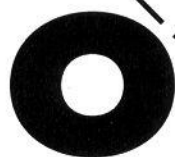


OCEANIC



OPTICS

BY CURTIS MOBLEY

The science of oceanic optics began at 4 p.m., 20 April 1865, when an Italian priest lowered a white disk over the side of a Papal sloop to determine water clarity in the Tyrrhenian Sea by measuring the depth at which the disk disappeared from sight. Oceanic optics—underwater optics including effects of the sea surface itself—has since developed into a field of vigorous basic and applied research. The importance of this research is seen in several recent actions. The Optical Society of America has expanded its technical group on Atmospheric Optics to Atmospheric and Oceanic Optics. The American Society of Limnology and Oceanography now recognizes optical oceanography as the equal of the traditional physical, biological, chemical, and geological subdisciplines of oceanography. And most significantly, in 1988 the U.S. Navy established the Oceanic Optics Program at the Office of Naval Research. This program provides a federal source of funding dedicated to basic research in oceanic optics.

The overall goal of oceanic optics research is to develop the capability to predict underwater light fields, given the lighting conditions just above the sea surface and environmental information specifying the sea surface condition, the types and concentrations of particles and dissolved substances within the water, and the nature of the bottom boundary. Achieving this goal requires not just mastery of the physics of radiative transfer, but also understanding the complex interactions between living oceanic organisms and the ambient light field. Oceanic optics finds applications in fields as diverse as remote sensing of oceanic biological productivity, computation of surface water heating rates, laser bathymetry, marine photochemistry, and underwater communications and imaging.

OPTICAL PROPERTIES OF SEA WATER

Sea water—including open oceans, coastal waters, estuaries and harbors—is an optical environment much different than other liquids or the atmosphere. The optical characteristics of sea water are usually specified in terms of its bulk inherent optical properties (IOPs), namely its absorbing and scattering properties.

The IOPs of sea water seldom resemble those of pure water. The difference occurs because the inherent optical properties of sea water are determined largely by the various particles and dissolved substances suspended within it; not by the water itself. The optically relevant constituents of sea water, other than the water itself, are living phytoplankton, non-living organic and inorganic particles, and dissolved organic matter. Each of these constituents contributes independently to the total absorbing and scattering properties of the water body, and therefore can be discussed separately. Because the types and concentrations of these particles and dissolved substances vary enormously in space and time, so do the optical properties of the world's oceans.

ABSORPTION

Pure sea water (pure water plus various dissolved salts) has a beam absorption coefficient characterized by a minimum value of 0.015 m^{-1} in the blue region of the visible spectrum (*i.e.*, absorption decreases the intensity of a collimated beam of blue light by a factor of $\exp(-0.015d)$ over a path d meters long), as seen in curve *a* of Figure 1. The absorption rises rapidly in the near ultraviolet to a value of about 0.14 m^{-1} at a wavelength of $\lambda = 300 \text{ nm}$ and a value of 3.1 m^{-1} at 200 nm . Likewise, the absorption increases in the



green and red regions to a value of 0.65 m^{-1} at 700 nm and continues to rise rapidly in the infrared. This absorption curve is characteristic only of the very clearest open ocean waters as are sometimes found, for example, in the Sargasso Sea.

Phytoplankton are single-celled plants containing chlorophyll and capable of photosynthesis. Cell shapes and sizes vary widely with species and growth state, but cell length scales fall in the 1 to 100 μm range. In open ocean waters, the smallest phytoplankton may be present in number concentrations of 10^8 cells per cubic meter of sea water, while the larger particles may be present only in thousands or fewer per cubic meter.

Since the effect of phytoplankton on oceanic absorption is via spectral absorption by their chlorophyll (and related pigments), the commonly used measure of phytoplankton concentration is milligrams of chlorophyll per cubic meter of sea water. Representative chlorophyll concentrations are 0.01 mg m^{-3} for very clear waters, $0.1\text{-}1.0 \text{ mg m}^{-3}$ for typical open ocean waters, $1.0\text{-}10.0 \text{ mg m}^{-3}$ for coastal waters, and up to 100 mg m^{-3} for estuarine waters. Chlorophyll is characterized by relatively strong absorption in the blue and red, and relatively less absorption in the green regions of the visible spectrum, as shown in curve *b* of Figure 1. Biologically productive ocean waters have high chlorophyll concentrations and therefore display a V-shaped absorption curve: high absorption in the blue because of the chlorophyll, high in the red because of the water itself, and a minimum in the green.

When phytoplankton die, their chlorophyll degrades, leaving a cell or cell fragment whose absorption is determined by the nonchlorophyllous cell components. There

are also living cells in sea water that do not contain chlorophyll. Curve *c* of Figure 1 shows the relative absorption typical of such organic particles. Inorganic particles may be present from river inflow, sediment re-suspension, or wind-blown dust. These particles are often quartz or other minerals that contribute little to absorption, although they can strongly affect the scattering properties of sea water.

Decaying organic matter also releases various humic acids into the water. This dissolved organic matter is characterized by high absorption in the blue, with an exponential decrease in absorption toward the red end of the spectrum, as shown in curve *d* of Figure 1. These substances are usually called "yellow matter," since in high concentrations they can shift the minimum of the total absorption coefficient all the way into the yellow region of the spectrum. Yellow matter can be the dominant factor in determining the total sea water absorption in coastal regions influenced by river runoff carrying large amounts of yellow matter derived from decaying land vegetation, e.g., near the mouths of the Mississippi or Amazon.

SCATTERING

The scattering properties of sea water are described by the volume scattering function, $\beta(\psi, \lambda)$, with units of $\text{m}^{-1} \text{sr}^{-1}$, where ψ is the scattering angle, $0 \leq \psi \leq 180^\circ$. The volume scattering function for sea water usually can be decomposed into a product of the form $\beta(\psi, \lambda) = b(\lambda) p(\psi)$. Here $b(\lambda)$ is the beam scattering coefficient, which has units of m^{-1} and specifies the overall strength of the scattering; $p(\psi)$ is the phase function, which has units of sr^{-1} and specifies the probability that a photon is scattered (in a given scattering event) through an angle ψ measured relative to the direc-

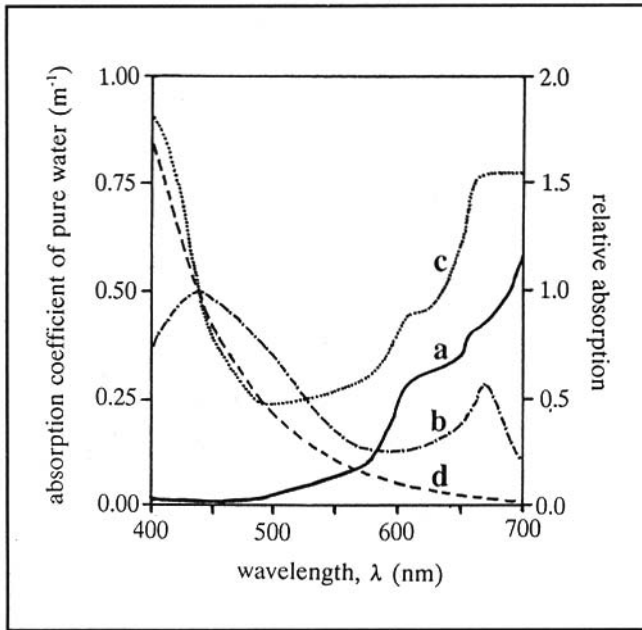


FIGURE 1. The absolute absorption coefficient of pure sea water is shown by curve a, with the scale on the left. The relative absorption coefficients of chlorophyll (curve b), nonchlorophyllous organic particles (curve c), and yellow matter (curve d) are shown with the scale on the right. Curves b-d are normalized to one at $\lambda = 440$ nm. The contributions of curves b-d to the total sea water absorption coefficient depend on the concentrations of the respective substances. (Figure redrawn from Ref. 1.)

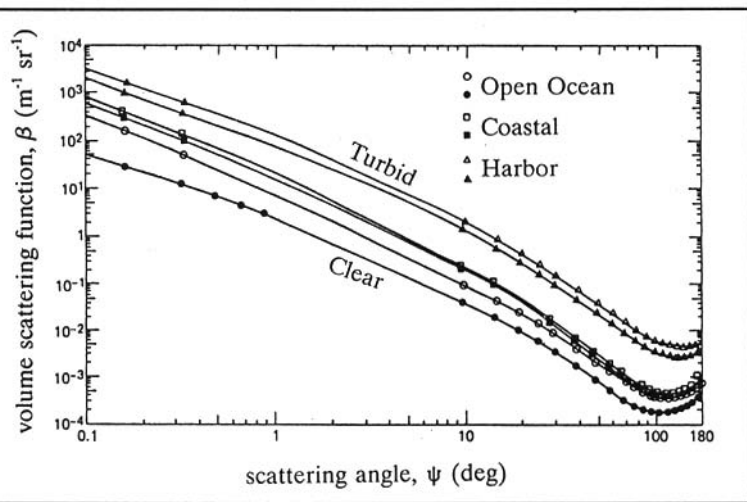


FIGURE 2. Volume scattering functions for various water types ranging from very clear to very turbid. (Figure redrawn from Ref. 2.)

tion of the incident photon.

Molecules of water or of dissolved substances are much smaller than the wavelength of visible light, so that scattering by pure sea water results from thermal density fluctuations and is described by a Rayleigh-like phase function: $p(\psi) = 0.062 (1 + 0.835 \cos^2\psi)$. The scattering coefficient for

pure sea water is found to depend on wavelength as $b(\lambda)^{-4.32}$

However, because of scattering by the ubiquitous suspended particles, oceanic phase functions are never similar to that of pure sea water. Most oceanic particles are large compared to the wavelength of visible light, so that scattering is dominated by Fraunhofer diffraction. Scattering by diffraction is primarily at very small scattering angles and is independent of the particle composition. Moreover, the polydisperse size distribution and random orientation of oceanic particles smooth out the scattering resonances that are seen in a monodisperse system. All of these effects conspire to give a phase function that is highly peaked in the forward direction and whose shape is nearly independent of wavelength and particle concentration and type. Figure 2 shows six volume scattering functions, $\beta(\psi, \lambda)$, measured in very clear to very turbid waters; note the similar shapes of these curves. The total scattering coefficient (proportional to the area under the curves) increases greatly as one goes from clear to turbid water: $b = 0.037 \text{ m}^{-1}$ for the clearest water of Figure 2 and $b = 1.824 \text{ m}^{-1}$ for the most turbid.

Typically one half of all scattering is at angles of less than a few degrees, and therefore the scattering coefficient is largely determined by forward scattering. However, for some purposes such as remote sensing, backscattered light may be of great interest. For large scattering angles, other scattering processes such as refraction through particles and reflection by their surfaces become significant. As suggested by the shape of the scattering functions for $\psi = 90^\circ$ in Figure 2, scattering by sea water itself (which rises by a factor of 1.84 in going from $\psi = 90^\circ$ to $\psi = 180^\circ$) is significant for backscattered directions and can dominate in clear waters at blue wavelengths.

MEASUREMENTS AND PREDICTIONS

The spectral radiance specifies how much radiant (electromagnetic) energy in a unit wavelength interval passes across a unit area per unit time, contained within a unit solid angle centered about a given direction; spectral radiance therefore has units of $\text{J s}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$. Spectral radiance is the fundamental radiometric variable in oceanic optics. The false-color image on page 15 shows an underwater spectral radiance distribution measured with an upward pointing electro-optical fisheye camera.³ The fisheye lens maps an entire hemisphere of directions onto a CID array; each array element collects photons from a particular direction and solid angle. Different magnitude ranges of the radiance are then displayed as different colors.

Radiative transfer theory is the mathematical and physical framework for understanding oceanic optical processes. The radiative transfer equation is an integro-differential equation that relates the spatial rate of change of the spectral radiance at a given location in a given direction to the values of the absorption coefficient, the volume scattering function, and the existing radiance distribution at that

location. To solve this complicated equation and thereby predict a radiance distribution like the one shown on the cover, we must be given suitable boundary conditions on the radiance, along with the IOPs—the absorption and scattering coefficients and the phase function—of the water body being studied.

However, nature has not been kind to us. It is quite difficult to measure the needed inherent optical properties, especially in situ. In fact, the only IOP that is routinely and accurately measured in situ is the beam attenuation, which is the sum of the absorption and scattering coefficients. The measurements commonly made are of various apparent optical properties (AOPs). They are “apparent” because they are not properties of the sea water alone, but also depend on the light field itself through environmental factors such as the incident lighting and sea state. Examples of AOPs are the radiance itself, various irradiances (which are weighted or unweighted integrals of the radiance over specified directions, usually the upward and downward hemispheres of directions), and the reflectance (ratio of upwelling irradiance to downwelling). Although the AOPs are functions of the IOPs, the environmental factors prevent us from obtaining the needed IOPs from measured AOPs in any simple fashion. Note, for example, that a passing cloud or a change in sea surface wave state can change the radiance transmitted through the sea surface, and therefore change the AOPs being measured within the water, even though the sea water IOPs are unchanged. We thus have a situation not uncommon in science: the quantities that are easy to interpret (the IOPs) are not easy to measure; the quantities that are easy to measure (the AOPs) are not easy to interpret.

Fortunately, it is not always necessary to predict the full spectral radiance distribution. For example, randomly oriented phytoplankton are equally likely to absorb a photon regardless of its direction of travel. Therefore, a plankton biologist may be content with a model that predicts the spectral distribution of photons at each point in the water, without regard for the directional structure of the light field. Many such special purpose models have been developed.⁴

CURRENT RESEARCH

The preceding discussion gives a simplified overview of the basics of oceanic optics. We now turn our attention to a few of the specific areas of current research interest. Much of this research relates to the central issue of oceanic optics: understanding and being able to measure all the sources (e.g., sunlight, bioluminescence, fluorescence, Raman scatter) and sinks (e.g., absorption by water, particles, and dissolved substances) of oceanic light so as to achieve energy conservation on a photon-budget basis.

Closure. To solve the radiative transfer equation, it is necessary to know the individual contributions of absorption and scattering to the total attenuation. (The directional struc-

ture of the radiance distribution will be different in low absorption-high scattering and in high absorption-low scattering waters, even though the total attenuation is the same in each case.) However, because of the difficulty of making absorption measurements uncontaminated by scattering effects, and vice versa, we are not yet able to make independent measurements of absorption, scattering and attenuation that satisfy the basic measurement closure relation: absorption + scattering = attenuation. This relation is nothing more than conservation of energy. All measurements must remain suspect until we develop instrumentation and measurement methodologies for individually determining absorption and scattering coefficients that yield a balanced closure relation.

Other types of closure problems exist. Inherent optical properties usually are determined from small volumes of water. For example, instruments commonly used to measure volume scattering functions “see” at most a few milliliters of water and therefore usually miss the occasional large (> 1 mm), but optically important, particles or marine aggregates (“marine snow”). Apparent optical properties, on the other hand, are determined by the integrated effects of very large volumes of water. It is not known how accurately IOPs determined on the small scale can predict large scale AOPs via the radiative transfer equation. This problem of achieving consistent sets of measurements on scales of centimeters to tens of meters is called scale closure.

Transpectral Scattering. Any attempt to achieve closure at a single wavelength will fail if there is a significant energy loss to, or gain from, other wavelengths. Processes responsible for such energy transfers in the ocean include fluorescence by chlorophyll and dissolved substances, and Raman and Brillouin scattering by water molecules.

Raman scattering provides an illustration of the importance of inelastic scattering in the underwater environment. In homogeneous water and in the absence of transpectral scattering, the radiance at a given wavelength approaches an asymptotic directional distribution at depth. This angular distribution of the light field is determined solely by the IOPs of the water body. As the asymptotic

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radiance distribution is approached, the irradiance reflectance (a weighted ratio of upwelling to downwelling energy) approaches a constant value. Since most photons are elastically scattered at small angles, solar photons (heading downward at the sea surface) generally continue to head downward. Only a small fraction of the solar photons is backscattered into upward directions, and consequently the reflectance is small, typically 0.02 to 0.05.

Figure 3 shows the measured reflectance at $\lambda = 589$ nm from very clear Atlantic waters. Note that the reflectance increases with depth to a value greater than 0.3 at a depth of 120 m. In the absence of Raman scattering, the reflectance would be about 0.04 for this water. However, a detailed model⁵ incorporating Raman scattering reasonably reproduces the observed reflectance, as seen in Figure 3. The phase function for Raman scattering is nearly independent of the scattering angle.

Therefore a downwelling solar photon (from a blue wavelength) that is Raman scattered is equally likely to generate an upward or a downward travelling photon (at a red wavelength). Raman scattered photons heading downward add only a small contribution to the downwelling solar photons. However, Raman scattered photons that head upward provide a source of upwelling red light that greatly exceeds the backscattered red solar light at depth, thereby increasing the irradiance reflectance at red wavelengths.

Submicrometer Particles. Although the optical effects of phytoplankton have been investigated for decades, it only recently has been recognized⁶ that submicrometer sized particles occur in enormous numbers in sea water. Bacteria, with sizes generally in the 0.4-0.7 μm range, occur in typical concentrations of 10^{12} m^{-3} in open sea water. Nonliving particles in this size range may outnumber bacteria by an order of magnitude. Recent work shows that these extremely small particles may have important optical properties.

Although the absorption and scattering efficiencies of bacteria are much less, on a per cell basis, than the efficiencies of phytoplankton and other large particles, the much greater abundances of bacteria more than compensate for their relative inefficiencies as light attenuators. Predictions

based on Mie theory (most oceanic bacteria are nearly spherical and are well suited to such analysis) and measured bacterial properties indicate⁷ that in clear ocean waters (chlorophyll content of 0.1 mg m^{-3}), bacteria may account for one half of the total scattering at $\lambda = 550$ nm, and 80% at 400 nm. Bacteria are thought to be much less significant than phytoplankton in determining oceanic absorption, but bacteria nevertheless may be important at blue wavelengths.

Another interesting effect of submicrometer particles is seen in recent measurements of the Mueller matrix elements for various species of phytoplankton. It is found⁸ that a certain species of phytoplankton, *Prorocentrum micans*, has a strong tendency to circularly polarize incident unpolarized light. This is reminiscent of the well known circular dichroism of a solution of sugar and water, in which the chiral sugar molecules are responsible for the optical activity. *P. micans* has some of the largest known chromosomes that retain a helical arrangement of their DNA. The pitch of the helix is roughly 250 nm, *i.e.*, half a wavelength of visible light. This observation and other evidence point to the helical strands of DNA as the structure inducing the circular polarization. Thus the submicrometer particles of interest here are the chromosomes imbedded within a much larger ($50 \mu\text{m}$) phytoplankton cell.

Instrumentation. The greatest hindrance to progress in understanding the oceanic optical environment is the lack of comprehensive data sets, *i.e.*, simultaneous measurements of IOPs, AOPs, and environmental conditions. Such data are necessary for identifying and quantifying relevant physical processes and for guiding the development of predictive models. The problem lies in the lack of instrumentation for conveniently making accurate in situ measurements of many variables of interest, in particular the absorption coefficient.

One can scarcely over-emphasize the difficulty of making optical measurements in the corrosive, high pressure environment 200 m below the sea surface, especially when the instrument is dangling over the side of a rolling ship. Moored instruments are subject to severe biofouling of optical elements which, if unchecked, completely changes both the spectral character and the intensity of the measured light after only a few days in the water. In spite of these difficulties, excellent commercially made instruments are routinely used to measure beam attenuation, chlorophyll fluorescence, and various spectral irradiances. Several unique instruments are also in use, *e.g.*, the recently developed 'electro-optical camera used to generate the image on the cover and the ancient scattering meter used to obtain the data of Figure 2 (this instrument is now 32 years old!).

Two instruments now under development address the need for in situ measurements of absorption. One of these is based on a well established theory⁹ that relates the absorption to certain moments of the radiance distribution; these moments can be measured by specially shaped mirrors. The

other¹⁰ is based on the use of a reflecting tube to counter losses by scattering and thereby obtain the absorption—an old idea now realizable with modern electronics.

The instruments just mentioned, and others under development, clearly show that the future of oceanic optics lies in high resolution measurements—high resolution in time,

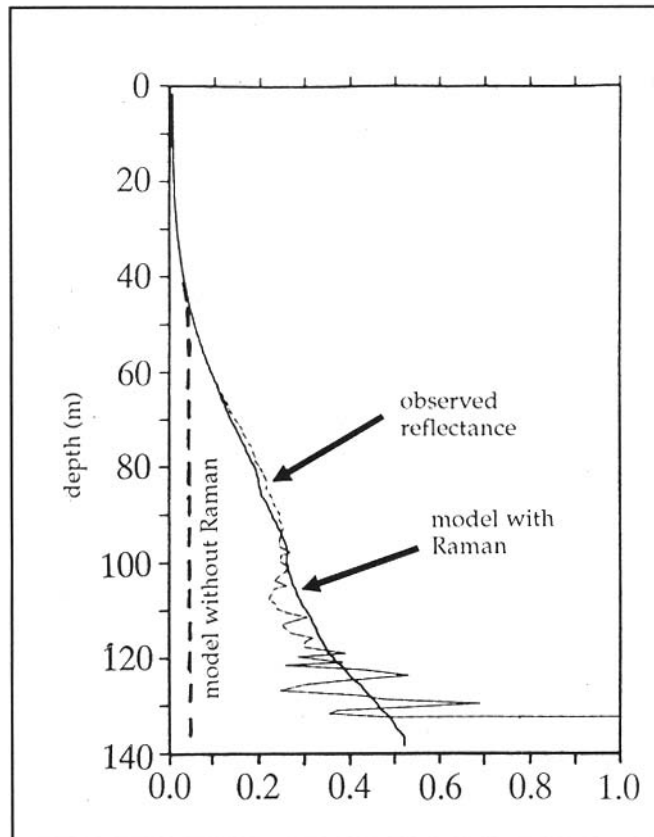


FIGURE 3. Observed irradiance reflectance (light line) and values predicted by a model including Raman scattering (heavy line), and omitting Raman scattering (dashed line). (Figure redrawn from Ref. 5.)

GREATER DEFINITION

IOP

INHERENT OPTICAL PROPERTY—ANY OPTICAL PROPERTY THAT DEPENDS ONLY ON THE MEDIUM, AND IS INDEPENDENT OF THE AMBIENT LIGHT FIELD WITHIN THE MEDIUM (E.G., THE ABSORPTION COEFFICIENT)

AOP

APPARENT OPTICAL PROPERTY—PROPERTY THAT DEPENDS BOTH ON THE MEDIUM AND ON THE AMBIENT LIGHT FIELD (E.G., THE IRRADIANCE REFLECTANCE)

space and wavelength. The information content of such data is vastly superior to broadband or monochromatic measurements taken at widely spaced times and locations. In the next decade, the resulting increase in data quality and quantity, coupled with modern computing power and a stable source of funding for investigators, surely will result in an increased understanding of oceanic optics that will dwarf even the impressive progress of the last decade.

FURTHER READING

Part I of *Light and Photosynthesis in Aquatic Ecosystems*¹¹ gives an excellent and highly readable introduction to oceanic optics; chapter nine of *Principles of Ocean Physics*¹² gives a more concise overview of the subject. A recent special edition of *Limnology and Oceanography*¹³ shows the broad range of basic research in oceanic optics. The 58 papers presented at the most recent oceanic optics conference¹⁴ cover basic research, instrumentation, and applications.

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