CORRELATION OF BEAM AND DIFFUSE ATTENUATION
COEFFICIENTS MEASURED IN SELECTED OCEAN WATERS

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Abstract

The beam (volume) attenuation coefficient, α, and diffuse attenuation coefficient, K, of optical radiation have been measured in selected U.S. East Coast, Bahama, and Puerto Rico Trench waters. The objective was to determine what, if any, empirical relationship exists between these two optical properties over a wide range of turbidity. α was determined from transmittance versus depth profiles made with a beam transmissometer. K was determined from relative irradiance versus depth profiles made with a relative irradiance meter. In order to eliminate data bias introduced by spatial movement, temporal fluctuations, and spectral dependency, α and K were measured simultaneously and at a common wavelength ($\lambda \approx 535$ nm). "Effective" (depth averaged) values of α and K, designated $\bar{\alpha}$ and $\bar{K}$ respectively, were calculated in order to characterize the variable data versus depth profiles at each station with single values. The empirical expression: $\bar{K} \approx 0.2\,\bar{\alpha} + 0.04$, applicable for the range $0.11\ m^{-1} \leq \bar{\alpha} \leq 1.6\ m^{-1}$, has been determined for data combined from all locations. The degree of concurrence of this relationship with data obtained by others is discussed. Definitions of α and K, and discussion related to their differences are also presented.

Introduction

Two attenuation coefficients commonly used to characterize the transmission of optical energy through water are: (1) beam (volume)* attenuation coefficient, α, and (2) diffuse attenuation coefficient, K. Both coefficients exhibit spectral dependence.** The magnitude of each coefficient can be determined from "in-situ" optical oceanographic measurements using, respectively, a beam transmissometer and a relative irradiance meter.

In order to investigate the relationship between α and K, NAVAIRDEVCEN (Naval Air Development Center) personnel conducted, during the period 1972-1975, extensive simultaneous in-situ measurements of these two attenuation coefficients in selected ocean waters. The primary objective of these measurements was to determine what, if any, empirical relationship exists between these two optical properties over a wide range of turbidity. This research was performed as a part of the NAVAIRDEVCEN's exploratory development work in air-to-underwater laser radar systems.

Beam Attenuation Coefficient

The beam attenuation coefficient, α, of water characterizes the amount of attenuation experienced by a collimated beam of monochromatic radiant flux traversing a fixed path length of homogeneous water such that the residual beam does not contain any scattered flux. Since the power content of radiant flux traversing through water is reduced exponentially with distance, beam attenuation is depicted mathematically as:

$$P_r = P_o e^{-\alpha r} \tag{1}$$

where:

P_o = initial radiant power of collimated beam of monochromatic flux

P_r = radiant power of nonscattered component of residual beam

r = water path length

α = beam attenuation coefficient of water

This equation is based on the fundamental assumption that if a photon is absorbed or scattered within the path length it is permanently lost to subsequent detection by a receiver; specifically, it is assumed that any photon having undergone a scattering event will not remain within or be returned to the beam.

* The term "beam" attenuation coefficient, rather than the more commonly accepted term "volume" attenuation coefficient is used in this paper to characterize α, since "beam" provides a convenient conceptual contrast to "diffuse," which describes K.

**Although the magnitude of each coefficient is highly dependent on optical wavelength, the spectral qualification associated with each is deleted for convenience.

It is evident from equation (1) that α has the dimensions of reciprocal length. Since the length of measurement is usually given in meters, α is commonly assigned units of m^{-1}.

Theoretically, the beam attenuation coefficient is related to the absorption coefficient, a, and the scattering coefficient, s, such that by definition:

$$\alpha = a + s \tag{2}$$

This summation of coefficients depicts the fact that two fundamental, mutually independent mechanisms, absorption and scattering, act together to yield total attenuation of a beam of light in water. It should be recognized that the magnitudes of a and s, and therefore α, are all functions of wavelength.

The magnitude of α is determined from a transmittance measurement of a beam of collimated monochromatic light traversing a sample path of water (usually one meter). α is calculated from this transmittance measurement via a form of equation (1):

$$\alpha = \frac{1}{r} \ln \frac{1}{T} \tag{3}$$

where T = transmittance = P_r/P_o.

The instrument used for this measurement is a beam transmissometer (sometimes called α-meter). Figure 1, which presents a general schematic of such an instrument, illustrates the concept of measuring α.

α is considered to be an inherent optical property of the water; i.e., it is an intrinsic physical quality fundamental to the medium itself. It is independent of light beam orientation or the existing lighting conditions within the medium. Ideally, the measurement of α is also independent of such geometric considerations as instrument size, configuration, and receiver acceptance angle. However, the practical measurement of α is complicated by the problem of distinguishing unscattered light from light which has been scattered into very small angles. This problem is particularly significant because small angle scattering dominates the total scattering phenomenon in natural waters. In order to perfectly satisfy equation (2) in the measurement of α, the FOV (field-of-view) of a beam transmissometer would have to equal zero, a physical impossibility since any practical measurement device has a finite acceptance angle. Any transmissometer's receiver with its finite FOV accepts a certain amount of unwanted small angle forward scattered light. This contamination yields a measured value of transmittance slightly higher than the true value; hence, the value of α calculated from such a measurement is slightly lower than the true value. Accordingly, in order to keep this error to a minimum, it is important that a transmissometer be properly designed with a minimum FOV (e.g., $< 1°$).

As pointed out by Duntley,[1] α is a scalar point function of position which can vary along any underwater path if the water is not macroscopically homogeneous. Since natural waters are generally inhomogeneous, α usually varies with depth. In order to facilitate comparison of the water's α at different geographic locations, it is desirable to assign to the variable α versus depth profile at a given station a single "effective" (depth averaged) value. This effective value, designated $\bar{\alpha}$, can be calculated by numerically integrating the α profile over the depth of interest.

Diffuse Attenuation Coefficient

The diffuse attenuation coefficient, K, characterizes the amount of attenuation experienced by a diffuse field of monochromatic light traversing a fixed distance of water. In oceanographic applications, K is a measure of the extent to which diffuse downwelling daylight diminishes exponentially with depth. For homogeneous waters, this type of attenuation is depicted mathematically as:

$$H_{Z_2} = H_{Z_1} e^{-K(Z_2 - Z_1)} \tag{4}$$

where:

H_{Z_1} = total downwelling irradiance at depth Z_1

H_{Z_2} = total downwelling irradiance at depth Z_2 (where $Z_2 > Z_1$)

K = diffuse attenuation coefficient of daylight between horizontal planes at depth Z_1 and Z_2

In a practical sense, Z_1 is usually assumed to be the sea surface. Thus, equation (4) can be simplified to:

$$H_Z = H_0 e^{-KZ} \tag{5}$$

where:

H_0 = solar irradiance at sea surface

H_Z = residual downwelling irradiance on horizontal plane at depth Z

Z = path length (depth) of measurement

K = diffuse attenuation coefficient of daylight in sea water

It should be noted that K, like α, is wavelength dependent. Futhermore, it is evident from equation (5) that K, like α, has the units of reciprocal length (usually m^{-1}) associated with it.

The magnitude of K is determined from the slope of a semilogarithmic plot of relative irradiance versus depth. The instrument used for this measurement is a relative irradiance meter (sometimes called K-meter). It consists of an upward-looking surface (deck) photosensor and an upward-looking underwater photosensor. The surface photosensor is used to normalize temporal fluctuations in solar irradiance. Each photosensor contains a flat plate Lambertian collector which accepts light over a hemispherical (180°) FOV. K measurements are frequently made with an underwater photosensor having a photopic response with a peak transmission near 555 nm. However, the broad bandwidth of a photopic response coupled with the water's selective absorption of wavelength with depth over a relatively long pathlength yields an effective response which is shifted towards the wavelength of maximum transmission for the given water. This effect is eliminated if the K measurement is monochromatic. Figure 2 illustrates the concept of measuring K.

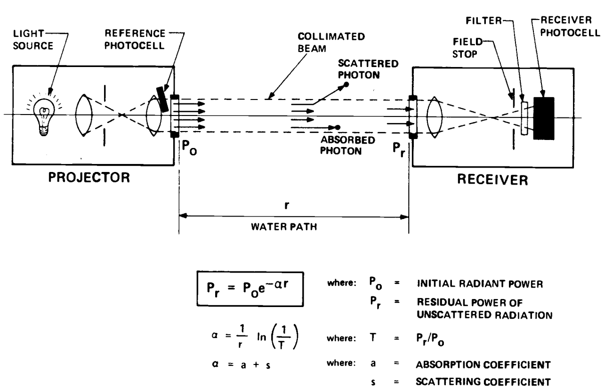

Fig. 1. Concept of Beam Attenuation Coefficient (α) Measurement

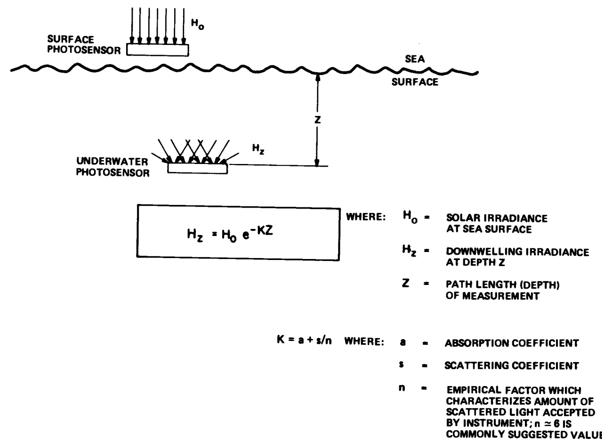

Fig. 2. Concept of Diffuse Attenuation Coefficient (K) Measurement

In terms of a and s, the magnitude of K is commonly described in the form of a useful first order approximation:

$$K = a + s/n \tag{6}$$

where n = a factor derived empirically which characterizes the amount of scattered light accepted by the instrument.

The quantities, a, s, and K have rarely been measured simultaneously; however, through inspection of a variety of measured data from different sources, SRI (Stanford Research Institute) empirically determined(2) that $n \simeq 6$*, such that:

$$K \simeq a + s/6 \tag{7}$$

In addition to being dependent on the absorption and scattering properties of water, the magnitude of K is a function of both the physical and geometrical considerations of its measurement. Therefore, K is considered an apparent rather than an inherent optical property of water. By definition, K characterizes the rate of decay of diffuse light. However, solar irradiance incident on the sea surface is not necessarily diffuse, particularly if the sky is sunny rather than overcast. For any given water there can exist an entire hierarchy of K values which vary in magnitude depending on the ambient light field and the geometry of measurement. For instance, even in perfectly homogeneous waters, K may vary with depth depending on changes in the angular radiance distribution with depth.(3) Only in the case where the source light field is perfectly diffuse (i.e., at the condition where the downwelling sunlight has reached a steady state asymptotic radiance distribution) would a monochromatic relative irradiance measurement yield a constant K value with depth in homogeneous waters.

*Some investigators have suggested values for n other than 6.

In addition to these subleties of measurement K, like α, is found to vary with depth if the water is optically inhomogeneous. Thus, in order to facilitate comparison of the water's K at different geographic locations, it is desirable to assign to the variable K at a given station a single "effective" (depth averaged) value, designated $\bar{K}$. This effective value is determined by numerical integration of the relative irradiance values over the depth of interest; in practice, it is determined by the slope of the straight line drawn between the two depth values of interest on the semilogarithmic relative irradiance versus depth profile.

Difference Between α and K

Although both α and K are functions of the absorption and scattering properties of water, they are distinctly different attenuation coefficients. Their difference lies in the following two areas related to their measurement:

1. The nature and distribution of the source light field (i.e., whether a narrow, collimated beam or a broad, diffuse field).

2. The acceptance characteristic of the receiver in terms of the ability to accept scattered light (i.e., whether a very small or a very large FOV).

In the measurement of α, the source flux is a narrow, highly collimated, well defined beam of artificial light. The receiver's narrow FOV (e.g., $< 1°$) accepts, ideally, only those photons from the beam which have neither been absorbed nor scattered within the intervening path. Hence, in terms of attenuation, α represents the total loss term which includes all the absorbed and all the scattered photons; i.e., $\alpha = a + s$.

However, in the measurement of K, the source flux incident on the sea surface is either an extended, uniform, collimated field of direct sunlight, or an extended, uniform, diffuse field of light from an overcast sky; in the former case the downwelling light field becomes relatively diffuse after several attenuation lengths underwater. In contrast to a beam transmissometer's narrow FOV, the K-meter's 180° FOV is very capable of accepting scattered light. As the diffuse field propagates down through the water, both the photons which are absorbed and the photons which are scattered into the back hemisphere are permanently lost to detection. However, the essentially infinitely broad extent of the downwelling flux sharply reduces the loss of photons due to forward scattering; it can be assumed that for the majority of photons scattered "out" of the detector's FOV there are photons from the adjacent region which are scattered back "in." Thus, in terms of attenuation, K represents the loss term which includes all the absorbed photons and a fraction of the scattered photons; hence, $K = a + s/n$.

Instrument ability to accept multiscattered light is not only dependent on receiver FOV but also on the path length of measurement. Practical measurement lengths for α are generally in the order of one meter (the ideal has been shown to be one beam attenuation length; i.e., $1/\alpha$ meters),[4] whereas those for K are usually much longer. Furthermore, instrument sensitivity to changes in the optical properties within the measurement path is a function of path length. An α-meter samples a fixed, relatively short water path and, hence, is highly sensitive to changes in the optical properties. However, a K-meter samples the entire water column between surface and underwater sensor. At any given depth the K-meter's underwater sensor measures the cumulative or integrated effect of fluctuations in the downwelling light field within the water column above it. Hence, K measurements are much less sensitive to optical nonhomogeneity within the water column than α measurements.

Comparing equations (2) and (6), it is obvious that the magnitude of K is always less than the magnitude of α. This difference in magnitude increases for increasing values of α in a manner which is dependent on the relative proportions of a and s within a given sample of natural water. It should be noted that the absorption coefficient, a, and the beam attenuation coefficient, α, represent practical limits in optical attenuation. Any practical K measurement would yield an attenuation value somewhere between these limits. Since $1/n$ of equation (6) is a relatively small fraction, it is evident that the magnitude of K lies much closer to the absorption coefficient, than to α.

In summary, α represents the magnitude of the exponential decay of unscattered (image forming) light, while K represents the magnitude of the exponential decay of diffuse light. Their difference is primarily due to the nature of the source beam pattern being measured and to the acceptance characteristic of the instrument's receiver.

Instrument Description

Beam Transmissometer

The beam transmissometer used for this reaseach is a sophisticated yet compact, reliable, easy-to-operate instrument system which has numerous salient features. These include the ability to profile temperature concurrently with transmittance (or alpha), to remotely monitor internal calibration, and to remotely control a filter selector. It also incorporates a real-time digital display of temperature, depth and transmittance (or alpha). Data can be recorded simultaneously on an XY_1Y_2 plotter and a digital printer. The instrument also has a one-of-a-kind ship/helicopter deployment capability. It was developed and custom-built for the NAVAIRDEVCEN by the SIO-VISLAB (Scripps Institution of Oceanography Visibility Laboratory) based on a previous design reported in detail by Petzold and Austin[5] of the SIO-VISLAB.

As shown in figure 3, the components of the NAVAIRDEVCEN's transmissometer system include an underwater sensor unit, a deck control/display unit, a Hewlett-Packard Model 136A XY_1Y_2 recorder, and a Systron Donner Model 5103 digital printer. Not shown is a 500 foot multiple conductor sea cable which connects the underwater sensor unit with the deck control unit. A detailed description of this transmissometer has been reported elsewhere(6) by this author. A sample, annotated data profile obtained with the instrument is shown in figure 4.

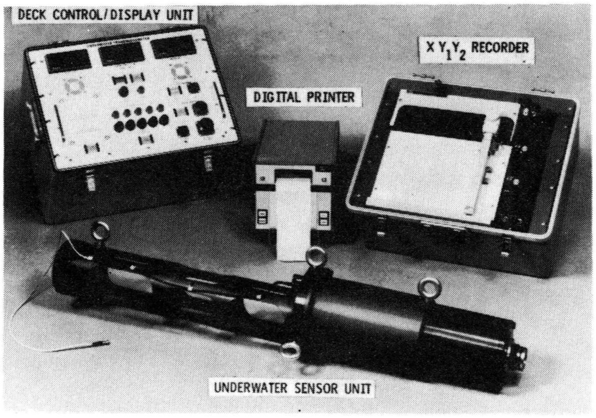

Fig. 3. Components of NAVAIRDEVCEN Beam Transmissometer

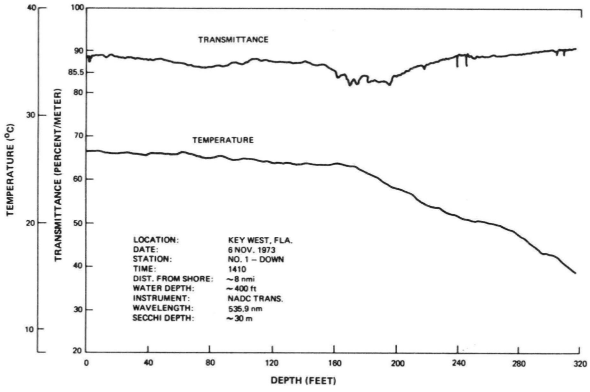

Fig. 4. Sample Data Profile Obtained With NAVAIRDEVCEN Beam Transmissometer

Relative Irradiance Meter

Since 1973, the NAVAIRDEVCEN has utilized a relative irradiance meter borrowed from the SIO-VISLAB. With the exception of some improvements and changes, it is an instrument similar to that reported by Austin and Loudermilk(3) in 1968. Instrument components include a deck sensor unit, an underwater sensor unit, a deck control unit, and a Hewlett-Packard Model 136 X-Y recorder, as shown in figure 5. Not shown is a multiple conductor sea cable which connects the underwater sensor unit with the deck control unit. A sample, annotated data profile obtained with the K-meter is shown in figure 6.

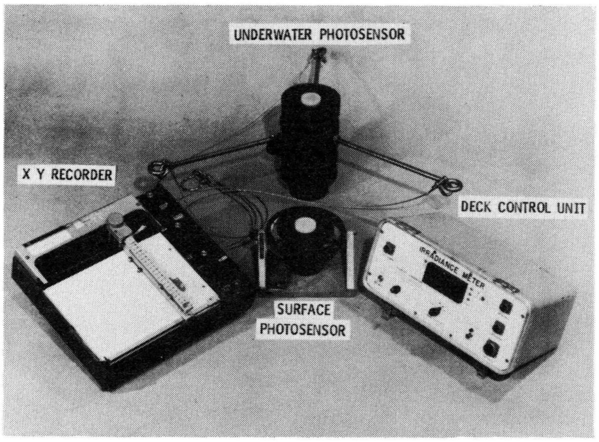

Fig. 5. Components of SIO-VISLAB Relative Irradiance Meter

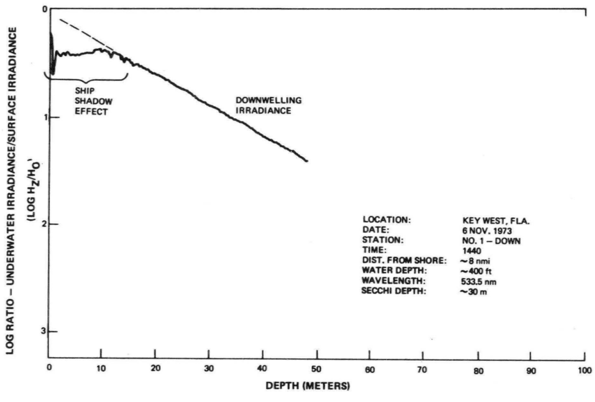

Fig. 6. Sample Data Profile Obtained With SIO-VISLAB Relative Irradiance Meter

The deck sensor unit consists of a flat-plate Lambertian collector and a photo-voltaic cell. The unit is gimbal stabilized to keep the collector horizontal while on a heaving ship.

The underwater sensor unit consists of a flat-plate Lambertian collector, a stack of five Wratten No. 74 filters, a photomultiplier tube detector, and a pressure transducer for accurate depth sensing. The stacked Wratten filters provide a relatively narrow (15.2 nm half-power) bandwidth with a peak transmission at 533.5 nm. A weight is suspended from the unit to provide horizontal stability under conditions of lateral drift due to shear currents.

Data Acquisition and Reduction

The α and K measurements were made at numerous stations in various U.S. East Coast, Bahama and Puerto Rico Trench waters. Figure 7 is a map indicating the measurement locations. Measurements were made from surface ships in a free-drift mode.

In order to reduce data bias due to spatial movement and temporal fluctuations in optical properties during the period of measurement, α and K were measured nearly simultaneously (generally, within 1/2 hour or less of each other). Measurements were made at almost identical peak transmission wavelengths of λ = 535.9 and 533.5 nm respectively, thus eliminating any potential data bias due to wavelength mismatch.

Data were obtained in both homogeneous and nonhomogeneous waters. Effective (depth averaged) values of α and K, designated $\overline{\alpha}$ and $\overline{K}$, respectively, as defined previously, were calculated for each data profile to a common depth in order to facilitate comparison. Ideally, it is valid to correlate at any given depth the numerical values of $\overline{\alpha}$ and $\overline{K}$ for a thin (e.g., 1 meter) stratum of water. However, because of difficulties in determining accurate values of $\overline{\alpha}$ and $\overline{K}$ for thin stratums in nonhomogeneous waters, relatively large depth increments were used for calculating effective values of α and K; generally this depth increment was equal to the maximum measurement depth of one of the instruments.

Results

Figure 8 presents a plot of $\overline{K}$ versus $\overline{\alpha}$ obtained at the various test locations. Although extensive data were obtained at each location, only data which met certain criteria of simultaneity in measurement are presented. Each point represents a simultaneous measurement of α and K at a given station.

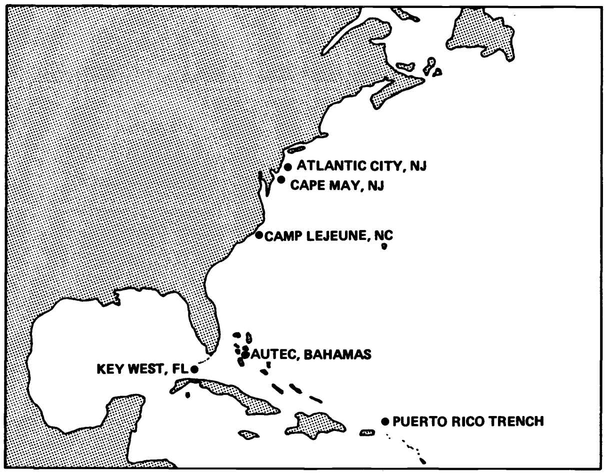

Fig. 7. Field Measurement Locations

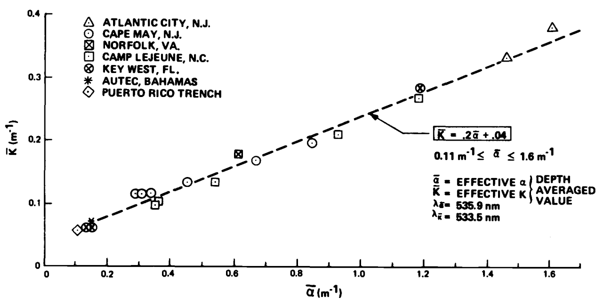

Fig. 8. NAVAIRDEVCEN $\overline{\alpha}$ versus $\overline{K}$ Data Measured in Selected Ocean Waters

Referring to figure 8, a least squares fit to a straight line as a first order approximation to the data yields the equation:

$$\overline{K} \simeq 0.2\,\overline{\alpha} + 0.04 \qquad (8)$$

This equation, which has a correlation factor of r = .98 associated with it, is applicable for the data range $0.11\ m^{-1} \leq \overline{\alpha} \leq 1.6\ m^{-1}$. For convenience, the equation's coefficients have been rounded off to two decimal places.

Discussion

General Validity of Empirical Expression

Inspection of equation (8) indicates that over the given range of $\overline{\alpha}$, the ratio $\overline{\alpha}/\overline{K}$ increases with increasing values of $\overline{\alpha}$, varying from approximately 1.8 to 4.4. This observation is in general agreement with that reported by Duntley(7), who indicated that this ratio ranges from 2 to 4 at the wavelength of minimum attenuation.

In spite of the fact that the data plotted in figure 8 were obtained from waters exhibiting diverse optical properties over a wide range of turbidity, the data exhibits surprisingly little scatter. The correlation factor r = .98 associated with equation (8) indicates a high degree of correlation between the two independent variables. The consistency of data from a variety of geographic locations suggests that equation (8) might, in general, be applicable for ocean waters within the given range of $\overline{\alpha}$, regardless of the geographic location. It should be noted, however, that such a generalization must be treated with caution, since, depending on local conditions, natural waters may exhibit extensive variability in optical properties.

Inspection of equation (8) also indicates that for any ocean water with a given $\bar{\alpha}$, the ratio $\bar{\alpha}/(K - 0.04)$ is constant, regardless of the geographic location. Considering equations (2) and (6), this implies that the optical properties a and s, which are constituents of α and K, appear to exist in fixed proportions to each other for any given α. Experimental data reported by Austin[8] supports this suggestion. For example, inspection of his α versus s data from a variety of natural waters indicates that the ratio s/α increases with increasing α in a relatively smooth and regular manner, independent of location. Austin's data indicates that the relative proportions of a and s change from absorption domination to scattering domination as one goes from clear to turbid waters. Again, it must be reiterated that it is somewhat speculative to ascribe universal validity to data from a relatively limited number of geographic regions.

Wavelength Dependence of Expression

Although equation (8) was generated from simultaneously measured data at a common wavelength of $\lambda \simeq 535$ nm, its utility could be maximized if it were spectrally independent within the blue-green region of the spectrum. Preliminary inspection of recently measured $\bar{\alpha}$ and $\bar{K}$ spectral data* within the region $430 \text{ nm} \leq \lambda \leq 610$ nm indicates, however, that equation (8) is, at least, imprecise (up to 30% variation observed between experimental data and calculated values using equation (8)) for correlating $\bar{\alpha}$ and $\bar{K}$ at any common wavelength within this region. Further investigation is being undertaken to determine the relationship between $\bar{\alpha}$ and $\bar{K}$ within the entire blue-green spectrum.

Validity of Expression for Very Turbid and Very Clear Waters

It is interesting to speculate on the validity of equation (8) for regions of $\bar{\alpha}$ outside of the range $0.11 \text{ m}^{-1} \leq \bar{\alpha} \leq 1.6 \text{ m}^{-1}$. Inspection of α and K data obtained by Petzold[9] in turbid San Diego harbor waters indicates that equation (8) might be applicable up to and/or beyond the $\alpha = 3.0 \text{ m}^{-1}$ region. For example, one set of Petzold's data consist of nearly simultaneously measured values of $\bar{\alpha} = 2.8 \text{ m}^{-1}$ (with $\lambda = 536$ nm) and $\bar{K} = 0.54 \text{ m}^{-1}$ (with $\lambda = 526$ nm). Using equation (8), a calculated value of $\bar{K} = 0.60 \text{ m}^{-1}$ is within 11% of the experimental value of $\bar{K} = 0.54 \text{ m}^{-1}$. Assuming, for the sake of discussion, that equation (8) is applicable for values of $\alpha > 1.6 \text{ m}^{-1}$, then the ratio $\bar{\alpha}/\bar{K}$ would reach an asymptotic limit of 5 for increasing values of $\bar{\alpha}$. More investigation of turbid water data should be made to determine how well equation (8) fits regions of high turbidity.

On the other extreme, inspection of simultaneously measured data from clear ocean waters indicates that equation (8) would not be applicable for the region $\alpha < 0.11 \text{ m}^{-1}$. For example, inspection of data obtained by Mertens[10] in "below-thermocline" waters near the Bahamas (where $\bar{\alpha} \simeq 0.049 \text{ m}^{-1}$ at $\lambda = 488$ nm and $\bar{K} \simeq .034 \text{ m}^{-1}$ at $\lambda = 478$ nm) indicates that the $\bar{\alpha}/\bar{K}$ ratio is significantly different for experimental values than for that predicted by equation (8). It is interesting to note that a curved extension of the data line from the point $\bar{\alpha} \simeq 0.11 \text{ m}^{-1}$, $K \simeq 0.06 \text{ m}^{-1}$ towards the point $\bar{\alpha} = \bar{K} = 0$ appears to provide a good fit to Merten's clear ocean water data. In any event, more investigation is required to establish an accurate empirical correlation between $\bar{\alpha}$ and $\bar{K}$ in clear ocean waters.

Comparison of Expression with Data Obtained by Others

Equation (8) has been compared to independent, simultaneously measured α and K data obtained in western Pacific waters by R. Wargelin[11] of NAVOCEANO, Suitland, Maryland, under the Strategic Straits program. NAVAIRDEVCEN has periodically received and reduced this NAVOCEANO optical data as it became available. Criteria in data reduction has been identical to that applied to the NAVAIRDEVCEN data. Except for differences in spectral response and bandwidth, the NAVOCEANO data were measured with equipment and under conditions similar to the NAVAIRDEVCEN data. The NAVOCEANO α-meter's peak spectral response was 527 nm whereas the K-meter's response was photopic with a peak transmission at around 555 nm. Because of the mismatch in the wavelength of peak response, it is difficult to relate NAVOCEANO's α data with their K data. The broad bandwidth of a photopic measurement is influenced by the spectral characteristics of the water, causing a shift in the effective wavelength of measurement from 555 nmi toward the wavelength of maximum transmission for the given water. Since most of the NAVOCEANO data were taken in relatively clear ocean waters, it can be assumed that the effective spectral response of the K measurements shifted toward the 527 nm peak transmission wavelength of the α measurement. Hence, because of these circumstances, there is some validity in comparing the two NAVOCEANO measurements. A least squares fit to the NAVOCEANO data has yielded an expression almost identical to equation (8). This agreement extends credibility to the NAVAIRDEVCEN empirical expression.

A comparison between the NAVAIRDEVCEN $\bar{\alpha}$ versus $\bar{K}$ data and similar data** reported by Prettyman[12] (originally reported by Duntley,[1] and Tyler and Preisendorfer[14]) indicates reasonably good agreement within comparable data regions. Furthermore, inspection of a set of data points** ($\alpha = 0.722 \text{ m}^{-1}$, $K = 0.172 \text{ m}^{-1}$) obtained by Duntley[13] in lake water indicates that for this particular case values predicted by equation (8) are within 7% of experimental values. These samplings of data obtained by other investigators in various natural waters indicate general consistency with the NAVAIRDEVCEN findings.

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* Unpublished data obtained by author near Santa Catalina Island, California, in June 1975.
**Wavelength of measurement unknown

An investigation has recently been undertaken by Austin[15] to compare K values calculated from equation (8) with values calculated from various other empirical and theoretical expressions. These include equations developed by SRI[2] (equation (7)), Preisendorfer,[16] and Timofeeva.[17] Preliminary analysis indicates some variations in the magnitudes of K calculated from each expression. Further investigation should be conducted in order to explain and/or reconcile any differences between these expressions.

Summary and Conclusion

An investigation was performed to determine if an empirical relationship exists between the beam attenuation coefficient, α, and the diffuse attenuation coefficient, K, of ocean waters. The expression: $\bar{K} = 0.2\,\bar{\alpha} + 0.04$, applicable for the range $0.11\ m^{-1} \le \bar{\alpha} \le 1.6\ m^{-1}$, was determined for experimental data measured at a common wavelength of $\lambda \approx 535$ nm and combined from various geographic locations. The high correlation factor associated with the expression suggests that it might be applicable, in general, to all ocean waters within the $\bar{\alpha}$ restriction. Preliminary investigation of recently obtained spectral data indicates that the expression is not readily applicable to the entire blue-green region of the spectrum. Comparison of the expression with experimental data reported by others indicates generally good agreement within the applicable $\bar{\alpha}$ region. Furthermore, inspection of data outside the applicable $\bar{\alpha}$ region suggests that the expression might be reasonably valid for $\bar{\alpha} > 1.6\ m^{-1}$, but not for $\bar{\alpha} < 0.11\ m^{-1}$. It should be pointed out that the NAVAIRDEVCEN $\bar{\alpha}$ versus $\bar{K}$ expression is empirically derived, that it's coefficients are rounded off to two significant figures, and that it represents a linear approximation to data obtained in relatively few geographic locations. Thus, the use of the expression must be treated with some caution; it may be useful for first order engineering approximations, but not for more precise requirements. Further investigation is recommended to verify and/or refine the expression and to determine the correlation between α and $\bar{K}$ outside of the applicable wavelength and α restriction. Further discussion related to this correlation effort will be presented elsewhere.[18]

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