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Toward closure of the inherent optical properties of natural waters

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Abstract. A fundamental relationship of inherent optical properties (IOP) is that the beam attenuation coefficient is the sum of the volume absorption and scattering coefficients ($c = a + b$). A relative calibration of a set of instruments can be provided using this IOP closure equation. Measurement of the true beam attenuation coefficient c is not practical as all attenuation instrumentation has some finite acceptance angle in which scattered light is collected. We provide a theoretical framework for measuring the attenuation and scattering coefficients in a consistent manner. Using this framework, we provide a practical version of the IOP closure equation. We apply the practical IOP closure equation to measurements made at Lake Pend Oreille, Idaho, in the spring of 1992. Results of this IOP closure indicate that the practical closure equation is a useful approach. Closure was achieved during some measurement sets but not at others. The intermittent lack of closure may be due to the method of determining the scattering coefficient from the general angle scattering meter or that the calibration of at least one of the instruments drifted during the time of the experiment.

Introduction

Several new techniques and devices for the measurement of the optical properties of water have recently been developed. Along with the new measurement techniques, methods for verification and testing of these new ideas and instruments must be developed. Closure of the inherent optical properties provides an important method of checking the performance of instrumentation. Closure is simply "the simultaneous verification of a mathematical relationship and a set of parameters by means of the independent measurement of the parameters" [*Zaneveld*, 1994, p. 62]. The inherent optical properties (IOP) are those properties of a water column that are independent of the radiance distribution [*Jerlov*, 1976]. They include the absorption coefficient a and the volume scattering function $\beta(\theta, \phi)$. Integration of the volume scattering function over all angles provides the scattering coefficient b:

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

Another IOP, the beam attenuation coefficient c, is defined to be the sum of the absorption and scattering coefficients:

$$c \equiv a + b. \quad (2)$$

Equation (2) provides the basis for closure of the inherent optical properties. Since (2) is exact, IOP closure is a test of the instrumentation only and does not test the mathematical relationship.

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An important aspect of closure is that it provides a method to check the consistency of individual IOP measurements. No such check is available when comparing measurements of a single or even two components of (2). For example, when multiple measurements of a single property, such as the absorption coefficient, are made in a natural water column, there presently is no way to know the exact value of the absorption coefficient, so that it is difficult to resolve which system provides the best measure of a. Measurement of the attenuation coefficient will help bound the possible values of a, but the true value of a remains unknown. With closure of the IOP we are able to determine if the measurements of a, b, and c are consistent with each other. When IOP closure cannot be accomplished, (2) cannot be used to determine which of the properties measured has an erroneous value. Other measurements or relationships must be used in order to isolate improper measurements. Even with IOP closure, it is possible, but unlikely, that all the measurements are in error by the same percentage.

Although IOP closure provides a method to check the performance of instrumentation, there have only been a few times when all three parameters have been measured [*Højerslev*, 1973, 1974]. During the closure cruises of Højerslev it was not possible to measure all three IOPs simultaneously. The temporal and spatial variability between measurements affected the ability to obtain closure at some of the stations. Another interfering factor in Højerslev's measurements is that the absorption coefficient was measured at a different wavelength than the attenuation and scattering coefficients. The results of Højerslev's IOP closure showed agreement from 3 to 40% between $a + b$ and c. Since the work of Højerslev, there has been little progress toward providing IOP closure. *Maffione et al.* [1991] describe

instrumentation that may be able to provide IOP closure on large volumes of water.

During the optical experiment conducted in 1992 at Lake Pend Oreille, Idaho, we measured a, c, and the scattering function from 10 to 170° [$\beta(10 \rightarrow 170°)$] using separate instruments. We will use these measurements in order to determine the present status of calibration and accuracy in the closure of the inherent optical properties.

Phytoplankton and dissolved organics were the dominant optical materials in the measurement region. A phytoplankton maximum was located between 10 and 20 m depth. The chlorophyll a levels associated with the phytoplankton maximum were over 3 mg/m^3. The chlorophyll a levels remained above 1 mg/m^3 down to depths of nearly 60 m. The dissolved organics became an increasingly important component of the absorption coefficient at depths below the phytoplankton maximum.

Theory

By definition,

$$c = a + \int_0^{2\pi} \int_0^{\pi} \beta(\theta, \phi) \sin \theta \, d\theta \, d\phi. \quad (3)$$

Equation (3) requires that the instrumentation used to measure the attenuation coefficient reject all scattered light, however, all transmissometers accept some portion of the forward scattered light depending on the transmissometer design [*Voss and Austin*, 1993]. For the collimated beam transmissometer used in these measurements the measured c can be written as

$$c_{\text{measured}} = c\Omega_m = a + \int_{\Omega_m}^{4\pi} \beta(\Omega) \, d\Omega = a + b\Omega_m \quad (4)$$

where Ω_m is the solid angle of the instrument, Ω is the solid angle, and $d\Omega = \sin \theta \, d\theta \, d\varphi$. Equation (4) is a pragmatic IOP closure equation. We have redefined c to include the scattered light collected by the nonzero diameter aperture. This redefined c is designated $c\Omega_m$. At the same time we have redefined b as $b\Omega_m$ which does not include the same amount of scattered light. The equation thus continues to be balanced. To ensure that all scattered light is accounted for once and only once, the measurement of b must include light at angles up to but not less than the acceptance angle of the attenuation measurement.

In choosing an acceptance angle, many factors must be accounted for. The first and foremost consideration is the application of the measurements. One common application of the inherent optical properties is in the computation of irradiances and the radiance field using the radiative transfer equation. For irradiance level calculations the IOPs as presented in (4) have been used with success in schemes such as *Gordon*'s [1973] quasi-single scattering model. Recent work by *Gordon* [1993] indicates that irradiance level radiative transfer can be accomplished disregarding scattering in the first 15°. Other schemes, such as the Delta-M method [*Wiscombe*, 1977], are used in order to truncate the highly forward peaked scattering function found in hydrological environments. This truncation reduces the number of terms in the Legendre polynomial expansion of the scattering function and allows radiative transfer models like the discrete ordinate model [*Stamnes et al.*, 1988] to be used to rapidly and accurately calculate the irradiance levels. Radiance level calculations can also use the IOPs as given in (4). The equation of radiative transfer in a homogeneous plane parallel medium without internal sources and transspectral effects is given by

$$\cos \theta \frac{dL(\Omega)}{dz} = -cL(\Omega) + \int_0^{4\pi} \beta(\Omega, \Omega')L(\Omega') \, d\Omega' \quad (5)$$

where Ω is the solid angle and $d\Omega = \sin \theta \, d\theta \, d\varphi$. Similar to the instrumentation, all radiative transfer models have some minimum $\Delta\Omega$ used in the integration of (5) [*Mobley et al.*, 1993]. The $\Delta\Omega$ in numerical integration is thus similar to the Ω_m in a measurement scheme. Both represent a minimum solid angle over which the radiance must, for practical reasons, be considered constant. Equation (5) can then be rewritten as

$$\cos \theta \frac{dL(\Omega)}{dz} = -\left[c - \int_{\Omega_m} \beta(\Omega, \Omega') \, d\Omega'\right] L(\Omega) + \int_{\Omega_m}^{4\pi} \beta(\Omega, \Omega')L(\Omega') \, d\Omega' \quad (6)$$

where Ω_m is of the same form as in (4) and the portion in the brackets is similar to the value of $c\Omega_m$ given in (4). The resolution of the radiance distribution in the model sets the maximum allowable acceptance angle for the attenuation measurements. In the modeling comparison of *Mobley et al.* [1993] the radiance field was divided into "quads" with a $\Delta\phi$ of 15° and a $\Delta(\cos \theta)$ of 0.1. Modeling can be done with smaller solid angles at the expense of increased computing time. A practical constraint on the models is the resolution of radiance measurements that can be used to validate the models. The early radiance detector used by *Tyler* [1960] had a solid angle of 0.01 sr. Newer camera type systems have reduced the solid angle to approximately 2×10^{-4} sr [*Voss*, 1989].

Use of the measured c in other radiative transfer problems depends on the application. Imaging applications are probably the most stringent, and here the required measurement depends on the specific field of view and instrumentation. At very small angles a beam is refracted at density inhomogeneities associated with turbulent flow. These density inhomogeneities are nonstationary and lead to a nonstationary scattering function. The simple radiative transfer equations (equation (5)) no longer applies, and so a time-averaged or time dependent radiative transfer equation must be used. For a very narrow beam in a turbulent medium (natural turbulence or instrument-induced turbulence) there is a very small probability that the beam will propagate without an interaction at a density interface. Scattering from nonstationary interfaces then cause the time-averaged scattering function and attenuation coefficients to become very large. We thus arrive at something akin to an uncertainty principle: the smaller the detection angle of a "perfect" beam attenuation meter is, the larger the time-averaged beam attenuation coefficient becomes. Fortunately, there are few applications in which very narrow angle forward scattering is important.

It is thus necessary to arrive at a practical approach toward the measurement of the beam attenuation coefficient

and the volume scattering function. For IOP closure and radiative transfer it is important that the instruments for the measurement of the beam attenuation and scattering coefficient be matched in order to ensure the accounting of all scattered light while ensuring that there are no overlapping regions where scattered light is accounted for a second time. The application determines the appropriate solid angle. In all cases the attenuation coefficient should be reported with the instrument's acceptance angle. The scattering coefficient or volume scattering function should also be reported with the range of angles covered by the instrumentation. The angular resolution of these measurements must be appropriate for the comparison of measurements and in creating a matched set of IOPs to be used in closure or radiative transfer modeling.

Methods

We made measurements of c and a using Sea Tech, Inc., transmissometers and single-wavelength reflecting tube absorption meters [*Zaneveld et al.*, 1990]. The filters used in the transmissometers and absorption meters had nominal wavelengths of 456 and 532 nm and a 10-nm full width at half maximum band pass. The acceptance angle of the transmissometers is 1.0°. The measurements of $\beta(\theta)$ were made using the general angle scattering meter (GASM) [*Petzold*, 1972] at nominal wavelengths of 440, 490, 520, 550, 610, and 670 nm. Data were collected with all instruments during 3 days of the experiment (May 4, 6, and 7, 1992).

Measurements were made from a barge operated by the Navy's David Taylor Research Facility in Bayview, Idaho. The barge was anchored in water over 200 m deep at the southern end of Lake Pend Oreille. Physically, all measurements were made close together, with the a and c meters located within a meter of each other on a single instrument platform and the GASM instrument located approximately 10 m away. Simultaneous measurements were made with all instruments at the same depth on May 4. On May 6 and 7 the c and a measurements were made within 1 hour of the $\beta(\theta)$ measurements.

Using the pragmatic definition of c given in (4), there is no need to make scattering corrections to the attenuation coefficient. A scattering correction must be applied to the reflecting tube absorption meters, however, since they do not collect all of the scattered light. The first-order correction to the absorption measurements is given by

$$a = a_m - \zeta b\Omega \tag{7}$$

with

$$b\Omega = \frac{c_m - a_m}{1 - \zeta} \tag{8}$$

where the m subscript indicates the measured value which includes the pure water value [*Zaneveld and Bartz*, 1984]. The value of ζ is the proportion of the scattering coefficient that is the error for the absorption meter. Mie scattering models indicate that the value of ζ ranges from 0.09 to 0.19 depending on the size distribution of the scattering particles. For this work we have used $\zeta = 0.13$ [*Zaneveld et al.*, 1992] which was determined by Monte Carlo simulations using the scattering functions of *Petzold* [1972] [*Kirk*, 1992].

We estimate the maximum error in the scattering coefficient as determined by the difference of the attenuation and absorption coefficients to be $\pm 0.1\ m^{-1}$. This estimate is based on the range of possible values of ζ and drift in the instrument calibrations during the experiment. The major sources of error were the instrument's electronic stability and changes in the calibration caused by the flow characteristics of the instrumentation.

The general angle scattering meter measures the scattering function with 1° resolution from 10 to 170°. However, to create a matched set of parameters as is required by (4) or (6), we must extend the measured scattering function to include scattering from 1.0 to 180°. One method to estimate the scattering coefficient was given by *Jerlov* [1976]. He suggested that the total scattering coefficient is approximately 32 times $\beta(45°)$. Applying this formula to the data of *Petzold* [1972], we found that this method gives the value of b to within a factor of 2. This method lacked the desired accuracy and also did not provide a matched data set. An alternate technique is to extrapolate the near-forward portion of the scattering function from the measured region. We used linear and second-order polynomial fits to the data from 10 to 100° in log-log coordinates in order to extrapolate the missing portion of the volume scattering function. Application of these extrapolation methods to Petzold's data indicated that there was no one method or range of angles that provided a good fit to all the volume scattering function curves. Therefore the extrapolation methods proved unsuitable for our purposes.

In order to estimate the small angle scattering and arrive at an estimate of the value of b_1 (where 1.0 is the aperture angle of the instrument which defines the instrument's solid angle for this set of measurements), we choose to fit the scattering function measured by the GASM in the 10 to 100° range to the family of scattering functions provided by *Petzold* [1972]. In doing this, we are assuming that the shapes of the Lake Pend Oreille scattering functions are bounded by those provided by Petzold. The shape of the scattering function depends on the particle size distribution, the complex index of refraction of the particles, the shape of the particles, and the wavelength of light used. Since Petzold's data include data from the Tongue of the Ocean and San Diego Harbor, we feel that his family of scattering functions contains the extremes of particle size distributions and that the Lake Pend Oreille scattering functions are contained within those given by Petzold. The measured scattering functions indicated that there is little change in the shape of the scattering function for the different wavelengths (Figure 1), especially in the near-forward direction. This allowed us to use Petzold's single-wavelength measurement for all six wavelengths. Extrapolation of the scattering function from 170 to 180° is less critical than the near-forward extrapolation because $\beta(\theta, \phi)$ is small in this region.

The GASM data were noisy due to the small scattering volume and fluctuations in the number of large particles in the volume. There were also missing points in the scattering minimum normally located just beyond 100° so we chose to use 100° as a cutoff point. The cutoff of 100° simplified the analysis procedure and provided the same results as the regressions to 170°. *Petzold*'s [1972] data are given in 5° increments, so that using the 100° cutoff provided 15 data points for the curve fitting. The fitting method used was a linear least squares regression without a constant. This provided a single multiplier χ such that

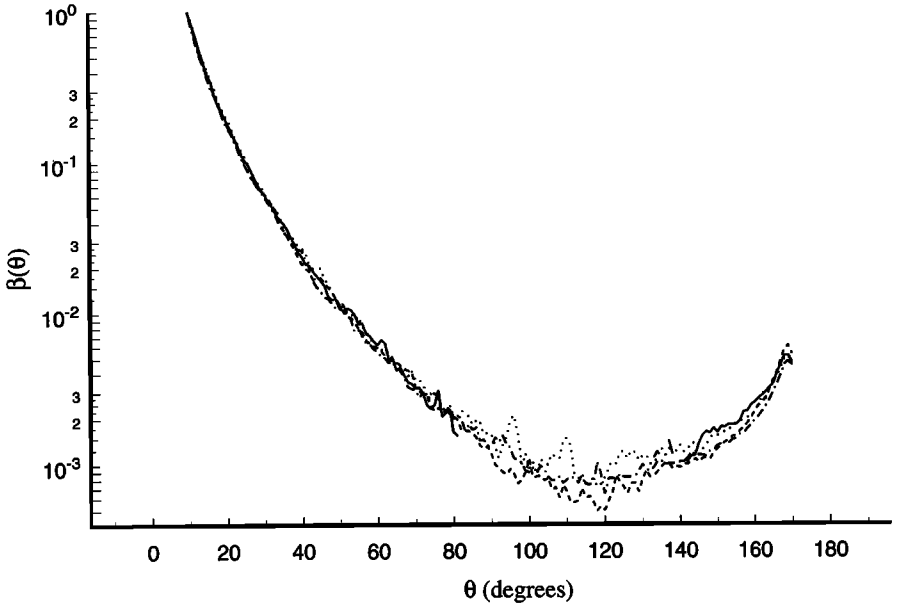

Figure 1. Scattering functions at 440, 490, 550, and 670 nm as measured by the general angle scattering meter (GASM) on May 6, 1992, at 15 m depth. The scattering functions are normalized to the value at 10° in order to remove changes in magnitude.

$$\beta_{GASM}(\theta) = \chi\beta_{Petzold}(\theta). \quad (9)$$

Since the value of b is determined by (1), the estimate of b_{GASM} is simply $\chi b_{Petzold}$. We will provide two estimates of b_1 from the fitting method. The first value, b_{1best}, is the estimate of b_1 provided by the curve of Petzold that produced the best fit to the measured curve as determined by the adjusted r^2 value. The second value, b_{1ave}, is the average of b_1 value estimates determined for curves that had an r^2 value >0.99. For the fits with $r^2 > 0.99$ the standard deviation of the b_{1ave} estimates as well as minimum and maximum values of b_1 are used in order to assess the possible range of b_1. In most cases, b_{1best} is within 1 standard deviation of b_{1ave}. The standard deviation determined for b_{1ave} provides an estimate of the error margin of the fitting method, although it does not include the errors associated with the GASM instrument itself. Note that the extrapolation contains approximately 65% of the total b_1, providing a large possible source of error.

Results

Since the GASM measurements were made at different wavelengths than the c and a measurements, the first problem is to determine the spectral shape of the scattering function in order to estimate b at the desired wavelengths. A regression was done at each depth for each day to determine if there was a λ^{-n} relationship to the scattering coefficient. Only on May 7 at 60 m was there an n value that was significantly different from 0.0 [$n = -1.3$ (0.3)]. Since, to first order, b showed no spectral dependence, we will compare values of b(440) to b(456) nm and b(550) to b(532) nm without making any corrections for wavelength dependence. For the case with an observed spectral dependence (May 7, 60 m) we will interpolate the 550 value to that at 532 nm.

Measurements using a Sea Tech, Inc., 660-nm transmissometer indicated that during the experiment there was an attenuation maximum in the upper 20 m of the water column. Below the maximum the value of $c_p(660)$ decreased slowly with depth (≈0.005 m^{-1}/m). Over the 3 days the value of $c_p(660)$ at the greater depths also decreased slightly. The coefficient of variation for waters deeper than 20 m is 7.5%. In the upper 20 m there are much larger changes as the magnitude and position of the particle maximum changed during each day as well as between days of the experiment.

On May 4, measurements of all three parameters were made simultaneously at 50 m depth. In Tables 1a and 1b the estimated values of b_1 are given as well as the standard deviation, minimum, and maximum values. The estimates of

Table 1a. Scattering Coefficients Determined From General Angle Scattering Meter (GASM) Data and the Associated c_1-a Measurements on May 4, 1992, at 50 m Depth

	GASM, 440-nm Wavelength	c_1-a, 456-nm Wavelength	GASM, 550-nm Wavelength	c_1-a, 532-nm Wavelength
b_{1best}	0.343	...	0.350	...
b_{1ave}	0.37	0.446	0.35	0.500
Standard deviation (b_{1ave})	0.02	0.004	0.02	0.007
Minimum	0.34	...	0.32	...
Maximum	0.39	...	0.38	...

All units are m^{-1}. The c_1-a estimates of b_1 are based on an average value for a 2-m depth interval centered on the reported depth. The standard deviation reported for the c_1-a measurement is the standard deviation of the 2-m interval. The estimated error in the c_1-a measurement is 0.1 m^{-1}. The "best" subscript is the estimate of b_1 provided by the curve of *Petzold* [1972] that produced the best fit to the measured curve as determined by the adjusted r^2 values. The "ave" subscript is the average of b_1 values determined for curves that had an r^2 value >0.99.

Table 1b. Scattering Coefficients

	15-m Depth		40-m Depth		60-m Depth	
	GASM, 550-nm Wavelength	c_1-a, 532-nm Wavelength	GASM, 550-nm Wavelength	c_1-a, 532-nm Wavelength	GASM, 550-nm Wavelength	c_1-a, 532-nm Wavelength
			May 6, 1992			
b_{1best}	0.68	...	0.37	...	0.31	...
b_{1ave}	0.80	0.75	0.38	0.44	0.32	0.31
Standard deviation (b_{1ave})	0.07	0.02	0.03	0.02	0.03	0.02
Minimum	0.68	...	0.33	...	0.27	...
Maximum	0.90	...	0.43	...	0.36	...
	5-m Depth		15-m Depth		60-m Depth	
	550-nm Wavelength	532-nm Wavelength	550-nm Wavelength	532-nm Wavelength	550-nm Wavelength	532-nm Wavelength
			May 7, 1992			
b_{1best}	0.82	...	0.39	...	0.21	...
b_{1ave}	0.85	1.10	0.41	0.624	0.21	0.28
Standard deviation (b_{1ave})	0.08	0.08	0.02	0.052	0.02	0.02
Minimum	0.72	...	0.37	...	0.17	...
Maximum	0.97	...	0.45	...	0.23	...

See footnote to Table 1a.

$b_1(456)$ are within the 0.1 m^{-1} estimated error for the c_1-a estimate of b_1. The same is not true at 532 nm, however.

On May 6 the $c(532)$ and $a(532)$ measurements were made 1 hour prior to the GASM measurements. Near 15 m the transmissometer indicated an attenuation maximum that increased in magnitude and depth throughout the day. The agreement between the two methods is good (Tables 1a and 1b and Figure 2).

On May 7 the $c(532)$ and $a(532)$ profiles were obtained half an hour before and after the GASM measurements. Data from both profiles are used to estimate $b(532)$ at the time of the GASM measurements (Tables 1a and 1b and Figure 2). As on May 4, the $b_1(532)$ determined by c_1-a is higher than the value of b_1 determined using the GASM data.

Since the measurements on May 4 were made simultaneously, it is unlikely that a source of error in the comparison can be attributed to natural variability. A 15-min long-time series of the c and a measurements was obtained during the time that the GASM measurements were made, and the time series did not indicate large variability over the short time period of the measurements. If the difference in b_1 estimates cannot be attributed to natural variability, then either the method of determining b_1 from the GASM data is at fault or at least one of the instruments was improperly calibrated. If the extrapolation was at fault, we would expect consistent differences in the estimates of b_1 for the 3 days because the particulate properties did not appear to change significantly from day to day. Since the extrapolated portion of the scattering coefficient is so large, small errors in the extrapolation can create large changes in b_1. It is also possible that there may have been some drift in the calibration of the instrumentation over time. In order to determine if one set of instrumentation was more stable over the measurement period, we compare the estimates of b_1 to the daily averaged attenuation values measured by a Sea Tech, Inc., transmissometer minus the contribution by pure water [$c_{1p}(660)$]. The attenuation measurements were made at a different location within the well and at different times than the other instruments. Results of the comparison are given in Table 2. The c-a estimate at 532 nm on May 4 is higher than what appears to be normal. On May 6 the b_{1ave} from GASM appears higher than on the other 2 days. On average, the

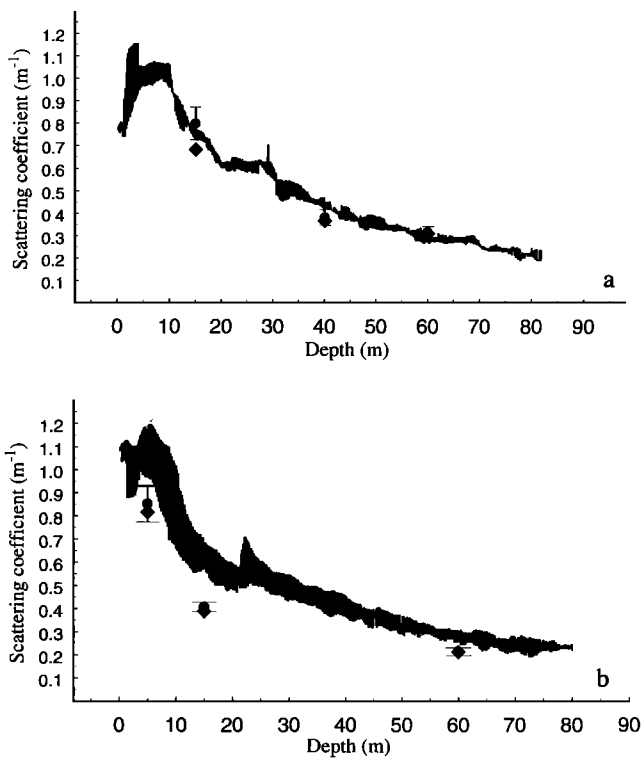

Figure 2. Depth profiles of the estimates of $b_1(532)$ from GASM (b_{best}, diamonds, and b_{ave}, circles, plus 1 standard deviation error bars) and $c_1(532) - a(532)$ (solid line) for (a) May 6 and (b) May 7. See text for details.

Table 2. The Relationships Between the b_1 Estimates and the Measured Value of $c_{1p}(660)$

Wavelength, nm	Depth, m	$c_{1p}(660)$, m^{-1}	GASM $b_{ave}/c_{1p}(660)$	c_1-a $b_1/c_{1p}(660)$
		May 4, 1992		
456	50	0.498	0.74	0.90
532	50	0.498	0.70	1.00
		May 6, 1992		
532	15	0.797	1.00	0.94
532	40	0.495	0.77	0.89
532	60	0.366	0.87	0.83
		May 7, 1992		
532	5	1.183	0.72	0.93
532	15	0.684	0.6	0.91
532	60	0.306	0.70	0.90

Abbreviations are b_1, total scattering coefficient from 1 to 180°; c_{1p}, total attenuation coefficient with pure water; GASM, general angle scattering meter; a, total absorption coefficient.

GASM estimates of b_1 are consistently lower than the c_1-a estimates which may indicate an error in the extrapolation or in the instrument calibrations.

Conclusions

The differences in the estimates of b_1 are not consistent over the 3 days. On May 6, at two of the three depths, it appears that closure was achieved, whereas on May 4 and 7 it does not appear that closure was achieved. Spatial and temporal variability may account for a portion of the differences in determining b_1 by the two techniques. The significant proportion of the scattering coefficient that must be determined by fitting the measured phase functions to those of *Petzold* [1972] provides a large source of possible error in determining the scattering coefficient from the GASM measurements. It is also possible that one or more of the instruments had calibration drift during the experiment. It is possible that the estimates of b_1 using the GASM data are too low on May 4 and 7, or it could be that the c-a estimate of b_1 was too high on all 3 days and on May 6, GASM overestimated the value of b_1.

The measurements taken at Lake Pend Oreille do take some steps forward in providing closure of the IOP when compared with the previous closure experiments of *Højerslev* [1973, 1974]. The instrumentation used at Lake Pend Oreille provided simultaneous measurements of a and c. In one case there were simultaneous measurements of $\beta(\theta)$, and in all cases the measurements of a, c, and $\beta(\theta)$ were made within an hour of each other. Thus we have reduced the temporal and spatial scales between the individual measurements. We have also provided measurements made on approximately the same spatial scale, allowing comparisons to be made without worrying about possible differences in the IOP with scale. Even when closure was not obtained, the percentage difference in the estimate of the scattering coefficient is within those observed by Højerslev.

There are still areas for improvement in providing IOP closure. One simple step is to carry out all three measurements at the same wavelength band. Although this step seems obvious, it has not been done for any of the three attempts at closure. The small differences in wavelengths in this closure attempt can be worked around but provide an additional and unnecessary source of errors. Two other steps that could reduce the errors are measuring the forward scattering component and more frequent calibration of the instrumentation. Measurement of the scattering function between 10° and the acceptance angle of the transmissometer is required in order to remove errors associated with the fitting methods. Improvements in our ability to measure the volume scattering function are essential if we expect to obtain IOP closure. Calibration of the instrumentation during the experiment, in addition to the pre- and postexperiment calibrations, is needed to remove the possibility of calibration drifts during the experiment.

It is also necessary to improve our scattering correction schemes for the absorption meter. Presently, a single correction factor is used, although the scattering correction varies with wavelength, particle size distribution, and the optical properties of the particles. Better methods of correcting for scattering errors include using measurements of the absorption coefficient at long wavelengths [*Zaneveld et al.*, 1992]. Such schemes would be able to account for changes in the particle size distribution that the present correction methods do not.

The time and space scales between measurements of the individual IOPs should be reduced further by mounting all of the instruments onto a single platform. Minimizing the distance between measurements will reduce errors in closure that are associated with the natural variability of the water being measured.

Closure of the IOPs does not provide absolute calibration but does indicate whether the devices are producing consistent results. The quality of this relative calibration depends on the temporal or spatial variability of the water column as applied to the measurement sequence. In this paper we have provided a solid theoretical framework for the consistent measurement of the beam attenuation and scattering coefficients based on a practical definition. It is imperative that all radiant energy be accounted for either as being considered directly transmitted or as scattered energy. This allows for closure of the equation of radiative transfer without the need to approach the absolute value of c (which is impossible to measure in any case) or $\beta(\theta, \phi)$ down to zero degrees. For most applications it is desirable to improve our measurement capabilities so that the volume scattering function can be measured to the same angles as the acceptance angle of the attenuation meters.

Notation

a total absorption coefficient, m^{-1}.
b total scattering coefficient, m^{-1}.
b_Ω total scattering coefficient excluding scattering within the solid angle Ω, m^{-1}.
b_1 total scattering coefficient from 1 to 180°, m^{-1}.
$\beta(\theta, \varphi)$ volume scattering function, m^{-1} sr^{-1}.
$\beta(\Omega, \Omega')$ volume scattering coefficient from solid angle Ω' to solid angle Ω, m^{-1} sr^{-1}.
c total attenuation coefficient, m^{-1}.
$c_{\Omega m}$ total attenuation coefficient as measured by a device with scattered light accepted in the solid angle Ωm, m^{-1}.
c_1 total attenuation coefficient as measured using a device with a 1° acceptance angle, m^{-1}.

$L(\Omega)$ radiance in a given solid angle Ω defined by θ and ϕ, W m^{-2} sr^{-1}.
z depth, m.
Ω solid angle, sr.
Ω_m solid angle of the instrument, sr.
ζ proportion of the scattering coefficient that is related to the scattering error of the reflecting tube absorption meter.
θ polar angle.
ϕ azimuthal angle.

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