SPECTRAL SCATTERING PROPERTIES OF TURBID WATERS

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Abstract

River water samples have been examined for optical scattering properties at wavelengths between 400 and 800 nm. Scattering coefficients were calculated from measurements of beam attenuation and absorption coefficients and are observed to vary with wavelength. At a fixed wavelength, the scattering coefficient is influenced by both phytoplankton concentration (as indicated by chlorophyll *a*) and suspended solids concentration. Measurements of small angle volume-scattering function indicate that the phase function at an angle of 1.5° is not constant for turbid waters and varies with both wavelength and beam attenuation coefficient. These data differ from previously published results for relatively clear oceanic and coastal waters. Caution is required when attempting to estimate scattering coefficient values from single-angle measurements of volume-scattering function.

Introduction

The oceanographic community has attempted to characterize water-quality parameters by optical methods for many years. For example, an optical method to determine suspended solids concentra-

tion would be valuable for geological and geochemical studies. Jerlov, 1968, indicated a relationship between the optical scattering coefficient, *s*, and the effective particle area per unit volume of ocean water. The particle area is related to particulate concentration for chemically similar waters having a "quasi-stationary" distribution of particle sizes. Unfortunately, a reliable method for direct measurement of *s* has never been found. Considerable research has been conducted to relate *s* to measured values of the volume-scattering function $\beta(\theta)$, at one or more angles, θ . Morel, 1973, used Mie theory for spherical particles and assumed different refractive indices and particle size distributions. That study indicated that the ratio of $\beta(\theta)$ to *s* is nearly constant for θ values between 4° and 6° . This suggests that measurements of $\beta(5^\circ)$ can be used to calculate *s* after appropriate calibration for the particular water body under investigation. Smith et al., 1974, presented measured $\beta(\theta)$ values from (1) the Tongue of the Ocean, (2) the California Coast, and (3) San Diego Harbor, where values of beam attenuation coefficient, α , ranged from 0.15m^{-1} to 2.2m^{-1} at a wavelength, λ , of 520 nm. In their data, the ratio of $\beta(\theta)$ to *s* for $4^\circ < \theta < 6^\circ$ was not constant. Instead, the phase function ($P(\theta) = 4\pi[\beta(\theta)/s]$) was constant

TABLE 1. Chemistry of water samples

Property	Sample			
	A	J	T1	T2
Chlorophyll <i>a</i> - $\mu\text{g}/\ell$	57.0	52.0	78.0	57.0
Organic Suspended Solids - mg/ℓ	7.3	9.6	10.6	12.4
Inorganic Suspended Solids - mg/ℓ	12.0	12.7	37.4	41.6
Total Suspended Solids - mg/ℓ	19.3	22.3	48.0	54.0
Particle Size Range - μ	1.6-32.0	1.6-32.0	1.6-32.0	1.6-40.0
Most Frequent Particle Size - μ	1.6-2.0	1.6-2.0	1.6-2.0	1.6-2.0
Greatest Volume Particle Size - μ	10.0-13.0	10.0-16.0	10.0-13.0	10.0-13.0
Dissolved Organic Carbon - mg/ℓ	9.0	12.0	9.0	8.0
Tannin and Lignin - mg/ℓ	0.37	0.37	0.30	0.38
Turbidity - FTU	5.0	11.0	22.0	19.0
Color - Pt Cl Units	40.0	40.0	50.0	40.0
pH	7.7	7.2	7.8	7.5
Conductivity - $\mu\text{mhos}/\text{cm}$	285.0	310.0	280.0	280.0
Chloride - mg/ℓ	28.0	35.0	26.0	26.0
Sulfate - mg/ℓ	42.0	44.0	42.0	45.0
Acidity - mg/ℓ	<2.0	<2.0	<2.0	<2.0
Nitrate - Nitrogen - mg/ℓ	0.68	0.69	0.73	0.70
Iron - mg/ℓ	0.39	0.46	0.88	1.2
Chrome - mg/ℓ	<0.05	<0.05	<0.05	<0.05
Date	11/10/78	11/12/78	11/9/78	11/12/78
Time of High Tide - e.s.t.	11:32 a.m.	1:32 p.m.	10:32 a.m.	1:32 p.m.
Time of Water Sample - e.s.t.	1:00 p.m.	1:20 p.m.	3:00 p.m.	3:00 p.m.

TABLE 2. Ratios of selected properties

Sample	ch a /TSS	OSS/TSS	Iron/ISS
A	2.95	0.38	0.033
J	2.33	0.43	0.036
T1	1.63	0.22	0.024
T2	1.05	0.23	0.029

for $1^\circ \leq \theta \leq 2.5^\circ$ for all three water types which suggested that the ratio $\beta(\theta)/s$ may be constant for $1^\circ \leq \theta \leq 2.5^\circ$.

This article examines optical scattering properties of turbid river water in which α values ranged from 11.7m^{-1} to 36.6m^{-1} . Spectral variations of s and $\beta(\theta)$ are examined for four water samples taken from the James and Appomattox Rivers near Hopewell, Virginia, during the period November 9 through 12, 1978. Of particular interest in this investigation is the ratio $\beta(\theta)/s$ at small values of θ .

Experimental Methods

Forty gallon (155 liter) samples were taken 20 cm below the water surface from selected sites in the James and Appomattox Rivers. Optical measurements were made at dockside within 1 hour of sample collection, and chemical analyses were completed within 24 hours of sample collection.

Optical measurements of α and $\beta(\theta)$ at small angles ($\theta = 0.37^\circ, 0.75^\circ, \text{ and } 1.5^\circ$) were made every 50 nm for $400\text{ nm} \leq \lambda \leq 800\text{ nm}$ with a spectral resolution of 10 nm. The Langley-developed Small Angle Scattering Meter (SASM) was used for these α and $\beta(\theta)$ measurements. The SASM operates on the same optical principle as the Scripps Institute of Oceanography ALSCAT instrument (see Austin and Petzold, 1975). To achieve high-turbidity capability, SASM measurements are made using various lengths of sample cells rather than in situ as ALSCAT. Repetitive measurements indicate that the standard deviation of the SASM measurements was better than ± 5 percent for α and ± 12 percent for $\beta(\theta)$.

Measurements of mixture absorption coefficient, a , at wavelengths and spectral resolution identical to those of SASM were made with the Langley SPectral Absorption Coefficient Instrument (SPACI). This instrument uses the measurement approach of Gilbert et al., 1969, and is described in more detail by Cherdak and Friedman, 1978. A series of unpublished laboratory experiments conducted with SPACI and SASM indicates that SPACI may be used to measure spectral variation of the absorption coefficient for turbid waters having $0.1\text{m}^{-1} \leq a \leq 15\text{m}^{-1}$. Repetitive tests and analytical analyses indicate a standard deviation of $\pm 0.1\text{m}^{-1}$ for $0.1\text{m}^{-1} \leq a \leq 1\text{m}^{-1}$ and ± 10 percent for $1\text{m}^{-1} \leq a \leq 15\text{m}^{-1}$ in the SPACI measurements.

Fig. 3. Scattering coefficient.

Results and Discussion

Chemical Properties

Four water samples (A, J, T1, and T2) were taken from three sites located near the confluence of the Appomattox River, the James River, and the Turkey Island Cutoff north of Hopewell, Virginia. (Samples T1 and T2 were taken at the same location but different points in the tidal cycle.) Chemical properties of the four water samples (as well as tidal conditions) are shown in table 1. These waters were characterized by significant differences in chlorophyll *a*, suspended solids, iron content, and turbidity. Only moderate differences were observed for particle size and other chemical properties. Relative comparisons of chlorophyll *a* (ch *a*), Total Suspended Solids (TSS), Organic Suspended Solids (OSS), Inorganic Suspended Solids (ISS), and iron are shown in table 2. These values indicate a wide range of particulate mixtures which in turn suggest the possibility of differences in the effective index of refraction. Unfortunately, mineralogy and refractive index measurements were not made on these samples.

Smith et al., 1974, discussed the importance

TABLE 3. Correlation of selected parameters

Sample	s_{550} m^{-1}	TSS mg/l	ch <i>a</i> $\mu g/l$	TSS/ s_{550} mg/l-m	ch <i>a</i> / s_{550} $\mu g/l-m$
A	11.2	19.3	57	1.72	5.09
J	13.9	22.3	52	1.60	3.74
T1	27.2	48.0	78	1.76	2.87
T2	18.6	54.0	57	2.90	3.06

Fig. 4. Spectral variation of $\beta(1.5^0)/s$.

of particle size distribution to the optical scattering process. Actual size distributions for the above water samples are shown in figure 1. Both particle volume and number, as obtained from Coulter analysis, are presented. Particle size distributions were similar for each of these water samples. It is assumed, therefore, that the optical properties of these waters may be compared as if they had "quasi-stationary" particle size distributions.

Optical Properties

Measured values of α and a are shown in figure 2 as a function of λ . The relative magnitudes of α and a vary for each sample

Fig. 5. Variation of $\beta(1.5^0)/s$ with α .

and some differences in spectral variation are evident as well.

Spectral variations of s , obtained by subtracting a from α , are presented in figure 3. Except for sample T2, s decreases as λ increases. As discussed previously, it may be postulated that s is proportional to particulate concentration under certain conditions. For the samples in this study, s was not directly proportional to either TSS or $ch\ a$ (an indicator of cellular material) as shown in table 3. However, a two-parameter (TSS and $ch\ a$) linear regression equation can be assumed for the constituent ranges of these water samples ($19.3\text{ mg/l} \leq \text{TSS} \leq 54\text{ mg/l}$ and $52\text{ }\mu\text{g/l} \leq ch\ a \leq 78\text{ }\mu\text{g/l}$). A least-squares fit to the data of this study yields the following result

$$s_{550} = 11.2 + 0.172 (\text{TSS} - 19.3\text{ mg/l})$$

$$+ 0.405 (ch\ a - 52\text{ }\mu\text{g/l})$$

$$\text{Correlation coefficient} = 0.97$$

$$\text{Standard error of } s_{550} = \pm 1.5\text{m}^{-1}$$

Although the above equation cannot be attributed much accuracy because of the low number (4) of water samples in this particular study, the equation does confirm the expectation that s is a function of the combined particulate mixture of $ch\ a$ and suspended solids. It further suggests that most of the differences in scattering between these particular water samples were caused by variations in $ch\ a$, rather than by TSS changes.

As previously discussed, Smith et al., 1974, hypothesized that the phase function, $P(\theta) = 4\pi[\beta(\theta)/s]$, is a constant for $1.0^\circ \leq \theta \leq 2.5^\circ$ for oceanic and coastal waters with "quasi-stationary" distributions of particle size and effective indices of refraction. This implies that the parameter $\beta(\theta)/s$ for $\theta = 1.5^\circ$ ($\beta(1.5^\circ)/s$) should remain constant and independent of either λ or α for different waters. Spectral variations of $\beta(1.5^\circ)/s$ for the turbid water samples of this study are presented in figure 4. A dependence on λ is evident which indicates that the phase function, $4\pi(\beta(\theta)/s)$, is not a constant in spite of the fact that particle size distributions were "quasi-stationary" as shown in figure 1. (Comparisons of

$\beta(\theta)/s$ for $\theta = 0.37^\circ$ and 0.75° show trends similar to those in figure 4.)

Values of $\beta(1.5^\circ)/s$ against α are presented in figure 5. Also shown are data for clearer oceanic and coastal waters from Smith et al., 1974. The data appear to fall along two lines (see dashed lines), depending on whether the waters are from the Appomattox or James Rivers. (Waters at both sites J and T flow from the James River below Richmond, Virginia.) It is not known why the lines vary in slope (which indicates a change in shape of the scattering phase function) but differences in mineralogy, particle index of refraction, and/or particle shape are among the potential causes. It is clear that caution is required when attempting to estimate the scattering coefficient from single-angle measurements of the volume scattering function for complex turbid water mixtures.

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