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Impact on the Computation of the Medium MTF by Estimation of the Total Scattering Coefficient

L. Estep

Naval Research Laboratory, Ocean Sciences Directorate, Mapping, Charting, and Geodesy Division, Stennis Space Center, MS 39529

Using both sea water data and research tank water data, coupled with the theoretical approach of Wells, calculations of the modulation transfer function (MTF) for the water medium are performed via use of the Wells Decay Function. Various approximate relationships are used to derive the value of b , the total scattering coefficient, which enters into the MTF calculation. The approximated b values are used to compute the water MTF. These estimated MTF calculations are compared with experimental data MTF calculations for which the actual water value of b was derived. Error assessments and recommendations for the various b relationships used in the MTF computation are made.

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Introduction

The effect of suspended particles in a water medium on the transport of light is normally dichotomized into two processes—namely, the dual effects of absorption and scattering. Absorption acts simply to remove photons that might have contributed to image formation. These

absorption attrition effects might be overcome for a given system by increasing the source flux or by using a more sensitive receiver. Scattering, however, in contradistinction, is more pernicious through two allied processes. Scattering can produce a foreground veiling glare that reduces the effective contrast of the target with respect to the background, and, by causing a redistribution of the trajectories of image-forming photons, scattering scrambles the information content originally presented by the target and background.

The modulation transfer function (MTF) is used to characterize the effects the medium has on the passage of image-forming light. It is not surprising that values of optical parameters that describe the scattering effects of the water medium are significant variables in the MTF expression. Wells^{1,2} has derived a transformation that converts the medium volume scattering function (VSF), $\beta(\theta)$ [$\beta(\theta)$ represents the fraction of radiant power in a beam that is scattered by angle θ per steradian per unit length along the beam], into a medium MTF expression via the use of a 'decay' function. The MTF expression so derived requires the value of the total (volume) scattering coefficient, b . The value of b is related to the VSF by the functionality

$$b = 2\pi \int_0^\pi \beta(\theta) \sin \theta d\theta, \quad (1)$$

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stated here in spherical coordinates and assuming azimuthal symmetry. Figure 1 provides a diagram showing the scattering process and identifying the scattering angle Θ . Azimuthal symmetry of the scattering process is assumed for scattering in water media.

Normally, b is not measured directly, because of either the lack of necessary instrumentation or simply the time-consuming nature of measuring $\beta(\Theta)$ for as many angles as practical while holding station at sea. Rather, the value of b is computed by using other more easily measured optical coefficients. Preisendorfer,³ Honey,⁴ Wilson,⁵ Timofeyeva,⁶ and Morel⁷ provide certain specific relationships that can be used to determine b for a given water mass. These various relationships are based on sundry data set interpolations or fitting procedures. The data sets and the conditions of their collection and subsequent processing provide the differences seen in the various expressions for estimating b . It would be useful to assess the value of these various expressions for the problems associated with imaging through ocean water.

The objective of this paper is to utilize Wells' results to compute the medium decay function, $D(\Gamma)$, for a homogeneous water mass (from which is easily determined the germane MTF for a stated range, R), using both the value of b computed with the above-mentioned relationships and experimentally derived values of b . The resulting decay function expressions will be compared to provide a measure of the errors introduced by using the various estimation methods. Finally, comments will be made on which model appears to provide the most accurate estimation of b for different water mass types.

Background and Methods

The medium MTF is the sine wave frequency amplitude response of the water path. Wells' transformation^{1,2} of the VSF into a medium MTF assumes the small angle approximation and assumes that the suspended particles are larger than the optical wavelength.

Wells' expression for the medium MTF can be written in the form²

$$T(\Gamma, R) = \exp[-D(\Gamma)R], \quad (2)$$

where R is the range of interest and $D(\Gamma)$ is the 'decay' function, with Γ the spatial frequency in cycles/radian. The decay function for non-absorbing waters may be written as²

$$D(\Gamma) = b - Q(\Gamma), \quad (3)$$

where $Q(\Gamma)$ is the frequency space expression of $\beta(\Theta)$, or as the Hankel transform of the VSF. $Q(\Gamma)$ provides for a

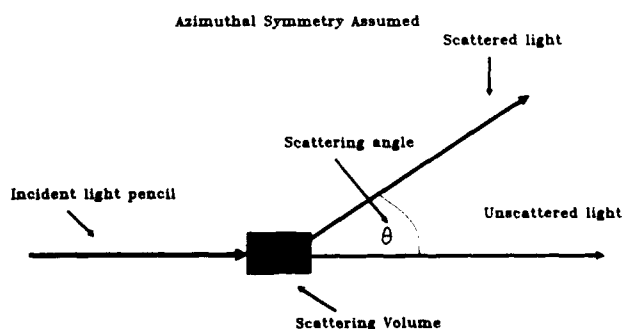


Figure 1. Scattering of an incident light beam by an elementary volume element.

recovery of power at lower spatial frequencies, where the scattering is too small to create blur for target constituents whose relative dimensions are large.¹ Here it is assumed that the scattering function is highly peaked in the forward direction. Thus, the small angle approximation may be used. In the oceans, this is a very robust assumption. The particles present are generally much larger than the wavelength of light incident upon them, and their refractive index approaches that of the water itself. Hence, the refraction that occurs is small, and, generally, diffraction dominates the scattering process.

It is important to notice that the decay function is independent of the range, R . For collimated light, $Q(\Gamma)$ is expressed by¹

$$Q(\Gamma) = 2\pi \int_0^\pi \beta(\theta) J_0(\alpha) \theta d\theta, \quad (4)$$

where $\beta(\Theta)$ is the VSF and $J_0(\alpha)$ is a zeroth order Bessel function with $\alpha = 2\pi\Gamma\Theta$.

It can be shown,¹ for nonabsorbing waters, that $Q(\Gamma)$ monotonically decreases as spatial frequency increases (i.e., as the potential for image detail increases), and, in the limit of high spatial frequency, $Q(\Gamma)$ approaches zero. In this region, $D(\Gamma)$ approaches b . Hence, the diminution of fineness of resolution of the image-forming light over a range, R , is due to an exponential-type decay of the relevant spatial frequencies, which is controlled by the value of b . If absorption effects are included, then the effects of absorption must also be taken into account, so that $D(\Gamma)$ may be written in the form

$$D(\Gamma) = a + b - Q(\Gamma), \quad (5)$$

where a is the absorption coefficient.

Table I provides the relationships used to estimate b knowing other optical parameter values for the water mass in question. In Table I, c represents the beam attenuation coefficient, k the diffuse attenuation coefficient, and Chl the concentration of chlorophyll- a .

The scattering data used in the computations were collected in a large research tank facility during laser backscatter experiments conducted at the Naval Research Laboratory⁸ (NRL). The tank water was cleaned by continuous pumping, filtering, and sedimentation. Then, beginning from the initial clear-water state, the water was made increasingly more turbid in a controlled sequence.⁸ The water was closed-circulated through the tank to keep the turbidity agent entrained. This system insured that the water in the tank could be assumed homogeneous. Ancillary supporting optical measurements were made. These measurements included the beam attenuation coefficient, c (which is the sum of the absorption coefficient, a , and the total scattering coefficient, b), the diffuse attenuation coefficient, k , and the

TABLE I. Relationships Used to Compute b^*

Name	Relationship	Parameters
Honey	$b = 6/5 \times (c - k)$	c, k
Wilson	$b = 1.18 \times (c - k)$	c, k
Preisendorfer	$b = c - 3/4 \times k$	c, k
Timofeyeva	$k/c = [0.19 \times (1 - w)]^{0.2}$	$c, k (w = b/c)$
Morel	$b = 0.30 \times (\text{Chl})^{0.62}$	Chl

* c represents the beam attenuation coefficient, k the diffuse attenuation coefficient, and Chl the concentration of chlorophyll.

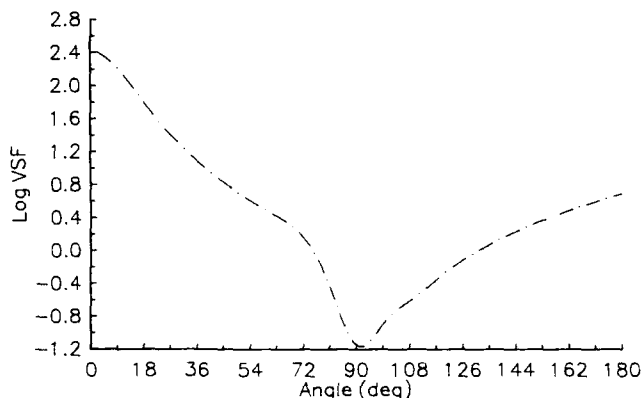


Figure 2. Measured VSF from sample experimental data.

VSF, $\beta(\theta)$. Figure 2 provides an example of an experimental VSF measured during the experimental runs.

The VSF measurements were fitted by a modified Heyney-Greenstein function⁹ so that values of the total scattering coefficient, b , could be computed, using Eq. (1) for the different water mass turbidities.⁸ The relevant wavelength for the tank data used in this work is 528 nm.

Results and Discussion

As shown in Eq. (2), the MTF can be determined by the negative exponential of the product of the decay function and the range. Hence, to make relevant calculations independent of the range, the decay function will be computed for the germane b values. The MTF can then be found easily by use of Eq. (2).

Figures 3, 4, and 5 provide the decay function for different experimental and estimated values of b . Here it is understood that the values of the decay function have not been normalized by the argument value of the Bessel function. Moreover, to provide for absolute attenuation,² the decay function now includes the effects of absorption. Figures 3, 4, and 5 provide six curves each. The solid line is the decay function computed with the experimentally derived b . The other curves shown provide the decay curves for b estimated using the relationships given in the legends. Note in these plots that, in the limit of high spatial frequency, the value of the decay curves tends toward the sum of the absorption and total scattering coefficients, $a + b$, as they should. In the limit of zero

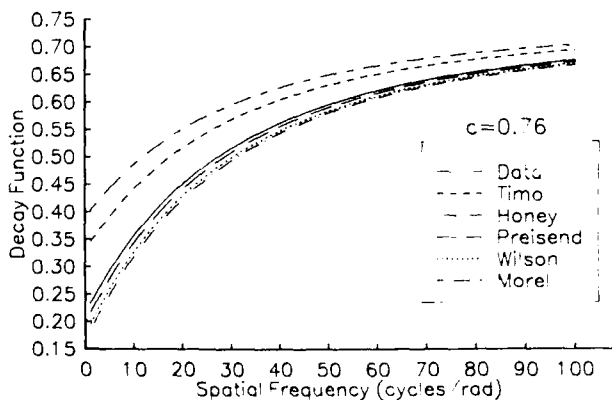


Figure 3. Wells' decay function as a function of spatial frequency and value of b used.

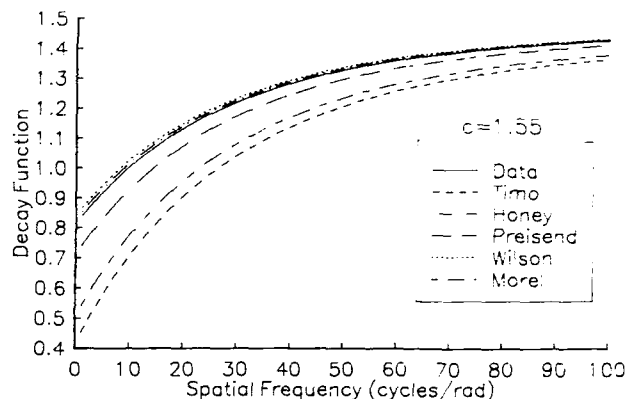


Figure 4. Wells' decay function for an intermediate value of b from test tank data.

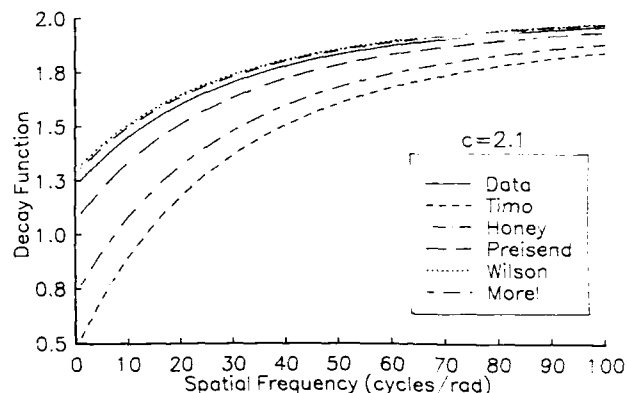


Figure 5. Wells' decay function for a high b value.

spatial frequency, the decay function approaches the value of the absorption coefficient. This occurs because the target in this limit is relatively large, so that any scattering would not create blur and the only loss would come through absorption effects alone.

The mean bias error is given in Table II. The mean bias error was computed by taking the mean of the difference between the different b -estimator-value decay functions and the experimentally derived b decay function.

Essentially, the decay curves shown signify how accurate the methods for estimating b are when compared with actual b values. Figure 6 provides a plot of b versus c values from the research tank data. Here it is seen that the Honey/Wilson (these two are very close) relationship over much of the range covered by the plot provides the most accurate estimate of b .

However, the values of b for the tank were relatively high. Perhaps in real world waters with lower values of

TABLE II. Mean Bias Error of the b Relationships Used Compared with Experimentally Derived b Values

Method	Mean Bias Error (%)
Timofeyeva	41.7
Honey	7.4
Preisendorfer	8.6
Wilson	6.9
Morel	40.1

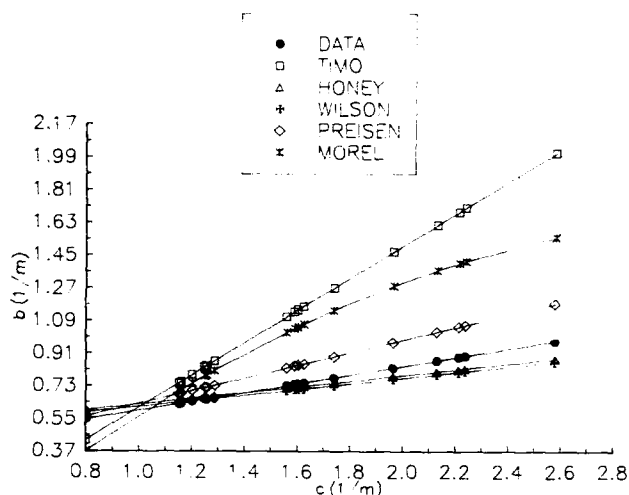


Figure 6. Research tank results for estimated and experimental b values.

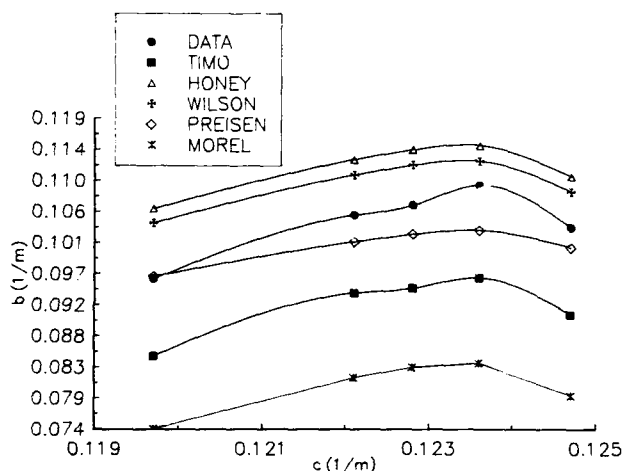


Figure 7. Sargasso Sea measured b data versus estimated b values.

scattering, a different method of estimating the value of b would be more successful. To check this proposition, an NRL data set for the Sargasso Sea region was used, for which the basic quartet of irradiances, upwelling scalar/cosine and downwelling scalar/cosine, were measured at a wavelength of 520 nm. Figure 7 exhibits the results of the calculation of b . It is seen that, in these very clear, oligotrophic waters, over a small range of c and b values determined by the data set, the Preisendorfer relationship appears to provide the most accurate estimate of b overall. This is closely followed by the Wilson relationship.

In our computations, it is assumed that the water path of interest is horizontal (that is, a plane-parallel, stratified medium is assumed). If slant or vertical paths are considered, then each layer of the medium represents a

different set of optical conditions—much like a new lens element of an optical system. Thus, for these cases, an MTF may be computed for each layer and the results cascaded to provide an overall medium MTF. The b values to be used for the MTF of such a medium must then be profiles of the b value, that is, values of b as a function of depth. Using the Honey/Wilson or Preisendorfer approach, profiles of k and c are needed. These may be obtained with standard optical instrumentation. However, the Morel relationship requires a knowledge of the chlorophyll concentration profile. Often this is obtained with a fluorometer that is calibrated to read the chlorophyll concentration values in the water. Kitchen and Zaneveld¹⁰ have recently shown that the chlorophyll maxima do not necessarily coincide with all potential scattering present, because of the possibility of seston (the total concentration of suspended material over the depth of interest) layer scattering at other depths. Thus, if the Morel relationship is used, some means of determining additional scattering layers independent of chlorophyll concentration appears to be needed.

Summary

Decay functions were calculated for both experimentally determined and estimated values of b . The relevant MTF may be calculated directly from the decay function curve, given the range, R , of interest [see Eq. (2)]. A table listing of average error over the b values used was given.

Of the relationships tried (Table I), the Honey/Wilson relationship proved to give the most accurate estimation of b for the relatively turbid research tank data. However, for the clear waters represented by the Sargasso Sea data set, the relationship of Preisendorfer gave better estimates of b .

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