Ocean Color Spectrum Calculations

W. R. McCluney

There is obvious value in developing the means for measuring a number of subsurface oceanographic parameters using remotely sensed ocean color data. The first step in this effort should be the development of adequate theoretical models relating the desired oceanographic parameters to the upwelling radiances to be observed. A portion of a contributory theoretical model can be described by a modified single scattering approach based on a simple treatment of multiple scattering. The resulting quasisingle scattering model can be used to predict the upwelling distribution of spectral radiance emerging from the sea. The shape of the radiance spectrum predicted by this model for clear ocean water shows encouraging agreement with measurements made at the edge of the Sargasso Sea off Cape Hatteras.

I. Introduction

A large number of techniques have been developed for sampling the ocean from top to bottom. But horizontal sampling of the ocean has been conducted on a reasonable scale only rarely, and then only at considerate expense of time and money. It is true that a suitably equipped research vessel can cover large areas of the ocean and collect a large amount of data in a single cruise. However, with the relatively small cruising speeds available today, the areal extent over which the measurements can be assumed to be synoptic is severely limited.

As the field of oceanography becomes more and more sophisticated, with many scientists actively involved in large-scale modeling of oceanographic parameters, the need for synoptic data will continue to increase. But until the number of suitably equipped research vessels increases several orders of magnitude and their maximum speeds increase very substantially, neither of which is very likely to happen in the near future, we will need to rely on data collected by aircraft and satellites to obtain the kind of large-scale synoptic data that is needed to build accurate models suitable for prediction. The need for synoptic data on the ocean, and especially the near-shore areas, is so great that much effort should be expended in this decade aimed at obtaining this data by remote sensing, both actively and passively from aircraft and satellites.

Due to the essentially opaque nature of seawater outside the visible and near ultraviolet portions of the electromagnetic spectrum, remote measurements of subsurface oceanographic parameters will necessarily be limited to these spectral regions. Subsurface here means the region from a few millimeters to a few tens of meters depth, the region of penetration of sunlight and skylight into the sea. Until the maximum weight and power limitations imposed on present-day scientific satellites is permitted to expand significantly, most of the subsurface information collected from spacecraft will necessarily be limited to the passive mode, wherein one monitors the incoming radiation from the sun and sky scattered upward at subsurface depths.

Of the many subsurface oceanographic parameters of interest to oceanographers, only a few can be expected to have a significant influence on the observed ocean color spectrum. In deep water areas the most obvious of these parameters are:

(1) Total particulate concentration.
(2) Concentration of organic particulates (mostly phytoplankton).
(3) Concentration of inorganic particulates (mostly silicas and other sediments).
(4) Average particulate index of refraction.
(5) Concentrations of various pigments such as chlorophyl and the carotenoids found in phytoplankton.
(6) Concentration and composition of dissolved substances.
(7) Parameters related to the shape and/or magnitude of the particle size distribution curve.
(8) Surface front location (frequently delineated by foam lines on the surface and by subtle changes in ocean color[1]).

In addition, for shallow water areas of sufficient clarity, it should be possible to determine the extent of bottom vegetation and other bottom parameters.

The author is with NASA Goddard Space Flight Center, Greenbelt, Maryland 20771

Received 2 March 1974.

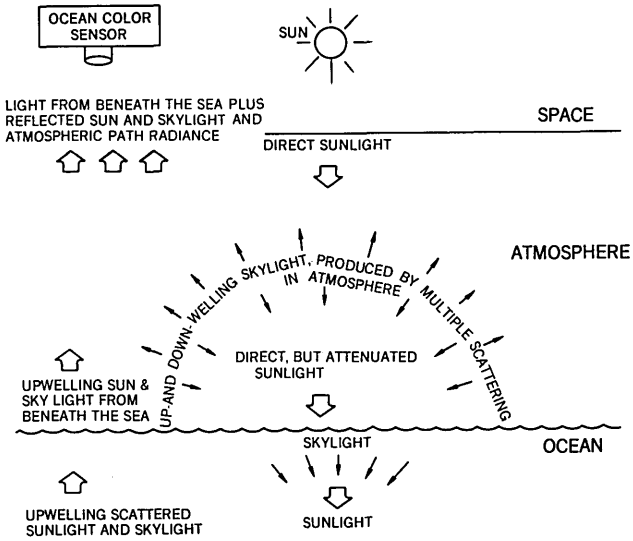

Fig. 1. Optical processes involved in remote sensing of ocean color.

By coupling ocean color data with sea surface temperature data it has been shown to be feasible to identify coastal and deep water upwellings and to map major ocean currents.[2] The loop current in the Gulf of Mexico and the Gulf Stream, with its meanders in the North Atlantic, are two prominent examples.

Although much work has been done in analyzing ocean color data gathered by a variety of sensors, including the multispectral scanner on NASA's ERTS-1 satellite, much of this analysis has been purely qualitative in nature. It is not yet clear which subsurface oceanographic parameters we can measure from space with acceptable accuracy on a quantitative basis. An experimental and theoretical effort is needed to identify these parameters, the measurement accuracies that can be expected for each one, and to develop the analysis techniques suitable for use with remotely sensed ocean color data.

There are two different approaches to the data analysis problem that can be taken. The first involves the measurement of optically important subsurface parameters together with the corresponding ocean color spectrum at a large number of different locations in the sea. Multivariate statistical analyses can then be applied to this data to identify correlations between variations in the subsurface parameters and corresponding changes in the ocean color spectrum. In the second approach, the optical processes taking place in the ocean are modeled mathematically so the ocean color spectrum can be directly related to the optically important subsurface parameters that influence it. Once this model has been developed and verified, it can be used to simulate a great variety of remote measurement situations with a considerable savings of time and money. Furthermore, it can then be extended with somewhat greater confidence to measurement situations not encountered in the model-development stage of the program.

The statistical approach to this problem has been discussed by Mueller.[3] The remainder of this paper will be concerned with the theoretical modeling approach.

II. Remote Sensing of Ocean Color

Figure 1 illustrates the optical processes involved with satellite ocean color measurements. The upwelling radiance just below the sea surface is made up of sun and sky light that has been multiply scattered, with spectrally selective absorption and scattering by both the molecular and particulate components in the sea water contributing to the shape of the upwelling radiance spectrum. Thus, the wavelength spectrum of this upwelling light will depend on the amount and kinds of dissolved and particulate substances in the water.

The light received by a high altitude sensor is composed of light emerging from the sea, path radiance produced by the atmosphere, and sun and sky light specularly (and diffusely in the presence of whitecaps) reflected from the surface of the sea. In clear deep water areas, viewed from a high altitude, the light emerging from the sea is a relatively small portion of the total light received by the sensor.

Recent measurements by Hovis[4] (reproduced in Fig. 2) have shown that the observed radiance at high altitude can be as much as five times that at low altitude. This points up the necessity to account for the effects of atmospheric path radiance and sea surface reflection in any high altitude ocean color data analysis program. It is also important to choose sun and look angles at the time of the measurement to minimize the effects of sun glitter.

Fortunately, considerable effort has already been successfully expended in the development of radiative transfer models of the atmosphere applicable to remote sensing problems.[5–8] Several years ago Cox and Munk developed a model for treating the specu-

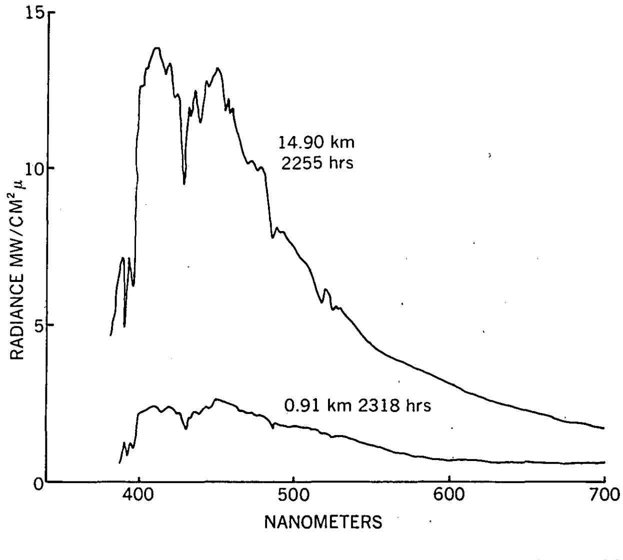

Fig. 2. Upwelling radiance spectra off Santa Catalina obtained by Hovis in 1971.

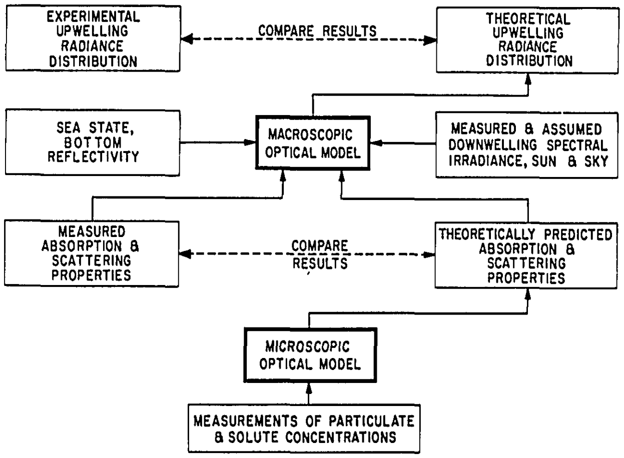

Fig. 3. Subsurface optical model of the sea for remote sensing of ocean color.

lar reflection of sunlight from the sea surface.[9] Strong and Ruff have demonstrated the application of Cox and Munk statistics to satellite observations.[10] Thus, only the subsurface portion of the over-all radiation transfer model remains to be developed in detail.

III. Optical Model for Ocean Color

A full-scale simulation of the optical processes involved in the remote sensing of ocean color is desired. The subsurface portion of this simulation can be conveniently divided into two components, the microscopic and the macroscopic, as shown in Fig. 3.

With the microscopic model, the concentrations and particle size distributions of dissolved and particulate matter are assumed known. If the spectral absorption and scattering properties of these substances are also known, the bulk absorption and scattering of the medium can be determined by straightforward procedures. Andre Morel has made considerable progress in describing the absorption and scattering properties of pure seawater.[11] Adding the spectral absorption of dissolved materials (called yellow substance or gelbstoff) is not difficult, if the specific absorption spectra and concentrations of these materials are known. In his book on optical oceanography,[12] Jerlov gives an absorption curve for yellow substance, but unfortunately the concentration corresponding to this curve is not given. Much work remains to be done in identifying the component materials present in yellow substance, determining their origins, measuring their absorption spectra, and developing better techniques for accurately measuring their concentrations.

The particulates contained in seawater present a fundamentally more difficult problem. Although Lorenz, Mie, and DeBye developed an excellent theory for the scattering of light by homogeneous spherical particles[13] (extended by Kerker to include layered spheres[14]), the major scattering particles in the sea are highly aspheric and in general inhomogeneous in refractive index; and the Lorenz *et al.* theory is not applicable. (In certain circumstances it may be applied to gain useful information about the nature of the scattering processes, but it is not generally applicable.) As a result, much theoretical and experimental work must be done in this area before an accurate, workable microscopic model can be developed that is capable of generating the spectral extinction and scattering properties of seawater over the full visible range. Once such a model has been developed, the information that it provides can be used as input data for the second portion of the subsurface optical model that is described next.

The macroscopic optical model takes the extinction and scattering properties of the medium (either theoretically or experimentally determined), together with the incident spectral irradiance of sunlight and skylight, the sea surface roughness, and information about the spectral albedo of the bottom (if the water is shallow) and predicts the upwelling spectral radiance emerging from the sea. The macroscopic model is based on radiative transfer theory and should include the effects of multiple scattering within the sea. Gordon and Brown have systematically applied a Monte Carlo radiative transfer model to the ocean color problem.[15] With the addition of a diffusely reflecting bottom to their model[16] they have been able to obtain good agreement with some early measurements of the ocean color spectrum in shallow water made by Duntley.[17]

An advantage of their model is that it uses realistic, measured scattering functions and makes no special assumptions as to the shape of those functions. A disadvantage, as with all Monte Carlo models, is that while it produces accurate upwelling irradiances entering a full 2π sterradians, the calculation of upwelling radiances over narrow angular ranges requires considerably more computation time for the desired accuracies. We shall see later, however, that this is not a serious shortcoming.

An accurate radiative transfer solution, such as the one developed by Gordon and Brown, will be needed for proper interpretation of remotely sensed ocean color data. For certain applications, as in remote sensor design sutdies, a simpler, approximate model may be adequate. Jerlov has discussed such a model,[12] which he used to determine the angular dependence of upwelling radiance at a single wavelength. It is a single-scattering theory for the sun-only case and for an infinitely deep ocean having a perfectly flat upper surface. This paper provides an extension of this model to include incident skylight and the spectral, as well as the angular variation in upwelling radiance emerging from the sea.

To put the single-scattering theory into a suitable format for the intended calculations, all ray propagation directions will be specified by the polar angles (θ,ϕ), measured with respect to the zenith. Angles in air will be identified with the subscript a and those in water with the subscript w. Unscattered downwelling light rays from the sun and the sky will be identified by a prime affixed to the angles describing their propagation directions. The singly-scattered, upwelling rays will remain unprimed.

Using this notation, the function $N_0(z, \theta_w', \phi_w')$ will be used to describe the angular distribution of unscattered (but attenuated) radiance from the sun and/or sky at depth z in a flat, homogeneous ocean. $N(z, \theta_w, \phi_w)$ will describe the upwelling singly-scattered light at depth z. Let $T(\theta_a)$ be the transmittance of the air–water interface for a ray passing into or out of the sea making the angle θ_a in air with the zenith. If η is the index of refraction of the water and $c(z)$ is the extinction coefficient at depth z, then the radiance $N_0(z, \theta_w', \phi_w')$ at depth z is related to the corresponding incident radiance $N_0(0, \theta_a', \phi_a')$ in air just above the water surface by

$$N_0(z, \theta_w', \phi_w') = T(\theta_a')\eta^2 \times \exp\left[\sec\theta_w' \int_0^z c(z')dz'\right] N_0(0, \theta_a', \phi_a'). \tag{1}$$

Similarly, the element $dN(z', \theta_w, \phi_w)$ of upwelling radiance due to single scattering in a layer of thickness dz' at depth z' is related to the element $dN(0, \theta_a, \phi_a)$ of radiance scattered from this layer and emerging from the water by

$$dN(z', \theta_w, \phi_w) = \frac{\eta^2}{T(\theta_a)} \times \exp\left[\sec\theta_w \int_0^{z'} c(z'')dz''\right] dN(0, \theta_a, \phi_a). \tag{2}$$

The bulk scattering properties of the medium may be described by the volume scattering function $\beta(\gamma)$, which may be defined by

$$\beta(\gamma) = d^2F_s(\gamma)/(H_{\text{in}}d\Omega dV), \tag{3}$$

where $d^2F_s(\gamma)$ is the element of power scattered from the element of volume dV into the element of solid angle $d\Omega$ making the angle γ with a collimated incident beam of irradiance H_{in}. Multiple scattering events are excluded by the infinitesimal nature of the scattering volume dV.

Combining Eq. (1) and (2) with the definition in Eq. (3) of the volume scattering function and performing the indicated integrations can be made to yield the singly-scattered radiance emerging from the sea for an arbitrary distribution of incident radiance $N_0(\theta_a', \phi_a')$:

$$N(\theta_a, \phi_a) = T(\theta_a)T(\theta_a') \sec\theta_w e^{-\sec\theta_w \int_0^z c(z')dz'} \times \int_0^{2\pi}\int_0^{\pi} N_0(\theta_a', \phi_a') \int_0^z \beta(z', \theta_w, \phi_w, \theta_w', \phi_w') \times \exp\left[\sec\theta_w' \int_0^{z'} c(z'')dz''\right] dz' \sin\theta_w' d\theta_w' d\phi_w'. \tag{4}$$

In this expression, $\beta(z', \theta_w, \phi_w, \theta_w', \phi_w')$ is the volume scattering function at depth z' and $c(z'')$ is the extinction coefficient at depth z''.

To simplify the use of Eq. (4) in ocean color spectrum calculations, and due to a lack of adequate data for the depth distribution of the optical properties of natural waters, we shall split the incident radiance $N_0(\theta_a', \phi_a')$ into sun-only and sky-only parts and we shall examine only the idealized case of an infinitely deep, homogeneous ocean.

In the sun-only case, we assume that $N_0(\theta_a', \phi_a')$ is constant over a small solid angle centered around the direction specified by the solar coordinates $\theta_a{}^0$ and $\phi_a{}^0$. Writing N_0 in terms of the spectral irradiance H_0 (λ) due to sunlight incident on a horizontal plane just above the water surface, and letting λ be the wavelength of light, Eq. (4) reduces to

$$N_a{}^0(\lambda, \theta_a, \phi_a) = \frac{T(\theta_a)T(\theta_a{}^0)H_0(\lambda)\beta(\lambda, \theta_w, \phi_w, \theta_w{}^0)}{\eta^2 c(\lambda)(\cos\theta_w - \cos\theta_w{}^0)} \tag{5}$$

Equation (5) gives the upwelling spectra radiance emerging from an infinitely deep, homogeneous ocean for the sun-only case. The coordinate system has been chosen so $\phi_w{}^0 = 0$.

In the sky-only case, we assume that N_0 (θ_a', ϕ_a') in Eq. (4) is constant over the full 2π steradians of the sky. If $H_s(\lambda)$ is the spectral irradiance due to skylight incident on a horizontal plane just above the water surface, then the sky-only version of Eq. (5) is

$$N_a{}^s(\lambda, \theta_a, \phi_a) = \frac{T(\theta_a)H_s(\lambda)}{\pi c(\lambda)\cos\theta_w} \int_0^{2\pi}\int_{\pi}^{\theta_w{}^c} \frac{T(\theta_a')\beta(\lambda, \theta_w, \phi_w, \theta_w', \phi_w')\sin\theta_w' d\theta_w' d\phi_w'}{\sec\theta_w - \sec\theta_w'}, \tag{6}$$

where $\pi - \theta_w{}^c = \sin^{-1}(1/\eta)$ is the critical angle.

Gordon has suggested a simple modification to the above equation that approximately considers the effects of multiple scattering in the sun-only case.[18] As will be shown in the next section, in certain cases this modified model gives very good agreement with the Monte Carlo calculations of Gordon and Brown for both the sun-only and the sky-only cases as well. Some results of the use of the modified model in the calculation of ocean color spectra will be given in a later section.

IV. Verification of the Quasisingle Scattering Model

Due to the strong forward scattering found in natural waters, a relatively simple assumption may be used to modify the single scattering model to partially account for the effects of multiple scattering. The assumption is that no downwelling or forward-scattered light is lost from the incident sunlight and skylight as they propagate downward in the sea. To implement this assumption, we must first note that the extinction coefficient c can be written as the sum of the absorption coefficient a, and the total scattering coefficient b, where

$$b = 2\pi \int_0^{\pi} \beta(\gamma)\sin\gamma d\gamma; \tag{7}$$

and γ is the scattering angle. We also need to define the forward scattering coefficient

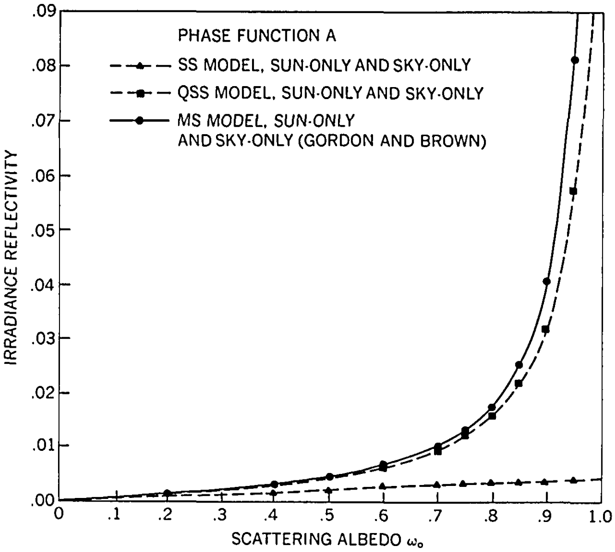

Fig. 4. Irradiance reflectivity vs single scattering albedo for three optical models of the sea using phase function *A*.

$$F = \frac{2\pi}{b}\int_0^{(\pi/2)} \beta(\gamma)\sin\gamma d\gamma \tag{8}$$

and the backscattering coefficient $B = 1 - F$. In the quasisingle scattering model the true extinction coefficient for single scattering c is replaced by $c^* = a + bB = c - Fb = c(1 - \omega_0 F)$, where $\omega_0 = b/c$ is called the single scattering albedo. Thus, all we have to do to convert our earlier single scattering equations to the quasisingle scattering case is to replace c by c^* wherever it appears in those expressions. In particular, the quasisingle scattering versions of Eqs. (5) and (6) are

sun-only case:

$$N_a^0(\lambda, \theta_a, \phi_a) = \frac{T(\theta_a)T(\theta_a^0)H_0(\lambda)\beta(\lambda, \theta_w, \theta_w^0, \phi_w)}{\eta^2(\cos\theta_w - \cos\theta_w^0)c(\lambda)(1 - \omega_0(\lambda)F(\lambda))}; \tag{9}$$

sky-only case:

$$N_a^s(\lambda, \theta_a, \phi_a) = \frac{T(\theta_a)H_s(\lambda)}{\pi\cos\theta_w c(\lambda)[1 - \omega_0(\lambda)F(\lambda)]}\int_0^{2\pi}\int_\pi^{\theta_w^c} \frac{T(\theta_a')\beta(\lambda, \theta_w, \phi_w, \theta_w', \phi_w')\sin\theta_w' d\theta_w' d\phi_w'}{\sec\theta_w - \sec\theta_w'}. \tag{10}$$

To test the validity of these equations the radiances were numerically integrated over 2π sterradians to give the total upwelling irradiances due to sun and sky emerging from the sea. These irradiances were then divided by the corresponding downwelling incident irradiances to obtain irradiance reflectances for comparison with the results of the Gordon and Brown Monte Carlo multiple scattering calculations given in Ref. 15.

To describe this comparison, we note that the scattering phase function P is defined to be β/b, where β is the volume scattering function, and b is the total scattering coefficient. Three scattering phase functions, designated *A*, *B*, and *C*, typical for the Sargasso Sea, were used by Gordon and Brown for their calculations. The irradiance reflectivity is plotted in Figs. 4, 5, and 6 as a function of ω_0 for each of these phase functions. The predictions of the single scattering (*SS*), quasisingle scattering (*QSS*), and multiple scattering (*MS*) models are shown for both the sun-only and sky-only cases in each figure.

There is a substantial difference between the single scattering and multiple scattering models for values of ω_0 greater than about 0.3. But with the quasisingle scattering model, as can be seen clearly in Figs. 4–6, good agreement with the *MS* model is maintained up to an ω_0 of about 0.85. The difference between sun-only and sky-only cases is less than 1% for all values of ω_0 used.

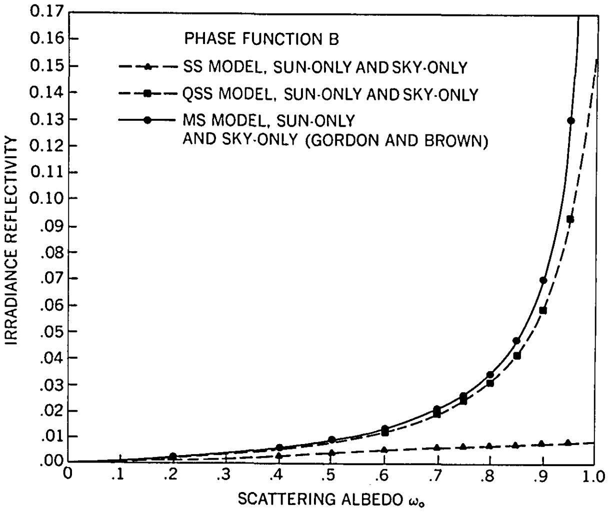

Fig. 5. Irradiance reflectivity vs single scattering albedo for three optical models of the sea using phase function *B*.

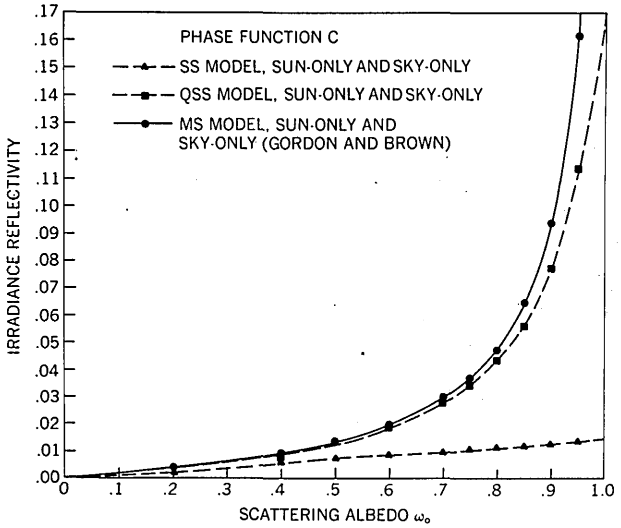

Fig. 6. Irradiance reflectivity vs single scattering albedo for three optical models of the sea using phase function *C*.

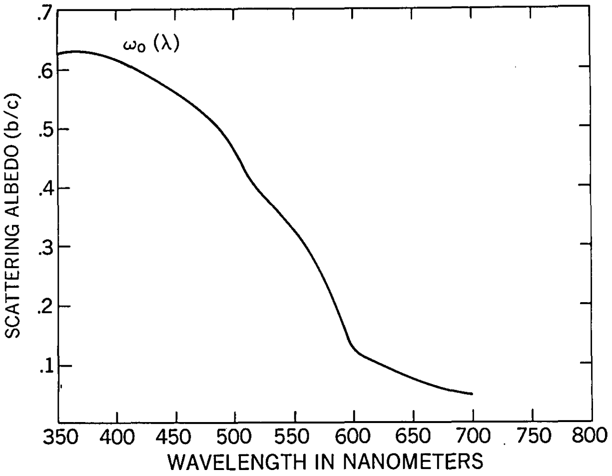

Fig. 7. Single scattering albedo spectrum predicted for clear, natural waters (Tyler *et al.*, 1972).

These results indicate the importance of the shape of the scattering function in remote sensing, for one can conceivably have substantially different reflectances for two different phase functions even though ω_0 might be the same in both cases. Since the upwelling radiance is strongly dependent on the shape of the scattering function, this dependence must not be overlooked.

A plot of the variation of ω_0 with wavelength for clear water similar to that found in the Sargasso Sea is shown in Fig. 7 for reference. The Sargasso Sea is a relatively homogeneous, somewhat stable body of very clear water having optical properties that remain quite constant with time. As such it affords a basis for comparison of different models. Even in the clearest of natural waters, scattering from particulates (mostly phytoplankton) predominates over molecular scattering, except in the case of blue light at large scattering angles where molecular and particulate scattering are roughly comparable. The data for Fig. 7 is derived from spectra of b and c for clear natural waters reported by Tyler *et al.*[19] We can see that ω_0 ranges from zero to 0.63 over this spectrum. The agreement between the *MS* and the *QSS* models is quite good as shown in Figs. 4, 5, and 6 for both sun and skylight cases over this range. In more turbid water one can expect somewhat higher peak values of ω_0. In such cases and for the limited regions of the spectrum over which this occurs, the accuracy of the *QSS* model may be limited. However, for the purposes to which the *QSS* model is intended, this limitation is not overly confining.

A more serious limitation is that the agreement shown in Figs. 4–6 applies only to calculations of upwelling irradiance. A remote sensor receives upwelling radiance from a much smaller solid angle than the 2π steradians used in these computations. A better test of the validity of the *QSS* model would be to compare *QSS* and *MS* calculations of upwelling radiance rather than irradiance. Unfortunately, however, the Gordon and Brown computed radiances are probably not accurate enough for a meaningful comparison. To obtain some information as to the errors that might result from this, the *QSS* model can be evaluated at several different look angles. When this is done using data representative of clear ocean water, as in the next section, and when the results are normalized at 520 nm and compared, it is found that the shape of the predicted spectrum is independent of look angle over the range from 0–60°.

Although this is not a precise test of the hypothesis that the *QSS* model is as good for predicting radiance spectra as it has been shown to be for irradiance spectra, it should be sufficiently valid for calculations not requiring high accuracy. In any event, the *QSS* model should be much better than the *SS* model for these calculations. Further proof will have to await more accurate calculations of upwelling radiance.

V. Ocean Color Spectrum Calculations

Before proceeding to use the *QSS* model Eqs. (9) and (10) for ocean color spectrum calculations, we shall examine them for any general implications that they might have for the remote sensing problem. We begin by writing these equations in terms of the phase function P and scattering albedo ω_0 defined earlier, and divide them by the incident irradiances to get:

sun-only case,

$$\frac{N_a{}^0(\lambda)}{H_0(\lambda)} = K_0\left[\frac{\omega_0(\lambda)P(\lambda)}{1 - \omega_0(\lambda)F(\lambda)}\right] \tag{11}$$

sky-only case,

$$\frac{N_a{}^s(\lambda)}{H_s(\lambda)} = K_s\left[\frac{\omega_0(\lambda)}{1 - \omega_0(\lambda)F(\lambda)}\right]\int_0^{2\pi}\int_{180}^{\theta_w{}^c} \frac{T(\theta_a{}')P(\lambda, \theta_w, \phi_w, \theta_w{}', \phi_w{}')\sin \theta_w{}'d\theta_w{}'d\phi_w{}'}{\sec \theta_w - \sec \theta_w{}'} \tag{12}$$

K_0 and K_s are wavelength-independent quantities. The radiance reflectances given by these equations contain the predicted spectral variation in the ocean color spectrum attributable to properties of the sea alone.

For the moment, let us make an oversimplification, by assuming that the phase function $P(\lambda)$ [and hence also the forward scattering coefficient $F(\lambda)$] is not strongly wavelength-dependent. In this case much of the spectral variation in the radiance reflectance would be due to the spectral variations in ω_0. If this were strictly true, the single-scattering albedo ω_0 would therefore be the predominant contributor to the observed upwelling ocean color spectrum. On a clear day the irradiance incident on the surface will appear white to a visual observer. This leads to the conclusion that the ocean is blue, mainly because the scattering albedo peaks in the blue portion of the spectrum. However, for accurate predictions of the upwelling radiance spectrum emerging from the sea, we cannot ignore the spectral variations in the shape of the scattering phase function that are, in fact, substantial.

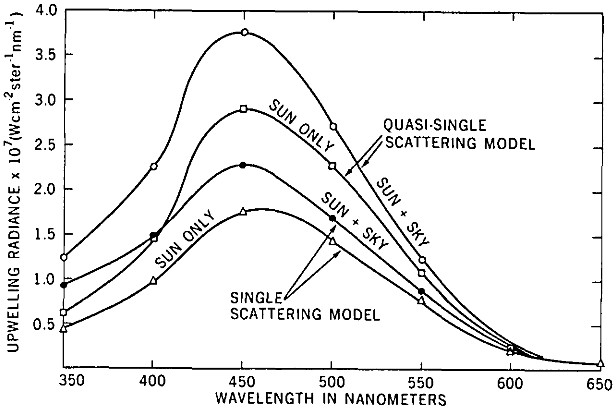

Fig. 8. Upwelling radiance spectrum predicted for the Sargasso Sea using two optical models of the sea.

Thus we see clearly the point made by Gordon and Brown in Ref. 15, that for a given phase function all that can be determined about the medium from remote observations is ω_0. Variations in the spectral distribution of upwelling radiance can be caused by $\omega_0(\lambda)$ and $P(\lambda, \theta)$ [or equivalently, by $c(\lambda)$ and β (λ, θ)]. If ω_0 and P(or c and β) are independent variables in the sea, then it may not be possible to unambiguously determine them separately from a single measurement of the upwelling radiance spectrum. Additional field experiments afford the only means of resolving this question.

The *QSS* model makes no assumptions about the shape of the scattering function or its wavelength dependence, other than the fact that the function is strongly peaked in the forward direction. Let us now use this model to calculate a hypothetical upwelling radiance spectrum for clear natural water such as that found in the Sargasso Sea. As input data we shall use the $c(\lambda)$ spectrum given in Ref. 19, a set of wavelength-dependent scattering functions based on measurements by Kullenberg in the Sargasso Sea,[20] and incident irradiances predicted by an atmospheric model for clear atmospheres developed by Curran.[21] To obtain the wavelength-dependent scattering functions, the scattering data of Kullenberg at 460 nm and 655 nm was linearly interpolated to give values for $\beta(\lambda, \theta)$ at 450 nm, 500 nm, 550 nm, 600 nm, and 650 nm. In addition the function at 350 nm and 400 nm was set equal to that at 450 nm, and at 700 nm it was set equal to that at 650 nm. This is an admittedly crude approximation of the wavelength dependence of the scattering function. But accurate measurements of β at more than two or three wavelengths at a time have not yet been made.

The input data that were used roughly approximate the situation for the Sargasso Sea on a cloudless, clear day. The resulting upwelling radiance spectra predicted by the *SS* and the *QSS* models for a zenith sun and nadir viewing are shown in Fig. 8. These results show clearly the affect of multiple scattering on the shape of the radiance spectrum. The slight shift of the peak wavelength toward the blue when skylight is added to the sun-only case is evident in this figure.

In Fig. 9 is shown a comparison of these theoretical results (for a 60° solar zenith angle) with the experimental results obtained by Hovis late in the afternoon on 17 July 1972 at an altitude of 305 m at the edge of the Sargasso Sea (a distance of about 250 km NE of Cape Hatteras).[22] The water is quite clear in this region and should not be much different from that found in the middle of the Sargasso Sea. Specular reflection of skylight and a small amount of sun glint are present in the Hovis data that are not accounted for in the theoretical calculations. Also shown in Fig. 9 is a normalized version of the experimental data drawn to compare the shapes of the two spectra. Although the theoretical and experimental data represent different locations and times, it is encouraging that the shapes of the two spectra are similar.

The ratio of the experimental curve to the theoretical curve shown in Fig. 9 (the normalization factor) is approximately 3.3. Although this ratio is for the upwelling radiance, it agrees in a very general way with measurements of upwelling irradiances made by F. J. Davis in 1941 at the surface of a deep, wind-roughened fresh-water lake.[23] For a solar zenith angle of 60°, Davis determined that the total upwelling irradiance, due to reflected sun and skylight, plus that due to upwelling subsurface light, was approximately 7.4% of the total incident light, integrated over the visible spectrum. The subsurface component was 2.5% of the total. Thus, the total upwelling irradiance was approximately three times the subsur-

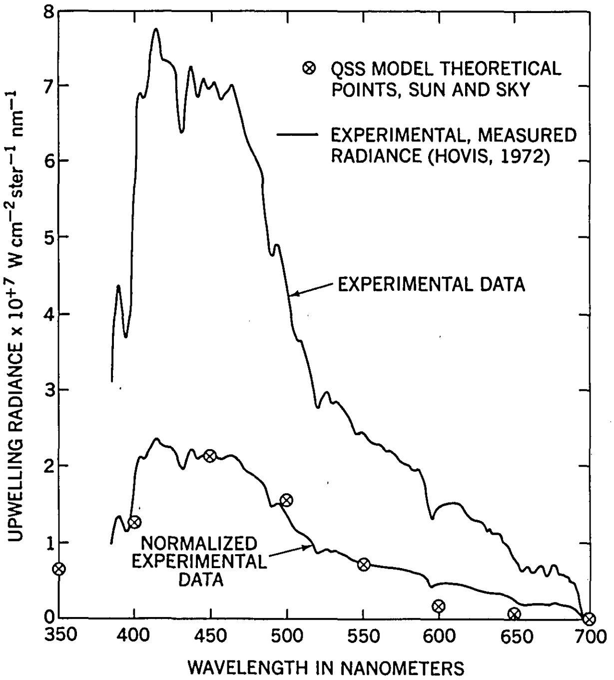

Fig. 9. Comparison of theoretical upwelling radiance spectrum for the Sargasso Sea with measurements made by Hovis at an altitude of 305 m, 250 km NE of Cape Hatteras in 1972.

face component. Although this is not in general likely to be true at all wavelengths in the visible, the Davis results tend to support the results shown in Fig. 9 and lend further support for the validity of the *QSS* model in predictions of upwelling radiance spectra.

VI. Conclusions

It is concluded that the quasisingle scattering model gives a reasonably accurate estimate of upwelling radiance spectra applicable to ocean color remote sensor design studies and for the development of ocean color data analysis techniques. The main advantage of the model lies in its simplicity. This permits calculations of radiance spectra with only a few seconds of computer *CPU* time. A single program can run 5 sun angles, 10 look angles, and 50 wavelengths in just a few minutes of *CPU* time. All that is needed is accurate scattering and extinction data. This data may either be provided experimentally or may be the prediction of a suitably formulated microscopic model based on assumed or measured concentrations of dissolved and particulate matter in the sea.

Although the ocean color spectrum predictions shown in Fig. 9 were made only for clear, open ocean water, the agreement shown in Figs. 4, 5, and 6 over a wide range of ω_0 insures that the accuracy of the model will be just as good in turbid water. This conclusion is further supported by the fact that the volume scattering function becomes even more strongly peaked in the forward direction with increasing water turbidity, making the quasisingle scattering approximation even more valid than it is for clear water.

By extending the model to include the effects of reflection from a shallow bottom, transmission and reflection of sun and sky light from a rough upper surface, and atmospheric path radiance, reasonably accurate estimates of the total upwelling radiance spectrum at high altitudes in or above the atmosphere should be possible.

The need for accurate measurements of the full spectral variations of the extinction coefficient and the volume scattering function should be obvious. These measurements are needed to provide realistic input data for the macroscopic model and to assist in the development of an accurate, useful microscopic model.

The author would like to acknowledge many helpful discussions with H. R. Gordon and O. B. Brown of the University of Miami, and Gary Wolford of NASA Goddard Space Flight Center for developing the computer code used to calculate *SS* and *QSS* model radiance and irradiance spectra.

References

1. V. Klemas, R. Srna, W. Treasure, and M. Otler, "Applicability of ERTS-1 Imagery to the Study of Suspended Sediment and Aquatic Fronts," *Proceedings of the Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1,* NASA Goddard Space Flight Center, 5–9 March 1973, edited by Stanley C. Freden, Enrico P. Mercanti, and Margaret Becker, pp. 1275–1290.
2. George A. Maul, "Remote Sensing of Ocean Currents Using ERTS Imagery," *Proceedings of the Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1,* NASA Goddard Space Flight Center, 5–9 March 1973, edited by Stanley C. Freden, Enrico P. Mercanti, and Margaret Becker, pp. 1365–1375.
3. James A. Mueller, "The Influence of Phytoplankton on Ocean Color Spectra," Ph.D. thesis, School of Oceanography, Oregon State University, Corvallis, Oregon, 1973.
4. Warren A. Hovis, "Measurements of Ocean Color," *Proceedings of a Symposium on the Significant Accomplishments in Sciences,* NASA Goddard Space Flight Center, Greenbelt, Md., 10 November 1971, pp. 24–29.
5. Benjamin M. Herman, S. R. Browning, and Robert J. Curran, J. Atmos. Sci. **28,** 419 (1971).
6. J. V. Dave, Appl. Opt. **9,** 2673 (1970).
7. Gilbert N. Plass and George W. Kattawar, Appl. Opt. **8,** 455 (1969).
8. R. E. Turner, W. A. Malila, and R. F. Nalepka, "Importance of Atmospheric Scattering in Remote Sensing, or Everything You've Always Wanted to Know About Atmospheric Scattering but were Afraid to Ask," *Proceedings 7th International Symposium on Remote Sensensing and Environment,* Willow Run Laboratories, Institute of Science and Technology, University of Michigan, 1971, pp. 1651–1697.
9. C. Cox and W. Munk, "Slopes of the Sea Surface Deduced from Photographs of Sun Glitter," Bulletin of Scipps Institution of Oceanography of the University of California (U. Cal. Press, Los Angeles 1956), Vol. 6, No. 9, pp. 401–488.
10. A. E. Strong and I. S. Ruff, Rem. Sensing Environ. **1,** 181 (1970).
11. Andre Morel, "Diffusion de la lumiere par les eaux de Mer. Resultats experimentaux et approche theorique." *Optics of the Sea (Interface and In-Water Transmission and Imaging).* AGARD Lecture Series No. 61, North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development, Sept. 1973.
12. N. G. Jerlov, *Optical Oceanography* (Elsevier Publishing Company, New York 1968).
13. N. A. Logan, Proc. IEEE **53,** 773 (1965).
14. M. Kerker, *The Scattering of Light and Other Electromagnetic Radiation* (Academic Press, New York, 1969).
15. H. R. Gordon and O. B. Brown, Appl. Opt. **12,** 1549 (1973).
16. H. R. Gordon and O. B. Brown, "An Examination of Factors Influencing Ocean Color Using Radiative Transfer Theory," *Proceedings Symposium on Remote Sensing in Oceanography,* 2–5 October 1973, Lake Buena Vista, Fla., American Society of Photogrammetry, Falls Church, Va., 1973, pp. 607–612.
17. S. Q. Duntley, J. Opt. Soc. Am. **53,** 214 (1963).
18. H. R. Gordon, **12,** 2803 (1973).
19. J. E. Tyler R. C. Smith, and W. H. Wilson, Jr., J. Opt. Soc. Am. **62,** 83 (1972).
20. Gunnar Kullenberg, "Scattering of Light by Sargasso Sea Water," Deep-Sea Res. **15,** 423 (1968).
21. R. J. Curran, Appl. Opt. **8,** 1857 (1972).
22. W. A. Hovis, NASA–GSFC, private communication.
23. F. J. Davis, Trans. Wisc. Acad. Sci. **33,** 83 (1941).