and a considerable quantity of data has been recorded in this way also.

Results processed to date have been encouraging; a most noticeable feature being their consistency. Fig. 6 shows some typical data; in this case data obtained while towing the instrument in the Solent at a depth of 0.5m behind a small boat. The plots are simplified for the sake of clarity, with only two of the channels and alternate points plotted, but they do serve to illustrate the potential of the instrument. The important point to appreciate is that the plots (a) and (b) are of individual values of R^*, not R, and therefore contain all the uncertainties relating to operating conditions. So, while changes in these may be seen as an indicator of varying water quality, indeed in this case the general trend follows rough turbidity estimates from secchi disc readings, it would be wrong to assign any absolute significance to them in that context. However, plots of ratios such as (d), are, in principle, independent of operating conditions and therefore constitute a suitable basis for interpretation in terms of water content.

A collaborative effort to relate measured colour ratios to simultaneous in-situ water quality measurement, using the now considerable amount of data already collected, is presently underway.

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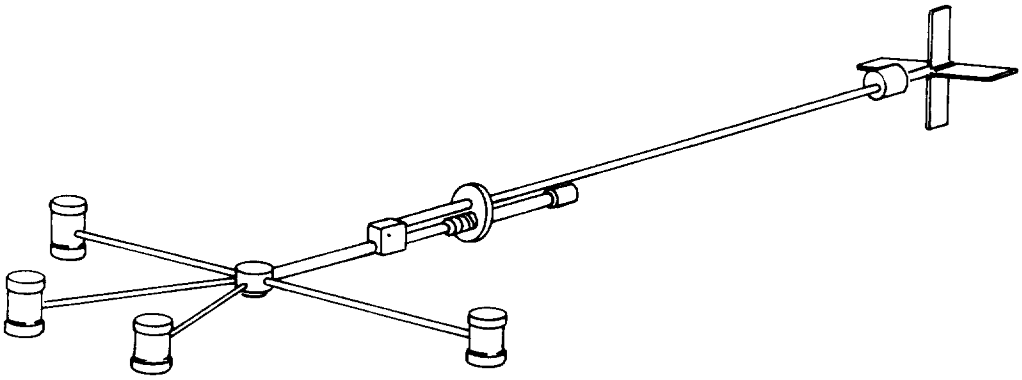

Figure 1 Underwater Sensor Unit

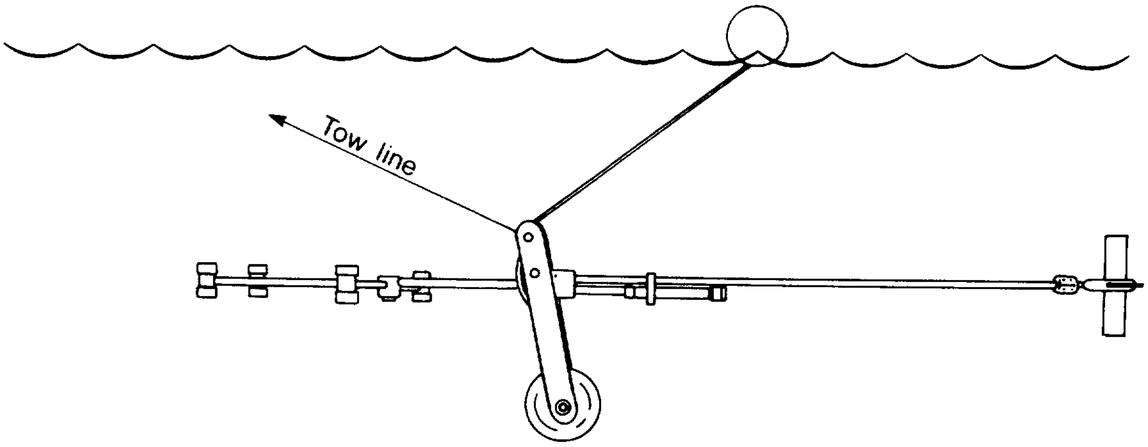

Figure 2 Underwater unit showing towing attitude

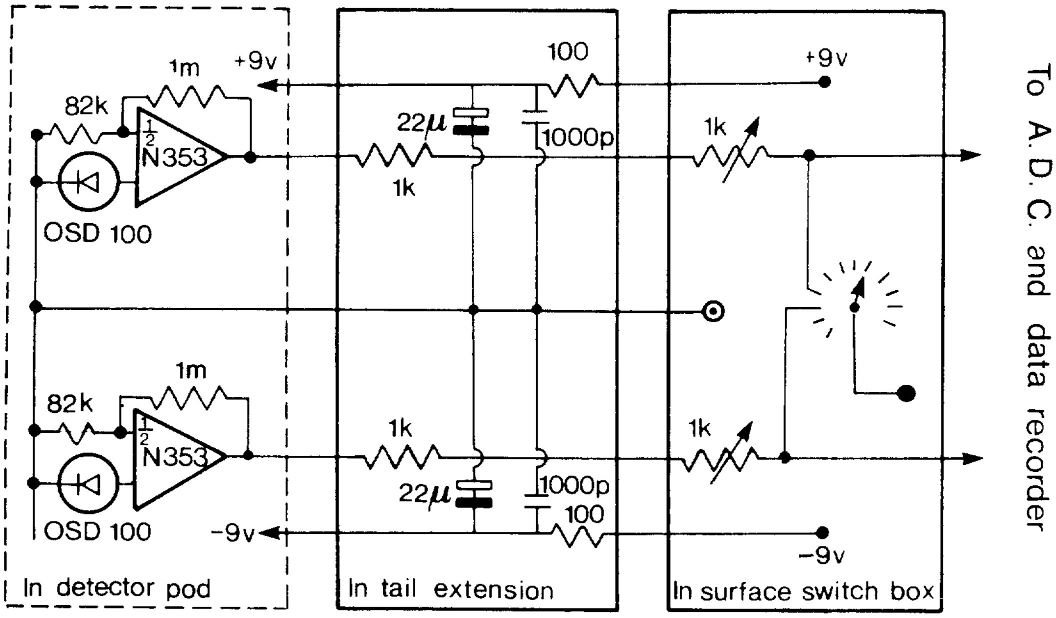

Figure 3 A single detector/amplifier/filter unit

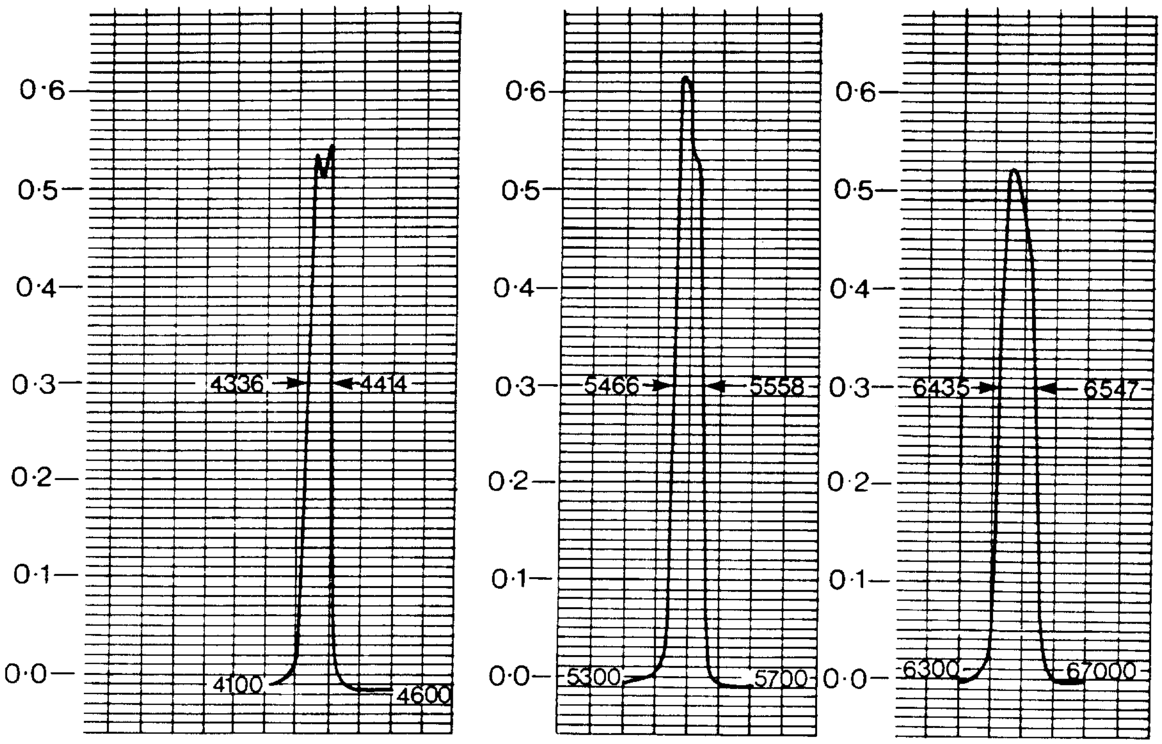

Figure 4 Optical filter transmission curves (manufacturer's data)

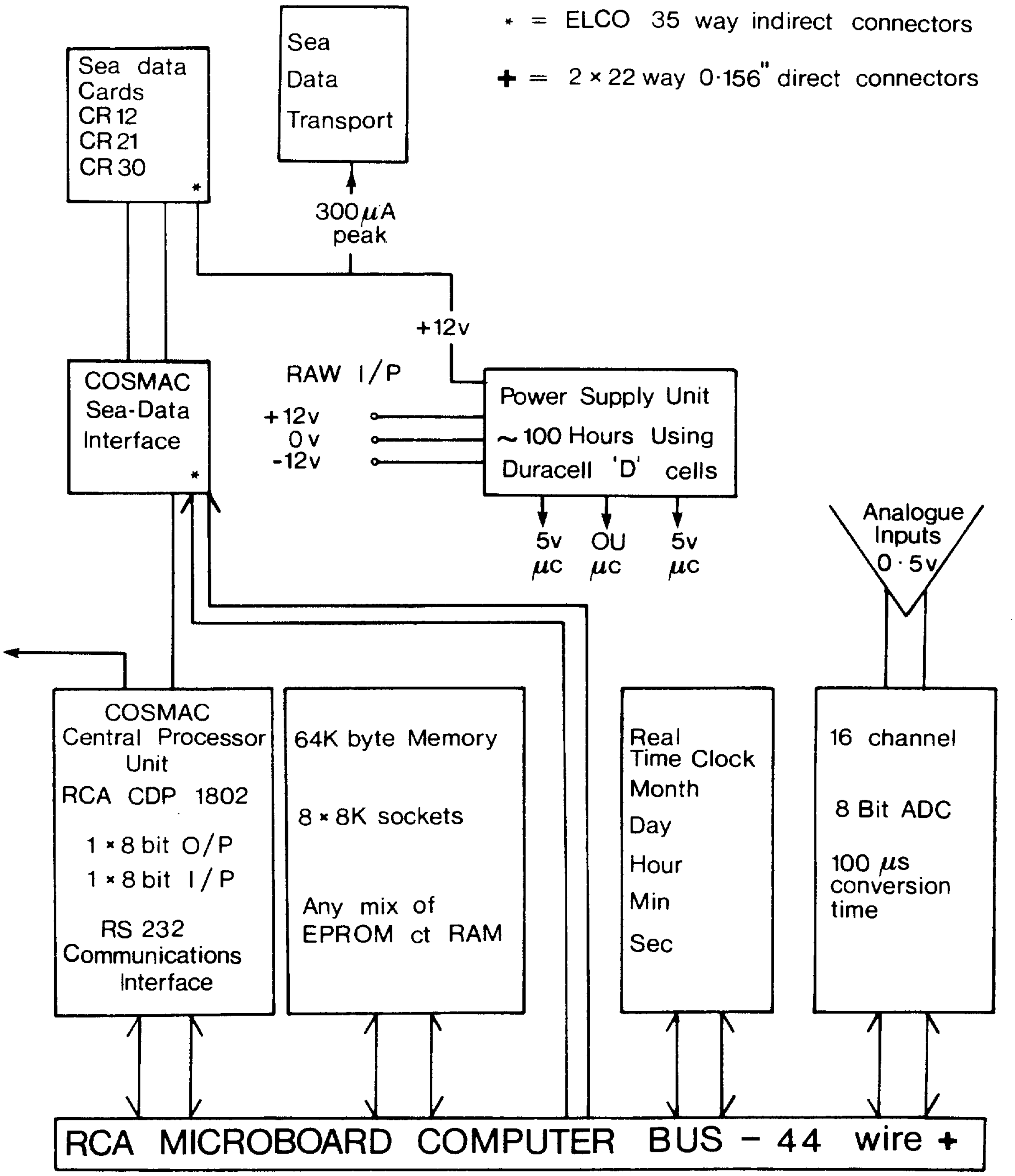

Figure 5 Schematic Diagram of Data Processing Equipment

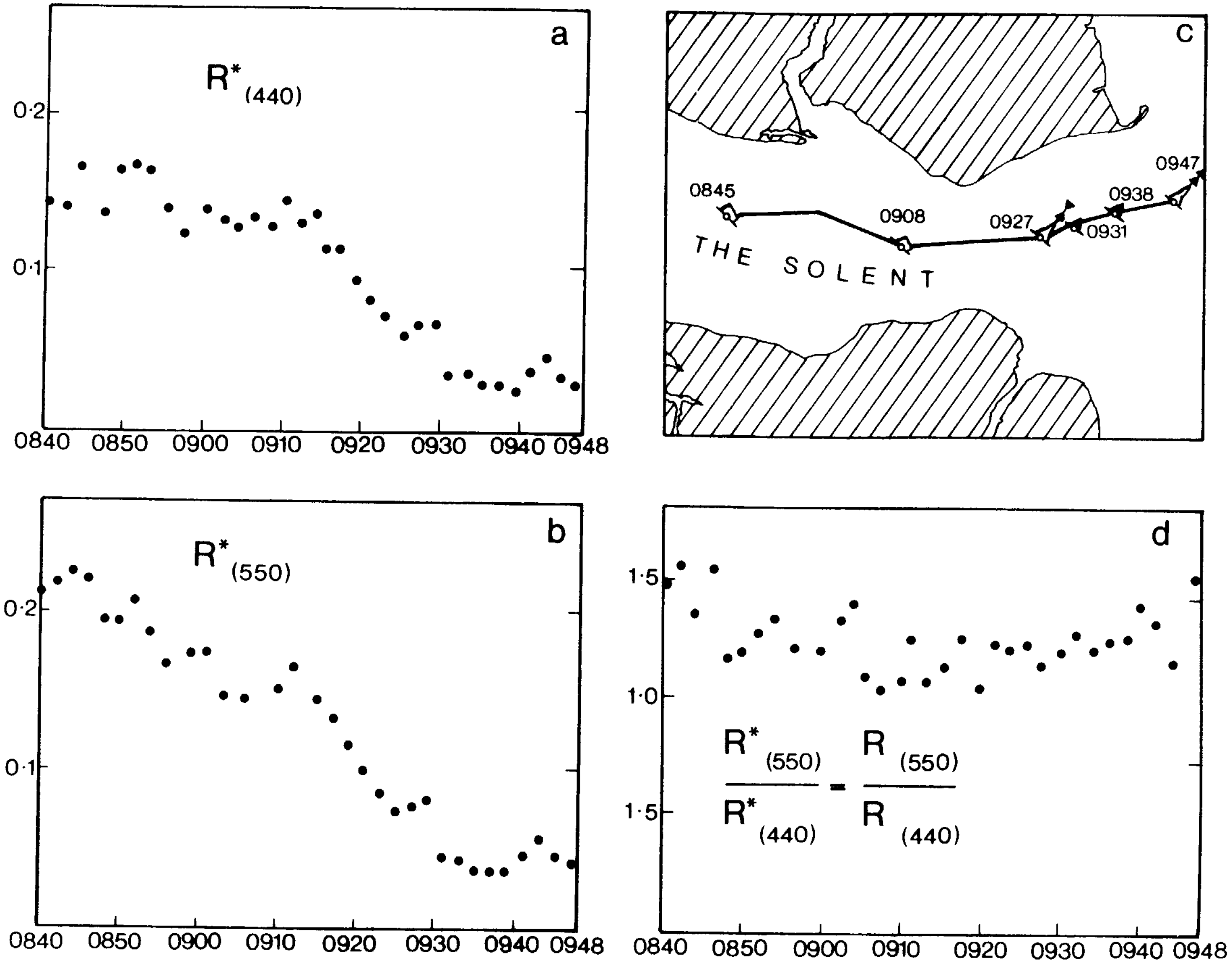

Figure 6 Survey carried out in the Solent along the track shown in (c) on 5 May 1988