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The effect of suspended particles in a water medium on the transport of light is normally dichotomized into two proceses. Namely, the dual effects of absorption and scattering. Absorption simply acts to remove photons which might have contributed to image formation. Such attrition effects might be overcome for a given system by increasing the source flux or by using a more sensitive receiver. Scattering, however, produces two more prernicious effects. Scattering can produce a foreground veiling glare which reduces the effective contrast of the target with respect to the background, and by causing a redistribution of the trajectories of image forming photons, 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 surprizing that values of optical parameters which describe the scattering effects of the water medium are significant variables in the MTF expression.

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IMPACT ON THE MEDIUM MTF BY MODEL ESTIMATION OF b

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I. 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 simply acts to remove photons which might have contributed to image formation. Such attrition effects might be overcome for a given system by increasing the souce flux or by using a more sensitive receiver. Scattering, however, produces two more pernicious effects. Scattering can produce a foreground veiling glare which reduces the effective contrast of the target with respect to the background, and by causing a redistribution of the trajectories of image forming photons, 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 surprizing that values of optical parameters which describe the scattering effects of the water medium are significant variables in the MTF expression. Wells[1,2] has derived a transformation which converts the medium volume scattering function, $\beta(\theta)$, 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 volume scattering function by the functionality

$$b=2\pi\int_0^{\pi}\beta(\theta)\sin\theta d\theta \tag{1}$$

stated here in spherical coordinates and assuming azimuthal symmetry. Normally, b is not measured directly due to either lack of appropriate instrumentation or simply the time consuming nature of the task. Rather, the value of b is computed by using other more easily determined optical coefficients. Preisendorfer[3], Honey[4], Wilson[5], Timofeyeva[6], and Morel[7] provide some specific relationships which can be used to determine b for a given water mass.

The objective of this paper is to utilize Wells' results to compute the medium decay function, $D(\Gamma)$, (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 determined 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.

II. Background and Methods

The medium MTF is the sine wave frequency amplitude response of the water path. Wells' transformation[1,2] of the volume scattering function into a medium MTF assumes the small angle approximation and that the suspended particles are larger than the optical wavelength.

Wells' expression for the medium MTF can be written in the form[2]

$$T(\Gamma,R)=\exp[-D(\Gamma)R] \tag{2}$$

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 may be written as[2]

$$D(\Gamma)=b-Q(\Gamma) \tag{3}$$

where $Q(\Gamma)$ provides for a 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. It is important to notice that the decay function is independent of the range, R. $Q(\Gamma)$ is defined by[1]

$$Q(\Gamma)=2\pi\int_0^{\theta}u(\theta)\,J_0(\alpha)\,d\theta \qquad (4)$$

where

$$u(\theta)=\int_0^{\theta}\beta(\delta)\,d\delta \qquad (5)$$

and $J_0(\alpha)$ is a zeroth order Bessel function with $\alpha = 2\pi\Gamma\theta$.

It can be shown[1] 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 diminuition 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.

Table 1 provides the relationships used to estimate b knowing other optical parameter values for the water mass in question.

Table II.

Name	Relationship	Parameters Used
Honey	b=6/5*(c-k)	c,k
Wilson	b=1/Ø.85*(c-k)	c,k
Preisendorfer	b=c-3/4*k	c,k
Timofeyeva	k/c=(Ø.19*(1-b/c))$^{b/2*c}$	c,k
Morel	b=Ø.3Ø*<Chl>$^{0.62}$	Chl

In Table II, 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 Oceanographic and Atmospheric Research Laboratory[8] (NOARL). 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[7]. Ancillary supporting optical measurements were made among which were water transmission, diffuse attenuation coefficient, and volume scattering function. The volume scattering function measurements were fit by a modified Heyney-Greenstein function[10] so that values of the total scattering coefficient could be computed for the different water mass turbidities[7]. The relevant wavelength for the tank data used in this work is 528nm.

III. Results and Discussion

As shown in equation (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 formed easily by use of equation (2).

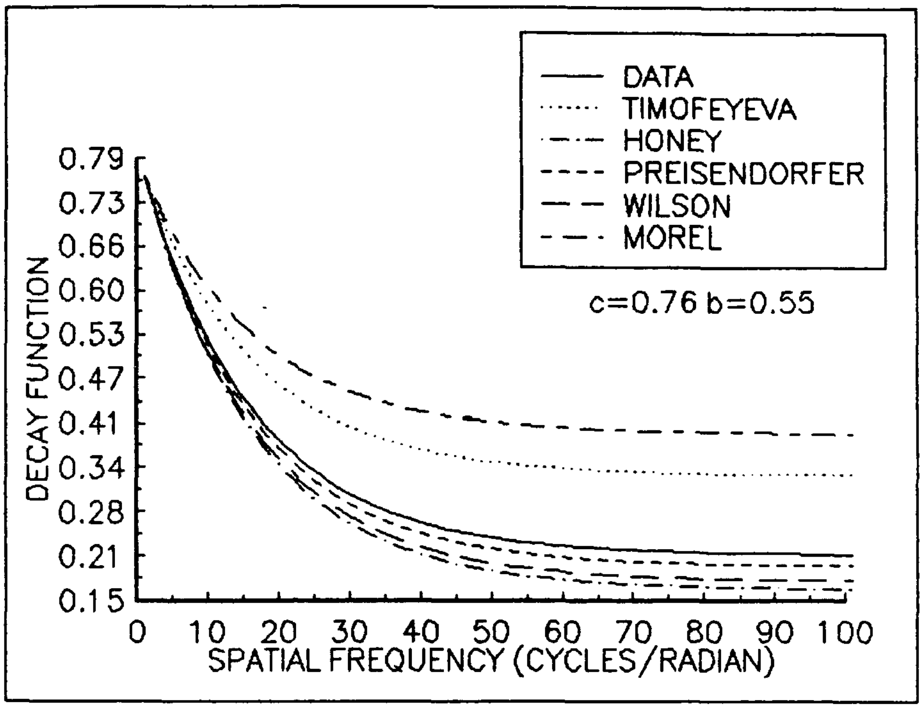

Figure 1. Wells' decay function as a function of spatial frequency and value of b used.

Figures 1-3 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 divided by the arguement value of the Bessel function. Figure 1 provides 5 curves. The solid line is the decay function computed with the experimentally determined b. The other curves shown provide the decay curves for b estimated using the methods given in the legend; and similarly for Figures 2 and 3.

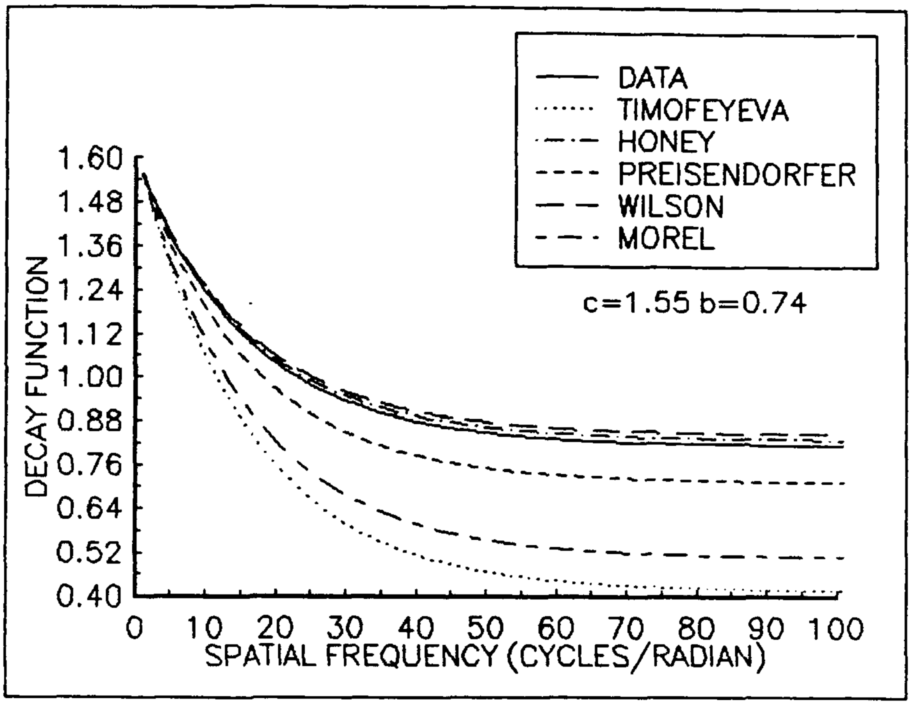

Figure 2. Wells'decay function for an intermediate value of b from test tank data.

The average error is given in Table 2.

Table 2.

Method	Error
Timofeyeva	41.7%
Honey	7.4%
Preisendorfer	8.6%
Wilson	6.9%
Morel	40.1%

The average error was computed by taking the mean of the difference between and estimators values of the decay function and the experimentally determined b decay function.

Essentially, the curves indicate how accurate the methods for estimating b are when compared to actual b values. Figure 4 provides a plot of b vs c values from the research tank data. Here, it is seen that the Honey/Wilson (since these two are very close) relationship over much of the range covered by the plot

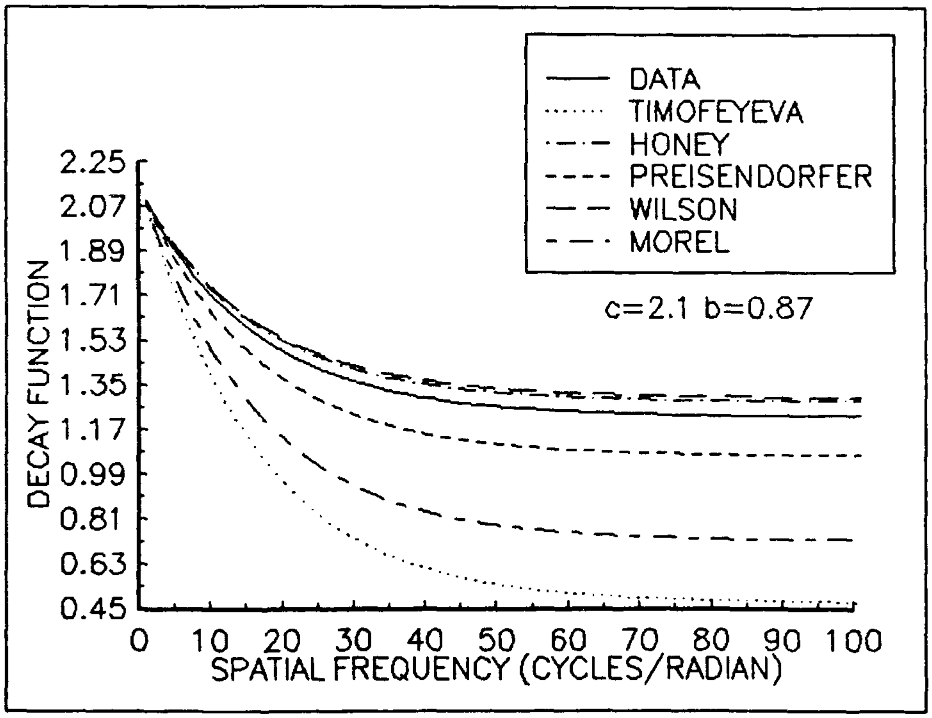

Figure 3. Wells' decay function for a high value of b.

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 scattering, a different method of estimating the value of b would be more successful. To check this, a NOARL dataset for the Sargasso Sea region was used for which the basic quartet of irradiances were measured. Figure 5 exhibits the results of the calculation. It is seen in these very clear, oligotrophic waters, over a small range of c and b values determined by the dataset, the Preisendorfer relationship appears to provide the most accurate estimate of b overall. This is closely followed by the Wilson relation.

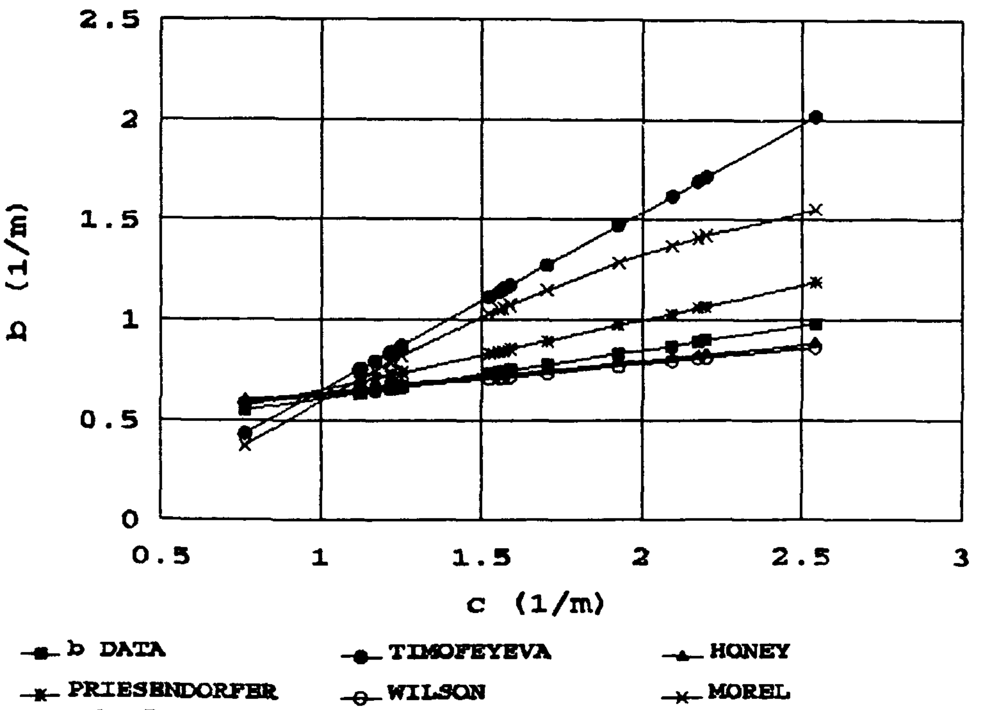

Figure 4. Research tank data results for b values.

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 result cascaded to provide an overall medium MTF. The b values to be used for such medium MTF's 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 relation requires a knowledge of the Chlorophyll a profile. Often, this is obtained with a fluorometer which is calibrated to read the Chlorophyll a values in the water. Kitchen and Zaneveld[11] have recently shown that the Chlorophyll maxima do nc necessarily coincide with all scattering present due to the possibility of seston layer scattering at other depths. Thus, if the Morel relationship is used, some means of determining additional scattering layers independent of Chlorophyll concentration appears needed.

IV. 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 equation (2)). A table listing average error over the b values used was given.

Of the relationships tried (Table I), the Honey/Wilson relation proved to give the most accurate estimation of b for the research tank data. However, for the Sargasso Sea dataset, the relation of Preisendorfer gave the better rendition of b.

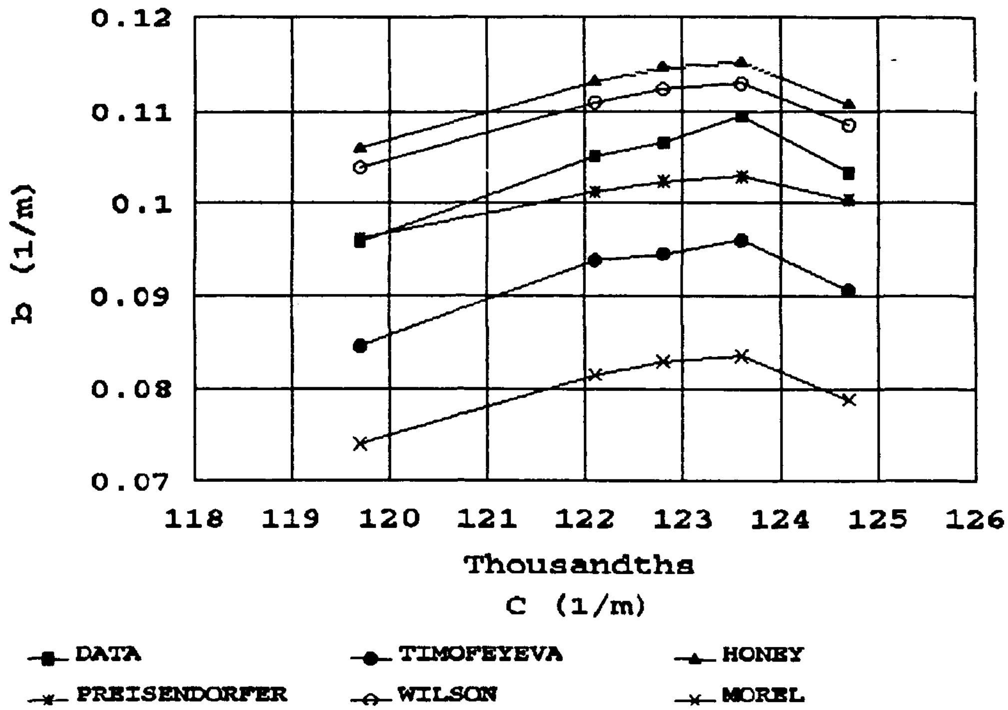

Figure 5. Values of b from a Sargasso Sea dataset.

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