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THE MEASUREMENT AND INTERPRETATION OF THE REFLECTANCE OF NATURAL LIGHT IN THE SEA

by Bruce Booty

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ABSTRACT

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THE MEASUREMENT AND INTERPRETATION OF THE REFLECTANCE OF NATURAL LIGHT IN THE SEA

by Bruce Booty

The correlation of the reflectance of light in water with measurements of water quality has become of increasing interest in recent years as it is seen as a key to the possible interpretation of remotely sensed ocean colour data. However, attempts to do this have met with only limited success. There has been a poor level agreement on the values of critical constants used in algorithms, and data collected at sea are characterised by a high level of variance.

The problem has been addressed with particular attention to the measurement of the sub-surface reflectance, R.

Theoretical and practical aspects of the measurement of R have been investigated, a number of optical instruments have been built and a programme of in-water optical measurements has been carried out to test and demonstrate hypotheses. Major sources of error have been identified and methods of overcoming them or limiting the magnitude of their influence have been proposed. A set of criteria for the design of a suitable instrument has been formulated, and both a prototype and a full ocean-going version of an instrument based on those criteria have been designed and built.

Data collected at sea using both versions of the reflectance measuring instrument have been used to develop a discussion of problems and possibilities associated with the interpretation of sub-surface reflectance data.

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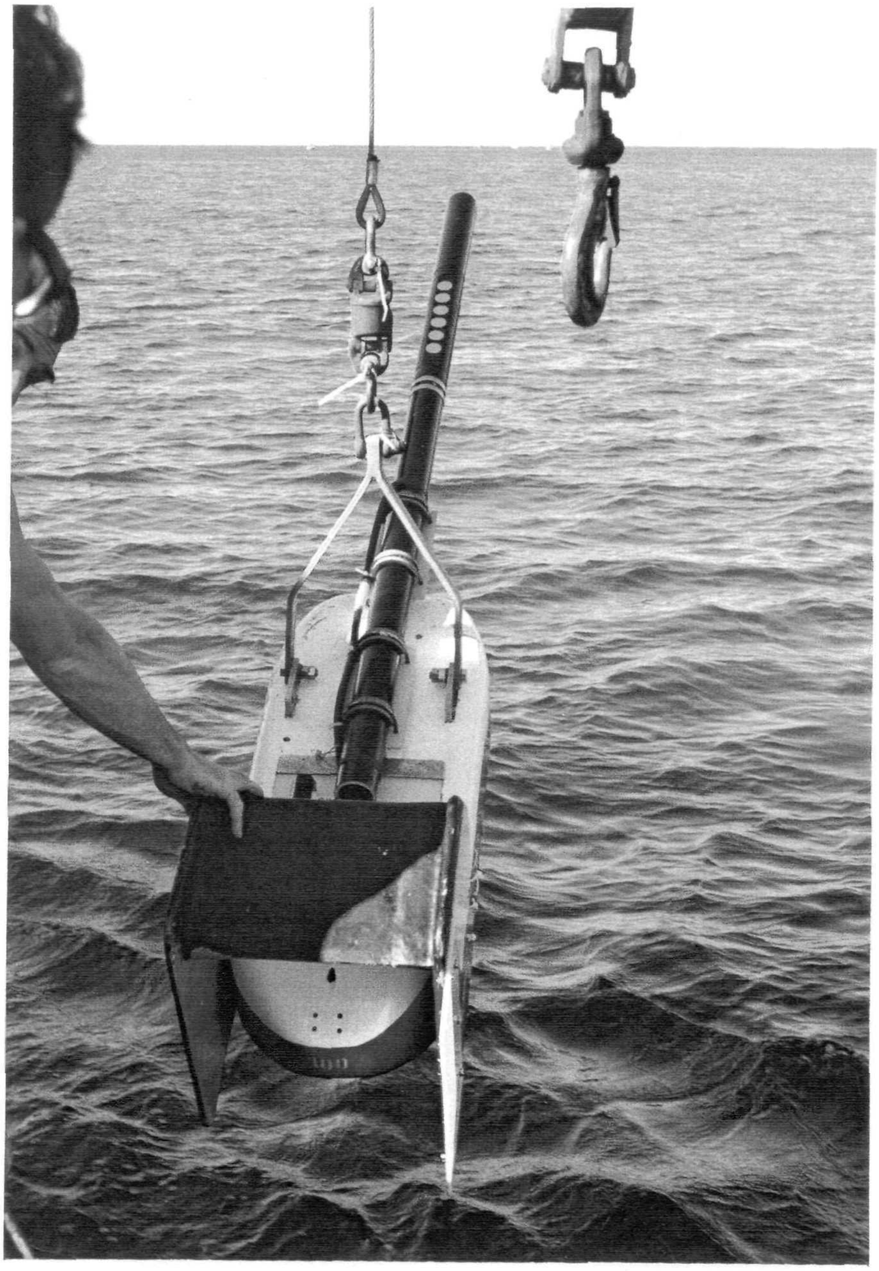


The ocean-going relative reflectance meter mounted on an undulating oceanographic recorder

"The variety of colour of water is no less remarkable than its infinite mobility. Water has its own tint: it reflects and transmits a true shade. But the colour actually seen depends upon the transparency of water, on the nature of the light that it is exposed to, on the nature of the bottom if of any moderate depth, on the angle at which the light falls, and on the objects around, whose colour is also reflected"

from 'The Representation of Water'

Professor Anstead 1863.

MEASUREMENT AND INTERPRETATION OF THE REFLECTANCE OF NATURAL LIGHT IN THE SEA

1. INTRODUCTION AND SUMMARY

The behaviour of light in water is profoundly influenced by materials dissolved or suspended in it. Indeed, the way in which the appearance of a sample of water is altered by the addition of only a minute quantity of an impurity is a matter for common observation. It is therefore not surprising that light, with in addition its ability to penetrate several metres into water, has come to be regarded as potentially a principal tool for the measurement of water quality, even though the complexity of the processes involved, and the difficulties of making optical measurements in water, are considerable. The term "quality" refers here to the degree of contamination of the water by materials of all descriptions.

Water colour is determined by selective scattering and absorption of light by both the water and any impurities it may contain. Ideally therefore, it is those inherent properties of the water sample which should be measured when attempting to assess its quality. This is entirely practicable in the case of a small sample in a laboratory, but not so on a much larger scale, where in-situ measurements in large bodies of water are required, perhaps on a routine basis. However, it is possible that a much more practical approach to the assessment of water quality on a large scale may be through observations of water colour. Such observations are now relatively easy to make using instruments mounted in aircraft or satellites, but there remains the problem of interpreting them.

The observed colour of a water surface is influenced by factors other than just the quality of the water. Surface condition and illumination play a large part. However, any analysis of the contents of a water column by optical methods must be based entirely upon changes which take place in the light during its incursion in the water column. Thus, in attempting to interpret ocean colour data, an important step, and a technique commonly pursued, is the measurement and comparison of light travelling downwards through the water column <u>after</u> it has penetrated the surface (the downwelling irradiance E_d), with the scattered light returning upwards <u>before</u> it leaves the surface (the upwelling irradiance E_u). The ratio E_u/E_d is termed the reflectance or, more commonly when referring to internal reflectance, the reflectance ratio, R. R is crucially dependent upon the inherent optical properties of the water column (see Chapter 2), which vary only with water quality. Thus, this apparently accessible property, R, has come to be regarded as a key to the possible assessment of water quality through optical observations. More specifically, interest lies in $R(\lambda)$, the reflectance ratio at any wavelength λ, which has a direct bearing on the observed colour of the water and hence a direct link to the longer term objective, that of interpreting ocean surface colour in terms of water quality.

In recent years a rapid growth in the quantity of available ocean colour data has given impetus to this line of investigation. Several remote colour sensors have been flown in satellites, notably the Landsat series, and also in aircraft. However, to date, the most comprehensive data sets available are those from the Coastal Zone Colour Scanner (CZCS), which was deployed on the Nimbus 7 satellite. In the seven and a half years following the satellite's launch in 1978, until the scanner was switched off in 1986, data were accumulated on a regular basis with the scanner operating at selected time intervals. The result is a substantial store of data which is still potentially of considerable interest to marine scientists.

With such a large stock of good quality ocean colour data already available, and the technology in place to gather more if required, it is generally accepted that ocean colour data gathering is some way ahead of the development of methods to make full use of them. Thus the quest for meaningful in-situ optical data from the sea, and a better understanding of how those data relate to water quality, is seen to be of increasing importance.

However, the difficulties of interpretation of the sub-surface optical data are considerable, and attempts to do so through considerations of data collected in-situ have so far met with only limited success. Some consensus of opinion has been established regarding a likely form of relationship between organic materials in the water column and measurements of R (see Chapters 2 & 8), although the level of agreement on critical constants is poor, but the same cannot be said regarding the influence of inorganic contaminants in the water column (see Chapters 2 & 9).

A major difficulty in both cases is that the results of field measurements are generally found to be specific to both the site and the circumstances of the measurement. That is to say, there is poor agreement on algorithms for data obtained in different places, at different times and in differing levels of contaminant concentration. In addition, data are frequently characterised by a high degree of variance, certainly higher than would be acceptable in most other physical measurements (see Chapters 2, 8 and 9).

Two basic questions were therefore in place at the start of this work. They were:-

(i) Are measurements of R, using current technology and practices, subject to an unacceptable level of uncertainty, possibly due to factors which have not as yet been fully appreciated, and if so, how might present practices be improved?

(ii) Are the difficulties being experienced in finding working algorithms, due to fundamental flaws in assumptions regarding the meaning of the data and the way in which they are being used?

Both questions have been considered during this study. Part 1 of this thesis (Chapters 3 to 6) is devoted entirely to consideration of question (i). This was the original objective and has been the main focus of attention throughout. Part 2 (Chapters 7, 8 and 9) consists of a <u>discussion</u> of question (ii) above, using as a basis, data and ideas which have been accumulated in the process of the main line of investigation.

The work began with a broad study of contributory factors and associated aspects, in an attempt to put into perspective the magnitude of the problem (see Chapter 2). There followed a study of the measurement problem (see Chapter 3), with the specific objectives of identifying areas of uncertainty and arriving at a set of criteria for the "ideal" instrument. These criteria subsequently became the guidelines for the design and manufacture of a prototype (see Chapter 4) and later, a full ocean going version of the instrument (see Chapter 5).

The main theme of the work, which was an exploration of the measurement problem, was developed through consideration of the factors involved (listed in Chapter 3), the design and manufacture of a variety of instruments (see Chapters 4 & 5), and a series of field trials carried out to demonstrate hypotheses (see Chapter 6).

The prototype (described in detail in Chapter 4) was originally intended only as a device with which to explore ideas and, as such, was built as simply and as cheaply as possible, using mainly available materials and surplus components. In the event however, it proved a remarkably able and useful instrument, and its deployment on a number of cruises has produced a considerable quantity of data. For the most part, these data have been useful only in terms of the development of a measurement capability, that is for purposes of verifying instrument performance and the validity of assumptions made regarding measurement philosophy. However, there are a few which can be associated with in-situ water quality measurements made simultaneously by others, using conventional methods, and these have been gathered together in Part 2 to form a basis for the post-experience discussions on the use and analytical potential of reflectance measurements. Although subsidiary to the main theme, it has been found possible to make a number of points on this aspect of the problem (see Chapters 8 & 9)

The design of an ocean-going relative reflectance meter, which was done in the light of experience with the prototype and taking into account the conclusions arrived at in the course of the measurement study, is regarded as a principal outcome of the work. A limited version of that instrument has already been used successfully during the 1990 Biogeochemical Ocean Fluxes Study (BOFS) cruise in the North Atlantic and, at the time of writing, a second, fully developed version, is being prepared for deployment during the BOFS Antarctic cruise due to take place at the end of 1992.

2. BACKGROUND

This chapter constitutes a summary review of the topic. It necessarily includes brief mention of the longer term remote sensing objective and also a discussion of the environment in which marine optical measurements are carried out, as the former has an influence upon the approach to the sub-surface measurements and, as will be seen later, the outcome of such measurements may be much influenced by the circumstances in which they are being made and by the history of the light before it enters the water column.

2.1 Terms and definitions

Nomenclature and definitions concerning units used in hydrological optics have been standardised to a large extent during the past two decades and in general conform to the recommendations of the International Association for the Physical Sciences of the Ocean (1979), though some differences are to be found in the literature. Definitions of the terms used in this thesis are as follows:-

(i) **Direction** is expressed in terms of a zenith angle, θ, relative to the vertical, and an azimuth angle, ϕ, relative to the vertical plane of the sun.

(ii) **Radiant flux**, Φ, is the rate of flow of radiant energy (watts).

(iii) **Intensity, I,** refers to the radiant intensity, which is the radiant flux per unit solid angle.

$$I = d\Phi/d\omega.$$

(iv) **Radiance, L,** is defined as the radiant flux, Φ, per unit solid angle ω, per unit area, A, perpendicular to the direction of propagation.

$$L = d^2\Phi/dAd\omega.$$

(v) **Irradiance, E,** is the vector radiant flux per unit area at any point in the water column.

$$E = \int_{2\pi} L(\theta,\phi)\cos\theta d\omega.$$

Less commonly, the scalar irradiance, E_o, at any point in the water column may be quoted and this is given by:-

$$E_o = \int_{4\pi} L(\theta,\phi) d\omega.$$

In either case, the suffixes u or d may be used to specify upwelling or downwelling irradiance perpendicular to the surface of the water, whereupon the limits of the integral are -2π or $+2\pi$ respectively.

(iv) **Reflectance, R,** more usually called the reflectance ratio when referring to reflectance **within** the water column, is the ratio of the upwelling to downwelling irradiance.

$$R = E_u/E_d.$$

(v) **Absorption** - The absorption coefficient, **a**, is defined as the proportion of incident flux absorbed by an infinitesimally thin layer of the medium at right angles to the direction of illumination. Thus, a flux $\Phi(0)$ is reduced to $\Phi(r)$ in a distance r according to the relationship:-

$$\Phi(r) = \Phi(0)e^{-ar}.$$

(vi) **Scattering** - The scattering function, $\beta(\theta)$, is defined as the proportion of the radiant flux per unit solid angle, per unit path length, which is scattered through an angle θ. Thus the total flux scattered per unit path length through angle θ will be $2\pi\beta(\theta)\sin\theta d\theta$, and the total scattering in all directions per unit path length, the total scattering coefficient, **b**, is given by:-

$$\mathbf{b} = 2\pi\int\beta(\theta)\sin\theta d\theta, \quad \text{for all angles } \theta.$$

The total forward scattering coefficient and backscattering coefficient are therefore obtained by integrating for values of θ between 0 and $\pi/2$, and $\pi/2$ and π, respectively.

(vii) **The narrow beam attenuation coefficient, α** (often referred to as c) is defined as the proportion of radiant flux lost per unit length from a narrow beam by both absorption and scattering.

$$\alpha = \mathbf{a} + \mathbf{b}$$

(viii) **Vertical attenuation, K**, is the exponential coefficient of reduction of light intensity with depth. In principle, an attenuation coefficient may be determined for radiance, scaler irradiance or vector irradiance. Each will diminish logarithmically with depth but the coefficient will be dependent upon the shape of the sub-surface light field and will therefore be different in each case. Most commonly however, and the case here, K is taken to mean the downwelling attenuation coefficient, $\mathbf{K_d}$, for the exponential decrease of vector irradiance with depth, z, given by:-

$$\mathbf{E(d) = E(0)exp{-}K_dz}.$$

Like α, K_d is an expression of the combined effects of absorption and scattering; the difference being that in the case of K_d only backscattering is effective in decreasing the downwelling irradiance. Hence:-

$$\mathbf{K_d(z) = a(z) + b_b(z)\{1 - R\}}. \quad \text{(Kirk 1983)}$$

(ix) **Optical distances.** Useful derivatives of α and K are the "attenuation length" and the "optical depth" defined as $\boldsymbol{\alpha r}$ and $\mathbf{K_d z}$ respectively. Unit "optical length" is then defined as $\mathbf{1/\alpha}$ and $\mathbf{1/K_d}$ respectively; being the distances in which a narrow beam of light, or downwelling irradiance will be reduced by a factor of e.

N.B. Most of the quantities defined above have a dependence upon wavelength, λ, and where this is significant it will be indicated.

2.2 Remote sensing of ocean colour

As has already been stated in the introduction, current interest in ocean optics is presently largely dominated by a need to achieve a much better understanding of the processes which give rise to the effects seen in the ocean colour data which have been obtained by remote sensing methods.

The basic steps involved in ocean colour sensing are illustrated in Fig. 2.1. A downward looking observer, in this case a satellite or aircraft borne instrument, sees water-leaving radiance, Lw, from the sea surface, resulting from reflection of the natural downwelling irradiance, Ew. At first sight then it would seem that these two parameters were the prime interests. However, both Ew and Lw are subjected to influences which are quite separate from, and only serve to mask, the influence of the water column on the transition of light from one to the other, so it is necessary to look more deeply into what is happening.

The natural light which comprises Ew comes via two routes; from the sun directly, and through scattering from

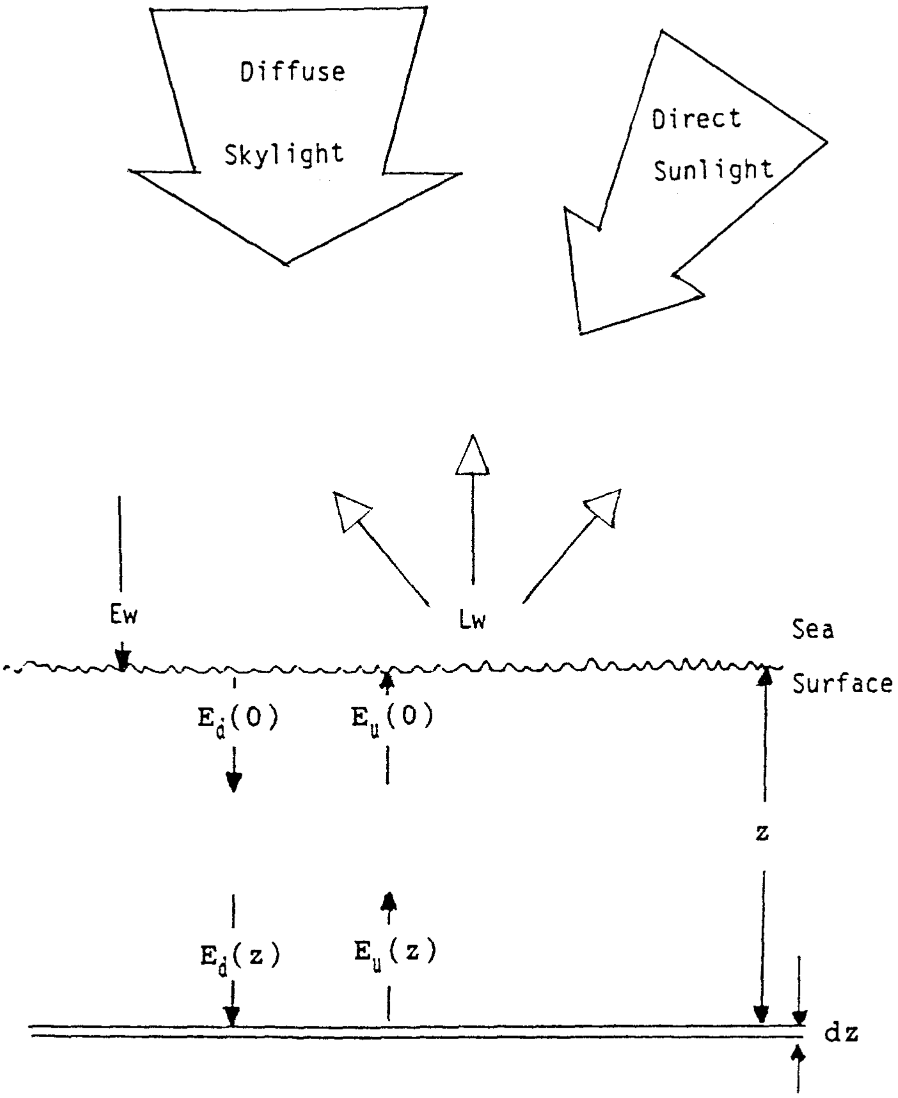


Diagram illustrating the basic stages in the conversion of downwelling irradiance to upwelling radiance.

Figure 2.1

the atmosphere (skylight). The ratio of the two depends upon prevailing atmospheric conditions. On a clear day, a large part of Ew will be unidirectional. On other occasions, the lighting will be more diffuse and the spectrum at sea level will be shifted slightly towards the blue. The directional variability is of particular importance in the context of the measurement of R.

In a similar way, Lw comprises light from two sources. There is that which has an in-water history and therefore carries information about the water and its contents, and that which has been reflected at the air-water interface without entering the water column. The latter of course, contains no such information, but rather is an unwanted background. In addition, a large proportion of the light entering a downward looking sensor will not have come from the sea but will be light which has been back-scattered by the atmosphere before reaching the sea.

Thus, the problems of remotely sensed ocean colour data collection and interpretation fall into two distinct classes. On the one hand there are, what might be loosely termed, information transfer difficulties, involving assessments of the combined effects of the atmosphere and the air-water interface. On the other, there are the problems involved in attempting to assess water quality on the basis of the behaviour of light within the water column. The latter is the main topic under consideration here but, as the former controls the circumstances within which all measurements must be made, it merits discussion.

2.3 Atmospheric considerations

Looked at from the point of view of a remote sensor, it is the atmosphere's effect on light returning from sea level which is the primary interest. Much of what an airborne sensor detects is background in that it originates elsewhere than from within the water column. It has been estimated (Sturm 1981) that, over the sea, between 97%(red) and 64%(blue/green) of all light entering a satellite-borne sensor is likely to be due to scattering of sunlight by the atmosphere (path irradiance), and a proportion of the remainder will be from scatter of skylight from the sea surface (glitter). Detection of reflection at the sea surface of the direct rays from the sun can be minimised by correct synchronisation of the satellite orbit.

For this application then, the process of atmospheric correction consists of estimating the signal due to scattering by the atmosphere and separating it from the wanted signal. The difficulty here is the complexity of the problem, due to the variable and inhomogeneous nature of the atmosphere. However, it has been found possible to obtain a degree of simplification by dividing the problem into two parts; scattering by the air molecules themselves, and scattering by materials suspended in the atmosphere (Gordon et al, 1980, and Smith and Wilson 1980).

The dimensions of the air molecules are small in comparison with the wavelengths of visible light, therefore the scattering by them is Rayleigh type, and their distribution throughout the atmosphere is fairly well understood, so estimating this component is a relatively straightforward matter for the specialist.

The effects of materials in suspension in the atmosphere are very much more difficult to assess. Particle sizes are generally large compared with the wavelengths of visible light, therefore the resulting scattering may generally be considered to be of the Mie type. But they vary in size and there are uncertainties regarding their distribution, so the problem is one of considerable complexity. However, progress has been made and empirically derived algorithms for atmospheric aerosol corrections have been developed. Useful summaries can be found in Robinson (1985) and Sturm (1985).

In addition, there is a degree of absorption by both components to take into account, but the effect of this is small in comparison with the scattering.

More relevant to the case in hand, where measurements are being made below the sea surface, are the effects of the atmosphere on solar radiation <u>before</u> it reaches sea level. The sun behaves approximately as a black body, obeying Wein's Law, with a surface temperature of about 6000K, and a maximum energy per unit wavelength at about 480nm. The visible part of the spectrum constitutes some 40% of the whole energy flux. The earth's atmosphere reduces and modifies that radiation, both spectrally and directionally, by selective absorption and scattering.

On a clear day, strongly wavelength-dependent Rayleigh scattering by air molecules predominates, giving the characteristic blue sky. The proportion of skylight to direct sunlight is determined by the atmospheric path length which, in turn, depends upon the sun's altitude. With the sun at a very high altitude, direct sunlight is likely to comprise some 70-80% of the total insolation at sea level. In very clear atmospheric conditions, this figure can be as high as 90%. With the sun at a low altitude, the proportion is likely to be nearer 50% (Kirk 1983). This leads to the important point, that changes in solar elevation result in variations, not only in the overall light intensity, but also in the structure of the illumination. This is a feature which, as will be seen later, is of considerable consequence in the making and interpretation of in-water optical measurements.

In less clear conditions, contamination of the atmosphere by dust and water vapour produces scattering which is largely of the Mie type. Mie scattering is less wavelength-dependent and has a characteristic longitudinal pattern, with a relatively small transverse component. Thus its effect is mainly to reduce intensity by scattering a proportion of the light back into the atmosphere, rather than to modify the radiance or spectral distribution.

A further important atmospheric factor, certainly the most obvious one to a casual observer, is cloud cover. Very thick cloud can reduce surface insolation by as much as 90% (Monteith 1973), though surprisingly, in some circumstances, cloud can actually increase the overall level of illumination at the sea surface, provided that it does not obscure the direct sunlight. Apart from its effect on intensity, cloud cover is an important factor from the measurement point of view, in that it renders the illumination diffuse to a very large degree. However, even the most complete cover does not render it entirely so. Radiance from the direction of the sun is always greater than that from the opposite horizon by a factor of at least three (Monteith 1973).

Broken cloud, which causes substantial and sometimes frequent changes in both the intensity and the structure of the surface illumination, presents a special problem and, as will be seen in subsequent chapters, one which is particularly difficult to handle from the point of view of the strategy of sub-surface light measurements.

Thus, the atmosphere, with its variability and uncertainties, acts in a complex way to create sets of sea-level illumination conditions, each of which must be regarded by a measurer as specific to the time and place.

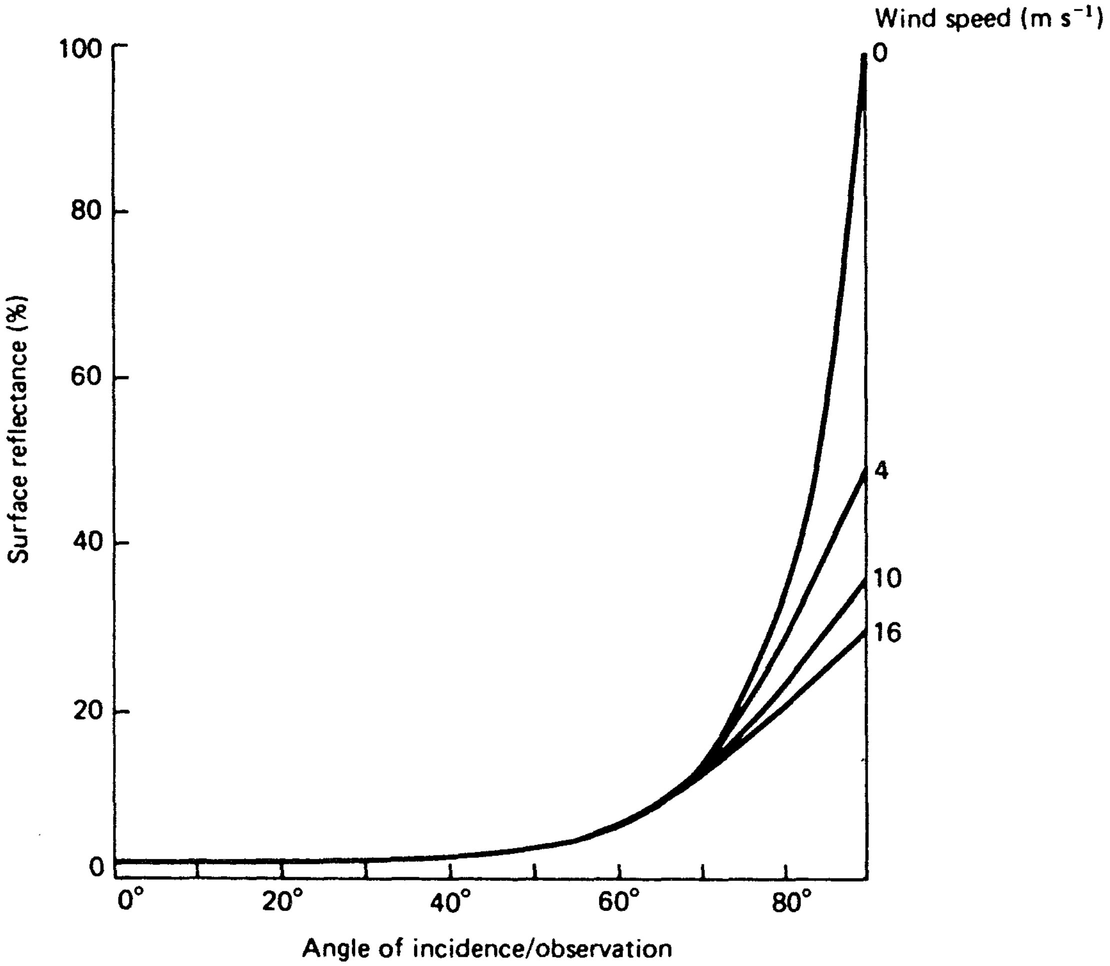
2.4 The air-water interface

Quantification of the air-water interface effects is a similar problem to that presented by the atmospheric effects in that, whereas the underlying physical principles are well understood, the complexity and wide variety of circumstances possible, make this also a very difficult factor to handle in general open water measurements.

On a perfectly calm day (a rare occurrence) reflection of the direct, parallel radiation from the sun by the smooth, flat surface of the sea, can be calculated using Fresnel's equations. These give fairly low values, say 2% - 6%, for angles of incidence up to 60° or so, but above that, reflectance increases rapidly to become 100% at a grazing incidence. Under the same surface conditions, reflectance for diffuse radiation is only slightly more difficult to calculate in that it is a summation of the reflectances for all angles of incidence between 0° and 90°. In the case of a perfectly diffuse light field, this has been shown to be 6.6% (Burt 1954). Using the same assumption, Preisendorfer (1957) has calculated a total reflectance of 5.2% for a cardioidal distribution of sky radiation. Thus, even in smooth water conditions, the reflectance at the surface is hard to assess, as it requires first an assessment of the composition of the illuminating light field. Computation of the downward surface reflectance for upwelling light is slightly simplified by the fact that it may be assumed to be composed largely of diffuse radiation.

In anything other than perfectly smooth water conditions, the problem becomes a great deal more difficult. In the presence of surface waves, the transmission of light through the surface in both directions is increased. Le Grand (1939) noted that, where there are waves, the average angle of incidence will be decreased for high solar elevations and increased for low elevations. This has little effect on the reflection at high elevations but substantially reduces it at low elevations. This is clearly to be seen in a plot of data from Gordon (1969) and Austin (1974), which appears in Kirk (1983) and is reproduced here as Fig. 2.2. Priesendorfer and Mobley (1986) have computed values of r+ and r-, the reflectance on either side of a sea surface as a function of wave height and noted how, within limits, the sea surface acts as "a wind driven radiometric valve to radiant energy", altering the surface reflectivity by up to 30%.

Superimposed upon the surface reflectance are the effects of refraction at the surface. The air water-interface is a boundary between two different optical densities and light passing through it, in either direction, will therefore be subject to Snell's Law which, assuming a mean relative refractive index of 4/3, means that the direction of all downwelling light just below the surface will be compressed within a cone with a half angle of about 49°. Thus an observer, or instrument, looking upwards through a smooth surface will see the downwelling light apparently concentrated into a bright circular patch, the so called manhole effect. This is a further structuring component on a downwelling light field already made asymmetric by circumstances of surface illumination.



Reflectance of water surface as a function of zenith angle of light (incident from above), at different wind speeds (data of Gordon J I and Austin R W) After Kirk 1983.

Figure 2.2

Significant roughening of the surface complicates the picture further as waves form lenses to break up and focus the light into complex patterns.

Thus the light field just below the surface will have a complex structure, determined by a number of factors which can never be considered "standard" or "average".

2.5 Sub-surface

Here again, a brief inspection of the behaviour of light in water reveals the fact that it is one of considerable complexity but, as with the atmosphere, the complexity comes about through a number of permutations of relatively well understood processes. In fact only two processes are possible, absorption and scattering. To an observer above the surface, all the information that is available are measurements of light entering the water and corresponding measurements of light leaving the water. If this information is to be used to analyse water quality through the determination of the optical properties of the water column, it is obviously necessary to eliminate all influences on the light other than those due to the water column and its contents. Thus measurements made just below the surface, of the ratio of reflected light returning up through the water column, the upwelling irradiance Eu, to light proceeding downward through the water, the downwelling irradiance Ed, are of considerable interest.

Recorded interest in this "reflectance ratio", its applications and its relationship with the inherent properties of absorption and scattering, go back at least to the early part of this century. Gamburtsev, in 1924, (quoted in Gordon and Morel 1983) for example, developed an expression for the relationship between the reflectance ratio, R, and the scattering and absorption coefficients, a and b respectively. This is not at all a straightforward matter. However, if we simplify the situation by assuming that the water column is homogeneous and the possibility of multiple scattering can be neglected, a relationship between R, the backscattering coefficient and the vertical diffuse attenuation coefficient can easily be deduced as follows:-

At any depth z (see Fig. 2.1), the downwelling irradiation $E_d(z)$, resulting from an initial sub-surface irradiance $E_d(0)$, is given by:-

$$E_d(z) = E_d(0)e^{-Kz} \text{ ....(i)}$$

where K is the vertical diffuse attenuation coefficient.

The upwelling irradiance at z, $E_u(z)$, due to backscatter in a thin layer dz, is then given by:-

$$E_u(z) = E_d(z)b_b dz \text{ ....(ii)}$$

where b_b is the backscatter coefficient.

By the time it reaches the surface, the small amount of irradiance due to scattering in dz will have been reduced by diffuse attenuation to:-

$$E_d(z)e^{-Kz}b_b dz = E_d(0)e^{-2Kz}b_b dz \text{ ....(iii)}$$

The total upwelling radiance just below the surface, will then be given by:-

$$E_u(0) = E_d(0)\int e^{-2Kz}b_b dz \text{ ....(iv)}$$

which, when evaluated for all values of z and divided by $E_d(0)$, gives the surprisingly simple result:-

$$R = \frac{1}{2}\frac{b_b}{K} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (v)$$

The vertical diffuse attenuation coefficient K, is an apparent property, related to the inherent absorption coefficient, a, but also involving the scattering function, $\beta(\theta)$, which is specific to the circumstances. To obtain an expression for R in terms of b_b and the inherent property a, is therefore not so straightforward and it is a problem which has received considerable attention.

Duntly (1942), developing upon Gamburtsev's expression, derived a relationship:-

$$R = \frac{1}{2}\,\frac{b_b}{a(1 + b_b/a)} \quad \ldots\ldots\ldots\ldots (vi)$$

which, bearing in mind that b_b may usually be expected to be very much smaller than a, is perhaps not sufficiently different from the rather too simple expression developed above to account for measured differences between a and K (see for example Jerlov 1974).

In more recent times there have been a number of approaches to the problem. Gordon et al (1975) carried out computations of radiative transfer in the ocean, having regard for various conditions of illumination. Their results, when fitted to the Gamburtsev-Duntley type expression:-

$$R = N\,\frac{b_b}{a(1 + b_b/a)}$$ gave values of N ranging from 0.32 for a sea whose surface is illuminated by

a high altitude sun on a clear day, to 0.37 for completely diffuse illumination.

Another approach, based on calculations of successive scattering events (Prieur and Morel 1975), has produced a similar relationship:-

$$R = 0.33 \frac{b_b}{a(1 + \Delta)} \quad \ldots\ldots\ldots\ldots\ldots(vii)$$

where Δ is a second order term dependent upon the sub-surface radiance distribution and is always very small.

In any particular case, of course, a definitive relationship could be obtained using (v) if the value of a/K were known for that specific set of circumstances. But that requires a knowledge of the radiance distribution which is dependent upon the scattering function, $\beta(\theta)$, and the conditions of surface illumination, which will normally be varying continuously.

To obtain a complete description of the radiance distribution at any point in the water column is not a simple task, and to monitor it in a real ocean situation is almost certainly an unrealistic objective at present. However, there is a method of expressing, or rather summarising, the structure of a light field. This is the concept of the average cosine, μ. This is simply the sum of the products of radiance in any direction and the cosine of that direction relative to a reference direction, divided by the total radiance in that part of the light field. Thus the average cosine for downwelling light, μ_d, for example, is given by the product of the radiance and the cosine of the zenith angle, ie $\int L(\theta\phi)\cos\theta d\omega$, for all elements of solid angle $d\omega$ in the upper hemisphere at the point in question, divided by the total downward radiance at the point, which is of course E_{0d}, the downward scaler irradiance.

$$\mu_d = \frac{\int L(\theta\phi)\cos\theta d\omega}{E_{0d}} = \frac{E_d}{E_{0d}} \quad \ldots\ldots\ldots\ldots(\text{viii})$$

and hence μ_d can be measured by using a scalar irradiance detector pair (Hojerslev 1975) together with a cosine detector pair. Following on from this it can be shown that:-

μ = a/K (Preisendorfer 1961).

There have been numerous measurements of both K and a, and a study of these shows that the range of ratios between the two is remarkably small in a wide variety of sea waters. Jerlov (1974), quoting measurements by Jerlov, Nyggard, Lenoble and Hojerslev, has tabled values of between 0.6 and 0.75 for the ratio a/K. Taking the mean of these and inserting it into equation (v) gives:-

$$R = \frac{1}{3}\frac{b_b}{a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(\text{ix})$$

which is presently accepted as a good working approximation if such is needed.

N.B. Both b_b and a are wavelenth dependent.

In the context of the present consideration, the foregoing serves mainly to emphasise the fact that there is a relationship between the reflectance ratio, R, and the inherent optical properties of the medium of the form-

$$R(\lambda) = F(Q,\beta)\frac{b_b(\lambda)}{a(\lambda)} \quad \ldots\ldots\ldots\ldots(\text{x})$$

The suffixes (λ) and (Q,β) indicate dependencies upon wavelength, radiance distribution and scattering function.

2.6 The influence of water quality upon optical parameters

There are two fundamental questions to consider in this context:-

(i) To what extent will the inherent optical properties of a water column be influenced by materials suspended or dissolved in it?

(ii) Can those materials be detected, identified and possibly quantified through optical measurements?

To answer the first question it is necessary only to look at some of the wealth of relevant data available. See for example Jerlov (1968) and Kirk (1983).

Absorption of light by pure water takes place mainly at longer wavelengths, where bands corresponding to small integer harmonics of the O-H bond exist. In the spectral range of practical interest, that is within the accepted water-window, absorption is small. Not many measurements have been made, due mainly to the extreme difficulty of obtaining and maintaining samples of very pure water, but those by Clarke and James (1939) (listed in Jerlov (1968)) give values for a of between 0.02 and $0.2m^{-1}$ for wavelengths in the range 400 to 600nm. They equate to transmittances of between 98% and 83% per metre. Later measurements by Smith and Baker(1981) agree quite well with Clarke and James' data. The addition of sea salts to pure water seems to have little influence. Certainly Clarke and James reported no significant change in attenuation with the addition of salts, and their findings have been confirmed by subsequent measurements (Sullivan 1963).

Scattering by pure water is explained by the fluctuation theory of Smoluchowski (1908) and Einstein (1910), which attributes the scattering to minute variations in the density of the water, creating domains which act as scattering centres. The expression derived is Rayleigh-like in that it indicates a λ^{-4} dependence, and its validity has been confirmed by measurements (Morel 1966). Here again though, values are small, more than an order of magnitude lower than the absorption in the range of wavelengths of interest. In the case of scattering however, the addition of sea salts is seen to have an effect. Values of b quoted in Morel (1974) are some 30% higher for pure sea water than for pure water.

It is plain to see from the profusion of data available, that the addition of the materials of all types which natural waters contain, profoundly affect their optical properties. Measurements of both a and b have been made at numerous locations throughout the world (see for example lists in Jerlov 1968 and Kirk 1983). In all cases, both coefficients are seen to be substantially larger for natural waters than for pure water, in many cases orders of magnitude larger. Consequently, it is reasonable to assume that assessments of these properties by optical methods, perhaps through the relatively accessible sub-surface reflectance ratio, is potentially a useful method of measuring water quality.

2.7 Water quality assessment through optical properties

Questions relating to the exploitation of the analytical potential of optical measurements in water have received a great deal of attention but, although there has been progress in some respects, some basic questions remain largely unresolved. Indeed there is a school of thought that is doubtful of a full and satisfactory resolution of some present difficulties. Smith et al (1974), for example, comment "to fully extract all the information concerning characteristics of particles in the sea (by optical methods) would require precise measurements of a, b and $\beta(\theta)$, and a full understanding of the Mie scattering theory as it applies to specific situations". Kirk (1983) expresses the opinion that "..all embracing analytical relations expressing the characteristics of the (sub-surface light) field in terms of the optical properties of the medium have not yet been derived. Given the complexity of the shape of the scattering function in natural waters, it may be that this will never be achieved".

Additional to the reservations above, the point is made here that the basis of any system of identification and quantification of materials in the water column by optical methods must be the effects those materials have upon the inherent optical properties of the water column.

If it is not possible to single out specific optical effects due to specific materials, then it will not be possible to develop a satisfactory optically-based analytical technique.

Thus, a great deal of attention has been given to the study of the influences which various suspended and dissolved materials have upon the optical properties of the water column and, bearing in mind the remote sensing objective, in particular upon the ratio $R(\lambda)$.

Jerlov (1968), citing values of a and b due to Clarke and James (1939), and LeGrand (1939), concluded that, while both are wavelength dependent in pure water and also in pure sea water, and absorption by suspended materials shows some wavelength dependence, scattering by suspended materials is largely independent of wavelength. However, more recent studies have shown that summary to be incorrect. In particular, absorption by organic material has been found to be strongly wavelength dependent and, to a lesser extent, scattering also. Measurements have shown that $a(\lambda)$ and $b(\lambda)$ vary significantly with phytoplankton cell size and concentration, eg Morel and Prieur (1977), Morel and Bricaud (1981) and Bricaud et al (1983). Thus, for organic materials in so called Case 1 waters, that is water containing only organic material, the development of a worthwhile optical analytical capability seems entirely feasible.

The organic materials responsible for the selective absorption of light in water fall largely into two groups. There are the photosynthetic pigments of the phytoplankton, which show marked absorption peaks at around 450 and 680nm and a minimum at around 560nm (Morel and Prieur 1977) and there is also a variety of substances, commonly called 'yellow substances' or the German 'Gelbstoff', which are the products of organic decay. The latter absorb strongly in the blue end of the spectrum but their absorption falls off rapidly at longer wavelengths.

This wavelength dependence has been exploited in many attempts to relate spectral reflectance to the type and quantity of organic materials in water. In particular, a technique based on the comparison of two reflectance ratios at selected wavelengths (possibly originated by Clarke et al 1970), has shown promise. Morel and Prieur (1977), for example, plotted the ratios of reflectances at 440nm and 560nm, $R_{(440)}/R_{(560)}$, as a function of chlorophyll concentration, Chl, and concluded that there existed a relationship of the form:-

$$Chl = A(R_{(440)}/R_{(560)})^B$$

where A and B are constants.

There have been many attempts in recent years to produce algorithms based on the above expression, eg Morel (1980), Clark (1981), Smith and Baker (1982), Carder et al (1986), Mitchelson et al (1986), Aiken and Bellan (1986) and others. They have been successful to a degree but algorithms are generally found to be site specific, with no general agreement on values for A and B.

This inconsistency may well be due to variations in species, size and density distribution, but there is evidence too, that the addition of inorganic material in the water modifies relationships. Topliss et al (1989) lists values of A and B which have been obtained at various sites, taking particular care to include only those which were specifically stated by their authors to have been obtained in Case 1 waters, that is waters which contain only organic materials derived from primary production (Morel and Prieur 1977). The constants in this Table show a greater degree of agreement than is found in more general lists. This is in line with the findings of other observers who have tackled the problem of chlorophyll quantification in the presence of inorganic sediments (eg Walter and Schuman 1985) and found them to considerably increase the uncertainty in the chlorophyll estimate.

There have been alternative approaches to the problem. A "spectral curvature" algorithm, (Grew 1980), based on the shape of the curve of irradiance reflection plotted as a function of wavelength between 460 and 521nm, has been used with some success by Campbell and Esaias (1983). The detection of the solar stimulated in-vivo fluorescence of chlorophyll has also been used for the purpose (Neville and Gower 1977, Gower 1980, Gower and Borstad 1981). Lin et al (1984), studying reflectance spectra in coastal waters, detected peaks at 682, 692 and 710nm and were able to show good correlations between their amplitude and chlorophyll concentration measurements. Thus, while in no way yet a precise science, the optical characterisation of water masses in terms of their organic content, is clearly a possibility.

The situation as regards inorganic materials is presently far less promising. There can be no doubt that the addition of quantities of inorganic material influences the optical properties of water profoundly. This is, if nothing else, a matter for common observation. However, attempts to correlate reflectance ratios to suspended inorganic sediment loads in 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, (Morel and Prieur 1977), have not been generally successful.

There are good reasons for supposing that this will be the case. Particle sizes are generally large in relation to the wavelength. Hence, the scattering caused by them will be of the Mie type, ie mainly in the forward direction. Much of the reflected light in Case 2 waters may therefore be expected to be due to scattering by the water itself. This has been established by Kullenberg (1968) who found that, while density fluctuations accounted for only between 3% and 11% (depending on wavelength) of all scattering in a sample of Case 2 water, it accounted for almost 90% of all backscattering. Thus, any reflectance ratio "signature" is likely to be characterised by the absorption component of the ratio.

In practice, the real difficulty is again the complexity and variety of possible circumstances. Particle size for example, might be anything from sub-micron to millimetre, with a distribution which is determined by bed characteristics, cohesivity of sediments and current velocity. Concentrations can be as low as 0.01 ppm in a deep ocean or more than 50,000 ppm in a fast flowing estuary (Gibbs 1974). In addition, particle shape, colour and refractive index are all features which have been shown to influence the optical characteristics of the hydrosol (Smith et al 1974, Holyer 1978, Bukata et al 1981, Whitlock et al 1982, Curran and Novo 1988, and others). Nevertheless, a number of suspended sediment algorithms for remotely sensed reflectance data have been formulated. A representative list is contained in Curran and Novo (1988). Here again, as with Case 1 waters, and not surprisingly in this case, there is no general agreement between formulations for different locations.

Some useful data in terms of progressing towards an understanding of the problem has been obtained from laboratory experiments, though it is generally recognised that it is impossible to properly simulate open water conditions in a laboratory. A feature which is common to much of the data, both laboratory and field data, is the asymptotic shape of curves relating reflectance to suspended sediment load. Bently (1987) for example, found a plateau commencing at about 70mg/l. Measurements by Novo et al (1989) show a similar shape with the asymptote at a slightly higher concentration. Others, Scherz (1972) and Scherz and Van Damelon (1975) for example, put the commencement of a plateau much lower at only 2 - 5mg/l. In some cases, results show a very much less marked inflection (Munday and Alfoldi 1979, and Khorram 1985) suggesting that the relationship may be logarithmic at higher concentrations. However, there can be no doubt that evidence exists to indicate that there is a possibility that the usefulness of optical methods may be limited to low concentrations in the case of inorganic sediments.

This topic will be considered in greater detail in Chapters 8 and 9, which make use of data collected in the course of the work described here.

2.8 Summary

The gathering of remotely sensed ocean colour data has become a relatively straightforward process, but abilities to make use of the data are still limited. The potential of optical methods for the identification and quantification of organic materials in large expanses of natural water has been established and is generally accepted, but the same cannot yet be said in the case of inorganic materials.

Much of the difficulty is undoubtedly due to the variety and the complexity of the possible combinations of the processes involved, though each individual process is well understood. However, as will be seen in Chapter 3, it is true also that practical difficulties associated with making in-situ optical measurements still present considerable obstacles to progress in the field.

PART I

The Measurement of R

Chapters 3, 4, 5 and 6, are devoted entirely to problems and possibilities associated with the measurement of R; question (i) in Chapter 1. The question of what exactly is being measured by a submerged light sensor has been addressed. Deficiencies in standard practices have been identified and demonstrated, and methods to overcome or avoid some of the difficulties have been proposed. A set of instrument criteria has been formulated and instruments incorporating those criteria have been built and used at sea.

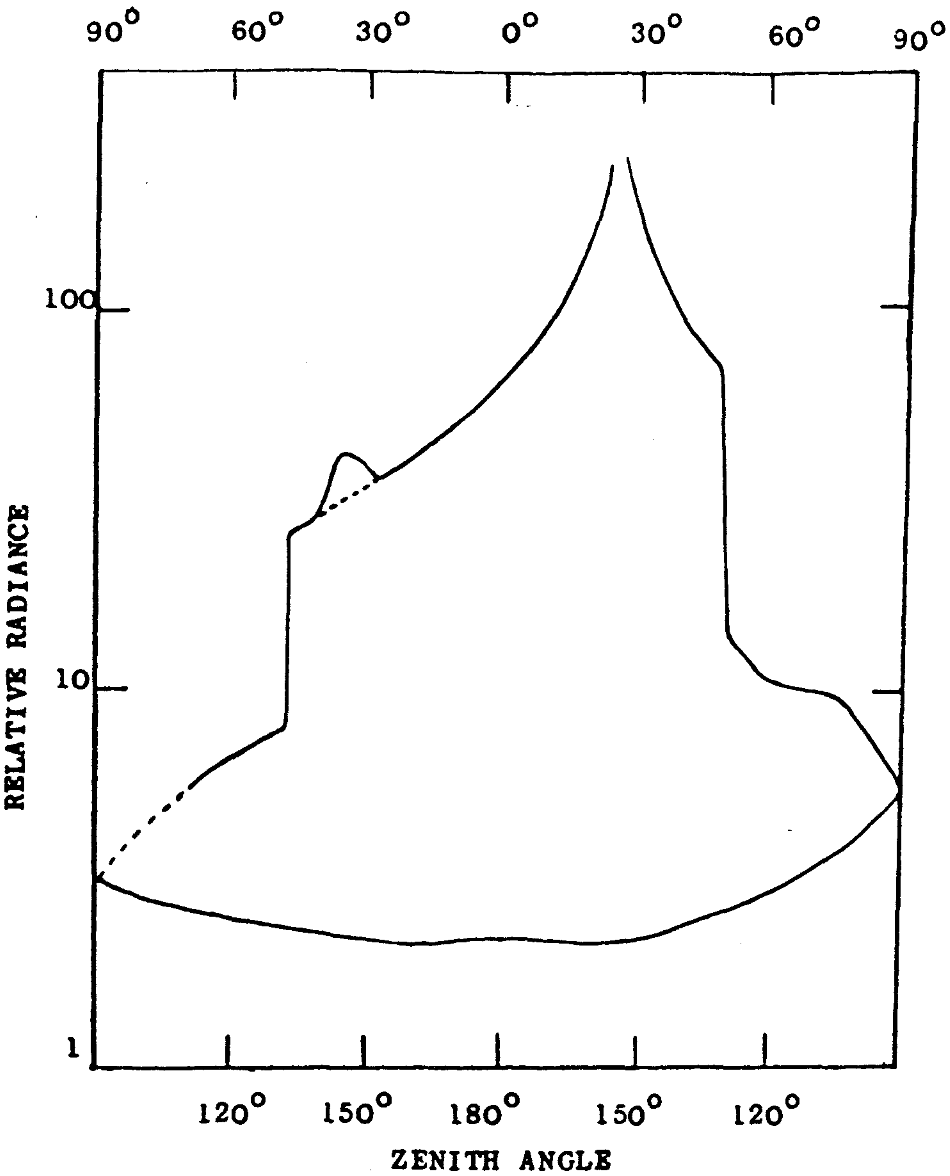
3. THE MEASUREMENT PROBLEM

It is important to keep in mind that the problem which is being addressed here is not simply that of measuring R in a stable environment. The ultimate objective is the interpretation of remotely sensed ocean colour data, and that will require measurements to be made as close as possible to the surface, where there are difficulties additional to those encountered at greater depths.

When considering how best to set about measuring R, the simple concept of two sub-surface light sensors, one pointing upwards to measure downwelling irradiance, E_d, and another, in the same plane, pointing downwards to measure upwelling irradiance, E_u, seems sound in principle, but in practice, the method is fraught with inherent difficulties. Some of the difficulties are obvious, some become apparent in the designing of an instrument and others are in danger of being overlooked altogether. This chapter will be devoted to considerations of the practical constraints and uncertainties associated with the measurement.

3.1 The sub-surface light field

This is the greatest cause of uncertainty. The sub-surface light field in any body of open water subjected to natural illumination, is both asymmetric and variable to a high degree. The polar diagram shown in Fig. 3.1 is typical of what is to be expected when high resolution sub-surface radiance measurements are made in calm water.



Radiance distribution in an upper layer of the sea
(after Smith 1974)

Figure 3.1

The Figure shows a peak of downwelling radiance in the direction of the main source of illumination. On either side of this, the downwelling radiance falls in a smooth way due to the combined effects of the cosine of the angle, the increasing water path length and surface reflection, until the edge of a circle, which subtends an angle of about 49° to the observer, is reached. This is the critical angle, beyond which, due to refraction, no direct illumination from above the surface is possible. At greater angles, the radiance, which can then come only from light scattered within the water column, drops off very sharply. Looked at from below, the effect is of a bright disc of light vertically above the observer (the so-called "manhole effect", familiar to divers), brightest at one point and surrounded in all directions by a relatively featureless, diffuse light. The radiance curve for the upwelling direction shows no such structure; the light field being diffuse and very much more symmetrical about the z axis.

With cloud cover, the then diffuse surface illumination will produce a less pronounced peak in the downwelling radiance. As has already been mentioned in Chapter 2, there is in any cloudy sky, no matter how thick or complete the cloud cover, a distinct brightness peak in the direction of the sun, so some asymmetry is always to be expected, unless the sun is directly overhead. The manhole effect will be present, whatever the circumstances of the surface illumination.

It should be stressed that the foregoing presents a picture of a flat water situation. In normal ocean circumstances, and particularly in this application where measurements are being made close to the surface, the distribution will be modified by surface roughness.

However, the essential features mentioned will always be present.

From an instrumental point of view, surface irregularities are likely to be important, especially in view of the fact that their effect is mainly upon the downwelling light field. Small waves can create lenses which may focus the downwelling light in such a way as to introduce high frequency temporal variability and even the possibility of momentary instrument saturation in near-surface measurements. The passage of long waves across the measurement area will result in a relatively slow transition of distortion of the downwelling light field as the surface angle to the normal varies, and the <u>shape</u> of the downwelling light field, as will be seen later, can have a profound influence on the measurement of R.

The greater the depth, the less pronounced these surface condition effects will be, because the downwelling light will become progressively more diffuse as the depth increases. However, in the context of the essentially near-surface measurements under consideration here, the effects of surface irregularities are a consideration.

3.2 Instrumental response

There are two characteristics of any light detector which together determine its output in any given set of circumstances. They are its spectral response and its light-collecting geometry.

No sensor will have the same response to all wavelengths. The commonly used silicon diode for example, is considerably more sensitive at the red end of the visible spectrum than it is at the blue end (see Fig. 4.5). This, coupled with the fact that the optical properties of natural waters are also wavelength-dependent, may produce results which are hard to interpret, or even misleading, if the relative spectral dependencies are not taken into account. This is mainly a problem for broad-band instruments used in absolute measurements. A common way of dealing with the uncertainty in those cases where spectral characteristics are not under investigation, is to use a blue/green filter, such as a Wratten 45, to restrict the operation of the instrument to the "water window" (the section of the visible spectrum which is most readily transmitted through the water), thereby reducing the degree of uncertainty on measurements at varying water depths (see for example Booty 1974 and Cocking 1976).

A knowledge of the light-collecting geometry of sensors is also crucial to the understanding of what is being measured. An attempt to demonstrate the importance of this has been made by considering the effects of varying the optical geometry in the particular case of the radiance distribution shown in Fig. 3.1. This was done by digitising the distribution at 2° intervals and determining ratios of the areas of the lower to upper parts of the distribution after weighting with various sensor geometries. The most interesting conclusions of the exercise were:-

(i) Assuming perfect cosine collectors (optical windows which result in a detector response proportional to the cosine of the angle of incidence of the incoming light), the ratio of the lower to the upper area is 3.2% (analogous to the irradiance ratio).

(ii) With perfect hemispherical collectors (optical windows which give a detector response which is independent of the incident angle of the incoming light), the ratio is 5.1% (analogous to the scalar irradiance ratio).

(iii) Using either (i) or (ii) would give results which are substantially insensitive to pitch or roll of the instrument. An axis tilt of 10^0 from the horizontal, for example, changes the area ratio by a maximum of 2% (depending which way it is tilted) in the case of the hemispherical collectors and, in the case of the cosine collectors, by a maximum of 0.3%. Thus, the tests indicate that there is a fair degree of tolerance in the "flying" attitude of an instrument for measuring vector irradiance.

(iv) Ratios of narrow angle sensor readings (a radiance ratio) would be extremely dependent upon deployment angle.

It is not suggested that the ratios quoted above are values of R, nor that the exercise represented in any way a proper analysis of the situation. The calculations are based on a two-dimensional representation of a three-dimensional distribution. It is mentioned here simply as a demonstration that ratios obtained using different optical geometries will differ substantially, and that it cannot be assumed that simply because two in-water light measurements, one upwelling and one downwelling, are made with the <u>same</u> sensor, the ratio between them is absolute and could be repeated using another sensor in the same way. Tyler and Smith (1966) mention the possibility of "undesirable and unsuspected systematic errors" which may occur if the optical geometry of a system is not fully understood and taken into account in the measurement of sub-surface light.

In principle, the problem of comparing different and varying radiance distributions is resolved if it can be said with certainty that the detectors are measuring true vector irradiance in each case, that is if they have perfect Lambertian (cosine) collection characteristics, and a reasonable approximation to a cosine collector is not too difficult to make. Almost any diffusing material with a flat surface gives a cosine-like response, but will generally deviate from a perfect cosine collector due to an edge effect. This is commonly recognised, and attempts to approach a perfect cosine collector by careful attention to the design of the edge of the window have been made. Some have been very successful (Boyd 1951, Austin and Loudermilk 1968, and Smith 1969). It should be mentioned however, that designs have been arrived at by iterative adjustment.

One further point which should be mentioned in this context is the immersion effect. The change in index of refraction which takes place between window and medium when an instrument is immersed in water will have an effect on the detector's response. This is due to a change in the amount of light being scattered back into the medium (Westlake 1965). The effect is wavelength-dependent, so it will alter a sensor's spectral response. Data on tests of the immersion effect in Smith (1969) indicate an in-water response reduction of between 20% and 28% for a cosine collector operating in the visible range, diminishing to 5% in the UV. This will not affect comparative measurements, providing such measurements are not made within a few collector diameters of the surface (Tyler and Smith 1966 and Smith 1969), but it is mentioned here as one of the several factors which combine to create the level of uncertainty which makes <u>absolute</u> sub-surface light measurements so difficult to achieve.

3.3 Temporal variability

In any real ocean situation, it may be expected that changes in the local sub-surface light intensity will be frequent and substantial. Some data from Goldberg et al (1984) is included here (Fig. 3.2) to illustrate the point.

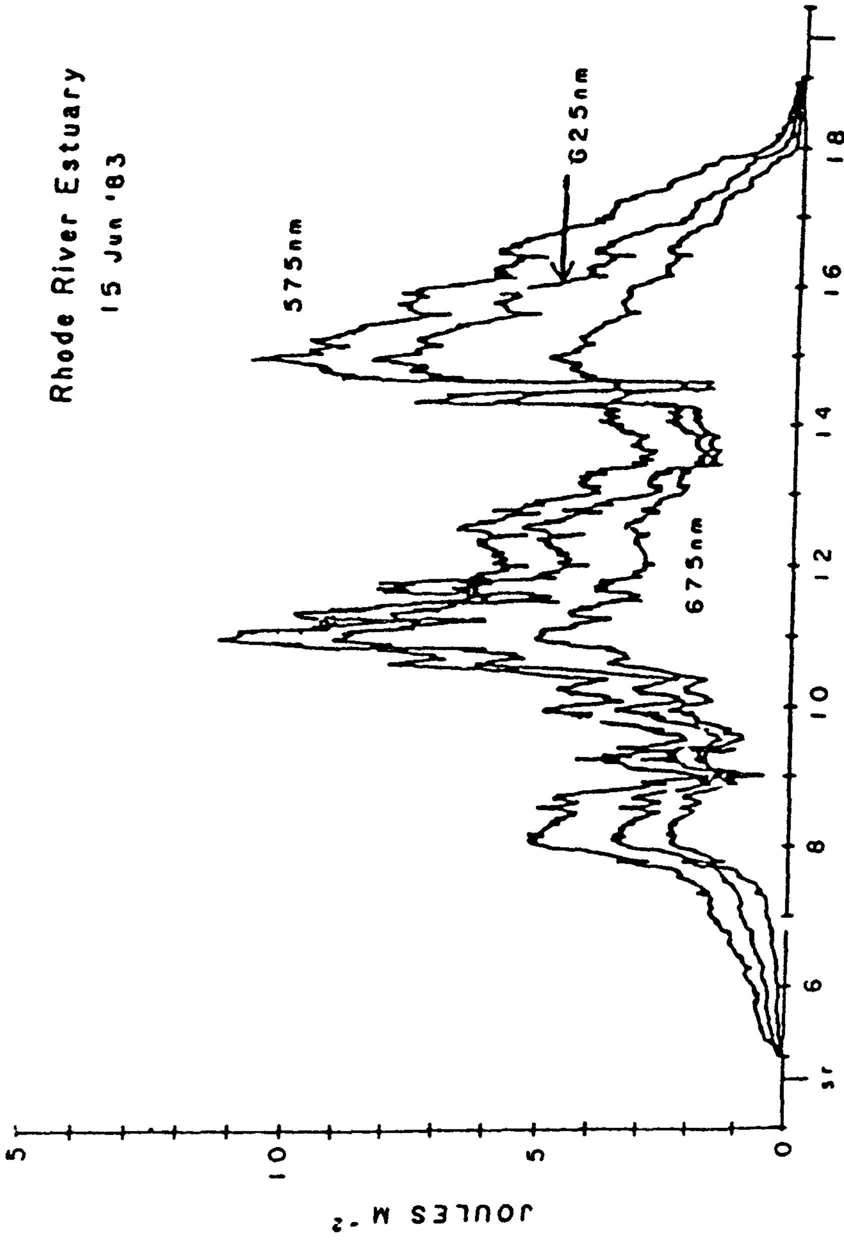
The principal reasons for the variability are the variable nature of surface illumination to be expected, particularly when there is partial cloud cover, together with the effects of a continuously changing surface shape. Measurements have been made in Southampton Water using a rotating, collimated, full spectrum sensor and continuous recording. The results show the expected asymmetric radiance distribution, but at the same time show higher frequency variations; presumed due to wave action (Boxall, personal communication). Certainly the data support the proposition that there are short term, as well as long term, variations in both intensity and distribution to be considered when making sub-surface light measurements.

Added to the above, are the effects of any variability of the quality of the water being measured.

Clearly, if the outputs from two or more sensors are to be compared, simultaneous sampling is essential. The use of a single sided instrument (that is one capable of measuring in only one direction at a time) cannot be considered for this application.

3.4 Shadowing

As with any physical measurement, the measurement of sub-surface light fields involves an intrusion into the



Plot of subsurface downwelling irradiance as a function of time. (Goldberg et al 1984) Shows typical pattern of intensity variation which would render sequential measurements, even measurements taken at intervals of only a few seconds, worthless for the purposes of computing R.

Figure 3.2

environment and consequently a degree of disturbance of the environment. The principal problem here is the shadowing of areas of interest by the instrument itself, that is self-shielding, but there are other considerations.

It is relatively easy to conceive of a light detector deployed such that it sees the downwelling light field without disturbing it, though in practice even this is not always so easy to achieve as might at first sight be supposed. It is often difficult to avoid shadowing by such things as supporting structures, cables, boats etc., and it is these relatively small shadows which are likely to get overlooked and create difficulties in the particular case of the measurement of R. The problem is that while the source of the light to the upward looking sensors may be very much reduced by an unfortunately placed small area shadow, the downward looking sensor, which is seeing light scattered from a wide and mainly unshaded area, is very much less affected. In such circumstances, the apparent reflectance ratio can be very much increased. This effect can be seen in Fig. 3.3, which shows some results obtained while towing one of the later model reflectance meters (see Chapter 5) alongside RV Squilla. In this case the instrument was being towed about 3m from the side of the ship at a depth of about 2m. Initially, the sun was on the opposite bow, such that that the instrument was mainly in the shadow of the ship. The point where the ship altered course, after 38mins, bringing the instrument completely out of the shade, can be clearly seen. The difference in apparent reflectance in this case is a factor of approximately seven. Clearly, reflectance measurements taken anywhere where there is a possibility that local surface shading may occur, are of no value.

The above example is an extreme case. Surface shading on a larger scale, by cloud for example, or shading on a smaller scale in turbid water, where the upwelling irradiance is more locally generated and hence both E_d and E_u may be affected simultaneously, will have a smaller effect. This particular example is included here simply to emphasise how very sensitive in-water light measurements can be to influences which might go unnoticed by the operator of an instrument.

A much more intractable problem however, is the measurement of upwelling light. In principle this simply cannot be done without the shadow of whatever is being used as a detector and its supporting system being superimposed upon the area under investigation. Hence the area under investigation is unrepresentative of the whole. Surprisingly, this is a factor which seemed not to have been mentioned in reported measurements of reflectance prior to the commencement of this study.

A brief test in a glass tank filled with turbidified water demonstrated the problem. Illuminated from above and viewed from the side, it was clear to see that a mock detector (a flat disc) placed just below the surface casts a distinct shadow into its own field of view. To be so clearly visible by eye, the reduction in light in the shaded volume must be considerable, so the question must arise, to what extent is the shadowing of a small but crucial volume of the whole field of view likely to affect the apparent value of R?

A further very basic but revealing test was carried out in Southampton water as a first attempt to confirm the existence of such a problem. This was in 1985, at the beginning of the work described here. The equipment was rudimentary in the extreme and no facilities were available for monitoring related parameters, so the experiment constituted no more than a perfunctory and qualitative first exploration of the problem. Later, when suitable instruments had been developed, the experiment was repeated in monitored circumstances (see Chapter 6). However, this first experiment did provide an important insight into the problem and played a large part in influencing the direction of subsequent thought and work, so it is considered appropriate to mention it here.

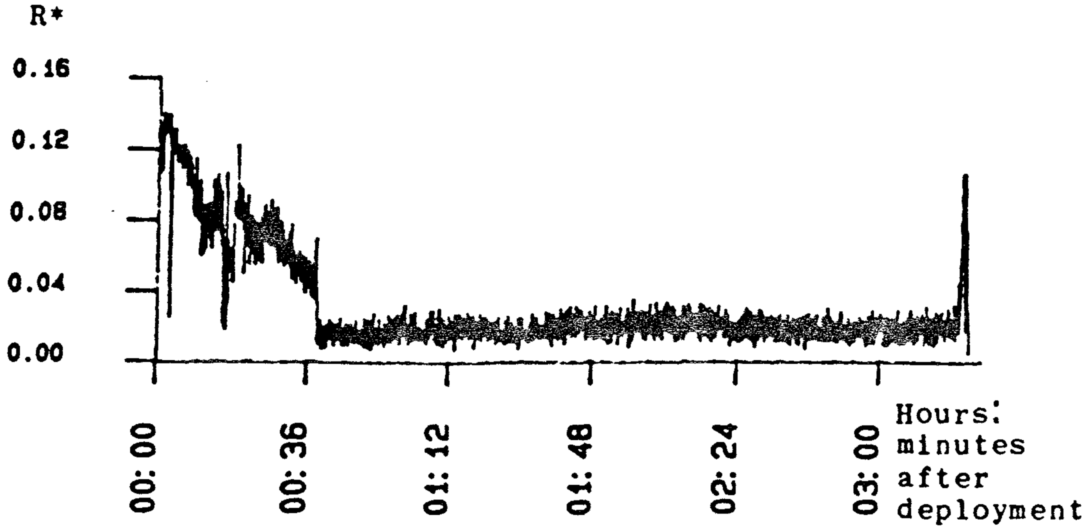
Two similar pairs of silicon diode light sensors were mounted in waterproof housings on opposite ends of a horizontal arm about one metre in length, such that there was an upward and a downward looking light detector at each end of the arm (see Fig. 3.4). The apparatus was suspended in the sea and it was established that the ratio of the output voltage from the downward looking diode to that from the upward looking diode was similar for each pair. At this stage no facilities were available and no attempt was made to calibrate the diodes as light detectors.

The assumption had already been made that, for reasons of self-shielding, the ratio of the light entering the downward-looking sensor to that entering the upward-looking sensor would not be indicative of the true value of R, but of an "apparent" ratio, R*, which is peculiar to the instrument. Thus, where self-shielding is the only corrupting factor, the ratio R* is given by:-

$$R^* = \frac{(E_u - \Delta E_u)}{E_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (i)$$

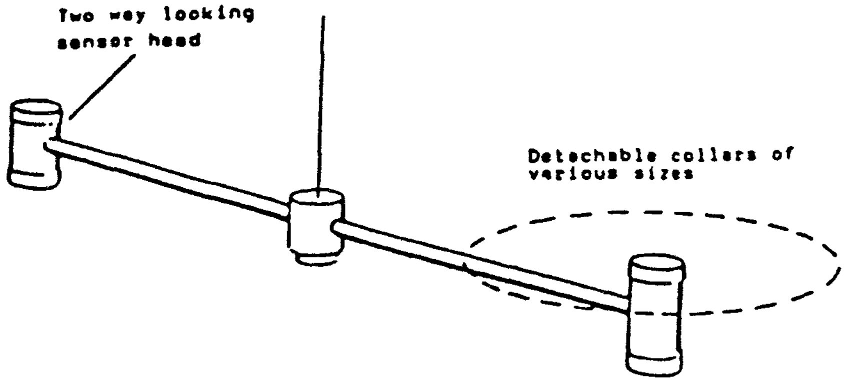
where ΔE_u is an upwelling "irradiance deficit" due to shading by the instrument of its own downward field of view. A self-shielding factor may then be defined as:-

$$R^*/R = 1 - \Delta E_u/E_u \quad \ldots\ldots\ldots\ldots\ldots (ii)$$



Ship shadow seen in reflectance measurements

Figure 3.3



Apparatus for exploring the effects of self shielding

Figure 3.4

To study this effect, collars were added to one detector pair to increase its shading area in steps (simulating a range of instrument sizes), while the other pair was maintained as a control. The expectation was that the degree of self-shielding might be seen to vary with instrument area and the hope was that, by interpolation of the results, it would be possible to obtain a correct value of R. In the event, neither the expectation nor the hope was realised. A varying self-shielding effect was clearly visible, with changes in instrument area altering the apparent reflectance ratio by more than 25% in many cases. This is 25% different from the reference pair, whose self-shielding potential was unknown but presumed small and constant. It was evident too that there was a critical size, above which the value of R* dropped rapidly in some circumstances. For the most part however, the results were confusing. They seemed not to be reproducible and demonstrated no consistent degree of correlation between shading area and shielding effect.

The reason for the apparent "failure" of this experiment became clear only when it was noticed that, in the conditions of intermittent cloud cover which prevailed, the collars had a considerable influence on the results when the sky was overcast but very little during breaks in the cloud cover. This led to the realisation that in the diffuse downwelling light in the overcast periods, the collars cast shadows into the centre of the field of view of the downward-looking detector, whereas during the clear periods, when much of the downwelling light field was due to direct sunlight, they cast shadows to one side, where the effect on R* was greatly reduced.

This highlighted the following important and hitherto not fully appreciated point. The magnitude of the self-shielding effect, which has subsequently been seen to be commonly as much as 30% in some circumstances, depends upon instrument dimensions certainly, but it also depends to a very great degree upon the shape of the sub-surface radiance distribution, which in turn is controlled by circumstantial variables such as solar angle and cloud cover. This was a disturbing conclusion for somebody intent upon measuring absolute values of R in the ocean. In addition it must cast doubts on some past results.

There is one further important ramification in this conclusion for large instruments, especially multi-sensor instruments used to obtain relative spectral reflectances, that is values of $R(\lambda_1)/R(\lambda_2)$. Here it will be seen that the outcome will depend on the positioning of related sensors within the instrument, relative to the shaded area.

One example of such an instrument was the Undulating Oceanographic Recorder (UOR) (Aiken and Bellan 1986) which had light sensors on either side, above and below fins, and following discussions with the designer and users of the UOR, some consideration has been given to the shading problem inherent to that instrument (Pilgrim 1988). Pilgrim notes that integrating equation (iv) (Chapter 2) for values of z between zero and one diffuse optical depth, 1/K, leads to the conclusion that some 86% of all the light entering a downward-looking detector originates from scattering within that depth below the detector. Assuming then that the degree of self-shielding in any situation depends upon the solid angle subtended by the shading area within the part of the water column which is the source of upwelling irradiance, whether it is a significant factor or not will depend upon the relationship between the optical depth and the dimensions of the instrument. Thus, the shading effect of any optical instrument will be greater in turbid, estuarine situations and when looking at longer wavelengths, than it is in clear ocean waters or at shorter wavelengths.

This is a valuable contribution in that it at least makes it possible to assess whether or not it will be safe to assume that the self-shielding factor of an instrument may be neglected in any particular situation. For example, in clear ocean waters, where the typical optical depth might be 30m or more (Jerlov 1976), the general dimensions of the UOR (about 1m) are small in relation to the optical depth; that is small in relation to the illuminated volume contributing the majority of the upwelling irradiance at the instrument. Hence, the shading effect of the instrument will be small. In an estuarine situation, where the optical depth might typically be less than 2m, an instrument of the size of the UOR will present a considerable shading problem.

Unfortunately, the criterion above does not tell us anything about the <u>magnitude</u> of the shading effect to be expected in any specific situation or set of circumstances. To calculate this presents a formidable task, and one which may not be possible in practice. Further, to attempt to do so confirms the fact that, as has already been suggested and later demonstrated (Chapter 6), there are other considerations, apart from instrument size and water turbidity, which profoundly influence the result.

The problem is to calculate ΔE_u, the loss in upwelling irradiance at the instrument due to light removed by shading by the instrument, from that volume of water which provides E_u. If we consider the model of a particular point x, situated in that volume, on a level z below an instrument, which has a substantial horizontal area A but a relatively small area light sensor at the centre of A (a typical ocean going instrument), then the downward irradiance removed from that single point, $d\Delta L_d(z)$ say, by the shading area A, will be given by:-

$$d\Delta L_d(z) = \int_{S(\theta\phi)} L_d(\theta\phi)(z)\cos\theta d\omega \ldots\ldots\ldots\ldots\ldots(iii)$$

where $L_d(\theta\phi)(z)$ is the downward radiance at x from the direction of the instrument, $(\theta\phi)$, and $S(\theta\phi)$ is $A\cos\theta/z^2$, the solid angle subtended at x by the shading area and centred upon $(\theta\phi)$. Note that the shape of $L_d(\theta\phi)(z)$ will vary significantly with z (see Chapter 6).

The loss of upwelling irradiance at the instrument due to $d\Delta L_d(z)$, the missing component from that single point, will then be given by:-

$$d\Delta E_u(0) = \int_{S(\theta\phi)} L_d(\theta\phi)(z)\ \cos^2\theta d\omega\ \beta(\theta)\ e^{-2Kz/\cos\theta} d\omega \ldots\ldots(iv)$$

Hence, the total loss of upwelling irradiance at the instrument, $\Delta E_u(0)$, brought about by the shading which the instrument itself produces, will be the sum of all such irradiance deficits, that is:-

$$\Delta E_u(0) = \iiint \int_{S(\theta\phi)} L_d(\theta\phi)(z)\cos^2\theta d\omega\beta(\theta) e^{2Kz/\cos\theta} d\omega d\theta d\phi dz \ \ldots(v)$$

computed for all values of θ, ϕ and z below the instrument.

The complexity of the above expression and, more to the point, the fact that it involves two distributions, $L(\theta\phi)$ and $\beta(\theta)$, both of which in any real ocean situation are complex, varying both temporally and with depth, and are difficult to measure and impracticable to monitor, emphasises the impracticality of attempting to assess the true value of R*/R from theoretical considerations for any particular instrument in any particular situation. Indeed, the information required to make the assessment amounts to a complete description of the sub-surface light field, and to possess that, would remove the need to make the reflectance measurement.

Nevertheless, while it may not be possible to arrive at a sensible computation of the self-shielding operating in any specific situation, it is possible to make some general observations regarding the likely significance of it in varying circumstances, and to add to the basic criterion already mentioned.

It will be seen from the above, that a principal obstacle to quantification, certainly <u>the</u> principal cause of uncontrollable variability and uncertainty <u>during</u> a measurement, is the complex and variable nature of $L_d(\theta\phi)$. The influence which this has may be seen by looking at the effects of the typical distribution illustrated in Fig 3.1.

Consider, for example, the simplified situation of a point vertically below ($\theta = 0$) an instrument placed in the particular radiance distribution shown in Fig. 3.1. If the shading area of the instrument is small, such that it subtends a half angle in the plane shown of, say 20° or less, at the point in question, the point will not be shaded from the majority of the downwelling light, which is in the intensity peak - at about 25° in this case. Increasing the size of the shading area to give a subtended half angle of more than, say 30°, encompasses the intensity peak, and a high degree of shading at the point will result. Increasing the area still further, will increase the shading effect at the point, though at a diminishing rate, until the edge of the refraction boundary is reached rate, until the edge of the refraction boundary is reached (49^o), after which the effect of increasing the shading area further (within reason) will be small, as no further **direct** sunlight can fall on the point. Thus, in this simplified situation, a curve of E_d at any one point below the shading area, measured as a function of shading area size will have two distinct changes in slope, with most of the variation taking place between them. The total shading effect, which is the sum of all such points, may therefore be expected to exhibit broadly similar characteristics and hence, so too will R* measured as a function of instrument area.

In any situation therefore, there is a critical size for an instrument if self-shielding is to be negligible. This will be dependent upon a number of factors, but a significant controlling variable is the shape, and in particular the degree of asymmetry, of the sub-surface downwelling light field. In a perfectly symmetrical downwelling light field (the sun vertically overhead or totally diffuse surface illumination), a small instrument might be expected to exhibit a high degree of self shielding. Whereas, in a situation where the downwelling light field is strongly asymmetric, an instrument might be considerably larger but still be below the size needed to affect the outcome to any great degree.

Therefore, when assessing the possible significance of self-shielding in an asymmetric light field, the Pilgrim criterion that self-shielding will be insignificant where $DK < 1$ (where D is the dimension of the instrument) is insufficient by itself. In an asymmetric light field, the relationship between DK and $\tan\theta_s$, where θ_s is the zenith angle of the downwelling intensity peak, also assumes crucial importance.

demonstrated (see Chapter 6). In tests, the basic shape of plots of R* as a function of instrument size was found to be as suggested by the reasoning set out above and was seen to persist in all cases. In addition, the degree of asymmetry of the sub-surface light field, which is controlled by ever changing surface illumination conditions, as well as decreasing with depth, was shown to be a principal factor determining the critical instrument size. In a typical sub-surface radiance distribution, which will be changing continuously with surface illumination conditions (if only due to the sun's passage), this characteristic introduces a high degree of uncertainty which is potentially more damaging than any larger systematic error.

Total elimination of this large element of uncertainty by means of instrument design seems impracticable, especially considering the wide range of conditions in which an instrument is likely to be called upon to operate. Clearly, it is necessary to take steps to counter the difficulty.

One approach would be simply to attempt to minimise the problem by minimising the shadowing potential of the instrument. In practice, this means minimising the overall size of the instrument in relation to its sensitive area. For a single sensor instrument, this means contriving to have the smallest possible sensor housing in relation to detector area and the minimum of supporting structure. For a multi-sensor instrument, it means that, in addition, sensor housings need to be separated from each other as much as possible to minimise mutual shielding. Even so, there are limits to this approach. Certainly, in the case of an ocean-going instrument, which is necessarily robust, it is difficult to see how self-shielding could be reduced to an acceptable level in all possible circumstances.

An alternative possibility is to aim at a more practical measurement, that is one which is less sensitive to the effects of self shielding.

At first sight it seems that this objective can be achieved using a multi-sensor, multi-spectral instrument to obtain relative spectral ratios (which are the basis of many algorithms) directly, rather than attempting to measure individual absolute reflectance ratios. All that is required is that the design allows for each sensor pair to be identical in respect of its self shielding potential. Thus, although the relationship between what the instrument measures at any one wavelength, the apparent reflectance $R*(\lambda)$, and the true reflectance $R(\lambda)$, will be indeterminate and will vary with conditions, it might be argued that symmetry of design can ensure that it will at least be varying at all times in the same way for each detector pair, that is for each wavelength. Hence, the ratio $R*(\lambda_1)/R*(\lambda_2)$ will be the same as the required ratio, $R(\lambda_1)/R(\lambda_2)$. This strategy has been used in the design of both the prototype relative reflectance meter (see Chapter 4) and in later ocean-going versions. It has been shown to overcome, to a very large extent, the variability introduced by variations in surface illumination conditions and as such is now regarded as a prerequisite for multi-sensor instrument measurements.

There is however, one further factor to keep in mind. The validity of the above approach hinges upon an assumption that the self-shielding potential of two sensor pairs will be identical if they are geometrically identical. Unfortunately, this is not so where the pairs are operating at different wavelengths because the degree are operating at different wavelengths because the degree of self-shielding depends upon K which, in turn, varies with λ. A measured ratio, $R^*(\lambda_1)/R^*(\lambda_2)$, will therefore differ from the required ratio, $R(\lambda_1)/R(\lambda_2)$, by a "spectral" factor, ς say, which is seen from equation (ii) to be given by:-

$$\varsigma = \frac{(1 - \Delta E_u/E_u)_{\lambda 2}}{(1 - \Delta E_u/E_u)_{\lambda 1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(vi)}$$

Thus, although efforts may be made to ensure that the instrument geometry is identical for all wavelengths, and by so doing, obtain <u>ratios</u> of values of $R^*(\lambda)$ which are far less sensitive to changing <u>external</u> circumstances than might otherwise be the case, there will be an uncertainty in the absolute value of a spectral ratio in any measurement where self-shielding is a significant factor. However, in most normal circumstances, the design strategy produces a considerable improvement in the quality of data obtained. Unlike the uncertainties brought about by the extremely variable circumstances of illumination, the spectrally induced uncertainty is a systematic second order effect, being a function of the water quality.

3.6 Summary and conclusions

This Chapter is a record of the reasoning followed prior to any real attempts to explore the topic through experiment. It will be seen that some basic conclusions regarding the measurement problem had already been reached at that stage. These may be summarised as follows:-

(1) While the theory of the behaviour of light in water is well established, there are practical constraints and uncertainties concerning the changing nature of sub-surface light fields, which combine to make accurate determinations

of absolute values of R an unrealistic objective in the case of field measurements in a real ocean situation.

(2) Comparisons of two or more reflectances at different wavelengths is a more realistic objective, but care is needed to ensure that changing circumstances affect all wavelengths similarly. That is to say, every effort should be made to ensure that, as far as is possible, the relationship between the true and the measured (apparent) reflectance ratio will vary in the same way for all sensor pairs, as the circumstances of surface illumination and instrument deployment vary. Even so, it is important to keep in mind that even comparisons of measurements made at two different wavelengths will contain a systematic error due to a wavelength dependence in their self-shielding potential. Hence, it remains essential to reduce that potential in every way possible.

(3) There are four essential criteria for any instrument for the in-situ determination of relative reflectance data. They are:-

(i) Local shadowing of the upward-looking sensors of the instrument must be avoided. This should not be a major difficulty in most instances, though it may place some restrictions on the manner of deployment.

(ii) There should be minimum self-shielding of the field of view of the downward-looking sensors. This is particularly important where measurements are being made in turbid waters and, as is required in this case, where measurements are being made very close to the surface.

(iii) **It is essential to keep in mind that, while a potential for self-shielding is built into the design of**

any instrument, the magnitude of the effect at any particular moment 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, the self-shielding characteristics of all downward-looking sensors must respond simultaneously, and as similarly to one another as possible, to changes in conditions of surface illumination. Outputs from sensors in a downward-looking array where the sensors are in close proximity to one another or are mounted around a relatively large opaque housing, cannot be compared one with another. Fortunately, it is not difficult to conceive of practical designs which go some way to meeting this particular criterion (see Chapters 4 and 5).

(iv) **Simultaneous interrogation of related sensors is absolutely essential in a real ocean situation.** The highly variable nature of the sub-surface light field in such a situation is such that any ratios obtained by sequential measurements, even measurements taken at intervals of only a few seconds from each other, must be regarded as suspect. It follows that a single-sided instrument capable of measuring light from only one direction at a time, is not suitable for the determination of reflectance ratios.

Any relaxation of the above criteria will result in an instrument which will produce ratios which are as much, or more, dependent upon conditions of sky, sea surface and deployment, as upon water quality.

Experiments carried out at a later date to demonstrate the effects of geometric variables in the presence of different circumstances of surface illumination are described in Chapter 6.

4. A PROTOTYPE REFLECTANCE METER

The prototype device described here was constructed mainly to test the idea set out in Chapter 3 that an instrument designed specifically for <u>differential</u> reflectance measurements was likely to be more worthwhile than attempting the measurement of <u>absolute</u> reflectances. 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. The identified need for simultaneous spectral measurement suggested that a multi-sensor unit, rather than a two sensor design with spectrum analysis capability, apart from being more simple and much cheaper to build, was likely to prove more satisfactory as a tool with which to explore the measurement problem. It was thought also that, the aim should be to develop a towable rather than a static instrument as this would have applications beyond those of simply testing measurement principles. However, it must be stressed that the production of a fully seaworthy survey instrument, with the strength to withstand towing at ship speeds in rough seas, was not envisaged in the early stages. Nevertheless, in the event, the prototype proved itself to be remarkably robust and seaworthy.

4.1 The general concept

It is useful in the first place to list the criteria which were required to be met by the instrument. They were:-

(i) It had to be capable of detecting and comparing upwelling and downwelling sub-surface light vector irradiances. This, as has already been pointed out, dictated a device capable of simultaneous upward and downward measurement.

(ii) It had to be capable of discriminating between two or more wavelengths.

(iii) As inter-wavelength comparison was an objective, it had to be designed such that all sensor pairs (wavelengths) responded, as near as possible, equally to any variations in environmental circumstances.

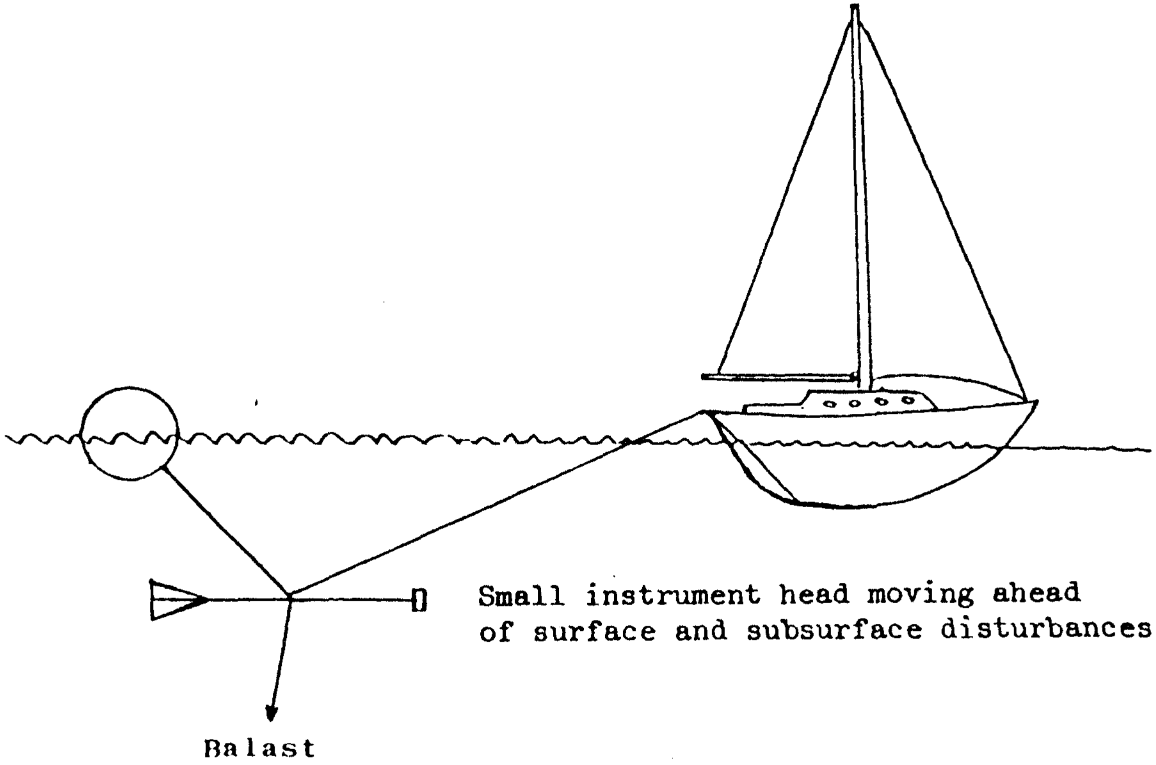
(iv) It had to be capable of maintaining a fixed, shallow operating depth and a fairly stable orientation while being towed.

(v) For the experimental purposes envisaged, real-time measurements were considered essential. This ruled out sub-surface, on-board recording, which offers some practical advantages for this type of instrument.

(vi) It was considered worthwhile aiming for the minimum possible interference to the light field though, as has been stressed, a conclusion already reached was that it was unlikely that this factor could be reduced to a tolerable level in some conditions of deployment, but had rather to be accommodated in the logic of the measurement.

The basic concept which developed in the light of the above criteria was one of a towable carriage supported by a float (Fig. 4.1) and carrying a number of light sensors, each masked by optical filters, arranged in upward looking and downward looking pairs. The tow was to be attached to

Figure 4.1



Schematic of the relative reflectance meter showing mode of deployment the instrument, rather than to the float, with the sensors travelling ahead of the instrument body. In that way the sensors move ahead of everything except the towing cable, in relatively undisturbed and unshaded water.

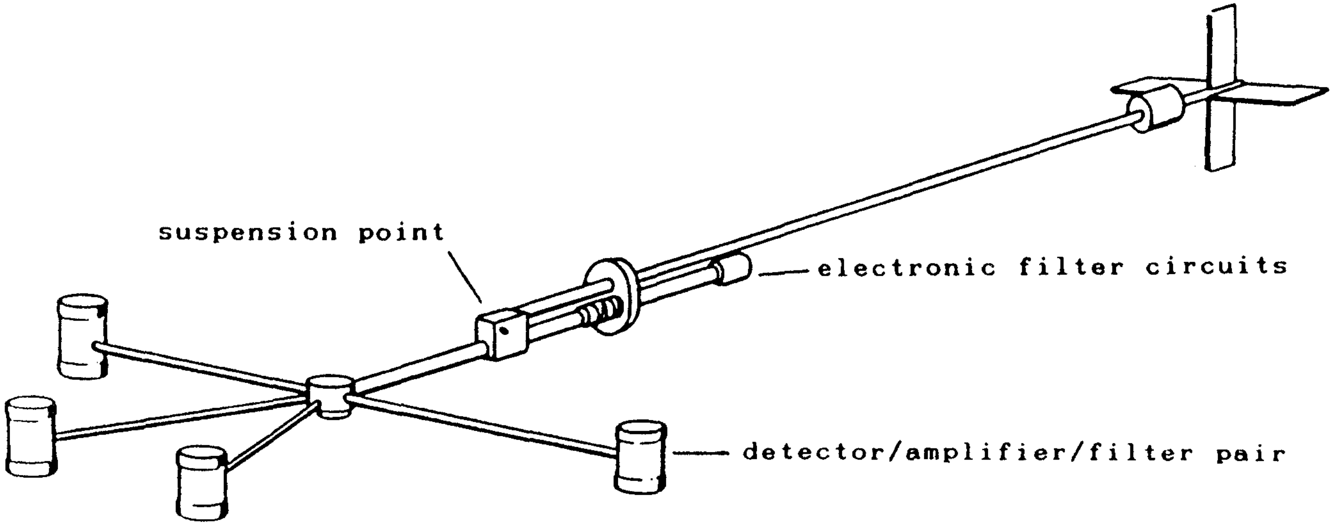
The problem of self-shielding was very much to the fore at this stage of the design and every effort was made to minimise it. In particular, care was taken to see that the geometric aspects of the self shielding potential of each sensor pair was the same and that mutual shielding was minimised.

Thus, the instrument shown in Fig. 4.2 was developed. It consists of four sensor pairs (potentially four wavelengths), each pair contained in the smallest possible housing. The housings are spaced on a "spider" of thin tubes to minimise mutual shielding. The length of the tubes was chosen as much on the basis of the strength and rigidity of the material available as anything else. A tail is provide to counter pitch and yaw when under tow, and the whole is suspended in a weighted semi-gimble to give roll stability. Flotation is provided by a glass-fibre float which is fitted with a fin to give it directional stability under tow. The instrument's "flying" attitude under tow is illustrated in Fig. 4.3.

4.2 Hydrodynamic considerations

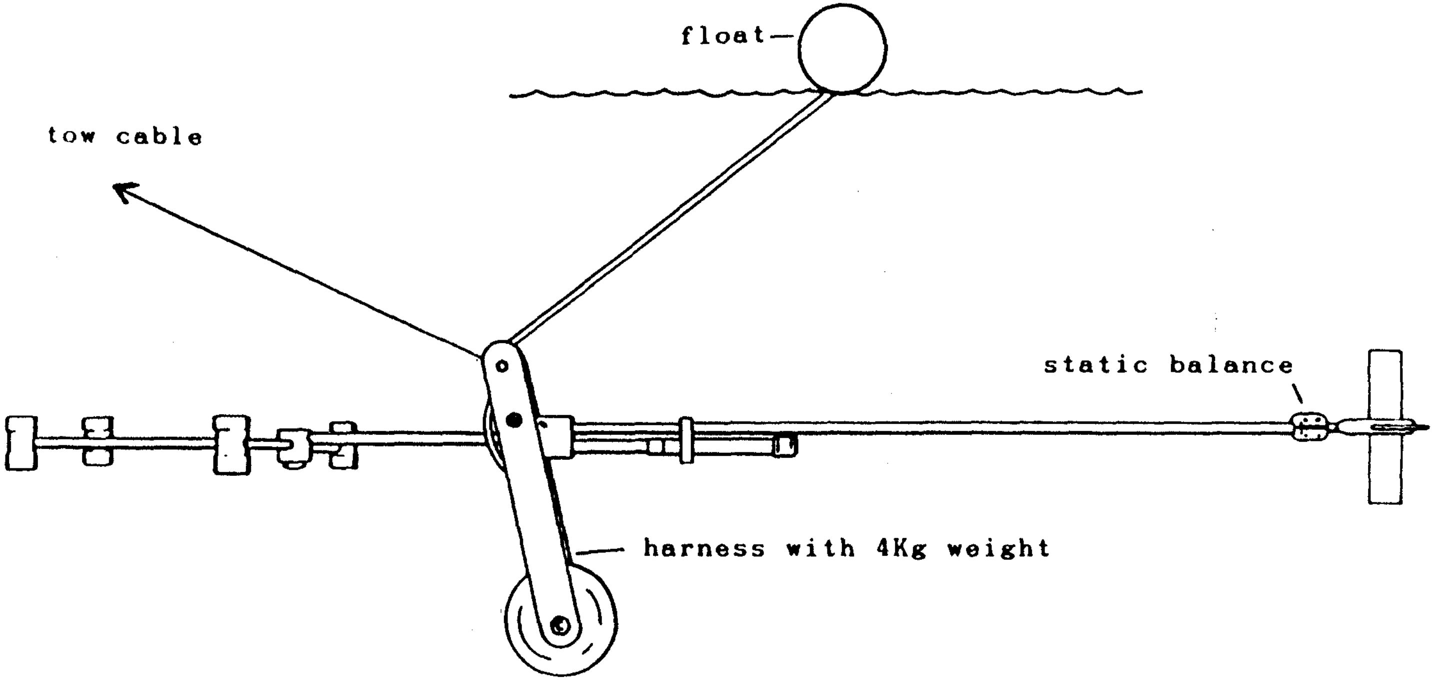
Having settled on an open framework design for purely optical purposes, the problem of how, or indeed if, it would be possible to make such a framework "fly" flat and level just below the surface as was required, was considered. An ideal sub-surface vehicle, heavy compared with the instrument and with a controlled depth capability,

Figure 4.2



The prototype relative reflectance meter

Figure 4.3



"Flying" attitude of the prototype relative reflectance meter which could be used to push the instrument in front of itself, was well beyond the limit of the resources available at the time and the surface float option described above was the most promising prospect. However, there remained some apprehension concerning the towability of the admittedly rather unhydrodynamic-looking sensor array, and there seemed little point in going ahead with construction only to find that it could not be made to tow in a stable way. Hence some thought and effort was put into trying to optimise the design from that point of view by calculation and tank testing.

Being only semi-gimbled, but relatively strongly so, with a righting moment of 2 to 3mKg easily accommodated within the design, it was considered (justifiably so, as it turned out) that roll would not be a problem. All that was required was to provide sufficient righting moments to control pitch and yaw; both being important for the effect they might have on the optical measurements, as well as for considerations of the overall stability of the instrument.

The approach was to estimate the drag likely to be caused by the whole instrument by summing that of the individual parts, converting this to a total maximum destabilising moment at an arbitrary maximum permissible deviation from the horizontal and then calculating the dimensions of a suitable fin to provide a counter moment. For the purposes of the estimate, the worst possible circumstances were assumed, ie the destabilising moment was assumed to be the sum of the drag of all the components acting in the same direction at some radius of gyration l_1.

The drag, D, on an individual tube or sensor housing is given by:-

$$D = 1/2\rho V^2 A C_d \text{ ....(i)}$$

where ρ is the density of sea water, V is the velocity, A is the cross sectional area and C_d is a drag coefficient. The drag coefficient for the framework tubes (long in relation to their diameter) was taken to be 1.2, and that for the sensor housings (short in relation to their diameter) 0.7 (Hoerner 1965). From this the total drag at 4 knots (the maximum speed likely to be used) is about 44N, giving a maximum moment of 44 l_1 mN.

To counter this moment, a fin providing a lift, L, operating at some convenient distance, l_2 say, is required. The lift, L, provided by a simple rectangular fin of area S is given by:-

$$L = 1/2\rho V^2 \; C_L \; S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(ii)}$$

where C_L is a coefficient given by:-

$$C_L = 2\pi/(1 + 2/R)\alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iii)}$$

R is the aspect ratio and α is the angle of attack.

When the instrument is travelling as intended, L is at right angles to the direction of travel, whereas D is in the direction of travel (zero moment when $\alpha = 0$), so the condition required is:-

$$D \; l_1 \sin \alpha \leq L \; l_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iv)}$$

Here it was necessary to make some arbitrary choices. A value of 5° was somewhat hopefully selected for α. This is the maximum allowable deviation from the horizontal, based roughly on the reasoning discussed in Chapter 3, though at that time the optical characteristics of the sensors had yet to be determined. It was decided that the ratio l_2/l_1 should be restricted to 4, to give a manageable tail length of 1.5m, assuming l_1 to be the full radius of the sensor array. An aspect ratio for a fin of 10:1 was selected on the basis of mechanical strength.

Putting these values into the equation, indicated that a rectangular fin of only 14cm^2 should be adequate; a surprisingly small value in relation to the overall dimensions and general unhydrodynamic looking shape of the proposed structure, but an indication that the assembly might not behave so badly under tow as was first supposed, so the decision was made to proceed with construction along the lines envisaged.

In practice, fins (vertical and horizontal) with twice the calculated area but half the aspect ratio, mounted on a 1m tail, gave a good margin of stability. Provision was made to "tune" the tail, should that be required, but in the event, no post-construction adjustment was necessary, apart from static balancing of the whole instrument in salt water. This was done using a sliding weight provided for the purpose.

The whole array was tested first in a wave tank at the Institute of Oceanographic Sciences' Deacon Laboratory (IOSDL) to speeds of up to 4 knots (the maximum available), and at those speed it behaved perfectly. Subsequent experience at sea has confirmed its capabilities in this respect. Even at slightly higher speeds, and in rough seas, it continues to fly flat and level in a quite remarkable way, though above 4 knots the float begins to be dragged below the surface.

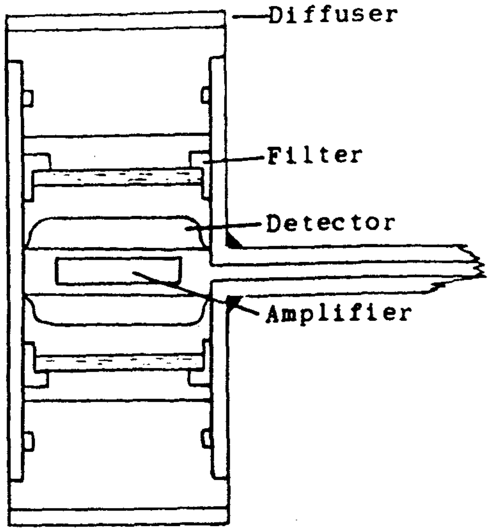
Some thought has been given to the problem of the behaviour of the float at speed, and various shapes have been tried, but one which is noticeably better than any other has not been found. The problem is that any reasonably sized float will be operating at well beyond its waterline speed for most of the time and is therefore required to plane. Thus, if higher speed operation is required, it will be necessary to consider the use of a "ski-like" device, or possibly a catamaran, instead of a float. However, bearing in mind the possible consequences for this relatively lightly built prototype if it were to collide with flotsam, it was decided that it would be prudent to accept the speed limitation set by the float for this particular version of the instrument.

4.3 The sensor units

There are eight individual sensors, arranged back to back in pairs in the underwater unit, giving the potential to measure R* at four wavelengths. Each unit comprises a photodiode sensor, an amplifier and a narrow band interference filter (see Fig. 4.4).

The question of what light sensor to use for this application had already been researched by Dr Simon Boxall of Southampton University's Department of Oceanography, and his choice, the OSD 100 manufactured by Certronics, has proved by experience to be a very good one. The OSD 100 is a silicon diffused photodiode with an active area of $1cm^2$. Used in the photovoltaic mode, it gives a satisfactory output in the required visible range 420-700nm, and remains useful down to 380nm or so. The manufacturer's data is shown in Fig. 4.5.

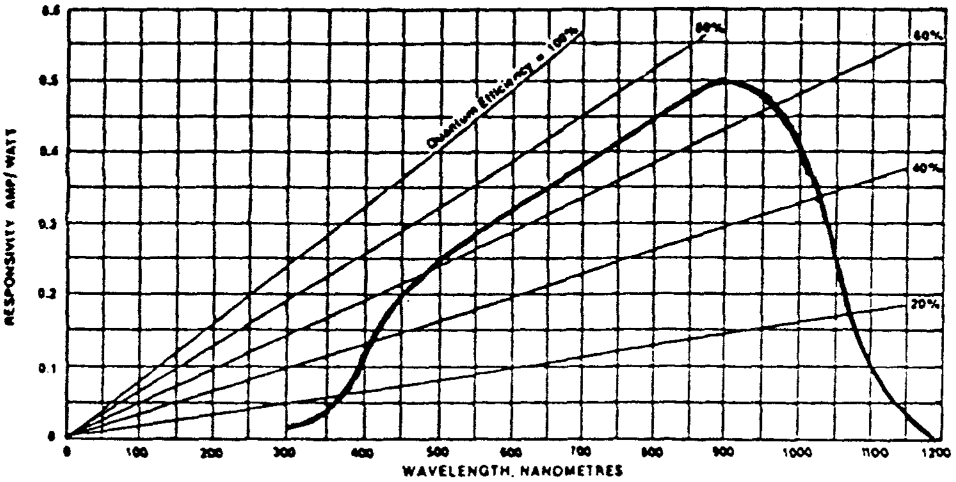
The chief characteristics which make this diode particularly suitable for this application are its smooth logarithmic response and its wide dynamic range. However, it was necessary to amplify the signal at source in order to transmit it by cable to the surface and also to provide a signal suitable for the data processing and logging unit employed. This presented some difficulties. Various



A complete two-way looking detector unit

Figure 4.4

Typical spectral response.
Responsivity: 0.2A/W at 450nm., 0.35A/W at 633nm., 0.5A/W at 900nm., 0.15A/W at 1064nm., 7.9mA/lm (2850°K source).



Response of the OSD 100 silicon diode (manufacturer's data)

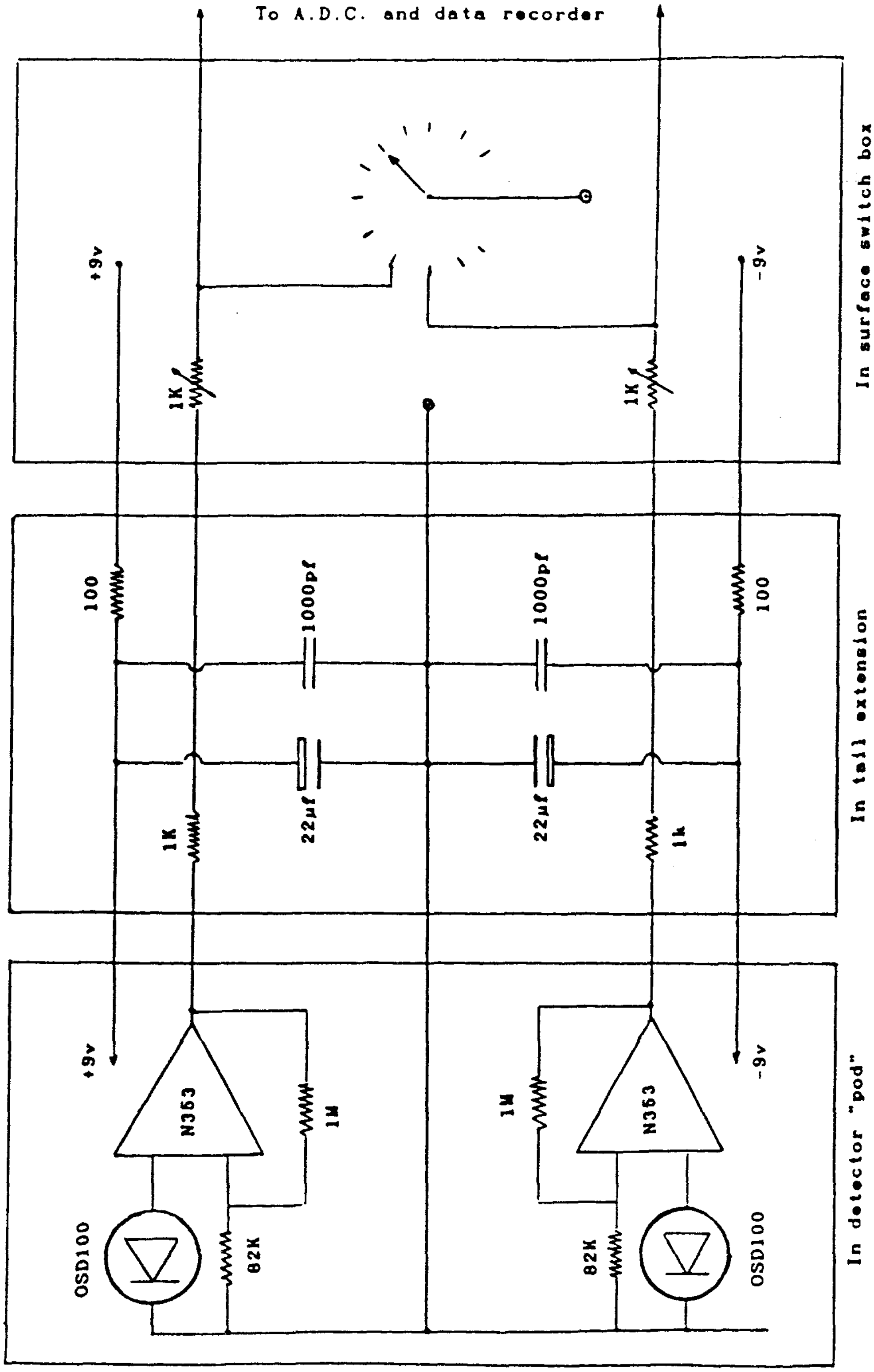
Figure 4.5

conventional circuit configurations recommended by the manufacturers were tried, but none had the characteristics necessary to fully exploit the detector's dynamic range in this application. In addition, all required the bodies of the individual diodes to be insulated from one another, which imposed a restriction on the mechanical design. Eventually, mainly through a series of experiments, the satisfactory circuit seen in Fig. 4.6 was developed. In practice, in order to keep the watertight casings as small as possible in relation to the detector area, amplifier pairs, each based on a single N353 (two op-amps in one IC), were sandwiched between pairs of OSD 100s to form extremely compact two-way looking detector pairs, each only about 1cm thick.

Calibrations of the detector-amplifier combinations were carried out at the Plymouth Marine Laboratory using a facility based on the "81 Optometer" manufactured by United Detector Technology Inc., and the very satisfactory calibration shown in Fig. 4.7 was obtained. Only one curve is shown here because all the detectors were found to be so very nearly identical, especially in the all important aspect of slope. It was found too that variations in the wavelength of the incident light did not alter the slope.

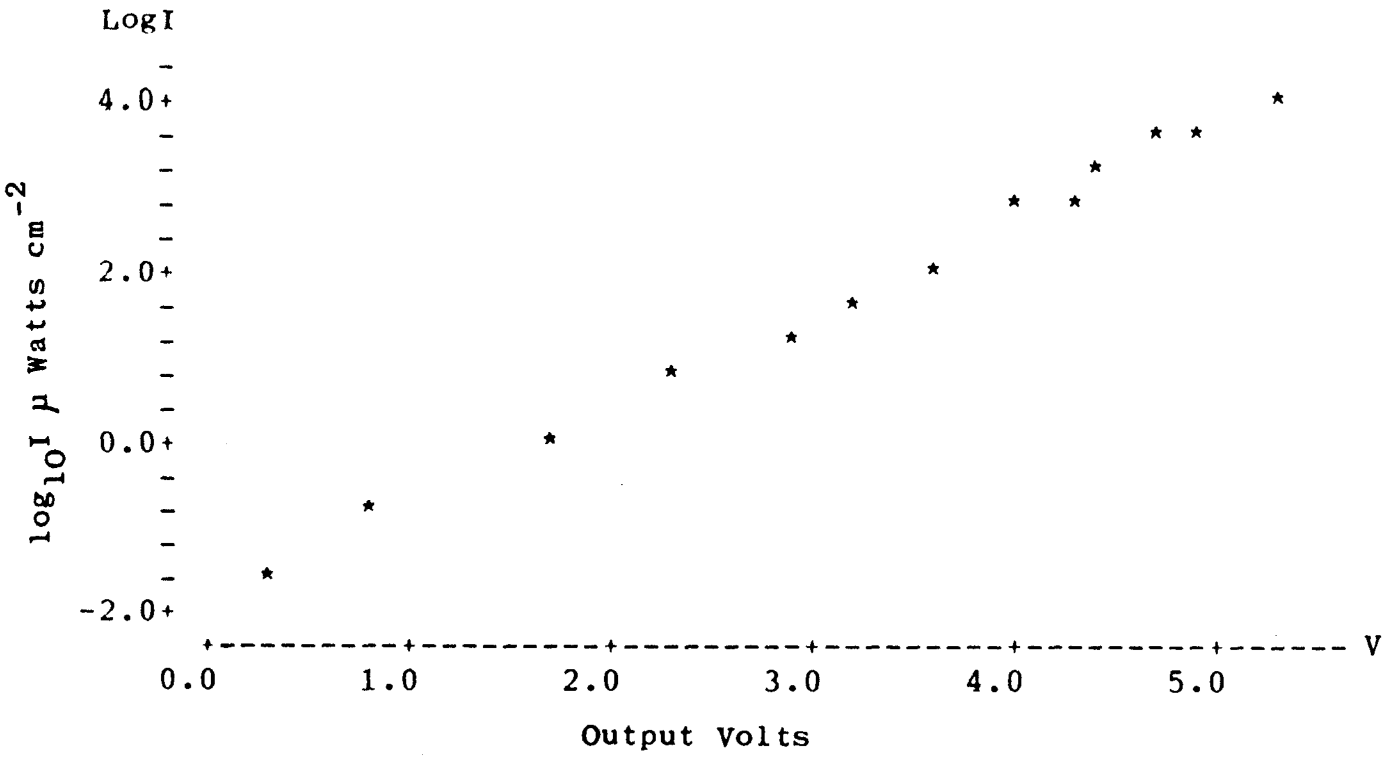
It was considered that the significant temperature coefficient of silicon diodes used in this way could be ignored in this case, where the objective was to make <u>comparative</u> measurements in a uniform temperature environment.

At first it was expected that some degree of adjustment would be desirable in order to bring all channels to a common sensitivity (though it should be stressed that this is not an absolute requirement for this



Signal circuit for one detector pair

Figure 4.6



The regression equation is
LogI = - 1.86 + 1.11 V R-sq = 100.0%

Figure 4.7

Detector/amplifier calibration

application) and there is provision for this in the circuit. In the event, all were found to be very nearly identical, and after initially selecting pairs, adjustment was never found to be necessary. The standard calibration check consisted of simply inverting the instrument. Any slight difference in the response ratio of a dectector pair could then be detected and compensated for by applying a correction. In practice, variations in comparative response which occurred during use were small and could normally be recovered by careful cleaning of the windows.

The main electronic difficulties, which were considerable at one stage, were experienced when the equipment moved from laboratory to operational use. Oscillations, which gave problems when using the relatively sophisticated signal processing and recording equipment with a long cable, but which were not apparent using ordinary DC test equipment in the laboratory, caused a great deal of trouble when the instrument was first used in the sea. However, a complete cure for all instabilities was effected through the use of the filtering and load circuits shown in Fig. 4.6.

A satisfactory instrument-to-vessel connection was made by simply passing the required number of conductors (eleven in this case) through a piece of plastic tubing, which is then made off in a watertight manner with a hose clip to an inlet tube at the instrument while the other end is in the open air on deck. The towing load is taken by a rope. This was thought by some to be a dangerous arrangement (though certainly very cheap) but in the event the "cable" has proved to be entirely satisfactory, having been used extensively from a variety of vessels and on occasions, at speeds and in sea states for which it was never really intended. An added bonus is the light weight and ease of handling. The technique has a great deal to commend it and is quite definitely recommended for instruments which are not going to be subjected to the sort of conditions which would require expensive connectors and cumbersome underwater cables.

4.4 Optical considerations

(a) The colour filters

The instrument has been designed for easy changing of colour filters. It was envisaged that it might be desirable to do this at sea and in a small boat if the number of wavelengths of interest on any occasion exceeded four. In principle therefore, with the existing availability of standard, off-the-shelf, narrow bandwidth interference filters for the entire visible spectrum, the instrument is potentially very versatile. In practice, the high cost of such filters made it necessary to consider carefully what wavelengths to invest in.

There are accepted methods and standards which have been established for colour analysis. For most purposes, these are based on the response of the human eye, which is a trichomatic device with an ability to distinguish three basic colours, blue, green and red. Any shade is then defined in terms of a mix of the three. Numerical standards, based on the response of the average human eye, have been established and are contained in a 1957 publication by the Commission International de l'Eclairage (CIE). Several other systems have been devised, mainly for specific scientific purposes. Most take the form of a collection of colours for comparison. Those due to Werner, Forel (modified by Ule to become the Forel-Ule scale used in oceanography) and Mansel, are perhaps the best known. Muromptsev (1986) notes that there are now more than twenty different systems in use for the classification of colour shades, mainly according to density and luminosity, but also according to wavelength distribution on coordinates of spectral models.

In this case, we are not so much concerned with colour perception, though it is ocean colour analysis which is seen as the end product of the general line of research, but with the effect of various ocean waters upon light of differing wavelengths. There is therefore, a strong argument in favour of selecting wavelengths in the first place which have the potential to be compared with existing data. With this in mind, it seemed that a selection from the wavelengths used in the CZCS would be a good choice. In the event, the prospect of an air-sea exercise in company with an aircraft carrying the Daedelus multispectral scanner also influenced the first choice.

Three sets of filters were selected. They were:-

(1) 435.8nm, with a half height bandwidth of 7.4nm. This is close to the CZCS band 1 (435nm), within the Daedelus band 1 (420-450nm) and close to the lower wavelength used in many existing chlorophyll algorithms.

(2) 550nm, with a half height bandwidth of 9.2nm. This corresponds exactly with the CZCS band 3, is within the Daedelus band 3 (520-600nm), and is the upper wavelength used in many existing chlorophyll algorithms.

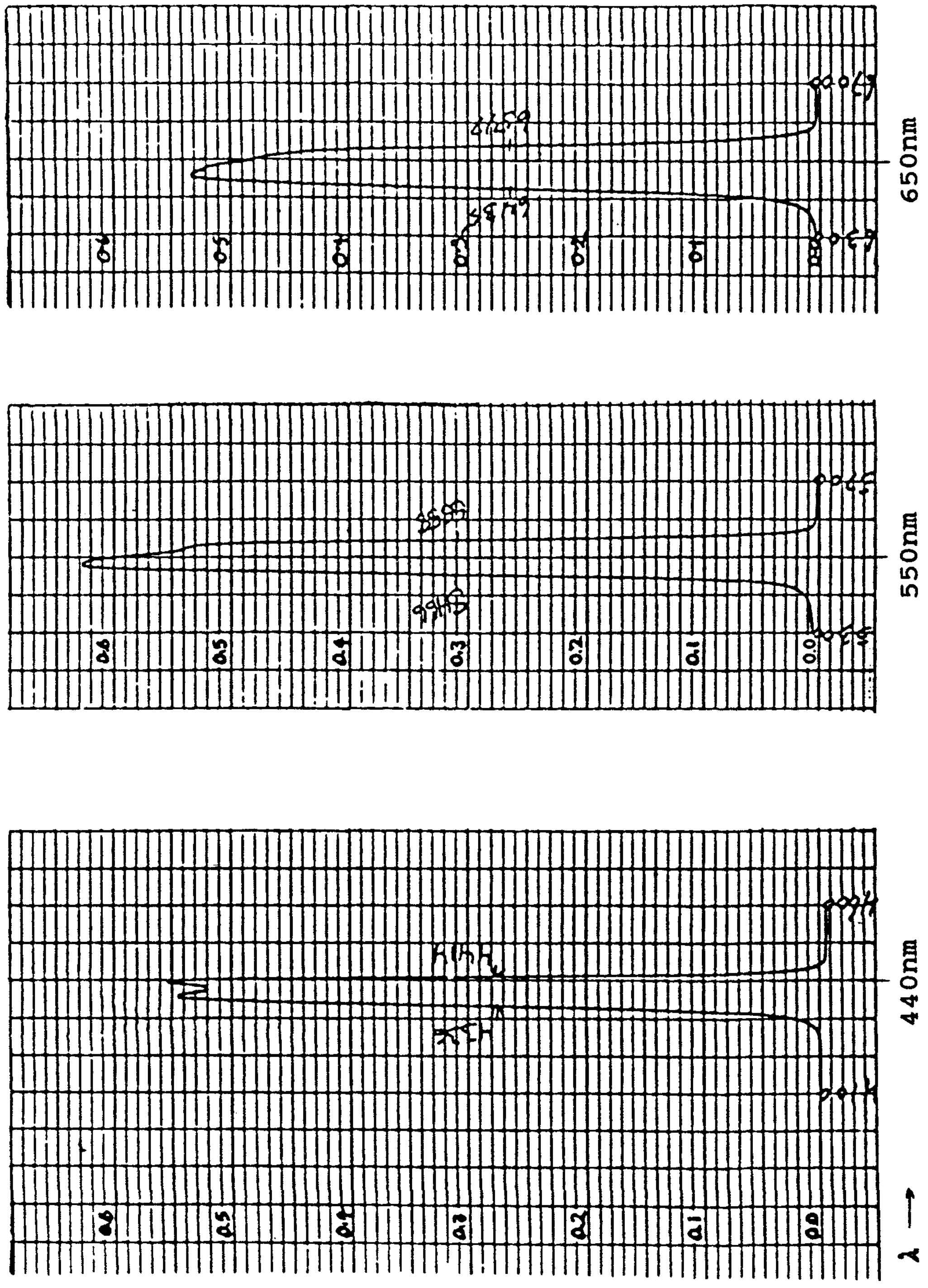
(3) 650nm, with a half height bandwidth of 11.4nm. This is perhaps the least ideal of the three. It is within the Daedelus band 5 (630-690nm) but outside the nearest CZCS

band, band 3 (670nm). Ideally, a red filter of a slightly longer wavelength would have been obtained, perhaps one at 685nm to detect fluorescence, but the 650nm filter was the only red available within the required time scale.

Manufacturer's transmission curves for each of the filters used are shown in Fig. 4.8. Tests to confirm these, using a Spectron spectrophotometer, indicated a very slightly broader spectrum in each case but this is not significant in this application. Further investigations using the same equipment but with the filters mounted on a goniometer, indicate that this is almost certainly due to the effects of the spread in angle of incidence of light at the colour filters. The filters, which are of the interference type, are calibrated by the manufacturers using well collimated light normal to their surfaces. Altering the angle of the incident light, shifts the transmission peak to one side. This is seen in the curves in Fig. 4.9. Consequently, using this type of filter close behind a diffuser, as is done here, broadens the transmission curve.

(b) The water windows

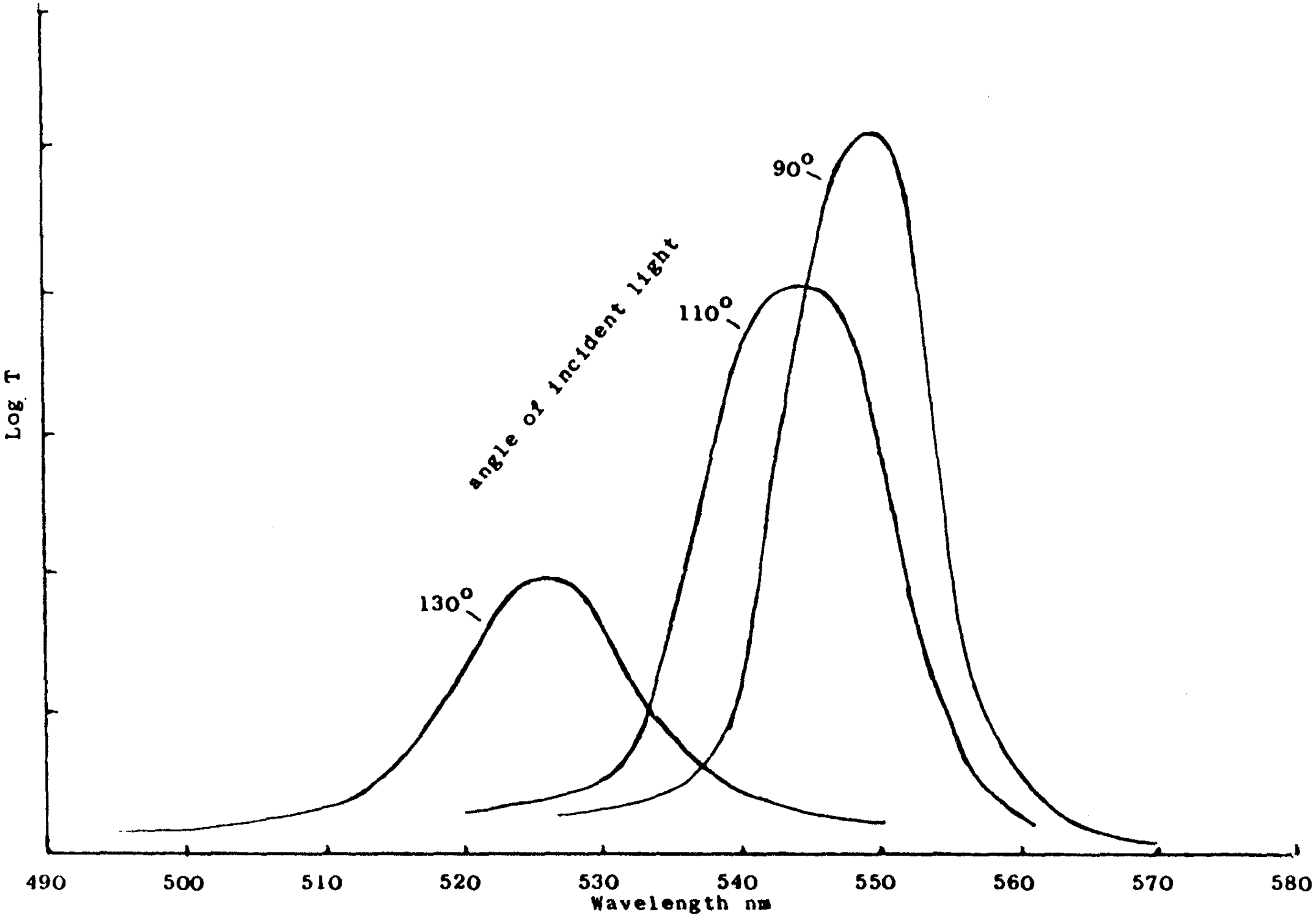
The optical water interface of any in-water instrument is likely to present problems. Indeed, it is almost certainly true to say that any in-water instrument which depends for its accuracy upon long-term consistency of transmission at a water window is doomed to failure. Degradation and contamination of a submerged window surface are inevitable, even over short spaces of time, and any calibration must therefore be suspect. In the case of this particular in-water unit, the problem is reduced because it is the ratio of readings taken through two identical windows which is the objective. Hopefully then, in the



Optical filter transmission curves. (manufacturer's data)

Figure 4.8

Figure 4.9

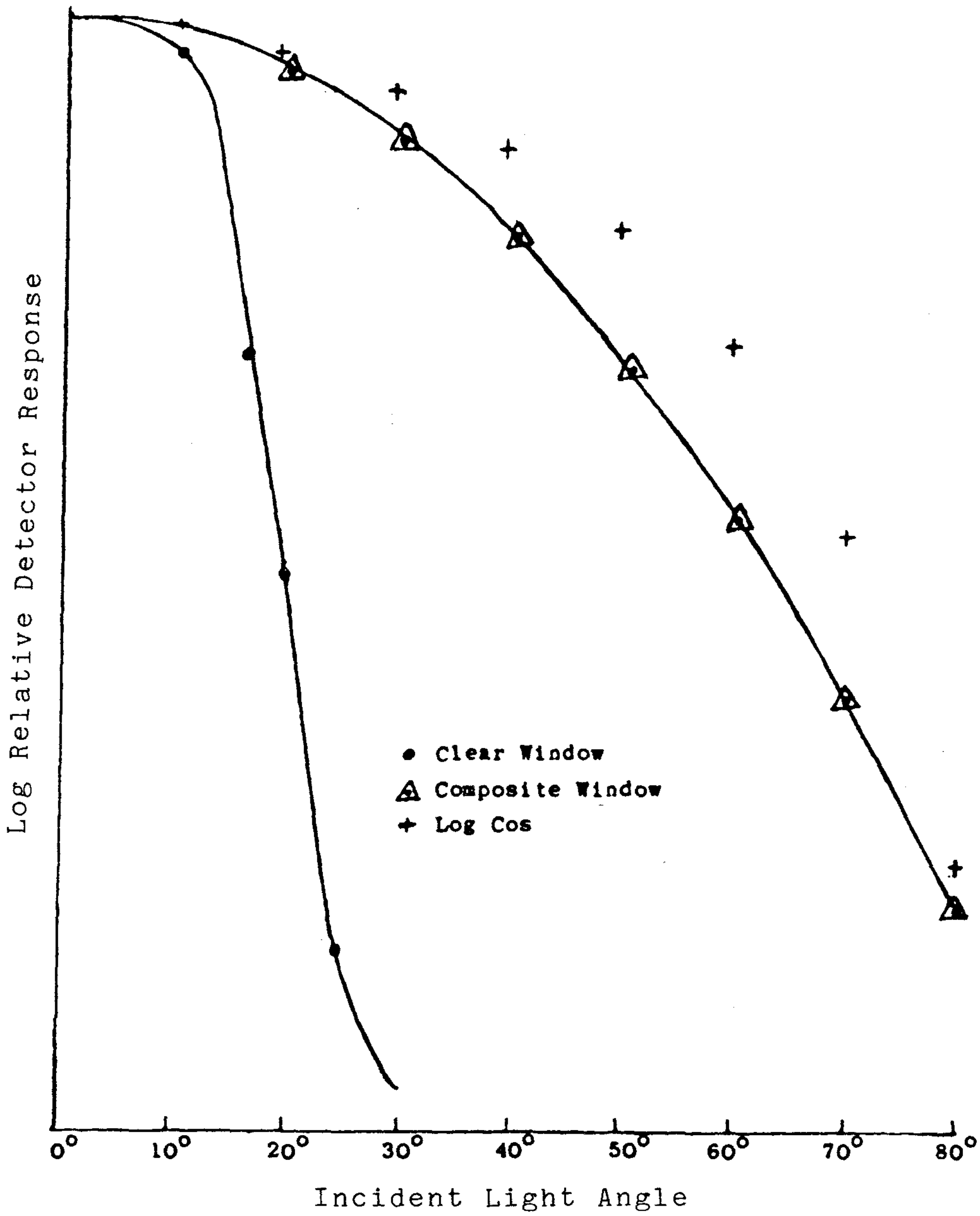


Shift in peak transmission with change of incident angle for an optical interference filter (Experimental results) majority of cases, changes in transmission will be the same for both windows of any detector pair and will tend to cancel. In this particular instrument, as mentioned earlier, a calibration check can be made at any time by simply turning the detector array through 180^0.

While the problem of window condition and its effects on detection efficiency may be lessened by the mode of use in this case, geometric uncertainties relating to the windows as optical receptors cannot be disregarded. The difficulty lies in the high degree of uncertainty associated with the radiance distribution in the water column (as discussed in Chapter 3), combined with uncertainties in the orientation and geometric optics of the detectors. This is particularly true in this application, where measurements are being made very close to the surface, in two very different shaped light fields. At much greater depths the problem may eventually be eased, as the downwelling and upwelling light fields become increasingly similar in structure (Priesendorfer 1959).

However, the declared objective here is to measure and compare values of R*, rather than R, and hence, it was considered that some small deviation from the ideal cosine collector was permissible provided that steps are taken to see that, as far as possible, R*/R is always the same at any instant for all wavelengths. To achieve this criterion, it is essential to do everything possible to ensure that all detectors respond similarly to any changes in the light field. In the first instance, therefore, consideration of the type of water windows to use was dominated by the thought that, as far as possible, all windows should be identical and remain so in use. Thus, simplicity of manufacture and ease of replacement rated high in the choice of design and material used, and it was with this in mind that the first windows to be used were simple, flat faced plugs cut from clear perspex and with "O" ring piston seals. No retaining system other than friction was necessary in this case because the instrument was vented to the surface via its cable. They were less than ideal as receptors (see Fig. 4.10), but they were the easiest design to make optically similar and this was an overriding consideration.

The use of a diffusing material to give a cosine-like response was rejected at first on the grounds that it might cause an unacceptable level of light loss in the necessarily thick plugs. However following some experiments, it was found that much improved, but still very reproducible plugs could be made using clear perspex for the main body of the plug and bonding thin (3mm) opal perspex sheet to the face to act as a diffuser. With these, as with the original design, the edges were completely masked, a feature which it was known would detract from their performance as cosine collectors, (Boyd 1951), but here again, it was considered that the all important characteristic, ease of accurate reproduction, would be more likely to be achieved if no attempt was made to optimise the edges. The result was a window which, while by no means perfect, did nevertheless have a light collection characteristic which was very much closer to the ideal cosine collector (see Fig. 4.10). No further attempt at improvement was made at that stage. There seemed little point in striving for perfection when the simpler design was probably adequate for the purpose and likely to be far more satisfactory from the point of view of achieving a high degree of uniformity in the eight windows. Later, when a precision engineered version of the instrument was manufactured (see Chapter 5), windows were made which had a small part of their edges exposed and that, in line with



Collection Characteristics of Detectors
Using Two Different Window Designs

Figure 4.10

what had been found by Boyd, did modify the window response. The result was a set of windows which were virtually indistinguishable from the ideal.

4.5 Data handling

The logistics of the interrogation of the instrument's output is a key factor in arriving at a meaningful result. In this case the output is a set of DC voltage levels, each varying logarithmically with light intensity, up to a maximum of around 5 volts when the instrument is in bright daylight. A very simple read-out system, consisting of a switchable junction box and a digital voltmeter, is incorporated in the instrument (Fig. 4.6). This has its uses for test purposes. Indeed, although originally provided simply as a convenience for development work, this facility has proved invaluable and has been retained and improved upon. However, such a system could never be considered for operational use as it totally prohibits simultaneous measurement and that, as has been stressed, is a fundamental requirement for this instrument.

The ideal is a system capable of looking at all the channels simultaneously and storing the information for future processing, but at the same time providing a real-time read-out for field work. Fortunately a system which could be modified to serve the purpose already existed. This was a system which was originally developed at IOSDL for use with acoustic Doppler current profilers, but has subsequently been employed in various forms for a number of data handling applications (Pascal and Perret 1988). It was with a great deal of help from Mr Griffiths of IOSDL, to whom I am extremely grateful, that some of the original hardware which had been used to develop the system was made available and was adapted for this application. A schematic diagram of the system which evolved is shown in Fig. 4.11.

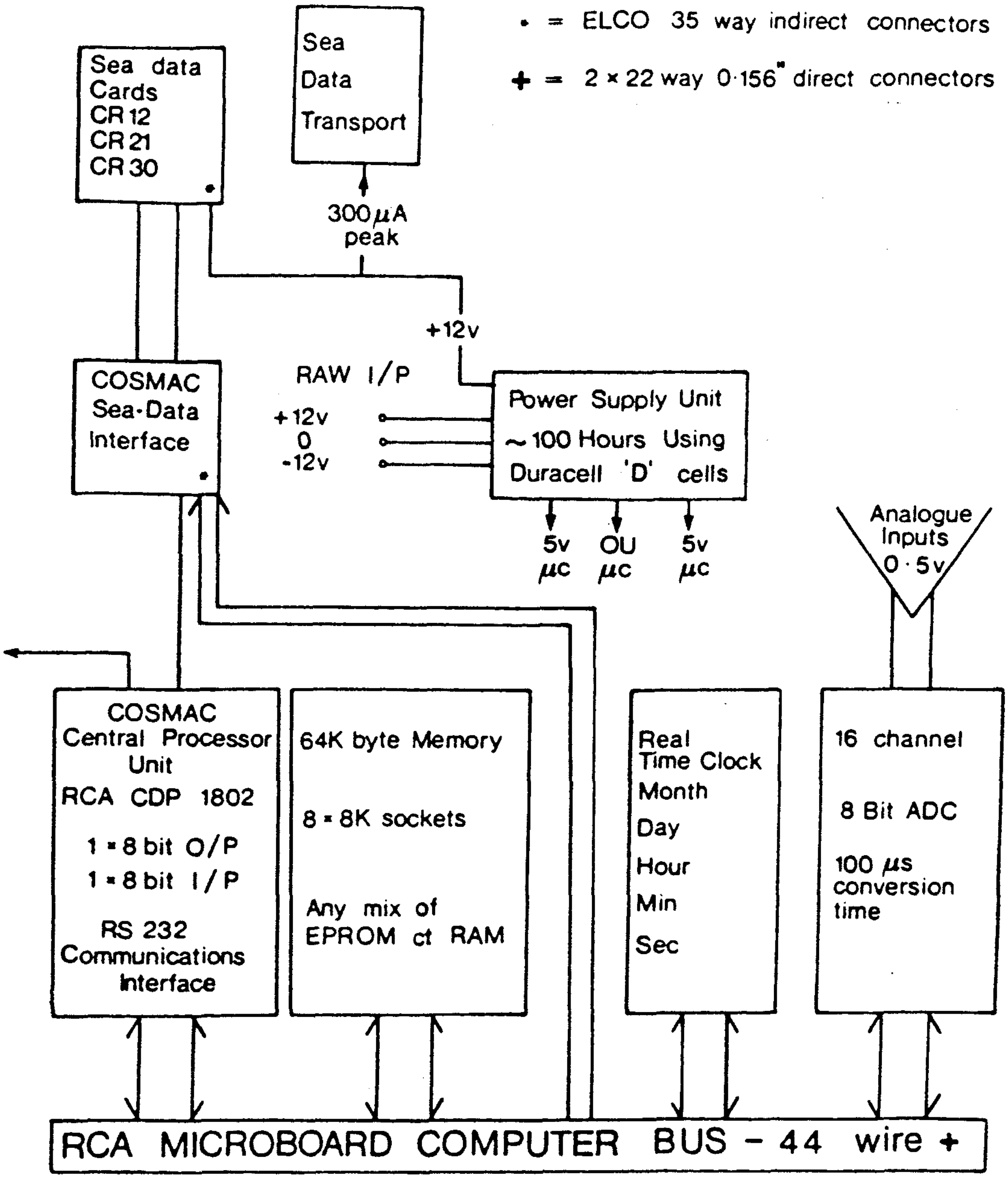
The equipment can be programmed to follow a wide range of sampling, processing and read-out routines, though this does entail the reprogramming of the main integrated circuit, which requires specialised equipment.

In practice, the routine chosen in the first place has proven to be satisfactory and a reason to alter it has not yet arisen. It was arrived at somewhat arbitrarily, the basic idea being 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. In the present programmed routine, all channel voltages are sampled simultaneously 128 times in a period of 18 seconds and the results are processed to give a mean for each channel. This procedure is repeated at 30 second intervals which, at the maximum cruising speed of 4 knots, gives a result every 60m (through the water) based on data collected over a distance of 36m.

Data can be recorded on the instrument's small paper tape printer (this has an advantage for small boat use in that it is battery operated) or, where circumstances permit, data can be fed directly into a personal computer.

The original equipment had, in addition, a Sea Data tape recorder but this has never been used. In practice, it is always preferable to have a real-time monitoring capability aboard the towing vessel.

The superiority of the simultaneous automatic



Schematic Diagram of Data Processing Equipment.

Figure 4.11

recording, as opposed to simple sequential measurements made manually, has been amply demonstrated using this system. For example, when using the now standard routine, values of the ratio $R*(\lambda_1)/R*(\lambda_2)$ measured in an open sea situation, where well mixed conditions may be expected, are usually found to be within, at most, one or two percent of one another (see Section 4.6). In similar circumstances, but with channels interrogated sequentially, repeated measurements of the same ratio are typically found to vary by as much as twenty or thirty percent. This is an obvious point, but one worth making, bearing in mind that values of R based upon comparisons made of readings which are separated by considerable time intervals, even as much as a complete redeployment of a single sided instrument, are commonly to be found in the literature.

In point of fact, it has often been found inconvenient to use the full data processing equipment, which is sensitive to adverse conditions (in a small open boat for example), so a facility has been provided for direct reading of the output voltage difference across each detector pair (each wavelength) using a digital voltmeter. This voltage difference is a direct indication of the value of R* at any instant so, in principle at least, it should be constant in a light field which is varying only in intensity. The arrangement is not ideal. There still remain temporal differences between wavelengths which have the potential to invalidate spectral ratios. In practice however, it does offer a manual read-out facility which is substantially better than the sequential alternative and it has often proved useful in providing data in circumstances where lower quality data, which might otherwise not have been obtained, was sufficient for the purpose in hand.

4.6 Use at sea and assessment of performance

The prototype has been used a great deal, mainly in sheltered waters but also on occasions in the open sea in moderately rough conditions. It has proven satisfactory and it seems likely that it will continue to be useful, even though a full ocean-going version is now available.

The constraints upon this type of measurement have been discussed in Chapter 3, where the point is made that it is unrealistic to assume that a sea-going instrument of this type will give true values of R in all circumstances, and even values of R* are likely to be subject to a very high degree of variability and uncertainty. Not surprisingly therefore individual sequential values of R* obtained using this instrument show variations on time scales of a few minutes or even seconds, which make it seem unlikely that they are always responding to changes in water quality.

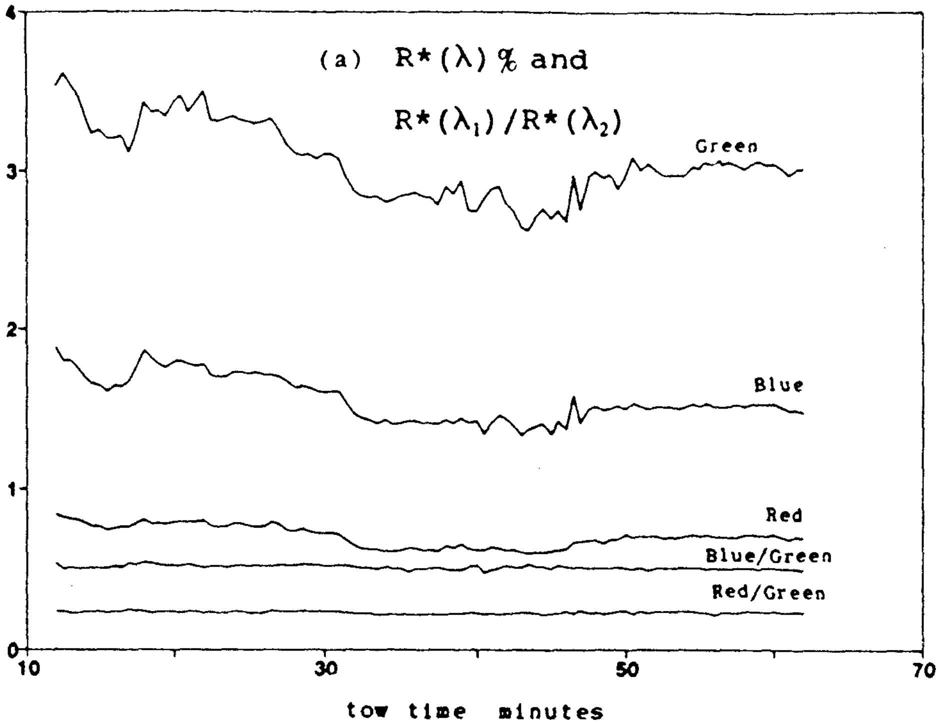
However, the basic idea underlying the measurement philosophy and design criteria upon which this prototype is based, was to produce an instrument which gives values of the ratio $R^*(\lambda_1)/R^*(\lambda_2)$ (not individual values of R or even R*), which are stable, will respond only to real changes in the optical properties of the water and are independent of the frequent and substantial changes of measurement conditions which inevitably beset all light measurements made in the sea. Therefore, the criterion of success is the stability in values of $R^*(\lambda_1)/R^*(\lambda_2)$ when measurements are made in well mixed water but in varying conditions of surface illumination. Situations which satisfy these criteria are not difficult to find in the open ocean but, for obvious practical reasons, the instrument's use has been limited to waters close to the shore, where the quality cannot generally be relied upon to remain constant for any long period of time or over any great distance, so measurements which have been made using it in the required circumstances are relatively rare. However, there are examples of data sets collected in circumstances which approximate to the requirements, and one such is shown here in Figs 4.12 and 4.13 to illustrate the instrument's capability.

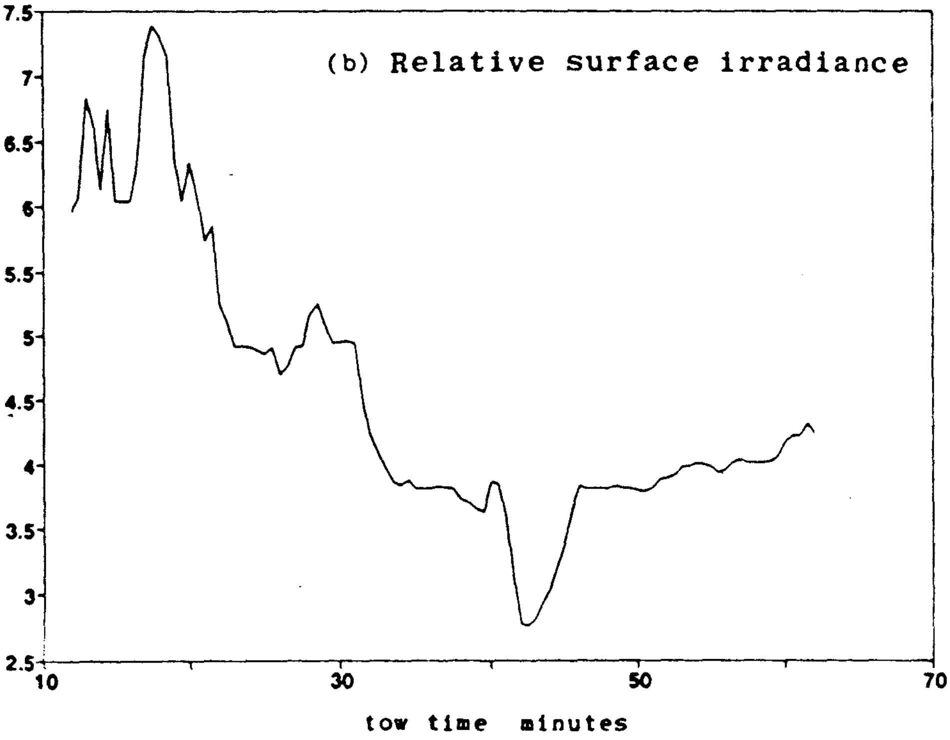
These data were collected at a depth of approximately 1m. The location was to the South and West of the Isle of Wight between stations 31 and 32 (see Chapter 7), in open water, where it is to be assumed that the water was well mixed. In this case, sediment readings at the start and finish of the set provided evidence to reinforce the assumption that water quality had remained reasonably constant throughout the one hour taken to complete the measurements. At the same time, conditions of surface illumination were varying with intermittent cloud cover; conditions which were subsequently shown to produce the greatest variation in R* (Chapter 6).

Fig. 4.12(a) shows simultaneous measurements of the apparent reflectance ratios at 436nm, 550nm and 650nm, made at half minute intervals, together with the ratios R^*_{Blue}/R^*_{Green} and R^*_{Red}/R^*_{Green}. Fig. 4.12(b) is a plot of the relative full spectrum surface irradiance.

It will be seen that R^*_{Blue}/R^*_{Green} and R^*_{Red}/R^*_{Green} are remarkably constant (the variance is less than 0.3% in both cases). At the same time, the variance on the individual values of $R^*(\lambda)$ is some 8% in each case.

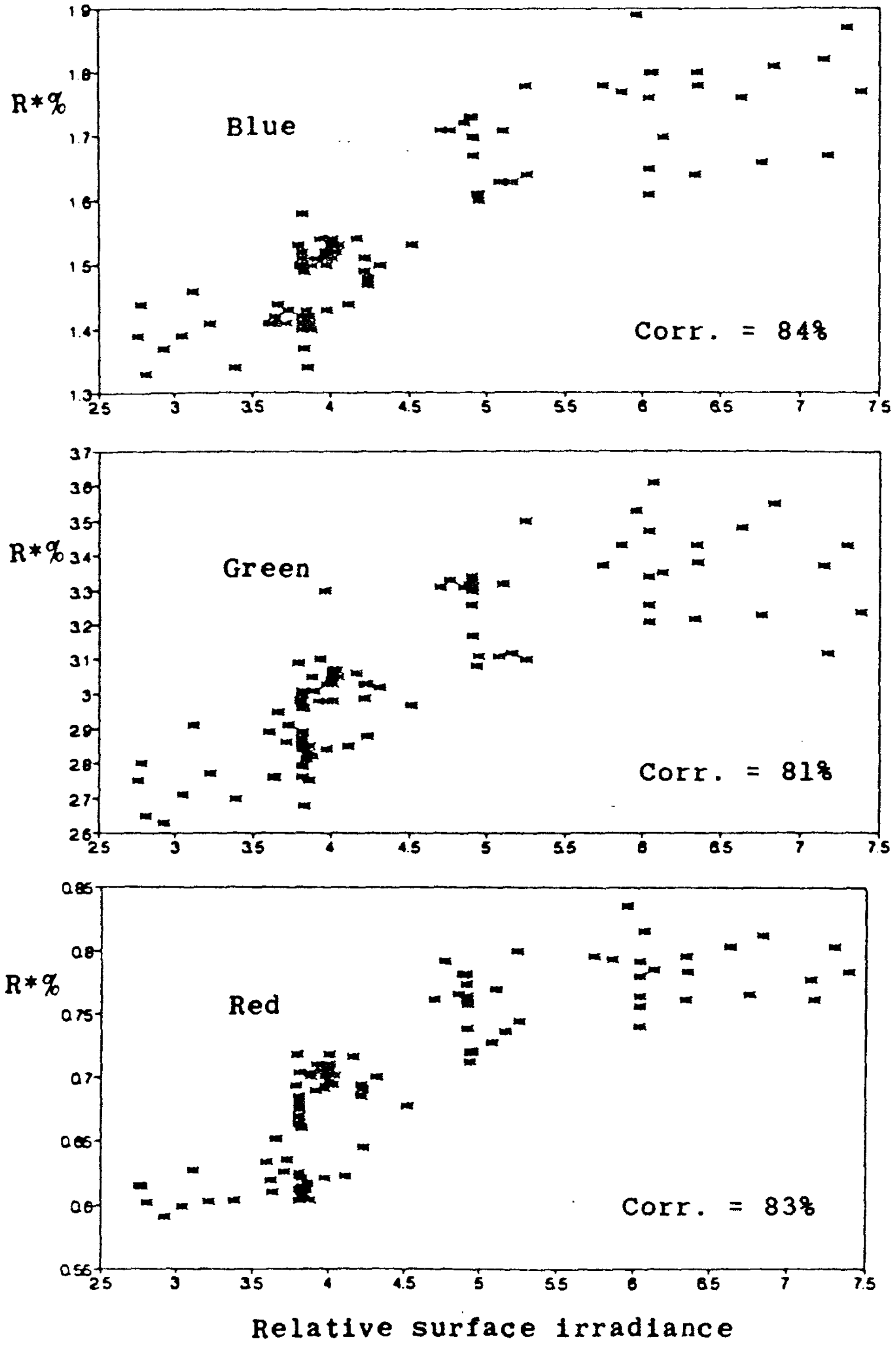
The argument which has been presented here is that measurement of the reflectance of natural light will





Profiles of $R^*(\lambda)$, $R^*(\lambda_1)/R^*(\lambda_2)$ and surface irradiance between stations 31 and 32

Figure 4.12



Plots showing R* responding to
variations in surface illumination

Figure 4.13

inevitably suffer from a sensitivity to the circumstances of surface illumination. This comes about though self-shielding, which in principle can never be entirely eliminated, or through any deviation from a perfect cosine response in the light collectors, as is the case here (see Fig 4.10).

The Effect can be seen in Fig. 4.13, which shows individual values R* for this set plotted against the relative intensity of surface illumination, supports this argument. There is a good correlation (over 80% in each case) between the measured values of R* and surface illumination. In this case where intermittent cloud cover is the source of the variation, the shape of the downwelling light field will be varying and this, as has been shown subsequently (Chapter 6), is a principal controlling factor in the measurement of R; R* increasing as the proportion of direct sunlight to diffuse skylight increases the asymmetry of the downwelling light field.

On the basis of this and other similar data sets, it is concluded that the objective, which was to make an instrument which would provide measurement of spectral ratios which were substantially independent of changing ambient lighting conditions, has been achieved.

4.7 Summary

It is again stressed that no attempt has been made here to achieve measurements of absolute values of R. A conclusion already reached in Chapter 3, is that there are too many uncertain variables, particularly at the shallow depth at which it is intended the instrument will be used, for that to be achieved with any degree of confidence.

Instead, the objective has been to build an instrument to determine a ratio $R^*(\lambda_1)/R^*(\lambda_2)$ which is dependent upon the optical properties of the water but largely independent of the circumstances of the measurement. It does this by accepting the limitations and uncertainties associated with the instrument's response to the varying shape of the sub-surface light field in changing circumstances, and avoiding the intermediate step of attempting to determine absolute values of R. Attention has been given in the design to ensure that indeterminate variations will, as far as is possible, cancel between detector pairs.

This strategy has been shown to be effective in overcoming the problems brought about by the inevitable sensitivity of any such instrument to the frequent and substantial changes which take place in the circumstances of the measurement. However, it has to be accepted that an uncertainty still exists in the absolute value of the ratio obtained when self-shielding is a significant factor. This is because the self-shielding potential of any instrument is dependent upon K, which varies with λ.

In the case of this instrument where, in addition to attention to symmetry between detector pairs, every effort has been made to reduce the shielding potential to a minimum, there is reason to suppose that the sensitivity of the self-shielding factor to wavelength will not be a problem in the majority of circumstances. Measurements detailed in Chapter 6, show that with values of K of the order of $1m^{-1}$, the critical size for an instrument with regard to self- shielding, was about 20cm in diameter. The total shielding potential of the collection of small detector housings used here (each only 2.5 cm in diameter), together with that of the thin open framework, would therefore be expected to present insignificant self-shielding in open ocean situations and would still be below the critical area in the majority of estuarine and coastal waters.

5. THE EXPLORATION AND DEVELOPMENT OF OPTICAL INSTRUMENTATION

While the prototype relative reflectance meter described in Chapter 4 was the principal instrument used in this work, several other instruments were devised and constructed for specific purposes as and when the need arose. In fact, by far the greatest amount of effort on this project was expended designing, constructing and testing instrumentation of one type or another; the main objective of the work being to explore measurement techniques. For the most part, instrumentation was literally home-made, using materials and technology which were to hand and inexpensive. Some sea-going instrumentation resulted, but the main interest was in producing devices for testing principles. This chapter is devoted to a brief description of each of the instruments which found use at sea, other than the prototype relative reflectance meter already described in detail in Chapter 4. It also includes a description of the ocean-going version of the relative reflectance meter, which may be considered to be one of the principal outcomes of this work.

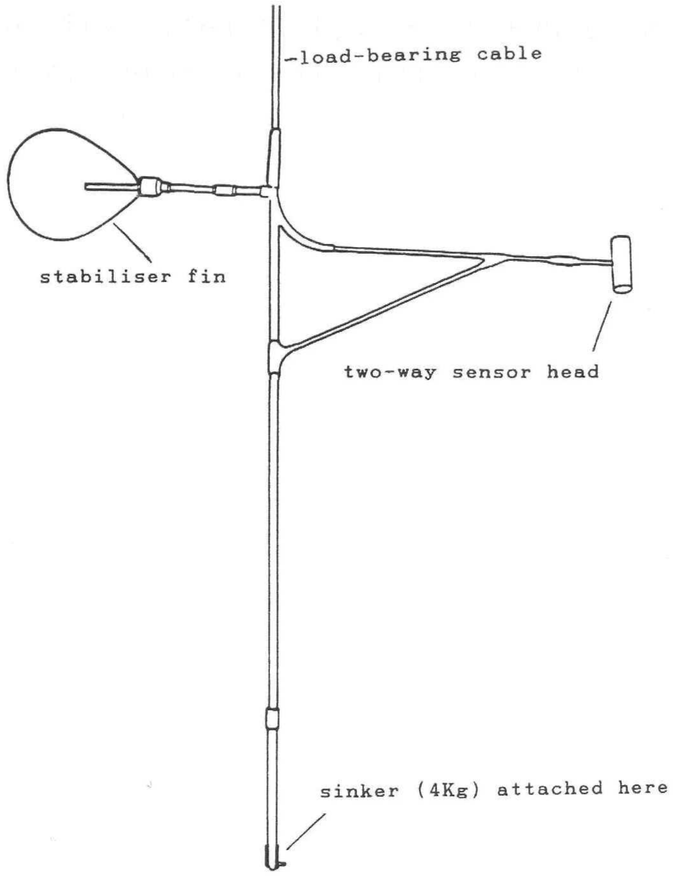
5.1 The upwelling and downwelling diffuse attenuation coefficient, K.

Two instruments for the measurement of K have been made; one a full spectrum instrument for general use by the Department (see Fig. 5.1) and the other under contract for the University of Newcastle (see Fig. 5.2).

A requirement for an instrument to provide assessments of turbidity in the many experiments which were carried out during this work, prompted the early manufacture of the first simple K meter. The basis was already to hand in the form of the self-shielding test rig described earlier in Chapter 3 and illustrated in Fig. 3.3. Thus, the instrument is basically one half of that test rig, that is a pair of detectors, one upward looking and one downward looking. The detector housing is mounted on a crucifix-like frame in a nominal attempt to avoid interference by the relatively heavy, load-bearing cable (see Fig. 5.1). A vane was added when it was found that some degree of directional stability was necessary if the instrument was to be used relatively close to the side of a vessel.

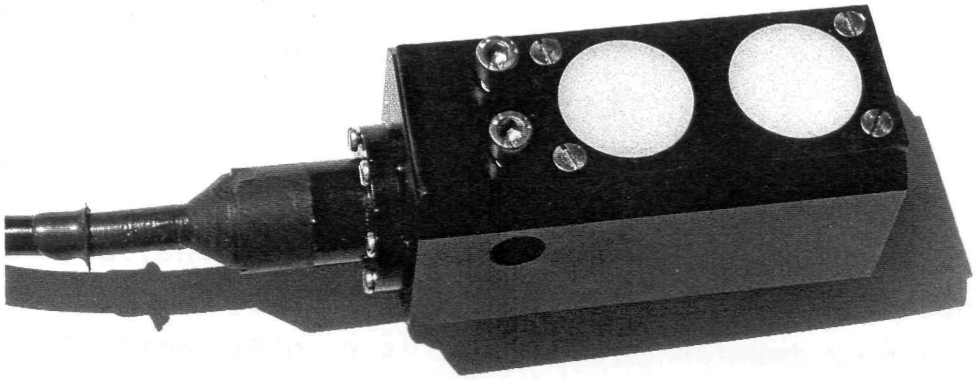
The detectors, their associated circuitry and their lenses are similar to those used in the relative reflectance meter. Hence, the instrument measures a good approximation to relative values of E_d and E_u. By taking readings as the instrument is lowered though the water column, it is therefore possible to obtain both K_{Ed} and K_{Eu}. It is worth mentioning here that K_{Eu} is likely to be a more reliable reference parameter than K_{Ed} because it is less affected by uncertainties in radiance distribution and surface roughness.

The instrument has been used on many occasions, both by students in the course of sea-going projects and as part of the investigations reported here, and it has been found to be entirely satisfactory. Its high sensitivity and wide dynamic range, obtained using the sensor technology developed for the relative reflectance meter, gives it the ability to work in a wide range of conditions, including the very high turbidities found in most estuaries. At the same time, it is rugged and simple to use. An added



The vertical attenuation (K) meter

Figure 5.1



Sensor head of the K meter built for Newcastle University

Figure 5.2

advantage, is the capability to measure K_{Ed} and K_{Eu} simultaneously by reference to voltage differences, which in addition therefore, yields a profile of R*(full spectrum) with depth (see Chapter 6).

A further K-meter, based on the above, has been manufactured to order for the University of Newcastle (see Fig. 5.2). Their requirement was for simultaneous measurements of K_{Ed}, for both the full visible spectrum and U-V. The latter has been achieved using a broad band filter, the Schott UG 11 which has a transmission curve with a width of about 100nm, centred at about 380nm. The plain OSD 100 is inefficient in this part of the spectrum but a version with enhanced sensitivity at shorter wavelengths has since become available. This is a precision engineered instrument and uses an improved window design (later employed in the ocean-going relative reflectance meter) which gives an excellent cosine response.

Both K meters are read using digital voltmeters. Values of K are based on detector calibrations done at the PML optical standard laboratory.

5.2 Radiance distribution

First thoughts concerning the influence of radiance distribution on the measurement of reflectance ratios were based on one published set of data on in-water radiance distributions (Fig. 3.1) and an early attempt to assess the effects of self-shielding (Chapter 3). The identified critical dependence of sub-surface light measurements upon the shape of the sub-surface light field (later demonstrated, see Chapter 6) made it clear that it would be necessary to measure the sub-surface radiance profile under various conditions and simultaneously with reflectance, if any practical exploration of the effects of interactions between it and a reflectance meter was to be attempted.

As has already been mentioned in Chapter 3, the University had earlier made some radiance measurements in Southampton Water using a very simple rotating, collimated detector (a silicon diode in a tube). Those measurements were revealing to some extent. They confirmed the expected asymmetric profile and also showed the periodic profile distortions due to wave motion. There were however, difficulties and limitations associated with the design. It was unwieldy, difficult to deploy, limited in its arc and restricted to full spectrum operation due to a combination of low sensitivity and strong collimation.

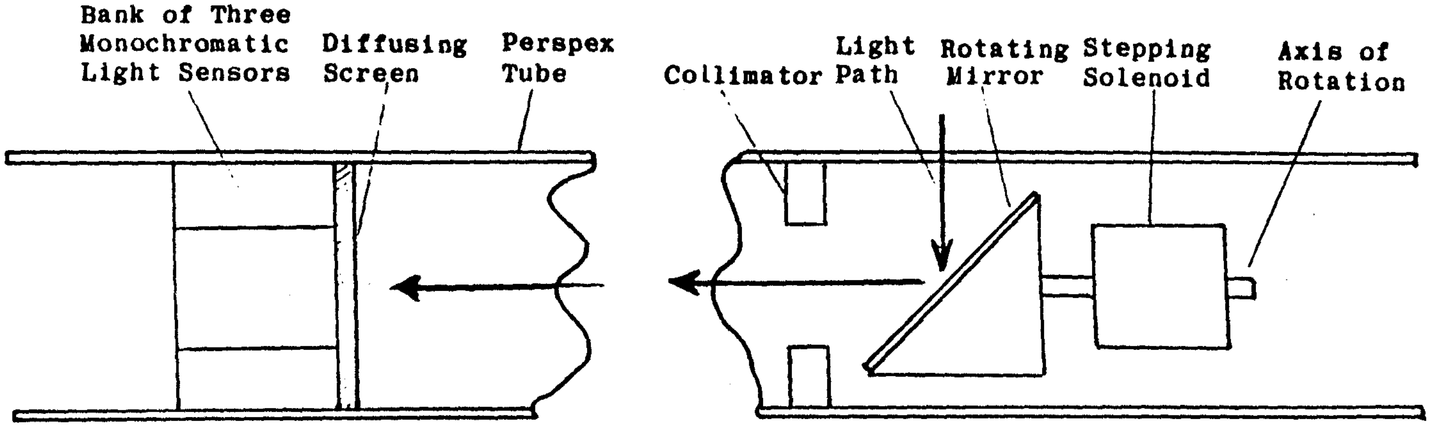
Attempts to upgrade the existing device by replacing the simple detector system with three less collimated, more sensitive detectors, each working at a different wavelength and incorporating detector systems similar to those developed for the relative reflectance meter, were not successful. There are a number of practical difficulties to be overcome in trying to rotate a sub-surface, multiple detector-amplifier-filter array, together with its associated wiring and power supplies, and sensing its orientation. In particular, the size of the collimators needed to give a reasonable degree of collimation and at the same time make full use of the detector area (essential when working in only a very small part of the spectrum), presents a considerable engineering problem in the sea. It soon became apparent that the existing rotating mechanism was inadequate for the task, and it was also clear that to make another one which was sufficiently sophisticated to do the job in a similar manner, would require a substantial commitment of both time and money.

This experience prompted a search for an alternative method of making the measurement, and the outcome was a device based on the principle of fixed sensors scanning a complete 360° arc with a mirror (see Fig. 5.3). The only moving part in this device is a small mirror, so the problems of detector wiring and, in particular, of collimator size and positioning, are eliminated, as the whole is accommodated in one, relatively convenient, stationary, watertight housing.

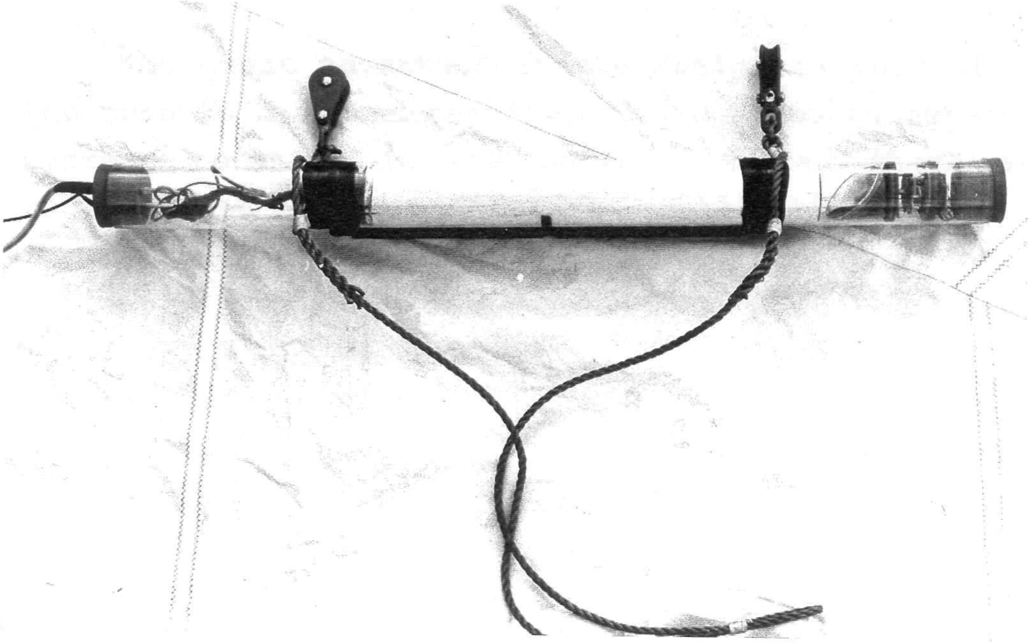
A working prototype based on this idea was built (see Fig. 5.4). It was made using only materials which were to hand but proved sufficiently practical to be used for the field experiments for which it was made (see Chapter 6).

It is contained in a perspex tube, 1m long and 70mm internal diameter. Three detector/amplifier/filter units, working in the red, green and blue, are mounted in one end of the tube, looking at a diffusing screen. Light from a mirror at the other end of the tube passes via a collimator to illuminate the screen. The mirror is mounted at 45° to the tube axis on a rotating shaft which is driven by a stepping solenoid, so that the mirror scans a full 360° in a vertical plane. A control box containing an identical solenoid, wired so that it rotates in unison with the mirror solenoid, provides a simple and reliable method of sensing the mirror angle at the surface. Rotating the mirror, with the tube suspended horizontally in the water, gives a vertical profile of the radiance at the three colours. Outputs from the detectors are amplified within the sub-surface unit and are recorded manually at the surface, using a digital voltmeter.

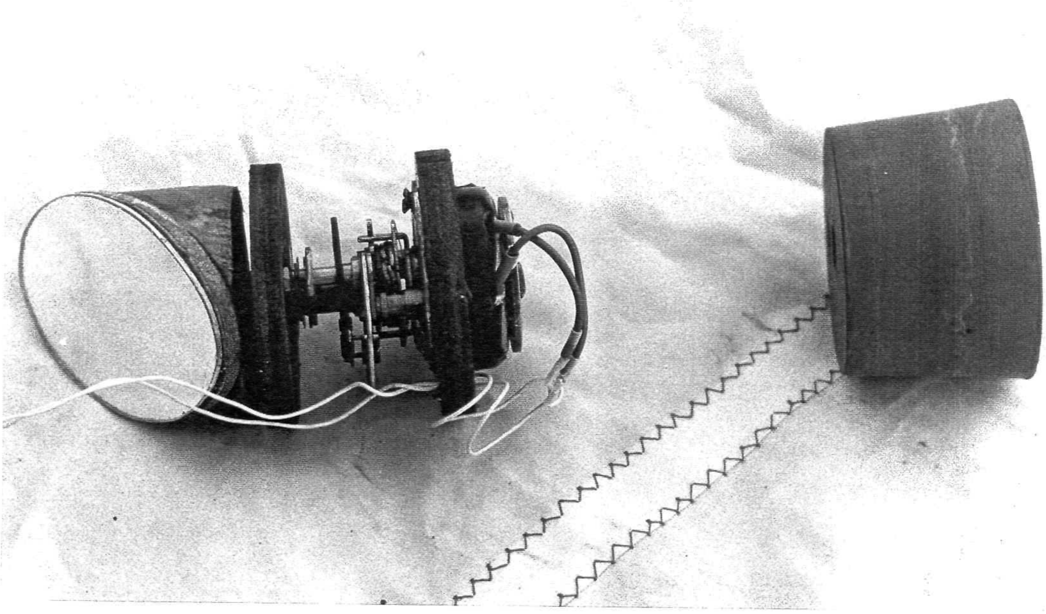
Figure 5.3



Schematic of the rotating mirror Radiance Meter



Total assembly



Mirror and mechanism

The rotating mirror radiance distribution meter

Figure 5.4

The great advantage of the design is that it avoids the need to have necessarily bulky collimated detector systems rotating in the water. Hence, there are no requirements for sealed bearings or slip rings, and none of the hydrodynamic problems associated with moving parts and cables in water; usually water which is itself moving relative to the instrument.

Even so, satisfactory deployment of such a device is still quite difficult in practice. The instrument is required to be maintained horizontal and in a fixed orientation to the sun if the two-dimensional distributions which it measures are to be meaningful. At first, a rigid deployment system was thought to be essential, but such a system proved impractical for use from a boat and so was eventually replaced by a twin rope suspension. The rope suspension system worked reasonably well in the very sheltered circumstances of the tests for which the instrument was built, but the lack of torsional rigidity inherent to any such suspension, would undoubtedly prove unacceptable in any more demanding circumstances or in deeper water.

The other major difficulty inherent to the measurement of radiance, is the conflict of sensitivity and angular resolution. To limit the field of view to a narrow angle, substantially limits the amount of light entering the detector. In this case, where cost dictated that relatively low sensitivity detectors should be used (as opposed to photomultipliers), a considerable loss of resolution had to be accepted in the interests of intensity gain. Thus the collimation was rather broad (approximately 11°) and the narrow bandwidth optical filters used in the other instruments had to be abandoned in favour of much broader bandwidth filters.

Nevertheless, although a less than ideal combination of available components and materials, the device worked well, and has not only demonstrated the practicability of the principle, but has also been used to explore relationships between R* and the radiance distribution (see Chapter 6). For that application the main requirement was simply for an indication of relative degrees of asymmetry in the sub-surface light fields.

Of more general interest, is the promise demonstrated for a compact, two axis instrument, working on the same principle and capable of measuring full 4π radiance distributions. Such an instrument would be capable of sensing its own azimuth while being induced to rotate about the vertical axis, thus removing the one remaining practical difficulty, that of deployment.

5.3 Relative reflectance

Having established the value of the principles incorporated in the prototype relative reflectance meter described in Chapter 4, consideration was given to the possibility of building a more seaworthy version of the instrument which could be towed at ship speeds, as opposed to small boat speeds. This was prompted by Southampton University's involvement in the Biogeochemical Ocean Fluxes Study (BOFS) programme. Part of the University's contribution to the programme was to be the design, development and deployment of an improved instrument for sub-surface reflectance measurements.

The remit was to build an instrument incorporating the features of the prototype described in Chapter 4, but with more channels, built more robustly to survive open ocean conditions and, above all, capable of being towed at a speed of at least 10 knots.

The open frame, spider-like form of the original, though advantageous from the optical point of view, is clearly not suited to high speed towing. If nothing else, the mechanical strength of such a shape would have to be considerable to withstand the loads placed on it at ten knots. In addition, such an unstreamlined structure would create considerable turbulence if it were to be towed at speed. Reluctantly therefore, it was conceded that the advantages of minimal self and mutual shielding would have to be compromised in deference to practical engineering and hydrodynamic considerations.

However, accepting that it is not possible to entirely eliminate self and mutual shielding in a robust, compact, hydrodynamic shape, it is nevertheless true that some optimisation of design can be achieved if we continue to adopt the view that the damaging effects of self and mutual shielding can be considerably reduced provided that:-

(a) the design is such that all detector pairs are affected as near as is possible equally by any change of environmental circumstances and:-

(b) that the sole objective is the measurement of <u>relative</u>, rather than <u>absolute</u> ratios.

It is possible to go a long way towards achieving the limited objective, (b), by mounting detectors in a straight line along the middle part of a thin, uniform cross-section spar which is long compared with the sensitive section. In this way, there are just two directions of illumination which give shielding "high spots". However, even if the sun's azimuth is directly in line with these high spots, because the spar is long and hence no one detector will be particularly nearer to an end than any other, all channels will be affected similarly by any change in the nature of the surface illumination. Thus, variation in the ratio $R^*(\lambda_1)/R^*(\lambda_2)$, due to environmental changes, will be minimised.

This was the hypothesis upon which the design of the ocean-going version of the instrument, seen in a modified form in the frontispiece photograph, was based. It uses the same sensor technology as the prototype but has five wavelength pairs, with narrow (~ 10nm) bandwidth interference filters at 440nm, 490nm, 520nm, 550nm and 670nm. A sixth channel, operating at 410nm, is included but the low sensitivity of the detectors at this wavelength makes it necessary to use wider (35nm) bandwidth filters. Sensitivity of both the 410nm and 440nm channels is increased in this instrument through the use of the "blue enhanced" silicon diodes mentioned earlier in Section 5.1.

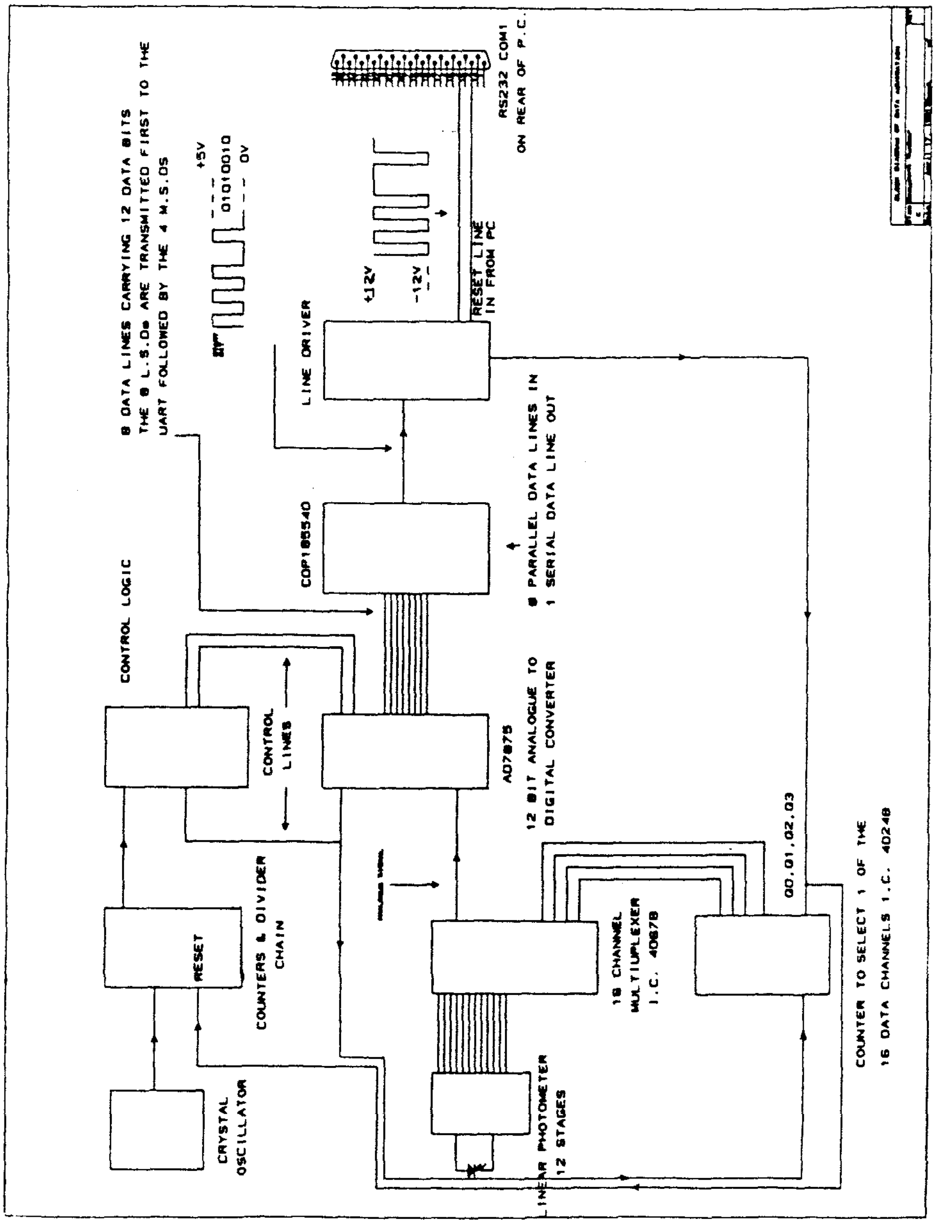
The body of the instrument is made up of three sections, a central "sensing" section, a long cylindrical nose forward and a tail section aft. The sensing section is a solid bar of aluminium alloy into which has been drilled a complex series of holes which overlapped to give a series of interconnecting chambers (Fig. 5.5). Each chamber contains a detector and an optical filter, and is sealed with a compound window identical to those used in the prototype (Fig. 4.4). However, as in the case of the K-meter built for the University of Newcastle, these are installed with 0.5mm of edge exposed which, in line with the experimental work of Boyd (1951) mentioned in Chapter 4, has produced a detector response which is indistinguishable from the ideal cosine collector.

Centre section of the ocean-going relative reflectance meter showing interconnecting chambers to contain sensors and filters

Figure 5.5

In most other key respects the design details follow closely that of the prototype instrument, with real-time data reading on board the towing vessel. The detector and amplifier combination in particular, had been the subject of a great deal of thought and development in the building of the prototype and in view of the proven capability of that instrument, there was no need to embark on further development of this aspect for the new instrument. However, the long body of the later design provides room for an additional electronic payload, which has made possible the use of sub-surface processing and multiplexing of the signals. This, in turn, has removed the need for a multi-core instrument-to-ship cable and made it possible to make use of a conventional, waterproof, load bearing cable for signal transmission and towing, a feature which is essential for a relatively high speed, ocean-going instrument. Fig 5.6 is a schematic diagram of the signal processing and data transmission electronics which have been designed and built for the instrument by the Electronics Workshop of the Department of Oceanography at Southampton University.

The first instrument built to this design was planned to be available in time for use on the June 1990 BOFS Atlantic cruise, but there were a number of manufacturing delays. In the event, in order to have an instrument operational in time for the cruise, a UOR (Undulating Oceanographic Recorder) (Aiken and Bellan 1986) was used as a temporary deployment vehicle. This, together with a great deal of help and advice, was generously made available by Dr Aiken of the Plymouth Marine Laboratory. The new instrument, with a shortened tail section, was bolted to the UOR (see frontispiece). To further simplify matters and ensure that an instrument would be available for the BOFS cruise, it was operated using the UOR’s own



Schematic of the data acquisition system for the ocean-going relative reflectance meter

Figure 5.6

internal signal processing and logging system. Data were thus recorded on board the UOR and processed upon recovery of the instrument at the end of each run.

In practice, this temporary, hybrid system, though not ideal, proved acceptable for the purpose, and provided the operators with a substantial stock of data. The unit was long relative to the UOR, but it did not destabilise the heavy UOR, and the required ten knot operating speed proved entirely practicable. The main differences between this and the planned normal mode of operation were the absence of the shallow operating, surface-following characteristic of the prototype, regarded as desirable for the main long term purpose of the device, and the absence of the real-time data read-out which had proved so useful in the prototype. In addition the added shielding potential presented by the UOR had to be accepted in this mode of operation. The UOR was less than a metre behind the sensitive section, so interference from it could not be ruled out. One very great advantage of the arrangement was that the UOR provided continuous monitoring of other parameters, including the chlorophyll concentration, using on-board sensors. On earlier cruises, using the prototype, associated measurements of chlorophyll concentration derived from water samples, had been found to be particularly unsatisfactory. This point is mentioned later in Chapter 8 where some of the data collected using the instrument in this way on the 1990 BOFS Atlantic cruise, is used in the discussion of the analytical potential of reflectance data.

Further development of this instrument to the level of full self containment has been undertaken by the technical staff of the University. A full instrument, to the original design with its own on-board signal processing and real-time data collection facility (but still relying upon a UOR body as a deployment vehicle), has been prepared for use on the BOFS exercise which is due to take place in the Antarctic Ocean in November and December 1992.

5.4 Summary comments

The measurement of three parameters has been explored. In the case of two of these, radiance distribution and relative reflectance, that exploration has resulted in a new approach to the design of an instrument for the purpose, and demonstrated its feasibility and capabilities.

It is important to stress that some of the instruments discussed in this report are products of the most easily and cheaply available hardware and materials. Some were totally home-made, using only limited facilities and skills. These were mainly attempts to explore principles, as quickly and as cheaply as possible.

Nevertheless, two instruments with full ocean-going survey capabilities have been produced. In addition, two of the early home-made instruments, built originally as test rigs proved to be useful in the longer term and remain available for measurements in sheltered waters.

6. SOME FIELD LABORATORY EXPERIMENTS

Results of laboratory tests to establish basic characteristics of the component parts of the prototype relative reflectance meter have been given in Chapter 4. They were all straightforward routine tests, carried out using established instrumentation. Calibrations were carried out at the Plymouth Marine Laboratory (see Section 4.3 and Fig.4.7) spectral and angular response measurements at the University of Southampton (see Section 4.4 and Fig. 4.9), and hydrodynamic proving tests in the wave tank of the Institute of Oceanographic Sciences' Deacon Laboratory.

In contrast, the experiments described in this section were essentially investigations and demonstrations of hypotheses detailed in Chapter 3. They were carried out in "field laboratory conditions", that is in an expanse of natural water, but with the environmental conditions carefully selected to test specific aspects of the measurement problem. The aim was to shed light on questions regarding the validity and reliability of in-water reflectance measurements, rather than to establish instrumental parameters or to collect data on the particular body of water used.

The test site was on the River Hamble. One of the main problems in the field experiments was finding exactly the right set of circumstances to test any particular point, and a great deal of time was wasted attempting to get results from further afield in more ideal (that is deeper and clearer) waters before the Hamble compromise situation was decided upon. In the Hamble location it was convenient to have instruments set up ready in a moored boat which was immediately accessible at all times. In that way, it was often possible to take advantage of a particular combination of lighting and tide at very short notice.

All of the tests were carried out around high water to obtain maximum depth with minimum current, both of which were necessary in the site used where the depth can drop to around 3m at some states of the tide and currents up to 3 knots are not unusual.

6.1 The combined effects of radiance distribution and optical geometry.

As was pointed out in Chapter 3, this factor plays a key role in reflectance measurements. It is a combination of the radiance distribution and the optical geometry of a detector, as well as the intensity, which determines the detector output in any given set of circumstances. This is a critical factor in the case of reflectance measurement as the two light fields being compared, E_u and E_d, are very different in shape. It is usual, and generally considered sufficient, to use detectors which are assumed to have a cosine, or near cosine response for reflectance measurements. In principle, a perfect cosine collector gives a measurement of vector irradiance, by definition. In practice however, a great many instruments have been used which are far from perfect in this respect. Therefore, in pursuance of question (i) in Chapter 1, an attempt was made to get some idea of the magnitude of the effect to be expected, and to see how that effect might vary with operational circumstances.

The objectives of this first test were:-

(a) to observe the radiance distribution in a body of natural water under different circumstances of illumination, and to observe <u>trends</u> in the changes which take place in those distributions as depth increases and,

(b) to observe the effects of a varying radiance distribution on R*, using detector pairs with two different collector characteristics, a near cosine collector and a more collimated collector.

The equipment used for measuring R* was the prototype reflectance meter, equipped for the purpose with near cosine collector pairs (see Fig. 4.10), operating at three narrow band wavelengths (see Fig. 4.8) and one full spectrum pair. The full spectrum pair was fitted with windows of the original design, which gave the detectors a degree of collimation (approximately 40°, see Fig. 4.10). Radiance distribution patterns were measured with the rotating-mirror instrument described in 5.3, which was designed and manufactured specifically for this series of tests. The quoted values of K are mean full spectrum measurements obtained from the top 5m of water, using the K meter described in Section 5.1.

There were practical constraints on the maximum depth at which the radiance meter could be used. It had to be deployed horizontally of course, but it also had to be maintained with its plane of rotation in the direction of the sun in order to monitor the maximum asymmetry of the sub-surface light field. In practice, this turned out to be difficult to do and it soon became clear that operations in the open sea would require a quite elaborate deployment system. However, the relatively simple double rope suspension system which was devised worked reasonably well within the confines of the River Hamble. Even so, practical difficulties of deployment restricted the operation of this particular instrument to a maximum depth of four metres. In point of fact, because of the restricted sensitivity of this well collimated instrument, it would not have been possible to obtain useful radiance measurements at much more than that depth in the majority of lighting conditions encountered.

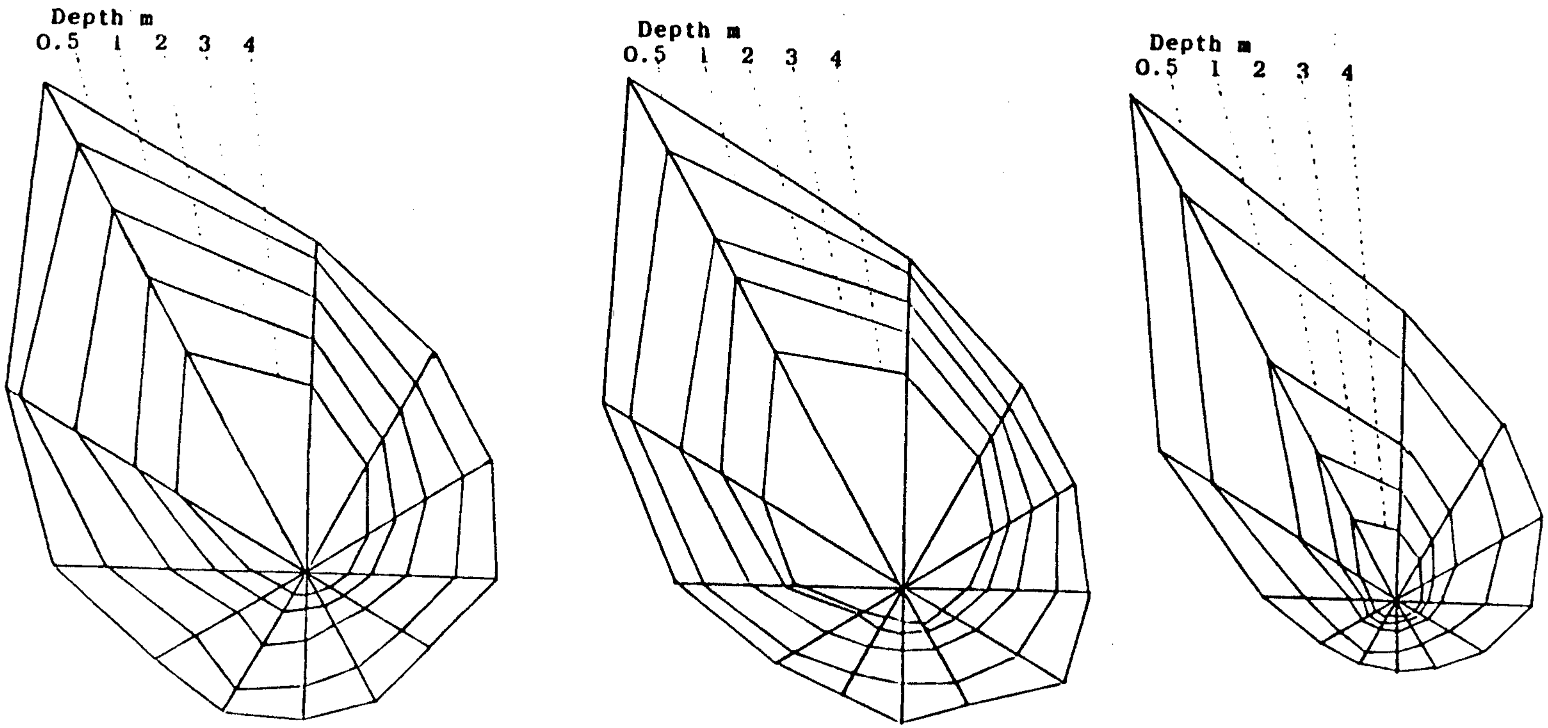
Measurements were made in calm water under three contrasting conditions of surface illumination:

(i) with a clear sky and the sun fairly high in the sky giving a high proportion of direct sunlight,

(ii) with a clear sky but with the sun close to the horizon giving mainly bright skylight conditions, and

(iii) with complete cloud cover giving lighting conditions which were as diffuse as possible.

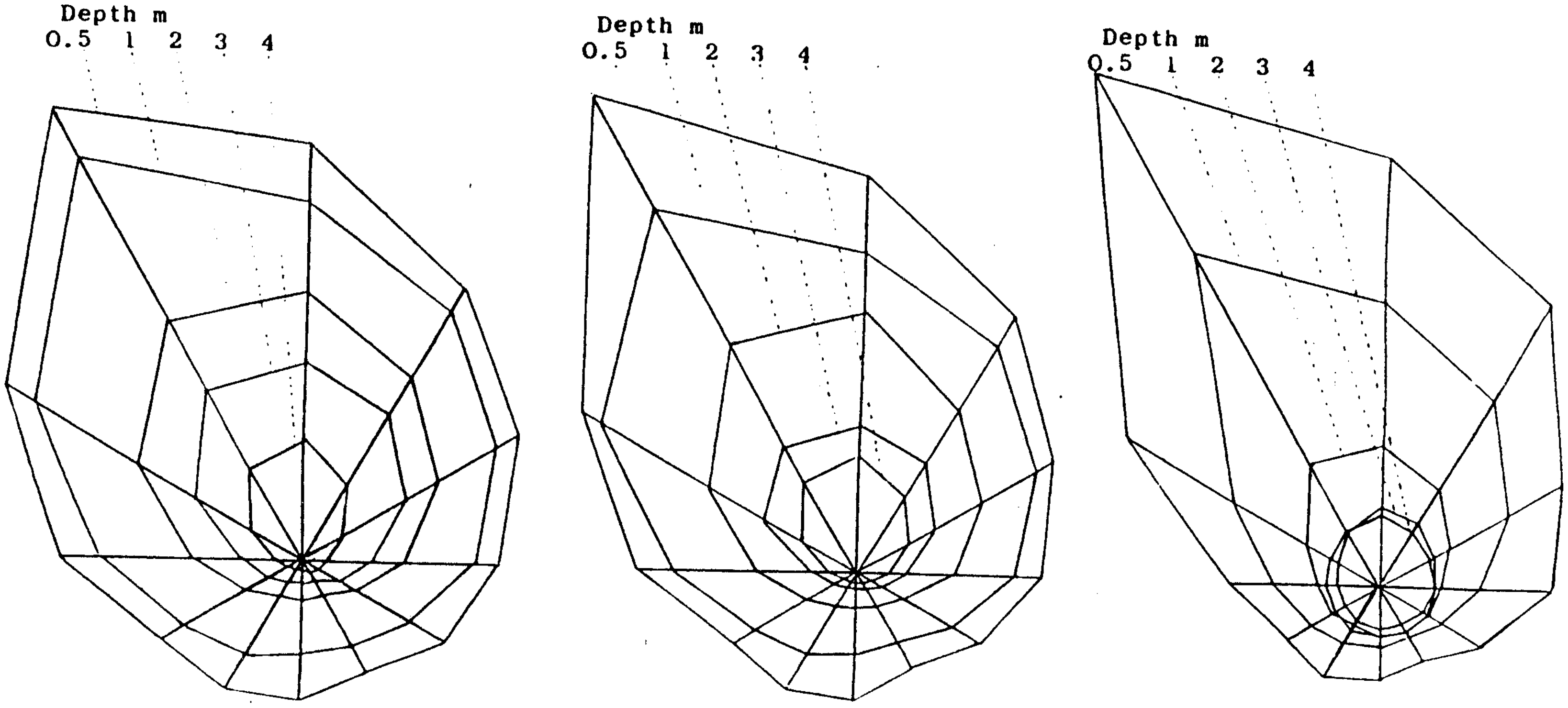
In each case, two dimensional radiance distribution patterns were measured in the plane of the sun and were plotted in the form of polar diagrams (Figs. 6.1, 6.2 and 6.3.) When looking at these figures, it is important to keep in mind the limitations of this very basic instrument, operating in some circumstances at the limit of its sensitivity. It is stressed that the lines joining adjacent points in individual diagrams are not intended to give anything other than a general <u>impression</u> of the shapes and to distinguish one set of points from another. Thus the maxima are not necessarily precisely defined in either their magnitudes or their directions. However, the



RED GREEN BLUE

Figure 6.1

Vertical radiance profiles. Type (i) situation

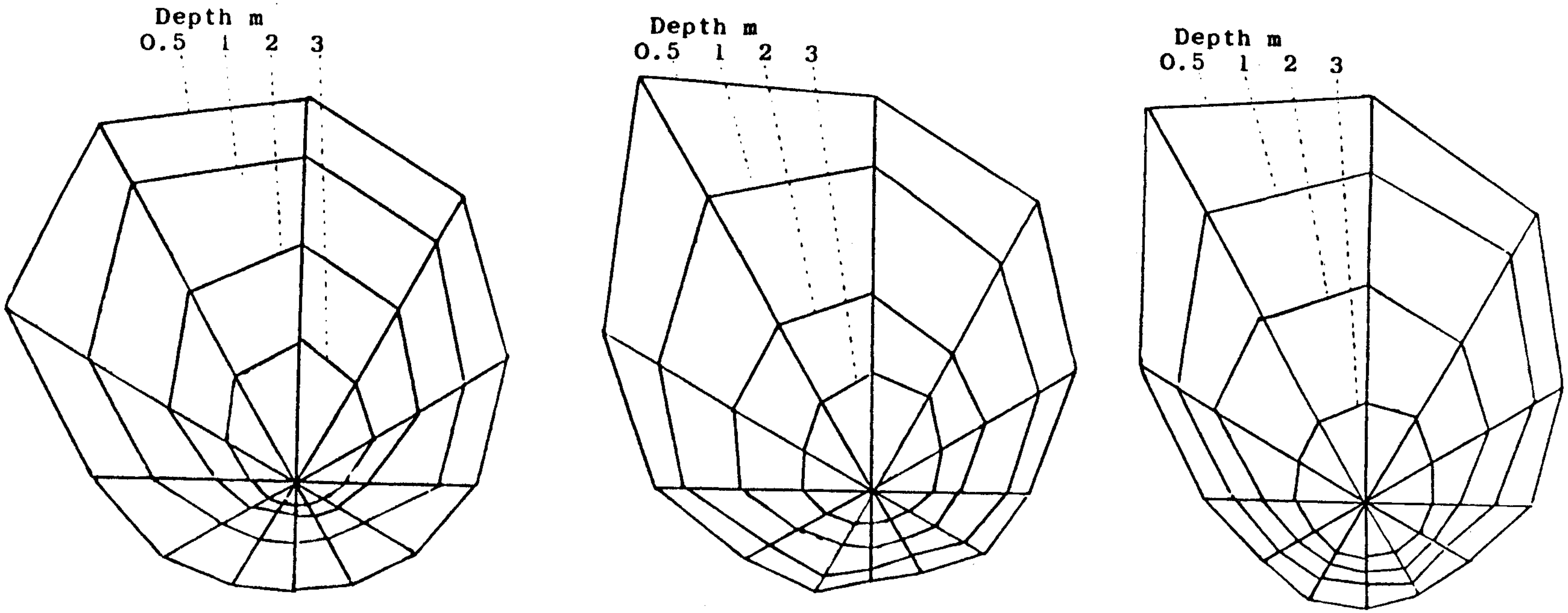


RED GREEN BLUE

Figure 6.2

Vertical radiance profiles. Type (ii) situation.

Figure 6.3



RED GREEN BLUE

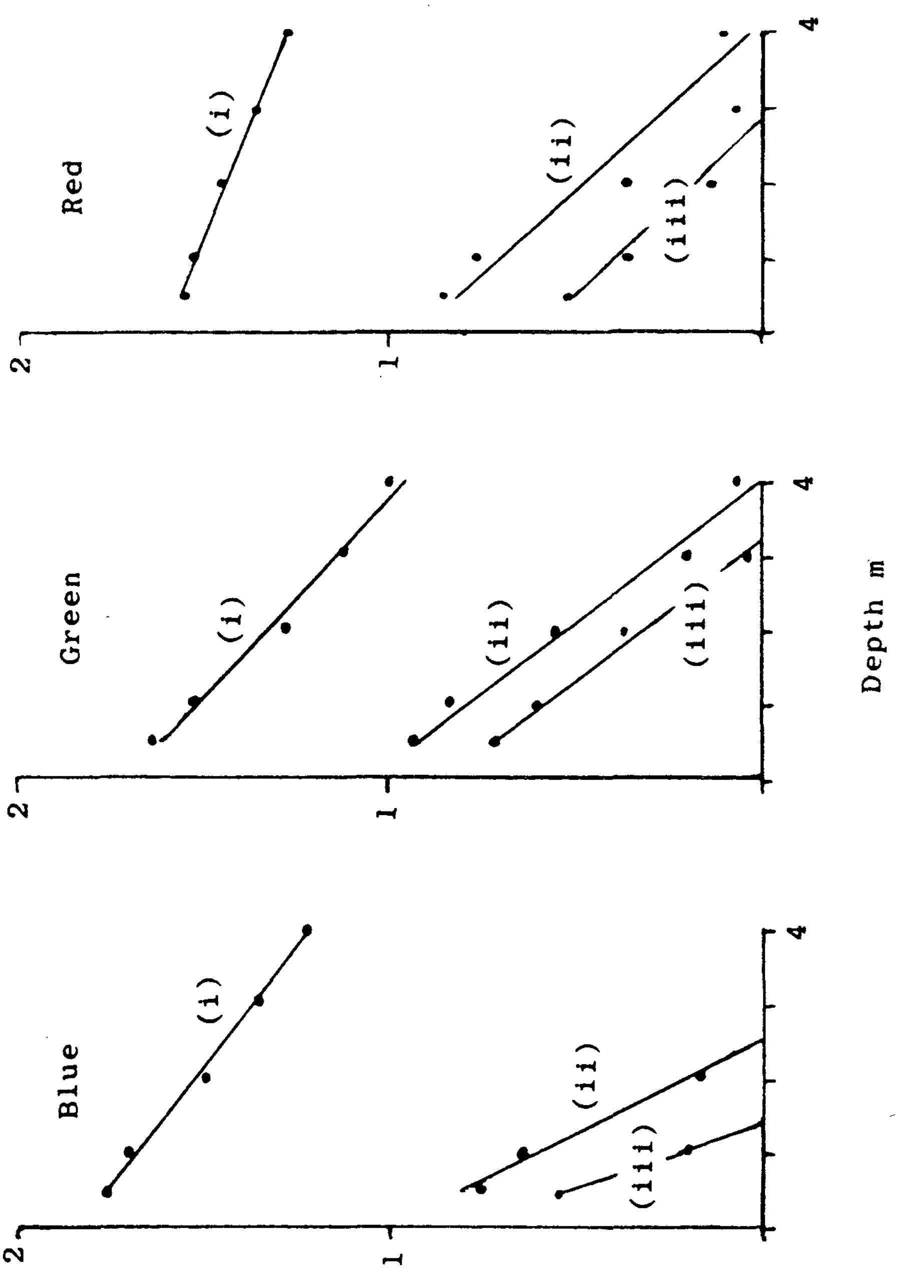
Vertical radiance profiles. Type (iii) situation fundamental differences between the different distributions are clear and sufficient for the purpose in hand.

Quantification of the all-important relative asymmetry in the downwelling light fields (see Fig. 6.4) has been achieved by defining the degree of asymmetry in each diagram as the difference of the two upper quadrants normalised to the downwelling radiance perpendicular to the surface. Thus the figure obtained for a perfectly symmetrical light field is zero.

It is important to appreciate that the objective of the exercise was to compare the <u>shape</u> of each of the distributions (and in particular the degree of asymmetry), with the outcome of reflectance measurements made at the same time. No attempt was made to obtain absolute light measurements. Individual diagrams have been reproduced here at sizes which best show the required characteristics. Thus, while dimensions within any one complete diagram are indicative of relative intensities, the dimensions of individual complete diagrams have no significance in terms of relative intensity.

Fig. 6.1 shows results obtained in Type (i) conditions. Here the sun was at an altitude of approximately 50° and there was no cloud. Turbidity was low by Hamble River standards, K being 0.6m^{-1}, and the water depth was 8m.

The diagrams are much as was expected in this case. In all three colours, there is a clear asymmetry in the downwelling light field, with a strong peak in the direction of the sun. The upwelling light is much more symmetrically distributed, though there is still some bias on the side nearest the sun. The asymmetry of the



Asymmetry of downwelling radiance

Figure 6.4

downwelling light field persists down to the 4m depth to which it was practicable to measure, though the expected decrease with increasing depth is apparent.

Fig. 6.2 shows a set of diagrams obtained in exactly the same way but under Type (ii) conditions. Here the sun was low in a clear sky, with an altitude of less than 20° throughout. The water on this occasion was slightly more turbid, with a mean value for K of $0.8m^{-1}$. The depth was approximately 7.5m.

The differences between these and the previous set of data are apparent and to some extent expected. There is certainly more vertical symmetry to be seen in the shallow water diagrams. It is clear too that almost complete symmetry around the vertical axis is reached within 3m of the surface and the distributions are broader. All this is in line with the supposition that a high percentage of the sub-surface illumination originates from the substantially diffuse source which is skylight; the direct sunlight being largely reflected from the surface at this angle.

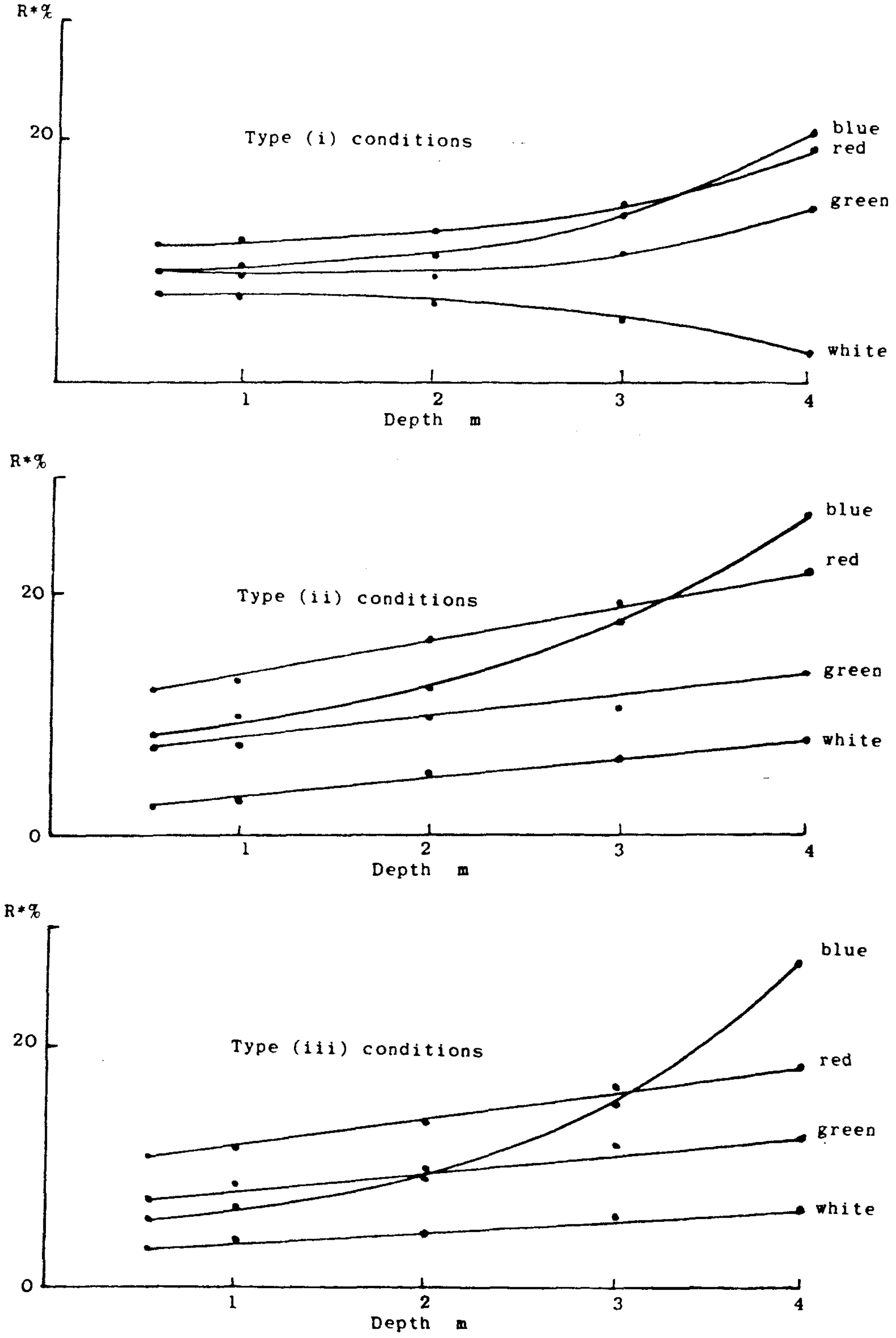
Measurements made in Type (iii) conditions are shown in Fig. 6.3. These were made with the sun fairly high in the sky (altitude about 45°) but under conditions of complete cloud cover. The turbidity of the water was $0.8m^{-1}$ and the maximum depth was 8m.

Here again, a very high proportion of the sub-surface illumination was from a diffuse source but, as was pointed out in Chapter 2, there is always a substantial variation in the brightness of the sky (never less than a factor of three), even when there is thick and complete cloud cover. Thus, it is not surprising to find that measurements in Type (iii) conditions yield a set of results which are only slightly different from those made in Type (ii) conditions; the major difference between the two being the overall intensity. In Type (iii) conditions, the sub-surface intensities at 4m were too low for the radiance meter, with its relatively strongly collimated optics, to give satisfactory results. The reflectance meter, which uses the same detectors but, being uncollimated, is a much more sensitive instrument, was operating well within its capabilities in the conditions.

The most interesting and important points to come out of this set of tests are apparent in Fig. 6.5. Here it is seen that, from the point of view of the reflectance meter, Type (ii) and (iii) conditions are similar to one another but, again from the point of view of the reflectance meter, Type (i) conditions are distinctly different.

In all circumstances the value of R* is seen to increase with depth (with one exception which will be discussed later). This may be expected in such circumstances where settling out of suspended materials will be taking place in the period of relatively still water around high tide. Also, the exceptional increase seen in every case in the chlorophyll-sensitive $R*_{blue}$ is to be expected in such circumstances, where stratification with a mixture of fresh water over saline may be expected to produce a chlorophyll concentration gradient and so markedly reduce the near surface blue ratio (see Chapters 2 and 8).

The notable difference between the three situations however, is the <u>manner</u> of the increase in R* in both the green and the red. In Type (ii) and Type (iii) lighting conditions, where the downwelling light fields are relatively symmetrical about the vertical axis, a constant



R* plotted as a function of depth in the three defined conditions of surface illumination

Figure 6.5

and gradual increase in $R*_{green}$ and $R*_{red}$ with depth is observed. In Type (i) conditions however, where there is a marked asymmetry gradient with depth, the situation is distinctly different.

The conclusion is drawn that the slightly collimated detector pairs (see Fig. 4.10) were responding to the substantial changes in radiance distribution seen in Type (i) conditions, to produce differing values of R*; the more asymmetric light fields having the effect of elevating R*. R* is therefore seen to be controlled by circumstances of surface illumination.

The influences of optical geometry combined with radiance distribution are seen to a much greater degree in the results obtained with the full spectrum (white) detector pair (Fig. 6.5). These are in line with what might be expected with substantially collimated detectors. With a 40^o acceptance angle (see Fig. 4.10), the detectors were seeing only about 6% of the total solid angle in each direction. Bearing in mind that the downwelling light is always more structured than the upwelling light and concentrated by refraction into a half angle of 49^o, seeing only the middle part of the distribution in each direction will yield lower values of R* than those obtained with cosine collectors.

Looking at the values of $R*_{(white)}$ in Fig. 6.5, it will be seen that the above reasoning is confirmed in all three cases. In the case of the Type (i) conditions which, as has already been pointed out, give by far the greatest degree of variation in the profile with increasing depth, the marked change in the collimated to cosine collector ratio can be seen as the symmetry of the downwelling radiance about the vertical axis increases with depth.

These results demonstrate the validity of the hypothesis put forward here that any deviation from true cosine collector characteristics in the detectors will render the instrument sensitive to the shape of the sub-surface light fields (upwelling as well as downwelling) and hence will result in an "artificial" variation of R* with both depth and, more importantly, with the circumstances of surface illumination. The uncertainty which this creates will therefore, be most damaging in Type (i) conditions. In these tests, differences are seen to be eliminated at relatively shallow depths, but in less turbid waters it is reasonable to suppose that they would extend to greater depths. In any event, the results confirm that the differences are worthy of consideration, and especially so in the gathering of in-water optical data for use in the interpretation of remotely sensed ocean colour data, which requires measurements to be made as close as possible to the surface.

6.2 Self-shielding

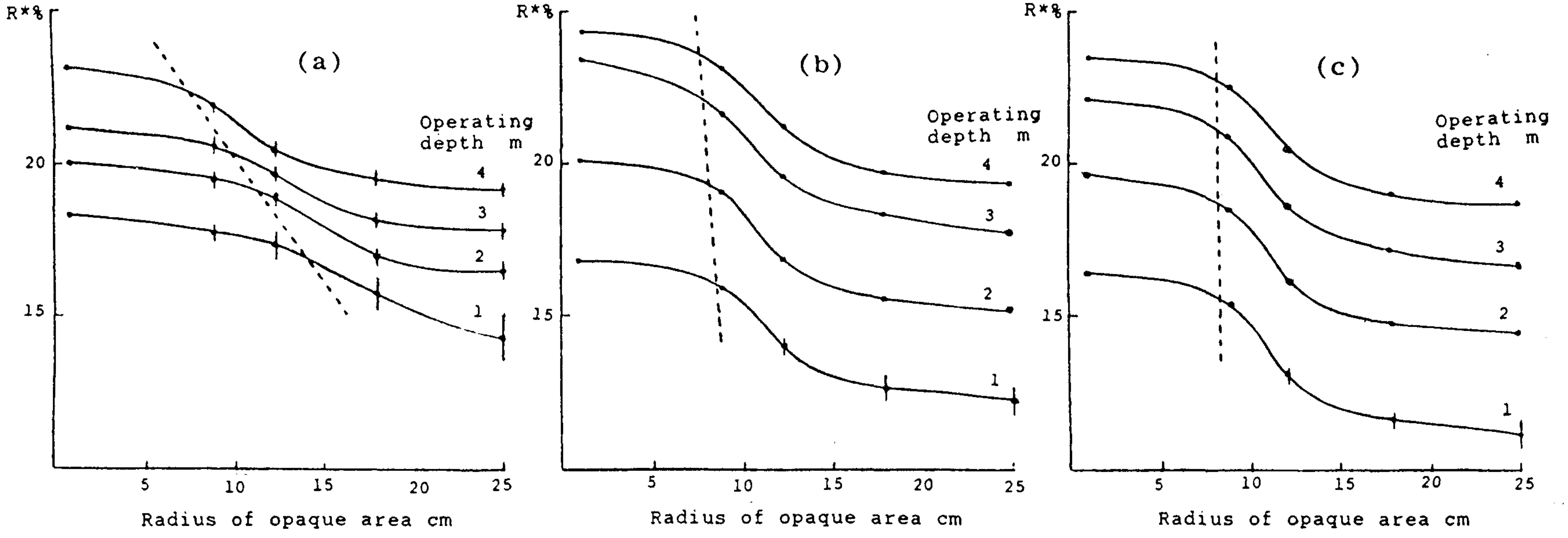
This series of tests constituted a more comprehensive repeat of the experiment mentioned in Chapter 3, which first gave the clue to the existence of a self-shielding factor which varied with conditions of surface illumination. The tests were carried out in conjunction with those described in 6.1 so that the circumstances of surface illumination were monitored. In addition, the instrumentation was considerably better than that which had been available for the earlier experiment.

The objective was to demonstrate, in a more controlled way than previously, the hypothesis that, while a potential for self-shielding is built into an instrument through the size and disposition of its opaque areas, the magnitude of the effect is dependent upon the circumstances of the measurement.

The instrument used to measure R* was the prototype K meter described in Chapter 5, which measures a reasonable approximation to both upwelling and downwelling irradiance. The windows used are the same as those used in the prototype relative reflectance meter. A set of collars was made, having radii of 9cm, 12.5cm, 18cm and 25cm. These could be fixed in position round the detector pair in a similar fashion to those described in Section 3.3 and illustrated in Fig. 3.3, thereby creating effective instrument areas of approximately 250, 500, 1000, and 2000cm^2. The detector housing itself is approximately 6cm^2 and the supporting arm a further 45cm^2. It is not practicable to make an assessment of the shading effects of the rest of the instrument, especially as its orientation to the sun is random, but it is thin and is always well to one side of the detectors, so its influence has been assumed to be small in relation to that of the collars.

Measurements of R* were made using each effective shielding area at five depths, 0.5, 1, 2, 3 and 4m, and the experiment was carried out in each of the three different conditions of illumination, (i), (ii) and (iii), as defined in Section 6.1. The results are summarised in Figs. 6.6, (a) (b) and (c) respectively.

The bars in Fig. 6.6 indicate a <u>range</u> of values obtained in those cases where significant differences were obtained in repeat measurements. Mostly this occurred at shallow depths and with the larger shields. It is important to appreciate that these and all of the other measurements discussed in this Chapter relate to situations



Type (i) conditions

Type (ii) conditions

Type (iii) conditions

Diagrams illustrating the effects of artificially created self shielding in different surface lighting conditions.

(The broken lines are to draw attention to the shift in the position of the point of inflection)

Figure 6.6

which were changing continuously. The objective in every case was to make a complete set of measurements, radiance, reflectance and self-shielding, in as short a space of time as possible, so that they might be said to have been made in circumstances which were as similar as it was possible to get. However, one of the main arguments pursued in this thesis is that R* can be very sensitive indeed to slight changes in environmental circumstances. Thus, no diagram is precisely reproducible but rather is representative of what is obtained in the type of circumstances prevailing.

The points of interest to notice in the figures are:-

1 It can clearly be seen that self shielding is a significant factor, capable of introducing errors of more than 30% in some circumstances.

2 The size of the shielding area (simulated instrument size) is a factor, there being a critical size for any set of circumstances, below which self-shielding is very small.

3 As the instrument size increases, the self-shielding effect is seen to exhibit the three stage process suggested by the reasoning developed in Section 3.4. That is:-
Stage 1, where the instrument size is insufficient to shield the main volume of water providing E_u from the downwelling radiance peak,
Stage 2, where the instrument size is sufficient to obscure part or all of the direct downwelling radiance from the critical volume of water, and
Stage 3, where detected upwelling light is composed entirely of diffuse light obtained through multiple scattering.

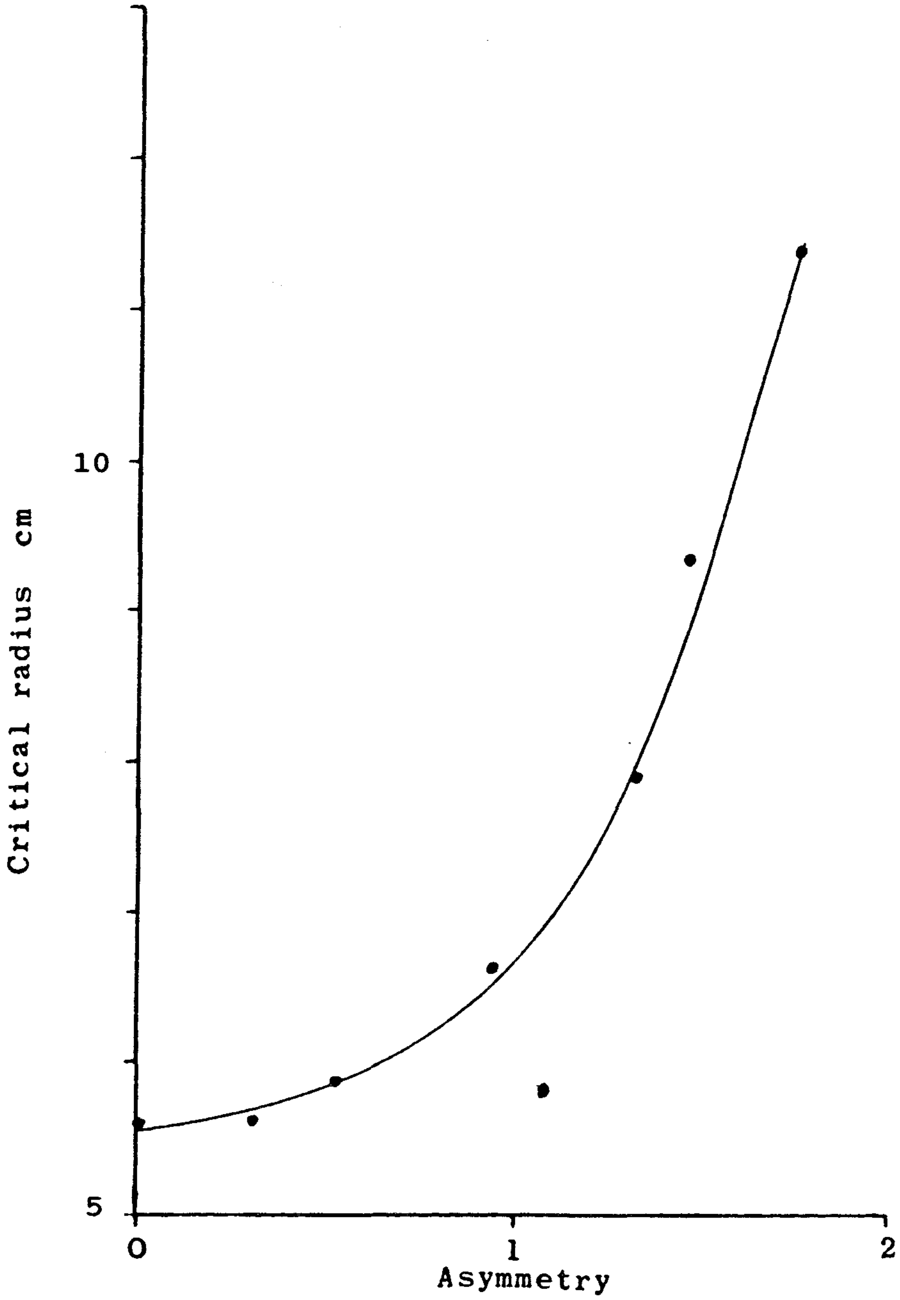
4 There is a significant difference between the change

in critical size with depth in Type (i) conditions, and in either Type (ii) or Type (iii) conditions. The broken lines in Fig. 6.6 are placed to draw attention to this essential difference. Type (ii) and (iii) conditions are very little different from each other in this respect.

From the standpoint of instrument design and use, points 3 and 4 above are the most important. It is seen that, in bright sunlight and at relatively shallow operating depths, an instrument could be quite large without the self-shielding being detrimental to the results. Operating at a greater depth, where the light field becomes more symmetrical, or in either Type (ii) or Type (iii) illumination conditions, the critical size is much smaller. It is seen in this example, that used in deeper water or in Type (ii) or Type (iii) conditions, an instrument which is only 20cm across may indicate values of R* which are 30% or more below the values which would be obtained using an instrument of half that size, or the same instrument in shallower waters in Type (i) conditions.

The important difference between the response to self-shielding in Type (i) circumstances and in Type (ii) or Type (iii) circumstances, is a consequence of the degree of asymmetry in the downwelling radiance distribution. In this case, with turbidities high compared with normal open ocean conditions, the move towards minimum critical size is rapid with depth (dashed lines in Fig. 6.5). In clearer open ocean waters, it is reasonable to suppose that a significant difference between results obtained under Type(i) surface illumination conditions and those obtained under other conditions will persist to a greater depth.

The graph in Fig 6.7, further illustrates and emphasises the critical dependence of the self-shielding



Variation in the critical radius of the shading area of a circular instrument with the degree of asymmetry present in the downwelling light field.

Figure 6.7

factor upon the asymmetry of sub-surface radiance. It shows the "critical radius" of the shading area (defined here as the point at which each of the curves in Fig 6.6(a) and (b) begins the steep part of its decent) plotted as a function of the asymmetry factor (as defined in Section 6.1 and displayed in Fig. 6.4) for green light in each circumstance.

It is interesting to note also the relationship between these findings and the "Pilgrim criterion" discussed in Section 3.4. The data under discussion here were obtained in conditions where 1/K was approximately 1.5m, and the measurements indicate that a significant self-shielding factor is apparent in <u>all</u> cases where the instrument is around 0.3m or more across. In the more symmetrical light fields, self-shielding is a problem for instruments of about half that size. **On the basis of these measurements therefore, indications are that the "safe" ratio of D to 1/K, that is the ratio at which an instrument may be operated in a symmetrical sub-surface light field without there being significant self-shielding, is < 0.1.**

These tests confirm what had been indicated by the first brief look at self-shielding described in Chapter 3. There is a major source of uncertainty in any in-water reflectance measurement, or indeed in any measurement of upwelling light, which is due to shielding of the instrument by itself. The magnitude of the error which this can induce is considerable (more than 30% has been observed here). More important is that the effect is variable and changes significantly with the circumstances of the measurement and in particular with the nature of the surface illumination. This factor is especially significant in the case of near-surface measurements made in clear sky conditions, so it is of particular importance in the context of the remote sensing application.

6.3 Summary and discussion

The results reported here were collected over a period of several months. A considerable quantity of data was gathered but much of it was of limited value, being incomplete for one reason or another. Several false starts were made only to have the data spoiled by a change in conditions part way through a set or by interference from other users of the water. However, a sufficient number of successful complete runs was eventually obtained to demonstrate and confirm the required points, and those which are illustrated here present a fair overview of the aspects which the tests set out to investigate.

It has been demonstrated that variations in the shape of the underwater light field, brought about by changing conditions of surface illumination, can lead to substantial variations in values of R*/R. In the location used for these tests, the main differences were sometimes largely eliminated at relatively shallow depths, but it is supposed that in much clearer ocean waters, where asymmetry in the light field will persist to greater depths, the variability will also extend to greater depths.

Variations are brought about through the interaction of varying shaped sub-surface light fields with both:-

(a) the optical geometry of the sensor units and,

(b) the potential of the whole instrument, including supporting structures, to create self-shielding.

In both cases, the variability of R*/R will be greatest when measurements are made nearer the surface and in Type (i) conditions, but its magnitude will be greatest when measurements are made in deep water and in Type (ii) or Type (iii) conditions.

A key point which has become apparent as a result of this work is the observation that there are mainly two quite different sets of circumstances; those where the direct sunlight plays a major role in shaping the downwelling light field (Type (i) conditions), and those where it plays a minor role (Type (ii) and Type (iii) conditions). Hence, just as it has been found convenient to classify waters into Case 1 and Case 2 for the purposes of interpretation of in-water optical data (see Chapter 2), so it is sound policy to think in terms of a sub-surface insolation classification for the purposes of comparison of in-water optical measurements; Class A, say, for operations in Type (i) conditions, and Class B for all others.

It is also worth stressing the point that conditions are never static for very long. Intermittent cloud cover is an obvious source of difficulty, and also surface roughening which changes the amount of direct sunlight which enters the water and hence influences the shape of the downwelling radiance distribution. But even without these, conditions must move from Type (ii) through Type (i) and back to Type (ii) again between sunrise and sunset. Indications are therefore, that the safest circumstances in which to make sub-surface reflectance measurements are the diffuse lighting conditions of persistent type (iii), where the shape of the downwelling light field is least influenced by variations in sea surface roughness and the sun's altitude throughout the day. It is unfortunate that this is at odds with the prospect for simultaneous sub-surface and remotely-sensed optical measurements.

PART 2

The Use of Reflectance Data

This section, Chapters 7, 8 and 9, is essentially a post experience discussion, adding to the brief review in Chapter 2, of the way in which reflectance data may be used and of their potential as indicators of water quality. Details of relevant data, that is data for which associated "sea truth" is available, collected in the course of the main objective of the work, described in Part 1, are given in Chapter 7. Those data are then used to support critical comments and suggestions made in the two Chapters following, 8 & 9, regarding the treatment, use and validity of reflectance data as indicators of water quality; question (ii) in Chapter 1.

7. SEA TRIALS AND DATA COLLECTION

Throughout the development of the prototype reflectance meter and its successors, every opportunity was taken to use the instruments at sea. Except in the case of the BOFS North Atlantic cruise, which was essentially a data collecting exercise, the main purpose of deployments was to gain experience in the use of the instruments, to explore their capabilities and to test ideas. A number of things could be predetermined through calculation and laboratory experiments but it was only through experience at sea that hydrodynamic characteristics and detector systems could be properly tested and optimised.

Nevertheless, one outcome of the many deployments is that a quantity of optical data has been collected, and in a few cases associated synoptic sea-truth data are available for comparison. The ocean-going instrument carries its own fluorometer for in-situ monitoring of chlorophyll concentration. In the case of data collected using the prototype, reliance has been placed on in-situ measurements of both chlorophyll and sediment concentrations made at the same time by others aboard the ship.

All of the prototype instrument data suffer to an extent in that they were assembled and correlated with associated data after the event. As such they are more sparse than might otherwise have been the case. Often, it has been found difficult to reliably relate the sea-truth measurements made simultaneously by others engaged in other projects on the various vessels from which the optical measurements were made. Also, many data were found to be inconsistent and had to be rejected. In particular, many measurements of chlorophyll concentrations made in samples collected at sea, frozen and later analysed ashore, were thought to be suspect and consequently were rejected.

An essential strength of those prototype instrument data which have survived critical appraisal is that they are culled from a store obtained using the same instrument and in the same way, but in a wide variety of locations and under a wide variety of environmental conditions, thereby removing any possibility that any conclusions based upon them may be specific to a particular site or set of circumstances.

Those data which are thought to be reliable in all respects have been assembled at the end of this Chapter and are used in an exploration of ideas relating to the interpretation of reflectance data in terms of water quality (see Chapters 8 & 9).

7.1 Major deployments

This section is devoted to a brief summary of the main deployment exercises, with emphasis on those which led to technical modifications or yielded measurements which can be related to water quality measurements made in conventional ways and used in later discussions.

The first major field test of the complete prototype instrument came in the summer of 1986 when it was used during a short research cruise of the MV Somerset, a training ship belonging to the College of Nautical Studies at Warsash, Southampton.

As a data collection exercise, this cruise was not a success, but from the point of view of the development of a measurement capability, it was an essential step. A number of detailed problems, mainly in the data sampling and recording equipment, became apparent during the cruise. At that stage of its development, the data handling electronics was totally dependent upon an initialising procedure which required shore-based equipment. Hence, when difficulties led to a complete breakdown of operations in the automatic mode, the system could not be restarted at sea. However, the subsequent manual, sequential operation (the only alternative available under the circumstances) served to highlight how dramatically different are results obtained with or without simultaneous sampling. Sequential sampling, using a digital voltmeter, even in conditions which were apparently stable, commonly resulted in successive values of R* which varied by 25-30%, as compared with the more common 1-2% found using the electronic simultaneous sampling process.

More immediately satisfactory was the hydrodynamic performance of the instrument. It proved exceptionally stable under tow, even in moderate waves, within the speed limit already discussed.

The other two principal uncertainties at this stage were the sensitivity and dynamic range of the detector systems. In the event, both were found to be satisfactory for general use in the wide range of conditions encountered. In fact, the instrument has subsequently proved to be entirely satisfactory in respect of these two aspects in all the conditions encountered to date, and no adjustment has been found necessary.

Following a period of further development and detailed refinement, a second opportunity to conduct proper sea trials of the instrument arose in June 1987 on a six day cruise, again aboard the Somerset, in sea areas to the east of the Isle of Wight and further south in the English Channel. The cruise was carried out in company with a small team making measurements of chlorophyll concentrations and sediment loads. The weather throughout was not ideal, with frequent periods of near gale force winds making rough sea conditions the norm rather than the exception. Nevertheless, the instrument behaved well and was deployed in all but the roughest conditions when other operations were also suspended. All previous difficulties had been attended to and a number of minor detailed improvements had been carried out, making the instrument substantially more reliable and much easier to handle than had previously been the case. This was the first cruise which provided data likely to be of value from an analytical point of view.

The chlorophyll measurements made during the cruise proved later to be unsatisfactory, with an unacceptably low level of agreement between repeat measurements. This was thought by those making the measurements to be due to maturing of the samples between collection and analysis. The suspended sediment measurements however, constituted a reasonable body of data, with some thirty or more samples with clearly identifiable corresponding reflectance measurements.

A similar but more comprehensively instrumented cruise, concentrating on a small area in the Western Solent and waters to the west of the Needles Channel, took place in 1988. On that occasion there were four optical instruments on board, the Biospherical MER from the Bedford

Institute of Oceanography (Canada), the Techtum Quantum Scanning Meter (a scanning spectrometer), an Undulating Oceanographic Recorder (UOR) from the Plymouth Marine Laboratory and the prototype relative reflectance meter.

As a data gathering exercise this was the most satisfactory. The reflectance meter had by that time reached a high degree of reliability and no difficulties were experienced in obtaining good quality data. Conventional water quality measurements were made throughout and some satisfactory comparable data were obtained.

A summary report on all aspects of the 1988 cruise has been published (Boxall and Reilly 1989)

The prototype instrument has been deployed on numerous other occasions since that date, mainly for test purposes and, on a few occasions, for teaching purposes, but almost always in an area in, or close to, Southampton Water. In addition, it was used extensively, for several months in the sub-surface optical experiments summarised earlier in Chapter 6. However, rarely did such usage produce comparative data of the kind which could usefully be added to the store obtained during the Somerset cruises.

The first version of the ocean-going relative reflectance meter has been used during the 1990 BOFS cruise in the North Atlantic. A substantial quantity of data has become available as a result and some of these are referred to later in a discussion of their potential in Chapter 8.

7.2 Measurement methods

The parameters included in the lists at the end of this Chapter were obtained in the following ways.

(i) **Position** - For the most part, the positions quoted in the data list at the end of this Chapter (the coastal water data using the prototype instrument) were obtained using Decca, which is considered to be accurate to better than 100m in the majority of cases.

(ii) **Relative reflectances (R*)** - These were each computed from the mean of at least three consecutive half minute interval print-outs, using :-

$$\log_{10}R^* = 1.1(V_{up} - V_{down} + \Delta) \quad \text{(Ref. Fig. 4.7, Pg 70)}$$

where V_{up} and V_{down} are the voltage outputs from the upwelling and downwelling light detectors respectively, and Δ is a correction for detector inequality (always very small in practice), obtained by reversing the instrument periodically as mentioned in Chapter 4.

(iii) **Chlorophyll concentrations** - These were obtained in two ways. In the case of the 1988 cruise, measurements were made using filtrates prepared on board and frozen until analysed ashore. Analysis was carried out using an AMINCO Fluorometer. Chlorophyll assessments for the BOFS data were made using the UOR's on-board flow-through fluorometer.

(iv) **Sediment concentrations** - Assessments of the total suspended sediment concentration was made by filtering using 0.2μm glass fibre filters. The filtrates were then ashed to assess the inorganic content. Particle size distributions were obtained, using a Coulter counter in the case of the 1987 data, and in the case of the 1988 data, by a nested filter process. Particle population and mean particle size were deduced from the particle size distribution measurements and the measurements of total suspended sediment.

(v) **Depths and currents** - These are a combination of on-board instrument readings and estimates made during the course of subsequent analysis of the data using such information as is available on the charts and in Admiralty tide tables and tidal atlases.

7.3 Data sets

The lists which follow itemise the main body of data used in the discussions of the analytical potential of reflectance data in Chapters 8 & 9. They are from the above mentioned second and third cruise aboard the Somerset.

Two other data sets, of a different format and too large to list (over 6000 points), are also used in the discussions. They are from the 1990 BOFS cruise and were obtained using the first ocean-going version of the relative reflectance meter carried aboard a UOR (see Chapter 5)

SUMMARY OF RESULTS 1987

Stn. no.	16	18	19	20
Posn.	50 41.4N 01 33.7W	50 40.5N 01 35.3W	50 40.0N 01 36.0W	50 38.2N 01 42.5W
Date.	9-7-87	9-7-87	9-7-87	9-7-87
Time. GMT	10 34	11 02	11 18	12 30
$R^*_{(436)}\%$	2.47	4.21	2.19	1.51
$R^*_{(550)}\%$	5.32	8.02	4.90	2.97
$R^*_{(650)}\%$	2.23	3.92	2.47	1.03
Chl. (s)μg/l				
Chl.(1m)μg/l				
Sed. (s)mg/l				
Sed.(1m)mg/l	1.3	0.6	4.4	1.8
Depth. m	35	17	13	25
Current. kts	3.5	3.0	2.8	2.5

Stn. no.	21	22	31	32
Posn.	50 36.0N 01 44.0N	50 36.0N 01 34.0W	50 38.2N 01 40 0W	50 37.4N 01 38 0W
Date.	9-7-87	9-7-87	10-7-87	10-7-87
Time.	13 12	14 42	11.12	12 03
$R^*_{(436)}\%$	1.95	2.18	1.95	1.61
$R^*_{(550)}\%$	2.94	3.96	3.89	3.23
$R^*_{(650)}\%$	1.23	1.64	1.07	1.02
Chl. (s)μg/l				
Chl.(1m)μg/l				
Sed. (s)				
Sed.(1m)	4.3	3.9	5.5	4.7
Depth. m	30	32	23	25
Current. knots	1.5	slack	1.7	1.5

SUMMARY OF RESULTS 1987

Stn. no.	33	35	36	38
Posn.	50 38.2N 01 36.0W	50 38.2N 01 42.0W	50 38.1N 01 38 8W	50 38.5N 01 36.8W
Date.	10-7-87	10-7-87	10-7-87	10-7-87
Time.	13 39	14 32	14 44	15 01
$R*_{(436)}\%$	2.03	3.35	5.01	4.77
$R*_{(550)}\%$	4.35	5.30	10.68	8.17
$R*_{(650)}\%$	1.85	2.05	4.88	4.04
Chl. (s)μg/l				
Chl.(1m)μg/l				
Sed. (s)mg/l				
Sed.(1m)mg/l	3.6	7.2	5.0	6.3
Depth. m	24	24	26	23
Current. kts	1.0	2.5	1.0	slack

Stn. no.	39	42	43	52
Posn.	- -	50 39.2N 01 37.5W	50 38.9W 01 37.2 W	50 42.2N 01 32.5W
Date.	10-7-87	10-7-87	10-7-87	13-7-87
Time.	15 29	16 37	16 44	11.40
$R*_{(436)}\%$	4.84	6.98	6.93	2.03
$R*_{(550)}\%$	8.79	19.18	19.67	5.15
$R*_{(650)}\%$	4.25	12.28	11.88	2.42
Chl. (s)μg/l				
Chl.(1m)μg/l				
Sed. (s)				
Sed.(1m)	4.8	4.6	-	7.1
Depth. m	-	13	15	56
Current. kts	-	1.0	1.0	0.2

SUMMARY OF RESULTS 1987

Stn. no.	53	54	55	58
Posn.	50 41.7N 01 33.4W	50 42.1N 01 33.0W	50 40.7N 01 34.5W	50 38.9N 01 37.5N
Date.	13-7-87	13-7-87	13-7-87	13-7-87
Time.	12 15	13 00	13 40	14.10
$R*_{(436)}$%	2.21	1.86	1.66	4.75
$R*_{(550)}$%	5.93	4.70	4.96	13.32
$R*_{(650)}$%	3.96	2.06	3.12	8.66
Chl. (s)µg/l				
Chl.(1m)µg/l				
Sed. (s)mg/l				
Sed.(1m)mg/l	9.2	9.5	15.6	13.5
Depth. m	40	50	20	15
Current. kts	slack	2.4	2.4	2.4

Stn. no.	59	60	61	62
Posn.	50 38.0N 01 39.5W	50 41.0N 01 37.0W	50 42.7N 01 36.8W	50 38.9N 01 36.8W
Date.	13-7-87	13-7-87	13-7-87	13-7-87
Time.	14.33	14.55	15.21	15.33
$R*_{(436)}$%	1.09	2.66	3.47	2.97
$R*_{(550)}$%	3.33	8,40	9.20	10.03
$R*_{(650)}$%	0.77	3.51	6.49	8.33
Chl. (s)µg/l				
Chl.(1m)µg/l				
Sed. (s)mg/l				
Sed.(1m)mg/l	6.6	11.5	10.8	11.2
Depth. m	25	12	15	12
Current, kts	3.0	1.0	1.0	1.0

SUMMARY OF RESULTS 1987

Stn. no.	63	64	65	66
Posn.	50 42.7N 01 32.0W	50 36.6N 01 52.5W	50 41.2N 01 46.8W	50 36.0N 01 43.7W
Date.	13-7-87	14-7-87	14-7-87	14-7-87
Time.	16.20	10.24	11.10	12.10
$R^*_{(436)}$%	5.31	1.93	2.36	1.64
$R^*_{(550)}$%	15.78	4.14	6.47	4.42
$R^*_{(650)}$%	9.90	15.78	2.48	1.91
Chl. (s)μg/l				
Chl.(1m)μg/l				
Sed. (s)mg/l				
Sed.(1m)mg/l	11.7	5.9	8.2	5.1
Depth. m	13	20	15	25
Current. kts	3.5	2.5	1.6	1.6

Stn. no.	67	68	69	70
Posn.	50 36.0N 01 35 9W	50 36.0N 01 28 0W	50 41.0N 01 36 8W	50 38 8N 01 44.4W
Date.	14-7-87	14-7-87	14-7-87	14-7-87
Time.	12.20	13.00	14.30	15.55
$R^*_{(436)}$%	1.77	1.88	2.80	1.69
$R^*_{(550)}$%	4.27	4.79	7.88	3.44
$R^*_{(650)}$%	1.74	2.55	4.06	1.78
Chl. (s)μg/l				
Chl.(1m)μg/l				
Sed. (s)mg/l				
Sed.(1m)mg/l	6.2	6.5	5.4	7.1
Depth. m	32	35	14	24
Current. kts	0.1	slack	1.5	2.6

SUMMARY OF RESULTS 1988

Stn. no.	01	02	03	04
Posn.	Y.mth Pier	Y.mth Pier	50 42.0N 01 32.9W	50 42.8N 01 31.2W
Date.	30-4-88	30-4-88	1-5-88	1-5-88
Time. GMT	16 40	17 30	10 45	13 50
$R*_{(436)}\%$	4.60	5.11	6.77	8.36
$R*_{(550)}\%$	11.27	12.63	15.28	19.37
$R*_{(650)}\%$	8.44	10.68	14.26	17.00
Chl. (s)μg/l	-	-	2.63	3.40
Chl.(1m)μg/l	1.75	1.78	1.28	1.66
Sed. (s)mg/l	4.7	4.3	3.6	2.7
Sed.(1m)mg/l	-	19.0	4.6	3.4
Depth. m	10	10	47.5	43.7
Current. knts.	0.5 E	0.4 E	1.2 W	2.5 W

Stn. no.	05	08	09	10A+B
Posn.	50 42.8N 01 30.6W	50 43.7N 01 29.1W	50 45.6N 01 25.5W	50 46.2N 01 22.8W
Date.	1-5-88	2-5-88	2-5-88	2-5-88
Time. GMT	14 40	09 40	10 31	11 40
$R*_{(436)}\%$	4.58	4.91	4.37	9.34
$R*_{(550)}\%$	11.24	13.35	11.38	19.42
$R*_{(650)}\%$	8.83	13.52	10.60	16.85
Chl. (s)μg/l	2.55	3.22	3.99	5.13
Chl.(1m)μg/l	1.43	2.78	3.95	3.16
Sed. (s)mg/l	3.4	6.0	3.0	3.3
Sed.(1m)mg/l	2.1	4.9	5.1	3.0
Depth. m	44.7	7.3	4.7	4.0
Current kts.	0.75 W	slack	slack	1.5 W

SUMMARY OF RESULTS 1988

Stn. no.	10C+D	11A+B	16C+D	17A+B
Posn.	50 46.2N 01 21.6W	50 44.1N 01 30.9W	50 47.0N 01 17.8W	50 42.2N 01 33.4W
Date.	2-5-88	2-5-88	3-5-88	3-5-88
Time. GMT	12 00	14 09	15 30	17 55
$R*_{(436)}\%$	4.24	3.63	3.28	4.52
$R*_{(550)}\%$	10.13	9.46	7.88	11.64
$R*_{(650)}\%$	9.22	8.00	7.16	10.31
Chl. (s)μg/l	4.77	4.33	5.31	-
Chl.(1m)μg/l	2.89	2.95	5.35	-
Sed. (s)mg/l	4.4	2.7	3.4	3.8
Sed.(1m)mg/l	3.0	1.9	3.0	4.2
Depth. m	8.1	3.4	12.2	11.4
Current. kts	1.5 W	1.8 W	1.4 W	3.5E

Stn. no.	17C+D	19A	20A
Posn.	50 41.8N 01 33.1E	50 38.8N 01 37.0E	50 42.7N 01 31.8E
Date.	3-5-88	4-5-88	4-5-88
Time. GMT	18 05	10 40	11 37
$R*_{(436)}\%$	2.77	4.74	6.60
$R*_{(550)}\%$	6.93	12.76	15.66
$R*_{(650)}\%$	3.89	12.19	15.50
Chl. (s)μg/l	-	0.57	0.73
Chl.(1m)μg/l	-	0.36	0.53
Sed. (s)mg/l	1.5	4.3	3.6
Sed.(1m)mg/l	2.1	4.7	4.4
Depth. m	45	25	38
Current. kts	3.0	0.1	slack

8 THE POTENTIAL OF SUB-SURFACE REFLECTANCE MEASUREMENTS FOR THE ASSESSMENT OF CHLOROPHYLL CONCENTRATIONS

This subject has already been discussed briefly in Chapter 2. The objective in this chapter is to extend that discussion to include thoughts and conclusions arising out of the experience and data acquired during the course of the essentially measurement-orientated studies which have formed the main part of this work.

As has already been outlined in Chapter 2, there are three main points of agreement common to much of what has been written on this subject. To reiterate and summarise, these are:-

(i) There has been a general acceptance, and a concentration upon, algorithms based on an equation of the form:-

$$\mathrm{Chl} = A \; R_{\mathrm{Blue/Green}}{}^{B} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

where Chl is the chlorophyll concentration in mg m^{-3}, $R_{\mathrm{Blue/Green}}$ is the ratio of the values of R for blue light (around 440nm) and for green light (around 550nm), and A and B are constants.

(ii) There is a poor degree of agreement on values which have been obtained for the constants in equation (i), particularly in the case of B.

(iii) It is widely accepted that the presence of materials in the water column, other than organic materials originating from primary production, mask the chlorophyll signature to an extent which renders the technique of limited value in many situations.

In this chapter the topic will be discussed under two separate headings; Case 1 waters and Case 2 waters. Reference will be made to data which has been collected during the course of, or as a direct result of, this work but suggestions made are not based entirely on those data.

8.1 Case 1 waters

Here we are considering the problem simplified, with the presence of nothing other than chlorophyll to modify the spectral reflectance characteristics of the water column. Numerous values of A and B in equation (i) above have been obtained by experiment, but they differ widely and are generally thought to be site specific. For example, from a list culled from Aiken and Bellan (1986), Carder et al (1986), Clarke (1981), Gordon and Morel (1981), Holligan et al (1983), Mitchelson et al (1986), Morel (1980) and Smith and Wilson (1980), we get a range of values of A from 0.5 to 0.8, and a much wider range of values of B from -1.3 to -3.9. This is unsatisfactory and it must give rise to doubts as to the validity of the assumption being tested.

In point of fact the relationship which has so often been used as a basis for interpretation is the logarithmic form of equation (i), that is:-

$$\log Chl = \log A + B\log R_{Blue/Green} \ldots\ldots\ldots\ldots (ii)$$

which does appear to offer the possibility of a solution for both A and B by linear regression of data. But of course, this is only if the original form of the relationship is valid and, as can be seen by inspection, equation (i) is not entirely satisfactory as it breaks down as Chl → 0, where it becomes necessary to postulate that $R_{Blue/Green} \rightarrow 0$ also. Clearly, an all embracing form of the relationship must include the constant $R_{Blue/Green}(0)$, the value of the Blue/Green ratio for pure water (Chl = 0). Without this term, plots of data using the logarithmic form must yield asymptotic curves (not straight lines), and values for B obtained by regression of the data will depend upon the range of chlorophyll concentrations present in the set.

It is relevant to note at this point that this aspect of ocean colour interpretation has been accommodated in the approach to chlorophyll algorithms developed for use with CZCS ocean colour data (Gordon et al 1983). Two distinctly different algorithms are used in that case. Both treat spectral ratios of water leaving radiance, L_w, in the manner seen in (i), that is they are of the form:-

$$\text{Chl.} = A\, Lw_{(\lambda 1)/(\lambda 2)}{}^{B} \ldots\ldots\ldots\ldots\ldots\ldots (iii)$$

but it is found necessary to use two values of both A and B. A = 1.13 and B = -1.71 are used where Chl < 1.5mg m^{-3}, and A = 3.326 and B = -2.439 are used for circumstances where Chl > 1.5mg m^{-3}. $\lambda 2$ is 550nm in both cases, but $\lambda 1$ is 443nm for the lower chlorophyll concentrations and 520nm for the higher.

In principle, the objection to equation (i) can be overcome if we hypothesise a revised version which includes the constant $R_{Blue/Green}(0)$ in such a way as to accommodate the difficulty, for example one of the form:-

$$\text{Chl} = A(R_{Blue/Green}(0) - R_{Blue/Green})^{B} \ldots\ldots\ldots (iv)$$

To pursue this idea and to apply it to a data set, it will be necessary to determine the value of $R_{Blue/Green}(0)$, and this can be done using the basic definitions:-

$$R = b_b/2K \quad \text{(Chapter 2, (v)), and}$$

$$K = a + b_b(1 - R) \quad \text{(Section 2.1, (vii))}$$

provided that we have the values of the inherent optical properties, a and b_b, at each wavelength.

Both the absorption coefficient, a, and the scattering coefficient, b, have been found to be difficult to measure in the case of pure water. This is partly because they are small, but also because of the difficulty of obtaining and maintaining samples of pure water for any length of time, so data are sparse. However, there have been a number of measurements made, notably in the case of a by Clarke and James (1939) and Smith and Baker (1981), and in the case of b by Morel (1966). The latter measurements have confirmed the validity of the Smoluchowski-Einstein fluctuation theory of scattering in pure water (see Chapter 2). The values which are used here are taken from tables in Smith and Baker (1981) which were compiled from a combination of their own measurements and what they regard as the best available laboratory measurements by others. They are, for a, 0.0145m^{-1} and 0.0638m^{-1} at 440nm and 550nm respectively, and for b, 0.0049m^{-1} and 0.0019m^{-1} at 440nm and 550nm respectively. We are considering here the case of pure water, where scattering is entirely due to density fluctuations, and the fluctuation scattering theory predicts scattering which is perfectly symmetrical about any axis perpendicular to the axis of propagation, so b_b in this case will be b/2. Using the above values of $a(\lambda)$ and $b_b(\lambda)$, equations (v) and (vi) yield values for $R_{Blue}(0)$ and $R_{Green}(0)$ of 7.9% and 0.77% respectively. The required value of $R_{Blue/Green}(0)$ is therefore <u>10.26</u>.

The Case 1 data obtained as a direct result of this work are those which were obtained during the 1990 BOFS

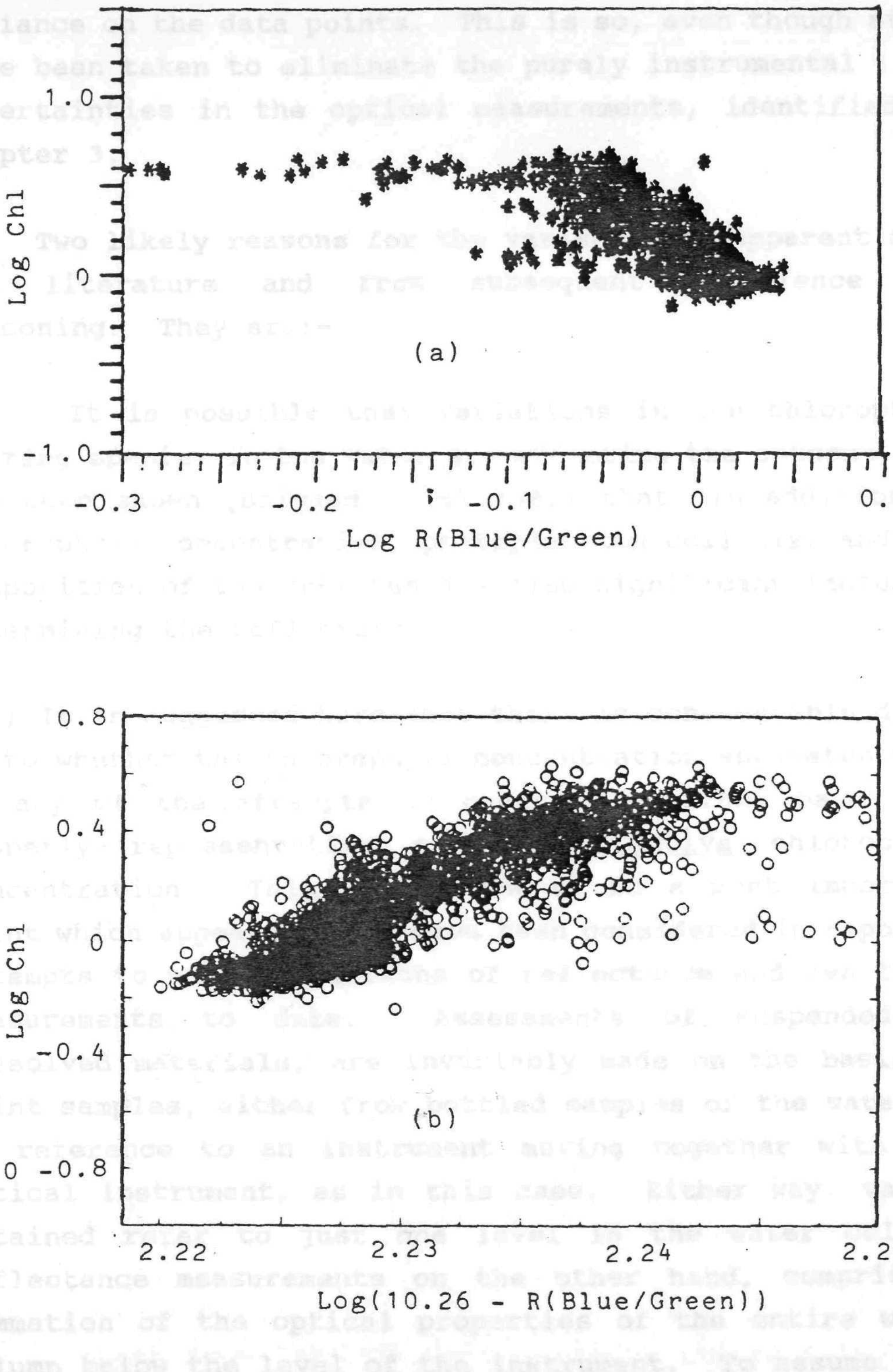
North Atlantic cruise using the ocean-going version of the relative reflectance meter mounted on a UOR in the manner described in Section 5.1. The data which was gathered on that occasion is being analysed by others and that analysis is outside the scope of this thesis, but it is interesting to consider a representative example of the data in the context of the present discussion.

Figs. 8.1 (a) shows a plot of the data from one of the Atlantic tows, tow D69006. It consists of some 3000 data points from a twelve hour tow, between 47° 08'.6N, 16° 51'.7W and 48° 12'.4N, 15° 28'.9W, a distance of approximately 84M. The data are plotted here in the conventional way, that is Log Chl as a function of Log $R^*_{440/550}$. Some degree of covariance between the ratios of reflectances at 440nm and 550nm and the chlorophyll concentration is apparent, and the resolution in this case is sufficient to see that the relationship is non-linear.

Fig. 8.1(b) shows the same data plotted in the manner suggested earlier, that is using equation (iv), and it is closer to a straight line than Fig. 8.1(a), as is indicated by linear regression analyses of both the plots which give a correlation coefficient of 73.3% in the case of 8.1(b) but 61.3% in the case of 8.1(a).

The exercise was repeated on a second similar sized data set from the same cruise, tow number D69008, and the results were similar. The data in that case showed a greater degree of variance and the correlation was not as good. Nevertheless, it was increased from 50.1% using equation (i) to 59.6% using equation (vi).

A difficulty in both cases is that the main point of interest, the shape of the plot, is being masked by



Two treatments of data from Case 1 waters

Figure 8.1

variance on the data points. This is so, even though steps have been taken to eliminate the purely instrumental uncertainties in the optical measurements, identified in Chapter 3.

Two likely reasons for the variance are apparent from the literature and from subsequent experience and reasoning. They are:-

(i) It is possible that variations in the chlorophyll bearing species in the water are affecting the outcome. It has been shown (Bricaud et al 1983) that, in addition to chlorophyll concentration, phytoplankton cell size and the composition of the detritus are also significant factor in determining the reflectance.

(ii) It is suggested here that there is considerable doubt as to whether the chlorophyll concentration estimates used in any of the attempts to create algorithms have been properly representative of the <u>effective</u> chlorophyll concentration. This would seem to be a most important point which appears not to have been considered in reported attempts to make comparisons of reflectance and sea truth measurements to date. Assessments of suspended or dissolved materials, are invariably made on the basis of point samples, either from bottled samples of the water or by reference to an instrument moving together with the optical instrument, as in this case. Either way, values obtained refer to just one level in the water column. Reflectance measurements on the other hand, comprise a summation of the optical properties of the entire water column below the level of the instrument. To assume that the two are correlated, is to assume also that the water column is always a well mixed, homogeneous medium. This is unlikely. Indeed, the BOFS Atlantic data show considerable

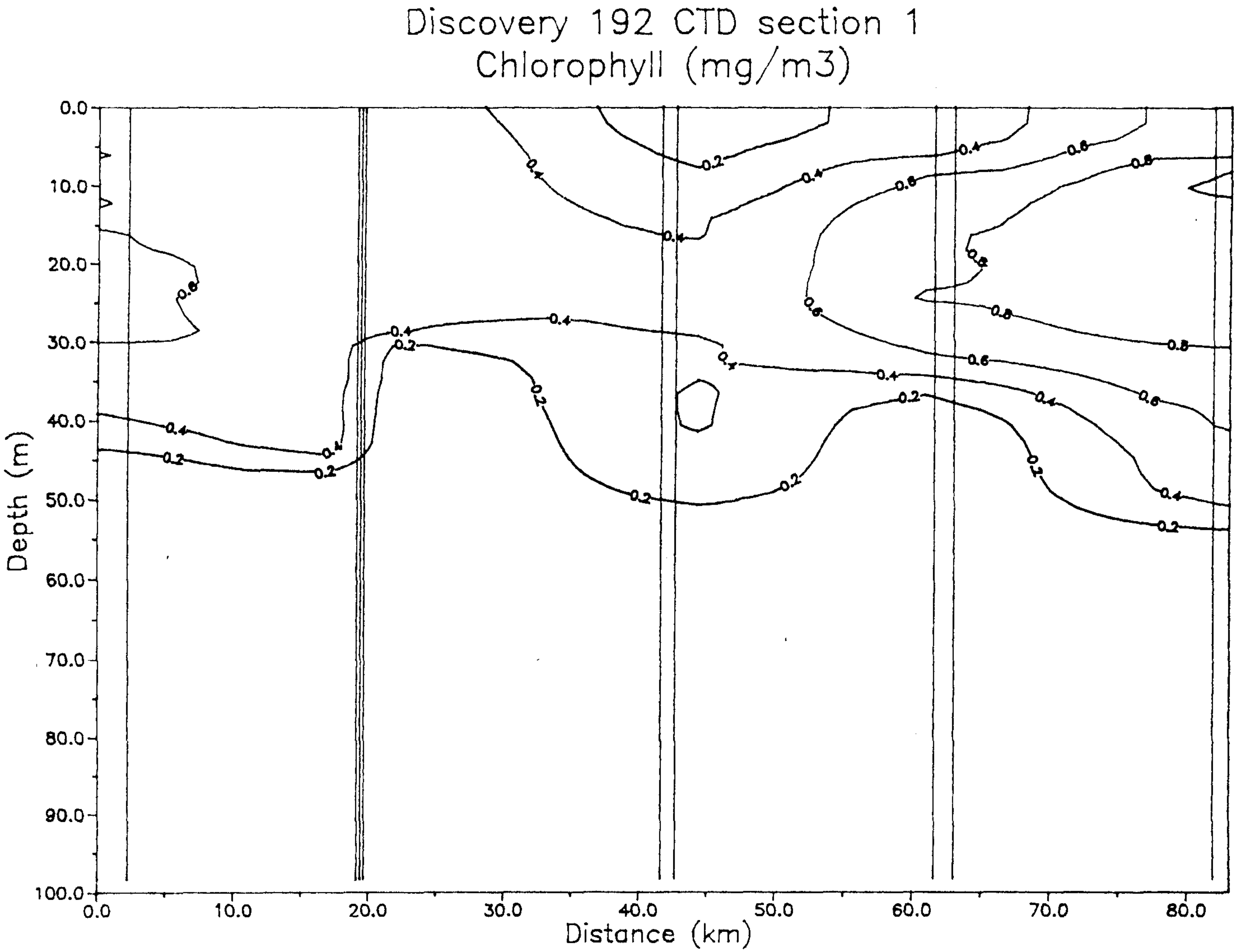


Fig. 8.2

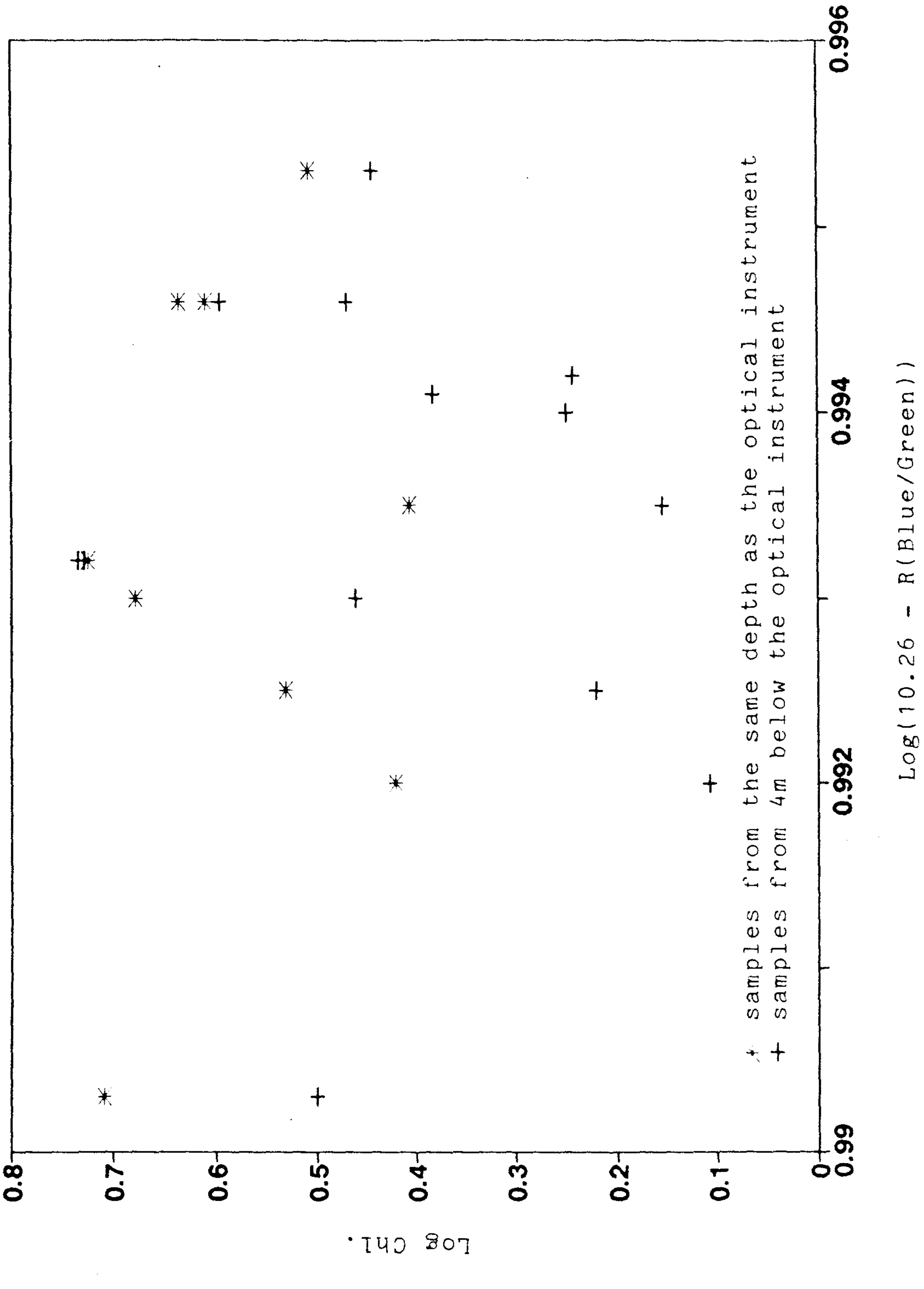
Data from the 1990 BOFS Atlantic cruise showing chlorophyll distribution in the water column.

stratification of the chlorophyll. Fig. 8.2, which shows a small sample of the chlorophyll data obtained in association with the reflectance data on that cruise, is included here to illustrate the point.

8.2 Case 2 waters

There is ample reference in the literature to the high degree of uncertainty to be expected in assessments of chlorophyll concentrations by optical methods in the presence of inorganic suspended materials (eg Walter and Schuman 1985 and Topliss et al. 1989). The few chlorophyll data from Case 2 waters which are available as a direct result of this work (see Fig. 8.3) do no more than add weight to the argument that quantification of chlorophyll in Case 2 waters will not be easily achieved. Further, the data and the experience of obtaining it serve to highlight two important aspects of the problem which are applicable in both Case 1 and Case 2 waters.

In the first place, data are sparse. This is mainly because less than 10% of all the chlorophyll data collected were considered reliable. The majority were rejected due to unacceptable inconsistencies (up to an order of magnitude) between estimates using samples taken very close to one another (successive samples at the same station), and also between samples from the same container in some cases. On the basis of this experience, it is concluded that the procedure of collecting, storing and subsequently analysing samples of water ashore, is subject to a high degree of uncertainty. Others workers (Phinney and Yensch 1985) have suggested that much of the uncertainty found in this field may be due to errors in measuring the chlorophyll concentration. An analysis of methods of



Chlorophyll data from Case 2 waters

Figure 8.3

chlorophyll assessment, carried out at The university of Southampton (Chaddock 1991) confirms that a high degree of uncertainty (variations of as much as a factor of three were observed) may sometimes be found in chlorophyll concentration estimates made using conventional methods.

A second feature to be seen in the data in Fig. 8.3 concerns the validity of the point sampling technique which has already been questioned in the previous Section. It will be seen that in all cases where two samples were taken at different depths, one closer to the surface, at the same depth as the optical instrument and the other deeper, the deeper sample invariably yielded a lower value of chlorophyll concentration than did the shallower sample.

8.3 Summary

The data which have become available during the measurement studies reported here, while confirming the difficulties and uncertainties associated with this line of investigation, also offer evidence to support the two principal suggestions put forward here. They are:-

(i) That the accepted relationship, equation (i) in Section 8.1, is asymptotic and that the inclusion of the constant $R_{(Blue/Green)}(0)$ in the algorithm is likely to produce a linear relationship which is applicable over a wider range of values of Chl than is the case when the hitherto accepted equation (i) is used.

(ii) That there is generally strong stratification in the chlorophyll concentrations, especially near to the surface. Consequently, chlorophyll assessments made on the basis of point samples cannot be regarded as necessarily representative of the whole optical range.

The two main points made above are ample reason for there to be a high level of variation and disagreement on the interpretation of data.

In addition, it is pointed out that there are aspects of the chlorophyll other than simply the concentration which have the potential to influence the reflectance and hence are likely to frustrate attempts to arrive at universal algorithms, even in Case 1 waters.

In Case 2 waters, there is the added complication of inorganic sediments to consider. These will influence the spectral reflectance themselves but it has also been suggested that chlorophyll might covary with inorganic constituents in Case 2 waters, with sediment particles acting as centres on which chlorophyll bearing materials grow (Carder et al 1986). There is evidence to support this proposition in the data sets discussed in Chapter 9.

The general conclusion is that, while there is demonstrably an <u>association</u> between chlorophyll concentration and spectral reflectance characteristics, and the selective absorption which leads to this is understood, there are complicating factors which make it unlikely that a <u>precise</u> in-situ technique based on in-water reflectance measurements is a possibility. However, the work has shown that, providing the technique can be made less dependent upon the vaguaries of natural illumination, it does offer the expectation of a viable method of estimating chlorophyll concentrations averaged thoughout the water column.

9. PROSPECTS FOR THE ASSESSMENT OF INORGANIC SEDIMENTS IN THE WATER COLUMN THROUGH THE MEASUREMENT OF IN-WATER REFLECTANCE RATIOS

It has already been stated in Chapter 2, there exists some consensus of opinion that the difficulties here may be insurmountable. Certainly it is hard to see any level of agreement in the literature, even such as that which exists in the case of chlorophyll algorithms. A number of algorithms have been created for inorganic sediments (a list appears in Curren and Novo 1989) but they differ substantially from one another and are site specific.

In the first place, whether or not the quantity of sediment in suspension is, by itself, a principal factor in determining the reflectance ratio, has to be considered. The asymptotic nature of much of the data collected so far, both from remote sensing and from laboratory experiments, is an indication that, at best, the technique is limited to low concentrations. See for example Scherz (1972), Klooster and Scherz (1974), Scherz and Van Damelan (1975), Rouse and Coleman (1976), Holyer (1978), Rimmer et al (1987), Bently (1987) and Novo et al (1989). A feature common to many data sets is an initial sensitivity of reflectance to sediment concentration, followed by a levelling off to a plateau where reflectance remains constant as sediment concentration increases. There is no general agreement on the point of commencement of a plateau. Quoted thresholds vary from 2 - 3mg/l up to more than 70mg/l with laboratory experiments yielding a more well defined and earlier commencement of a plateau than in the case of field measurements.

Some observers have found the development of the plateau to be more gradual, leading to the suggestion that there is a logarithmic relationship over some part of the range (Munday and Alfoldi 1979, and Khorram 1985).

However, if we consider the simplest case in this context, that of a homogeneous suspension of identical particles with a concentration such that scattering and absorption by the particles is much greater than by the water, there is reason to suppose that R will be independent of sediment concentration, as both the absorption and the scattering (Mie scattering in this case) will be dependent upon particle population. The results of some instrument calibrations carried out by the author (Booty 1974), though for an entirely different purpose, are relevant.

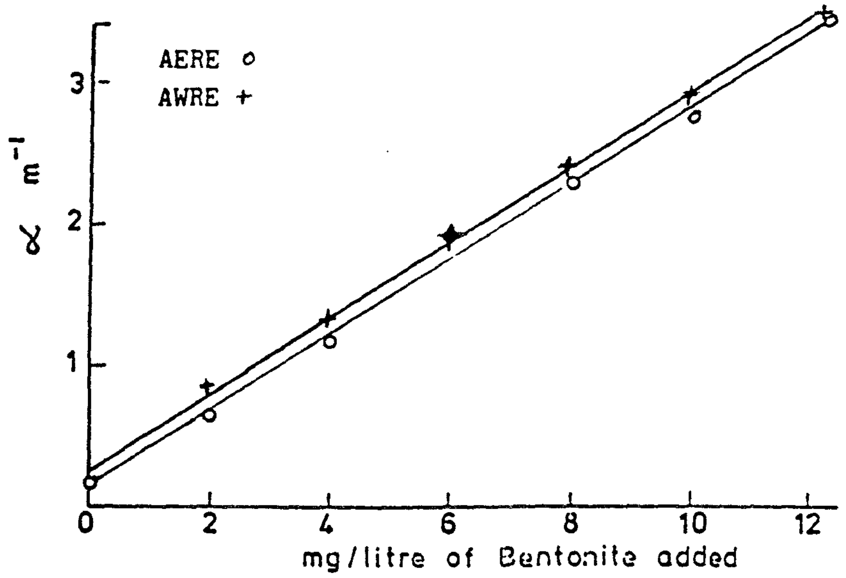
The objective of the tests was to investigate the operation of two in-water instruments, a narrow beam transmissometer and a nephelometer. The instruments were being developed as part of a programme being carried out at the Atomic Energy Research Establishment, Harwell, to assess the potential of in-water video methods for the underwater inspection of ships and structures for certification purposes (Booty & Tandy 1977).

The instruments were fitted with Wratten 45 filters to restrict measurements to the "water window" and remove the complication created by the initial strong absorption of the red end of the spectrum. The tests were carried out in a large indoor tank lined with a black non-reflective liner. The water was filtered for several days while being kept in darkened and dust-free conditions in an attempt to obtain the cleanest possible starting point. Water with a narrow beam attenuation coefficient of around 0.2 m^{-1} was sometimes achieved in this way. The water was then progressively turbidified using measured quantities of bentonite (grain size 5μ). A circulating pumping system prevented settling during the course of each calibration series.

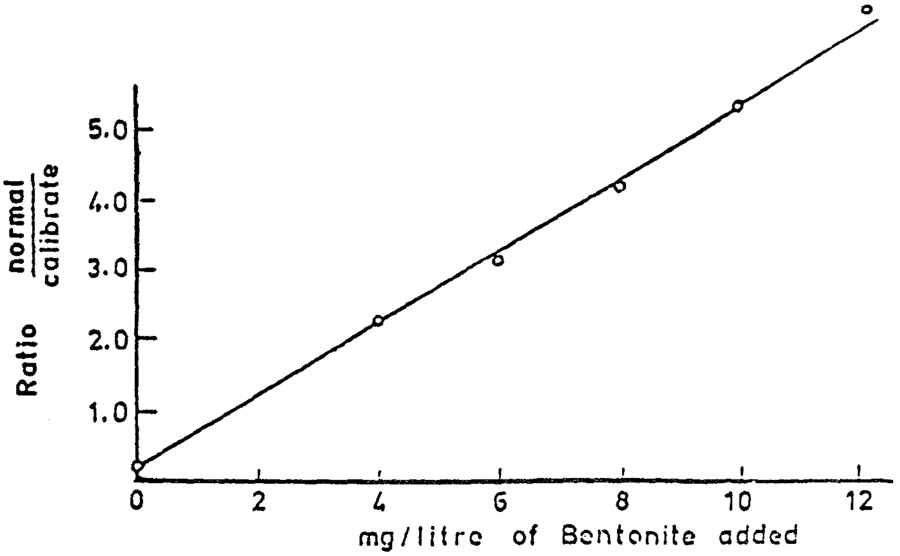
Simultaneous measurements of both the narrow beam attenuation coefficient, α, and the relative coefficient of scattering at 140°, (β_{140}), were made and plotted as a function of sediment load. A typical set of calibration results is shown in Fig. 9.1. In all cases, as in Fig. 9.1, linear relationships were obtained between the two coefficients and the sediment load, indicating that the ratio of the scatter at 140° to the narrow beam attenuation coefficient becomes constant above sediment loads of about 2-3mg/l (the lines do not go through the origin).

If we make the assumption that $\beta(\theta)$ is approximately the same in each case, as has been found to be true for a wide variety of sediment laden waters (Timofeeva 1971, Petzold 1972), and therefore $\beta(140^{\circ})$ is proportional to b_b, these results indicate that the ratio $b_b:\alpha$ varied little above the 2-3mg/l threshold in this case. But $\alpha = a + b$, and therefore the sum $a/b_b + b/b_b$ is a constant. It follows that the ratio of $b_b:a$ will be similar in all cases, varying only in as much as the shape of $\beta(\theta)$ varies. Thus, at least in the special circumstances of these tests where the nature and the size of the particles is the same at each concentration and the light observed is restricted to a broad spectral band in the Blue-Green region, it may be assumed that R remained constant above a low threshold.

A theoretical model of several in-water optical



Calibration of AERE and AWRE transmissometers (narrow beam attenuation coefficient)



Calibration of AERE Nephelometer at 140°

Some instrument calibration results showing linear relationship between quantity of turbidifying material and both absorption and scattering.

Figure 9.1

parameters by Llewellyn (1987) further supports the hypothesis. In this the reflectance ratio is depicted as being independent of sediment load above a threshold of 2mg/l.

Assuming at this point in the discussion that the above is so, the problem remains to identify those aspects of the hydrosol, other than simply the sediment concentration, which control either, or both, the magnitude and the spectral characteristics of reflectance. The fact that other physical properties of the individual particles will covary with sediment load is relevant to this.

There is evidence in the literature to show that reflectance in water, is influenced by a number of sedimentary factors other than the concentration alone. These include:-

(i) The range of particle concentrations (Novo et al. 1989), ie. different algorithms are obtained for light concentrations and heavy concentrations of sediment.

(ii) Particle size and size distribution (Whitlock et al 1981).

(iii) Refractive index of the particulate material. Zaneveld (1974) describes a method of determining refractive index through the measurement of $\beta(45_0)$ at two wavelengths.

(iv) Density of the particulate material. This is difficult to assess in a polydispersal hydrosol as particle shape is a factor. However, Carder et al. (1974) report measurements which show refractive index to be related to a quantity they term "apparent density"; a parameter derived from the mass of suspended material, the number of particles and the mean size of the particles.

(v) Particle shape (Bukata et al 1981)

(vi) Colour of the particulate material (Novo et al 1989)

(vii) Population density of particles (Holyer 1978)

(viii) Covariance of chlorophyll with sediment loads (Carder et al 1986)

(ix) Particle surface area per unit volume of water (Carder et al 1974)

In the context of this work, it should be noted also that the influence of any of the above listed variables may be modified by the geometry and form of the instrumentation, and the circumstances of the measurement.

Relevant data which have become available as a direct result of this work are sparse but there are sufficient to comment on effects of some of the variables. An important feature of these data is that they were obtained in a variety of circumstances and locations (see Chapter 7), therefore observations will be of general significance. In addition of course, the relative reflectance data, the spectral ratios, are considered to be high quality data.

The data are summarised in Table 9.1 and a comprehensive list of cross-correlations between parameters is seen in Table 9.2.

Considering first the figures for sediment concentration (the top line in Table 9.2), it will be seen

R*%			mg/l	$R^*(\lambda_1)/R^*(\lambda_2)$			part. pop.	mean wt.	mean size	spec. density
Blue	Green	Red		B/G	R/G	R/B	l^{-1}	mg$\times 10^{-4}$	μ	
2.47	5.32	2.23	1.3	.464	.419	.903	11643	1.117	4.181	.2672
4.21	8.02	3.92	0.6	.525	.489	.931	9953	0.603	4.463	.1351
2.19	4.90	2.47	4.4	.447	.504	1.128	12653	3.477	4.230	.8220
1.51	2.97	1.03	1.8	.508	.347	.682	8897	2.023	3.994	.5065
1.95	2.94	1.23	4.3	.663	.418	.631	6225	6.907	4.010	1.7224
2.18	3.96	1.64	3.9	.551	.414	.752	9829	3.968	4.279	.9273
1.95	3.89	1.37	5.5	.501	.352	.703	5204	10.568	4.217	2.5060
1.61	3.23	1.20	4.7	.498	.372	.745	26454	1.777	3.502	.5074
2.03	4.35	1.85	3.6	.467	.425	.911	7255	4.962	4.410	1.1252
3.35	5.30	2.05	7.2	.632	.387	.612	10487	6.886	4.055	1.6982
5.01	10.64	4.88	5.0	.471	.459	.974	21516	2.324	3.652	.6364
4.77	8.17	4.04	6.3	.584	.494	.847	20754	3.036	4.363	.6959
4.84	8.79	4.25	4.8	.551	.484	.878	8692	5.522	4.323	1.2774
6.98	19.18	12.28	4.6	.364	.640	1.759	23069	1.994	3.950	.5048
2.03	5.15	2.42	7.1	.394	.470	1.192	16422	4.323	4.726	.9147
2.21	5.93	3.96	9.2	.373	.668	1.792	32903	2.796	4.063	.6882
1.86	4.70	2.06	9.5	.396	.438	1.108	11318	8.394	4.093	2.0508
1.66	4.96	3.12	15.6	.335	.629	1.880	57802	2.699	4.040	.6681
4.75	13.32	8.66	13.5	.357	.650	1.823	45440	2.971	3.665	.8106
1.09	3.33	0.77	6.6	.327	.231	.706	10489	6.292	3.643	1.7271
2.66	8.40	3.51	11.5	.317	.418	1.320	21481	5.354	4.190	1.2778
3.47	9.20	6.49	10.8	.377	.705	1.870	19782	5.460	4.009	1.3619
2.97	10.03	8.31	11.2	.296	.829	2.800	64274	1.743	3.686	.4729
5.31	15.78	9.90	11.7	.337	.627	1.864	22587	5.180	3.857	1.3430
1.93	4.14	1.00	5.9	.466	.242	.518	12953	4.555	4.191	1.0869
2.36	6.47	2.48	8.2	.365	.383	1.051	6474	12.666	4.693	2.6989
1.64	4.42	1.91	5.1	.371	.432	1.165	11811	4.318	4.259	1.0139
1.77	4.27	1.74	6.2	.415	.407	.983	52736	1.176	3.662	.3211
1.88	4.79	2.55	6.5	.392	.532	1.356	18723	3.472	3.916	.8866
2.80	7.88	4.06	5.4	.355	.515	1.450	11964	4.514	3.040	1.4849
1.69	3.44	1.78	7.1	.491	.517	1.053	17385	4.084	4.377	.9331

Summary of data and derived parameters

Table 9.1

Table 9.2

	R*%			$R^*(\lambda_1)/R^*(\lambda_2)$		
	B	G	R	B/G	R/G	R/B
* Sediment concentration mg/l	13	4	4	43	3	16
Mean particle weight gmx10^{-7}	20	18	24	4	33	24
Mean particle size μ	8	21	25	27	17	28
Specific density	.2	.2	.2	0	.3	.2
Particle population l^{-1}	9	28	42	48	62	70

Percentage correlation between reflectance and sediment parameters listed in Table 9.1

* Sediment concentration correlations make use of a few additional data not included in Table 9.1

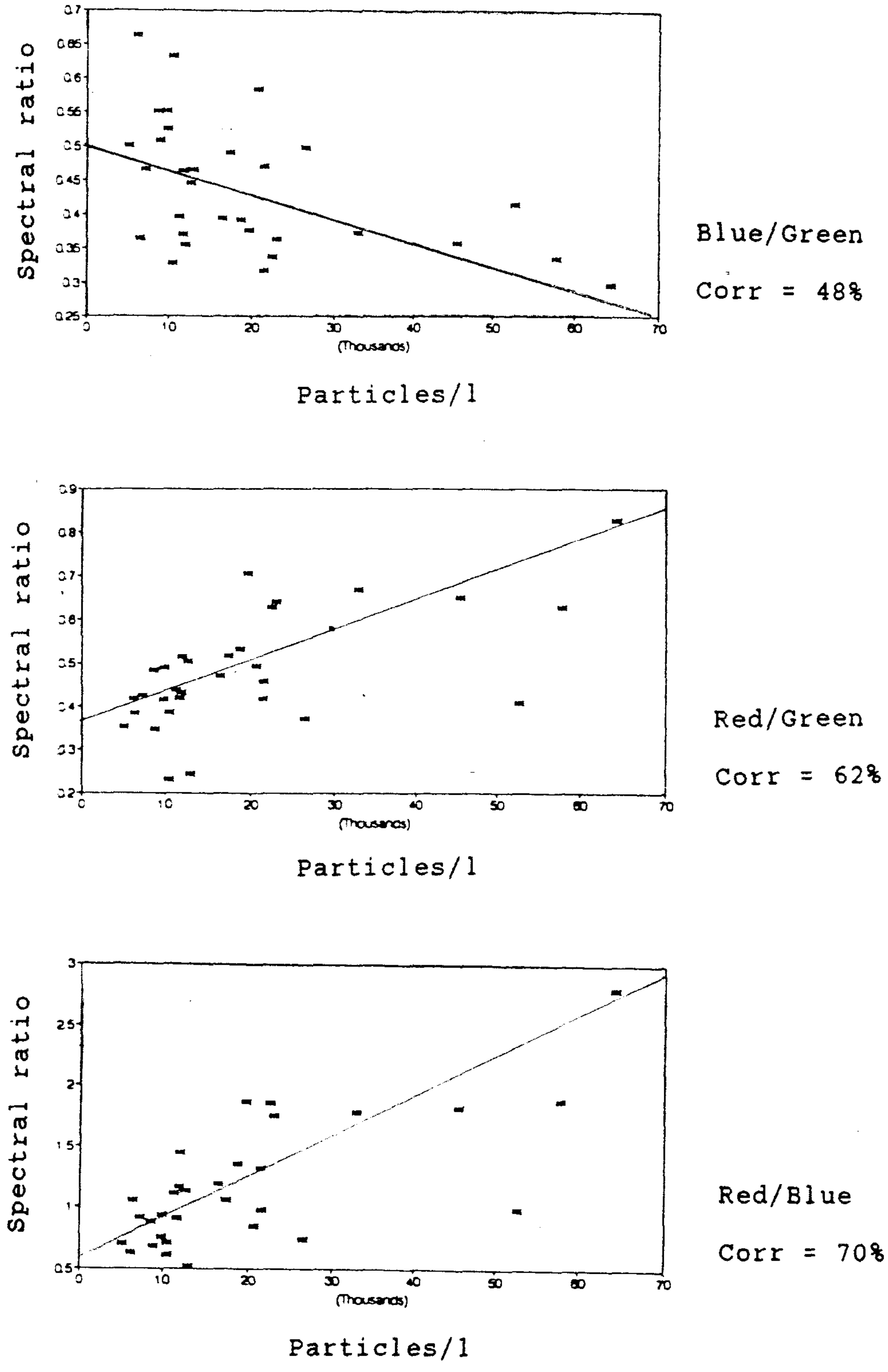
that the data support the proposition made above that reflectance is not strongly controlled by sediment concentration alone. There is a poor degree of correlation in this case with both $R^*(\lambda)$ and the spectral ratios, $R^*(\lambda_1)/R^*(\lambda_2)$. A notable exception is the Blue/Green spectral ratio which shows a significantly greater degree of correlation with sediment concentration than is seen in the other five cases. This, added to the fact that the coefficient in this case is negative ($R^*_{B/G}$ decreases with increasing sediment concentration), suggests that what is being seen here is not a direct sedimentary effect but is rather an observation of the covariance of chlorophyll with sediment concentration suggested by Carder et al (1986).

Looking now at the rest of Table 9.2, there appears to be little connection between reflectance data and either the weight or size, and the correlations drop to zero in the case of specific density.

Only in the case of relationships between reflectance data and particle population density (that is the total number of particles per litre obtained by summing of the particle size distribution data) are there marked correlations to be found. Fig. 9.2 shows plots of the relevant data. Two features are apparent in these.

Firstly, in the case of the Blue/Green ratio the correlation is the smallest of the three (not very different from the equivalent correlation with sediment concentration) and the slope is negative. This adds further weight to the idea of a covariance of chlorophyll and inorganic sediment.

Secondly, the correlation appears to increase with increasing wavelength difference in the spectral ratios,



Spectral ratios as a function of particle population

Figure 9.2

indicating that reflectance in the Red is increasing faster with increasing particle population than is the reflectance in the blue. It is suggested here that the mechanism responsible for this is as follows.

Scattering from the water is due to density fluctuations and is dependent upon λ^{-4}. It is therefore predominantly blue. Scattering from suspended particles, on the other hand, will be Mie scattering, the magnitude of which is given by:-

$$b = KN\pi D^2/4$$

where b is the total scattering coefficient, N is the number of particles per unit volume, D is the particle diameter and K is an efficiency factor which is proportional to λ^2. Scattering by the particles will therefore be predominantly red and will be governed by the product ND^2, or $NV^{2/3}$, where V is the volume of suspended sediment. Therefore, any given volume of suspended material will produce more scattering (mainly in the red) if it is made up of a large number of small particle, than if it is made up of a small number of large particles. Thus, as the particle population density increases, it is to be expected that the ratio of scattering at longer wavelengths to scattering at shorter wavelengths will increase, as indeed it does in this data, with the greatest degree of dependence occurring when the difference between the two wavelengths being compared is greatest.

To summarise, the data which have been collected in the course of this work show little covariance of reflectance with sediment quantity, particle size or particle weight. However, they do provide evidence to support the propositions that:-

(a) the particle population density is a principal factor exerting control on the spectral characteristics of reflectance, possibly through the mechanism suggested above, with reflection of the Red increasing as the number of particles increases, and

(b) there is a "chlorophyll factor", with the presence of particles in the water increasing the amount of chlorophyll present and thereby modifying the spectral characteristics of the reflectance.

It should be mentioned that Point (b) has a potential to frustrate attempts to quantify the sediment, as does the presence of inorganic sediments in the case of attempts to quantify chlorophyll.

One further possibility which cannot be tested with the data collected during this work but which merits consideration in this context, is the use of reflectance as an indicator of dynamic processes in the water column. In any volume of sediment laden water, whatever the nature of the sediments, the quantity in suspension, the maximum particle size and the range of particle sizes, will be determined by the availability of materials of course, but also by the energy of the water motion which creates and maintains the suspension. Hence, it is not surprising to see that reflectance is modified by water velocity, with the effect being particularly noticeable where velocity gradients exist. There are satellite photographs which show striations in places, such as off headlands, where variations in water velocity are found (see for example, Robinson 1985). However, here too the potential is for the making of relative rather than absolute measurements.

On the basis of data obtained during this work and the lines of reasoning followed here, it is concluded that, even though every effort may be made to minimise difficulties inherent to the measurement of R, absolute measurement of the <u>quantity</u> of inorganic sediments in suspension using this type of optical data, that is the formulation of algorithms which are universally applicable, is unlikely to be achieved. On the other hand, <u>relative</u> assessment of specific factors, including dynamic processes, may be a possibility. Even so, the complexity of the problem and the difficulties of obtaining representative data in any real ocean situation should not be underestimated.

10. SUMMARY AND CONCLUSIONS

The work described here was carried out on a part time basis over a period of more than seven years. The line of investigation was prompted by the difficulties and uncertainties which have beset the interpretation of remotely sensed ocean colour data, but the principal topic of investigation has been just one part of that problem, the measurement of sub-surface reflectance and its potential as an indicator of water quality.

The majority of what has come out of the study has already been disseminated through publication (Booty 1989) and through talks, discussions and collaboration with other workers in the field. Hence, some of the problems which have been identified in the course of the study are now routinely taken into account in the design and use of instruments for measuring sub-surface reflection of light, both by members of the Department at Southampton and by others.

Progress and direction were dictated by opportunities and by the development of instrumentation, most of which was carried out on a minimal budget, but the overall objectives were clear throughout and are defined in Chapter 1 by the placing of two fundamental questions relating to the validity of the measurements being made and of assumptions in approaches to the treatment of data obtained. This summary is directed mainly towards consideration of those questions and an assessment of the contributions which this work has made towards improving practices in the field.

10.1 The measurement of R

This has been the main interest throughout, and problems associated with it have been considered in some detail. The principal objective was clearly set out at the beginning of the work in the form of a two-part question (Question (i) in Chapter 1, page 4) concerning the validity of measurements of R made using the then widely accepted instruments and techniques.

It has become clear that the answer to the first part of Question (i) is in the affirmative. A number of aspects of the measurement of R have been identified which had certainly not been taken into account prior to the commencement of this work but which are capable of introducing a high degree of uncertainty into the outcome. The second part of the Question, "how might present practices be improved", has also been tackled with some success.

A principal conclusion is that the "perfect" instrument, that is one capable of yielding <u>absolute</u> values of R in <u>all</u> circumstances, is an unrealistic objective in the case of a sea-going instrument. It is concluded also, through consideration of apparent factors, together with confirmatory results obtained in the experiments which were carried out to test hypotheses (see Chapter 6), that some of the standard practices in this field have been unsatisfactory in the past and, given the constraints within which such instruments have to work, that some measurement difficulties will persist.

The main underlying cause for concern and uncertainty is identified as the inherent variability of the sub-surface insolation in which such measurements are made and, in particular, the variability of the shape, or angular radiance distribution, of the underwater light field. This, in turn, influences the results obtained in ways which are frequently not readily apparent but are substantial and are peculiar to the instrument being used.

Three factors have been identified, which are vital to the outcome of any sub-surface light measurement but which have apparently not been taken into account in measurements prior to this work, and their importance has been demonstrated. They are:-

(i) The temporal factor. Such is the changing nature of the sub-surface light field, both in intensity and in shape (see Chapters 3 & 6) that only simultaneous measurements of both E_d and E_u may be considered satisfactory for the purpose of determining R. **It has been stressed therefore, that any single-sided instrument, that is an instrument which measures E_d and E_u separately on separate deployments, must be totally unsuitable for the measurement of R.** In retrospect, this seems an obvious point but, surprisingly, many of the instruments which have been used for measuring R in the past have been single-sided.

(ii) Optical geometry. In principle, the measurement of R using natural light in open water can only be achieved using perfect cosine receptors. **With any other optical geometry, not only will there be an uncertainty in the definition of the parameter being measured but the outcome of the measurement will depend upon factors other than the quality of the water.** This is because the shape of the downwelling and upwelling light fields will always be different from one another (very different in the near surface) and changing continuously. The variability which may be brought about by using non-cosine collectors (even near-cosine collectors) in changing circumstances of incident light has been demonstrated (see Chapter 6).

(iii) Interference of the downwelling light field by the instrument (self-shielding). The effects of self-shielding and the considerable uncertainty which it introduces in a changing light field, have been considered (see Chapter 3) and demonstrated (see Chapter 6). **Here again, the magnitude of the effect is critically dependent upon the circumstances of the measurement.**

It has been concluded that it is possible to identify circumstances where the self-shielding factor may be neglected. Experimental data suggest that self-shielding of an instrument of dimensions D operating in water with a diffuse attenuation coefficient K, will be insignificant in all cases where $DK < 0.1$. However, this limit is dependent upon the symmetry in the downwelling radiance distribution and is substantially relaxed in an asymmetric light field.

It is concluded that it is unlikely that it would be practicable to calculate the magnitude of the self-shielding effect in those cases where it is significant. To do so would require a detailed knowledge of the sub-surface light field, which implies a knowledge of factors which are difficult to measure and continuously varying.

It is stressed that the potential which an instrument has for errors due to both (ii) and (iii) above is a function of its design, but the magnitude of the ensuing errors is critically dependent upon the circumstances of the measurement. Hence, both (ii) and (iii) introduce a high degree of uncertainty into any measurement.

On the basis of the above considerations, and also taking into account experience with the numerous observations which have been made, it is concluded that all measurements of R must be treated with caution, even if the design criteria detailed in Chapter 3 are met. Certainly it is likely to prove very difficult to measure absolute values of R in moderately turbid water, and especially so in the case of the near-surface measurements which are required for the purposes of interpreting remotely sensed ocean colour data.

Thus, the useful concept of the measured, or apparent, value of R, that is R*, has been introduced here, and is used extensively in this text.

Two strategies for accommodating the inevitable uncertainties which must be associated with the measurement of reflectance are suggested. They are:-

(i) <u>To add depth of meaning to measurements by classifying the measurement conditions</u>. Experiments have indicated that there are only two significantly different sets of circumstances to be considered in this context, those described in Chapter 6 as constituting a Type (i) situation and all others. Thus, the idea is advanced here that, just as it has been found useful to classify water masses into Case 1 and Case 2 for purposes of interpretation (Morel and Prieur 1977), so there is some point in classifying surface illumination conditions for measurement purposes into just two groups. That is:-

Class A say, where direct sunlight forms a large part of the total downwelling light (Type (i) conditions on Chapter 6), and hence the symmetry of the sub-surface light field will vary continuously with depth, time of day and cloud cover, and:-

Class B where, through atmospheric conditions or angle of incidence of the direct sunlight, the surface illumination is mainly diffuse.

Measurements made in Class A surface illumination conditions cannot necessarily be compared with measurements made in Class B conditions.

(ii) To abandon altogether the idea of attempting to measure absolute values of R for analytical purposes and aim instead at a more attainable objective, that of making true comparisons of the apparent reflectance, R*, at differing wavelengths (Chapter 3), with an instrument which has been designed specifically for the measurement of comparative, rather than absolute, ratios (see Chapter 4).

From an analytical point of view, option (ii) above should not be unacceptable. Indications are that algorithms in terms of ratios of reflectances at different wavelengths are likely to prove the most successful. However, the approach does assume that the ratio $R(\lambda)/R^*(\lambda)$ will be the same for all values of λ. Hence, an important prerequisite in the case of a multi-detector instrument used for this purpose, is that the optical geometry of each of the detector pairs used to measure E_u and E_d, and the circumstances in which they are operating, must be similar for each wavelength.

An appreciation of the above point makes clear the fact that the use of a relatively large, multiple-detector instrument to measure $R(\lambda_1)/R(\lambda_2)$, and in particular one where the detectors are distributed about the opaque area, is certain to introduce an unacceptable level of error and uncertainty into the spectral ratio.

In point of fact, it has been shown (Chapter 3) that, even if the objective is restricted to comparative measurements, an instrument's potential for self-shielding leads to an element of uncertainty in the results. This is because the degree of self-shielding of any particular instrument operating in any particular set of circumstances is a function of wavelength.

Nevertheless, it was considered that, if not a perfect instrument, a much better instrument than was currently available could be designed if the objective was restricted to comparative measurement. A set of design criteria for such an instrument was formulated and the spider-like instrument designed to meet those criteria was constructed and tested at sea (Chapter 4).

A more towable design, a carriage made in the form of a spar, which does not set out to avoid self-shielding or mutual-shielding entirely but instead arranges for them to exist in a manageable way, has also been introduced (see Chapter 5).

10.2 The analytical potential of reflectance data

The subject under consideration here is Question (ii) from Chapter 1 (page 4), concerning the validity of assumptions in respect of the meaning of reflectance data and of accepted ways of treating such data.

Here also, the answer to the question is in the affirmative. Reasoning and experimental evidence have been presented to support a proposition that some hitherto widely accepted assumptions concerning the meaning and treatment of reflectance data are unsound.

The bases of the comments on this topic have been, to some extent though not entirely, the data which have been collected in the course of the mainly measurement-orientated investigations. A considerable quantity of reflectance data has been collected but for the most part, a reliance has been placed on associated chlorophyll and sediment concentration measurements made by others. This was not always satisfactory and in retrospect it is hard not to harbour severe doubts regarding the reliability of some sea truth measurements made by conventional methods, particularly in the case of chlorophyll.

However, on the basis of such comparative data as are available (see Chapter 7) and other considerations discussed in the main text, it has been possible to formulate and test some ideas, and to comment on this aspect of the problem (see Chapters 8 and 9).

In the case of chlorophyll, the collected data bear out the basic conclusions reached by others, that direct quantification of chlorophyll through measurements of reflectance ratios is unlikely to be achieved in Case 2 waters, but that there is some prospect that it may be possible in Case 1 waters.

The widely accepted practice of attempting to obtain constants for an assumed relationship of the form:-

$$C = A\, R_{Blue/Green}{}^{B},$$

where C is the chlorophyll concentration and A and B are constants, has been criticised (see Chapter 8) and a modification involving the constant $R_{Blue/Green}(0)$, the value of $R_{Blue/Green}$ for pure water (C = 0), has been proposed. A value for this constant has been estimated on the basis of published values of inherent optical coefficients, and has been used to test the modified relationship by applying it to data collected during the BOFS Atlantic cruise. The result of the exercise offers some indication that the suggested manner of treating the data is likely to prove more satisfactory than the presently accepted approach.

The small quantity of comparative chlorophyll data which has been obtained from Case 2 waters in the course of this work, apart from showing negligible correlation between chlorophyll concentration and reflectance, serves mainly to highlight a second major suggestion made here, **that the usual practice of comparing reflectance measurements with sea truth measurements obtained from point samples in a stratified water column is totally unsatisfactory**. This difficulty alone has the potential to invalidate comparative measurements.

Prospects for the quantification of inorganic sediment loads in a water column through reflectance measurements do not appear to be good. Not only does there appear to be no evidence in the data collected during this work to suggest that a relationship exists between reflectance parameters and the quantity of sediment in suspension but further, there seems to be positive evidence elsewhere that, above a low threshold, reflectance is insensitive to sediment concentration alone.

From considerations of the data which have become available as a by-product of the measurement studies, only two positive facts emerge. They are:-

(i) that one principal factor controlling the spectral characteristics of reflectance is the population density of the particles in suspension, and:-

(ii) that there is evidence in the data to support the proposal by Carder et al.(1986), that chlorophyll concentrations are increased in the presence of suspended sediments.

It is clear from published data that there are several other factors (listed in Chapter 9) which influence the magnitude and spectral characteristics of reflectance within a sediment loaded water column. However, the data collected during this work, which are essentially not specific to either site or circumstances, showed negligible correlation of reflectance parameters with either the quantity of sediment or the size and weight of the particles. It is therefore concluded that prospects for reflectance measurements (which by inference include remotely sensed ocean colour data) as potential tools for absolute quantitative analysis of sediments, are poor.

It is suggested that there is a possibility that techniques could be developed to use reflectance data for comparative assessments of dynamic processes in the sea, as the quantity and limiting size of particles to be found in suspension depends upon the available energy.

10.3 Instrument manufacture and development

By far the largest volume of the work on this project has consisted of the design, manufacture and development of a collection of optical instruments for use in the sea. Many ideas were tried; some were developed and some rejected, but the net result has been the creation of six currently useful instruments (see Chapters 4 and 5).

Three of the instruments, those which were used for the measurement studies and many of the reflectance data gathering exercises, were literally home-made, for the most part out of materials which were already available or obtainable at low cost. Two of these, the prototype relative reflectance meter and the vertical attenuation meter, have proved to be useful in the longer term, though they were originally intended only to test principles.

The third instrument in this group, the radiance distribution meter, while in no way a true sea-going instrument in the existing form, has been given special mention here because it has demonstrated the practicability of a novel rotating mirror design for multi-spectral radiance measurements. The success of the prototype, designed and used solely for the purposes described in Chapter 6, suggests that the principle has much to offer and that it would be possible to incorporate it into a convenient instrument capable of operating on two axes to give radiance distributions in three dimensions.

Three more instruments were built to designs developed from the prototypes. These were professionally made to designs based on the findings of this research. The UV vertical attenuation meter was built under contract for the University of Newcastle. The manufacture of the two ocean-going relative reflectance meters, was funded by the BOFS project. One of the ocean-going relative reflectance instruments has already been used in a major international programme of measurements in the North Atlantic, though it was not then being used or deployed as originally intended. At the time of writing, the other, which has been fully developed to the original specifications and is self-contained in respect of its data gathering, processing and recording, is being prepared for use in the Antarctic on the second BOFS cruise.

10.4 Some recommendations and concluding remarks

This has been very much an exploratory investigation, widening as it progressed, and there are clearly a number of substantial difficulties still to be overcome.

In particular, the subject of interpretation seems beset with difficulties. Measurement difficulties aside, the root causes of these is seen to be the complexity of the systems under investigation and the wide range of possible combinations of the processes involved. Indeed, it is impossible not to entertain considerable doubts as to whether optical reflectance data will ever be regarded as reliable quantitative indicators of materials in the sea. The one possible exception to this is chlorophyll in Case 1 waters, where absorption of blue light is the clearly identified cause of a spectral signature.

There is still a great deal of work to be done on just the water column element of the remote sensing sequence before the technique can be accepted or rejected as a suitable one for use in the quantitative analysis of large areas of natural water. More knowledge is required; not so much concerning the fundamental processes which are going on in the water column, but rather about the way in which those processes combine to form an overall effect. It seems likely that this can only be obtained in laboratory (perhaps "field laboratory") conditions, where the circumstances of experiments can be controlled.

The present common practice of attempting to find correlations between reflectance measurements and corresponding sea truth data in large areas of natural water is not a satisfactory approach to the problem.

The experiments discussed in Chapter 6, to test various aspects of the optical measurement problem, were all carried out using unsophisticated equipment and in less than ideal conditions. There is no doubt that it would be possible to refine them and to improve on the data obtained. However, to do so would require a considerable investment in both time and money, and the experiments already carried out have demonstrated the pitfalls which have been identified. It is concluded therefore, that further refinement to the study of the measurement problem would be of limited value and would not be an effective use of resources at this stage.

From the purely instrumental point of view, which was the principal objective of this study, progress has been made as a result of the work described here. Uncertainties have been identified and demonstrated, solutions have been suggested and explored, and instrumentation has been improved, both at Southampton University and elsewhere.

A point which should be not be lost is that the quest for improved instrumentation has also led to a much improved appreciation, both by the author and by other workers in the field, of the environmental factors and the way in which those factors influence the outcome of any measurement.

With regard to the future of such measurements, it is apparent that the relatively inexpensive quantum detectors which are commonly used for this work impose a constraint on the high resolution spectral measurements now being made, through their limited conversion efficiency, particularly at shorter visible wavelengths. A move towards the use of photomultiplier detectors is necessary.

If this topic is to be pursued, an instrument based on perhaps two, high sensitivity detectors (photomultipliers), sensing light from two small receptors via a spectral scanning device, should be under consideration at this time.

Finally it should be said that many years of experience have served to impress an awareness of the gulf which exists between theory and practicality in this field. On the one hand there are modes developed from sound theoretical bases, dealing with the propagation of light in idealised circumstances, through a static, homogeneous medium, devoid of boundaries. On the other, there is the practicality of an ever changing mixture of diffuse and directional light, permeating through a dynamic, stratified hydrosol of a wide variety of materials, being measured with imperfect instrumentation, where optical ideals are frequently and necessarily compromised in the interest of sea-going practicality.

Thus, although this work has resulted in progress in the primary objective, it is important to appreciate that much of that progress has been in the direction of identifying deficiencies in techniques. Solutions to some of the difficulties have been suggested and explored, but there are still aspects of practices in the field which are unsatisfactory. Indeed, attractive though the prospect may be, the practicality of using an <u>apparent</u> optical property of a medium to make <u>quantitative</u> assessments of the quality of the medium is questionable in a situation where there are so many variables, both within and outside of the medium, each capable of having a profound effect on the outcome of a measurement.

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