Chapter 2

Beam Transmission and Attenuation Coefficients: Instruments, Characterization, Field Measurements and Data Analysis Protocols

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2.1 INTRODUCTION

Beam transmittance $T(\lambda, r_{\mathrm{T}})$ over an optical path of length r_{T} m, and the beam attenuation coefficient $c(\lambda)$ $\left[\mathrm{m}^{-1}\right]$, are introduced in Chapter 1 (Sect. 1.3). The two variables are related by equation (1.6). A ***beam transmissometer*** is an instrument that combines a source of collimated spectral radiant flux $\Phi_{\mathrm{o}}(\lambda, 0, 0, \bullet)$ and a co-aligned detector, to measure the flux $\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet)$ transmitted over distance r_{T}, to measure $T(\lambda, r_{\mathrm{T}})$ (Fig. 1.4 and related text in Sect. 1.3, Ch. 1). A beam transmissometer is also frequently called a ***beam attenuation meter***, or a ***c-meter***.

2.2 TRANSMISSOMETER DESIGN CHARACTERISTICS

In concept, a beam transmissometer is a relatively simple instrument to build, and the derived beam attenuation coefficient is needed in many optical studies of the sea. Therefore, instruments of this type have been in use for many years. While a great number of different transmissometer designs have appeared, most follow one of the two basic designs illustrated in Fig. 2.1.

Direct and Folded Path Transmissometers

Probably the most common transmissometer design uses a collimated light beam[1], with a source in one housing and a detector facing the source (Fig. 2.1, top panel). In such an ideal ***direct-path transmissometer***, either a white light, or a light emitting diode (LED), source is combined with a pinhole to provide a point source. A lens is inserted into the path to collimate the light beam, an interference filter is inserted to select the waveband of the measurement, and the light is passed into the water through a window. At the other end of the optical path, the light enters the detector assembly through another window and is focused by a lens. An aperture at the focal point removes off-axis scattered light, and the transmitted light falls on the detector. Although this instrument is conceptually simple, it is difficult to build. The alignment of components is critical, and something as simple as the filament in the source sagging as the instrument is moved can create significant apparent changes in the derived beam attenuation coefficient. Several commercial transmissometers[2] including, some laboratory spectrophotometers, and the

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[1] Cylindrically limited beam, as opposed to collimated beam, transmissometers will be discussed later in this section.

[2] Certain commercial equipment, instruments, or materials are identified in this chapter to foster understanding. Such identification does not imply recommendation, or endorsement, by the National Aeronautics and Space Administration, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

(former) SeaTech and WET Labs field instruments use this basic design. Design variations include the addition of a reference detector and placing the wavelength filter in the detector housing.

The folded pathlength design (Fig. 2.1, bottom panel) uses one or more reflectors to create a longer pathlength. The basic idea for this design can be attributed to Petterson (1934). Initial designs used plane mirrors to expand the pathlength (Wattenberg, 1938; Timofeeva, 1960). The introduction of prisms to separate the incident and reflected beam (Nikolayev and Zhil'tsov 1968; Petzold and Austin 1968) and of concave mirrors as the reflectors, have led to improved versions of this general design. An optical pathlength of 10 m was achieved by Jerlov (1957) by using multiple reflections between three concave mirrors. A currently available commercial instrument with a folded path is the HOBILabs c meter.

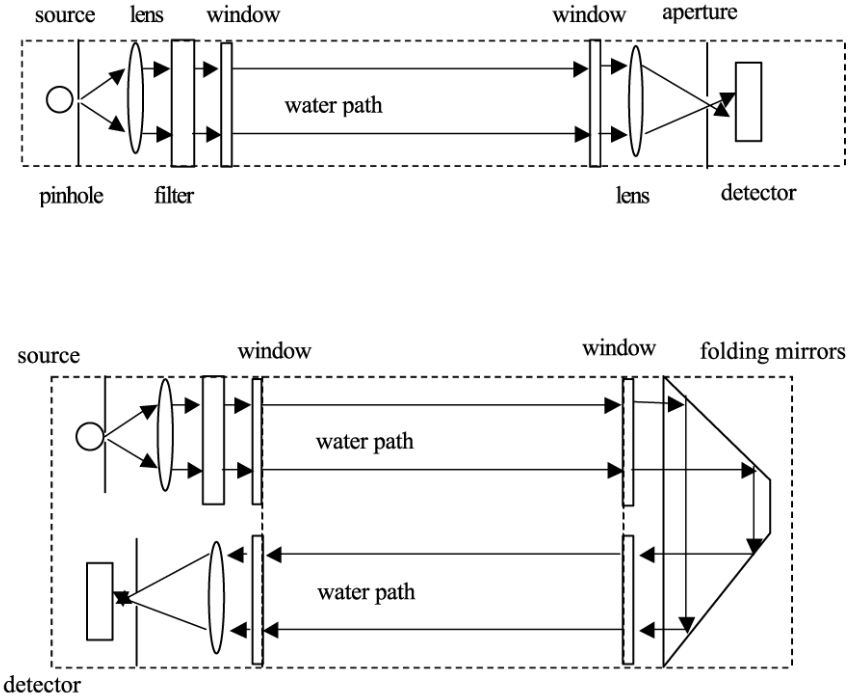

Fig. 2.1 Schematic illustrations of direct path (top panel) and folded path (bottom panel) beam transmissometers designs.

Other Types of Transmissometers

A ***variable pathlength transmissometer*** is probably the most desirable, and elusive, c-meter design concept. One desirable factor would be such an instrument's ability to adjust the pathlength to make it optimal for the measuring conditions (see *Pathlength Considerations*, below). More importantly, the variable pathlength instrument is self-calibrating. To understand this property of such an instrument, examine the basic equation (1.6) for transmissometer measurements. For any transmissometer measurement over pathlength r_i, the dark-corrected detector output $V_T(\lambda, r_i)$ is proportional to the flux reaching the detector window $\Phi_T(\lambda, r_i, 0, \bullet)$. If two transmissometer measurements are made using different path lengths, r_1 and r_2, the transmittance over the pathlength difference between the two measurements is simply

$$T(\lambda, r_2 - r_1) \equiv \frac{\Phi_T(\lambda, r_2, 0, \bullet)}{\Phi_T(\lambda, r_1, 0, \bullet)} = \frac{V_T(\lambda, r_2)}{V_T(\lambda, r_2)}, \tag{2.1}$$

and $c(\lambda)$ may be calculated from (1.6) with $r_{\mathrm{T}} = r_2 - r_1$. The assumptions implicit in this calculation are that the beam attenuation coefficient is constant over the time and space extents of the measurements, and that the optical alignment and electronic properties of the instrument also are constant over time.

Barth *et al.* (1997) describe the design and application of a variable pathlength instrument for use in coastal waters. However, they also note that the errors in alignment made their instrument unsuitable for clear water applications. The requirement to exactly repeat the optical alignment at two distances is the most difficult aspect of building a variable pathlength instrument. Small changes in the alignment of the reference detector, or reflector will introduce large errors in the beam attenuation coefficient by causing the focal point of the beam to wander relative to the aperture in front of the detector. If biofouling exists, the spatial gradients in the fouling will cause $V_{\mathrm{T}}(\lambda, r_{\mathrm{i}})$ to vary if the alignment is not perfect. Additionally, if the beam is not truly collimated, but instead has a slight divergence, the beam divergence will cause a different area of the detector window to be illuminated in each measurement, and any spatial gradients in the optical properties of the window will translate into errors in $c(\lambda)$.

Many laboratory ***benchtop spectrophotometers*** have a design very similar to a collimated beam transmissometer. A complication that arises when using laboratory spectrophotometers to measure beam attenuation is that much of the scattered light is kept in the sample by the total-internal-reflection at the glass-air interface. This makes it more likely that multiply scattered light will be received at the detector. This problem can be reduced by the addition of light baffles within the sample cuvette.

Source and Detector Characteristics

The transmittance ratio $\dfrac{\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet)}{\Phi_{\mathrm{o}}(\lambda, 0, 0, \bullet)}$, *i.e.* the ratio of the flux transmitted to the detector window divided by the flux entering the water at the source window, must be known to compute $c(\lambda)$ from (1.6). A transmissometer does not actually measure either of these quantities. A transmissometer's detector output signal $V_{\mathrm{D}}(\lambda)$ represents its response in the presence of flux $\Phi_{\mathrm{D}}(\lambda)$, the part of $\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet)$ that arrives at the detector after passing through the instrument's detector assembly window and other optical elements (Fig. 2.1). Because of reflections and absorption during transmission through windows and other optical components, $\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet) > \Phi_{\mathrm{D}}(\lambda)$, but assuming the optical throughput is linear, $\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet) \propto \Phi_{\mathrm{D}}(\lambda)$. The detector's "dark" response $V_{\mathrm{D}}^{\mathrm{dark}}(\lambda)$ is any signal output that is present when the source is off and $\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{i}}, 0, \bullet) = 0$. If the detector's electrical response is linear, $\Phi_{\mathrm{D}}(\lambda) \propto \left[V_{\mathrm{D}}(\lambda) - V_{\mathrm{D}}^{\mathrm{dark}}(\lambda)\right]$ and we may write

$$\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet) = \mathrm{C_D}\left[V_{\mathrm{D}}(\lambda) - V_{\mathrm{D}}^{\mathrm{dark}}(\lambda)\right], \ \mathrm{W\ nm^{-1}}, \tag{2.2}$$

where $\mathrm{C_D}$ is a constant, with units of $\left[\mathrm{W\ nm^{-1}V^{-1}}\right]$, accounting for the combined effects of optical losses and the detector's flux responsivity.

A measure of the flux $\Phi_{\mathrm{o}}(\lambda, 0_{\mathrm{i}}, 0, \bullet)$ is still required if the transmission is to be determined. A beam splitter before the source window can be used to shunt a proportion of the source light to a reference detector to provide a measure of the flux being sent into the water. Because of losses associated with the source windows and beam splitter, the reference detector receives, and responds to, a flux proportional to $\Phi_{\mathrm{o}}(\lambda, 0_{\mathrm{i}}, 0, \bullet)$ and we have that

$$\Phi_{\mathrm{o}}(\lambda, 0, 0, \bullet) = \mathrm{C_R}\left[V_{\mathrm{R}}(\lambda) - V_{\mathrm{R}}^{\mathrm{dark}}(\lambda)\right], \ \mathrm{W\ nm^{-1}}, \tag{2.3}$$

where $V_{\mathrm{R}}(\lambda)$ and $V_{\mathrm{R}}^{\mathrm{dark}}(\lambda)$ are the reference detector response and ambient (dark) signals, respectively, and $\mathrm{C_R}$ is a second system response constant.

The transmittance may now be written as the ratio of (2.2) and (2.3)

$$T(\lambda, r_{\mathrm{T}}) = \frac{\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet)}{\Phi_{\mathrm{o}}(\lambda, 0, 0, \bullet)} = \mathrm{C_T} \frac{\left[V_{\mathrm{D}}(\lambda) - V_{\mathrm{D}}^{\mathrm{dark}}(\lambda)\right]}{\left[V_{\mathrm{R}}(\lambda) - V_{\mathrm{R}}^{\mathrm{dark}}(\lambda)\right]}, \tag{2.4}$$

where $\mathrm{C_T} = \dfrac{\mathrm{C_D}}{\mathrm{C_R}}$.

If the source output is constant, the constant $\left[V_{\mathrm{R}}(\lambda) - V_{\mathrm{R}}^{\mathrm{dark}}(\lambda)\right]$ may be absorbed in $\mathrm{C_T}$ and (2.4) reduces to

$$T(\lambda, r_{\mathrm{T}}) = \frac{\Phi_{\mathrm{T}}(\lambda, r_{\mathrm{T}}, 0, \bullet)}{\Phi_{\mathrm{o}}(\lambda, 0, 0, \bullet)} = \mathrm{C_T}\left[V_{\mathrm{D}}(\lambda) - V_{\mathrm{D}}^{\mathrm{dark}}(\lambda)\right], \tag{2.5}$$

and there is no need to use a reference detector[3] output to calculate transmittance.

Depending on a transmissometer's design, we must determine the coefficient $\mathrm{C_T}$ in either (2.4) or (2.5). It is not practical to determine the system response constants based on first principles, because they are dependent on the optical component throughputs, the combined response(s) of the detector(s), and electronic circuits. Instead , a system's calibration constant $\mathrm{C_T}$ [dimensionless in (2.4), or in V^{-1} in (2.5)] is typically determined by measuring the instrument's output in a "standard" medium having a known beam attenuation coefficient $c_{\mathrm{STD}}(\lambda)$. For oceanographic transmissometers, the "standard" medium is highly purified water (Sect. 2.3 below), and $c_{\mathrm{STD}}(\lambda) = c_{\mathrm{w}}(\lambda)$ (Ch. 1, Sect. 1.2).

Transmissometer Response Temperature Dependence

The source output, responsivity of the detector, and performance of other electronic components tend to be temperature dependent. This causes the calibration constants to be temperature dependent. Two approaches are used to remove the temperature dependence, 1) add compensating electronics that allow the voltage output to remain constant over a temperature range, or 2) measure the temperature of the instrument and determine the how the constants change with temperature. The first technique is used in many single-wavelength transmissometers, such as the Sea Tech and WET Labs transmissometers. The second approach is used in the WET Labs ac-9 spectral absorption and beam attenuation meter.

Spectral Characteristics

Many areas of research in ocean optics require knowledge of the spectral beam attenuation coefficient $c(\lambda)$ at more than one wavelength λ. Several c-meters have been built to provide this spectral information. Matlack (1974) used an instrument with a grating monochromator to measure $c(\lambda)$ in the wavelength range from 385 nm to 565 nm. Using a pair of circular wedge interference filters, Lundgren (1975) was able to measure the beam attenuation coefficient at wavelengths between 340 nm and 730 nm. More recent transmissometers that use a monochromator as the detector include the one described by Barth *et al.* (1997), and the WET Labs Histar. Another design for obtaining the spectral beam attenuation coefficient utilizes several interference filters mounted in a wheel that rotates them through the beam. Examples of filter-wheel c-meter designs include the VLST (Petzold and Austin 1968) and the WET Labs ac-9 (Moore *et al*. 1992; Van Zee *et al*. 2002).

Beam Geometry, Detector Acceptance Angle and Scattered Light

Real transmissometers do not have perfectly collimated sources or detectors. Unlike the idealized detector concept of Fig. 1.4 (Ch. 1, Sect. 1.3), a detector with a finite acceptance angle, or Field of View (FOV) ψ_{FOV}, detects photons that are singly scattered in the range $0 < \psi \le \psi_{\mathrm{FOV}}$. Therefore, the flux

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[3] A reference detector may be used in a feedback circuit to stabilize an LED source. However, the reference detector signal is not usually included in the instrument's data output stream in constant source output designs of this type.

$\Phi_{\mathrm{T}}^{\mathrm{M}}\left(\lambda, r_{\mathrm{T}}, 0, \bullet\right)$ arriving at a transmissometer's detector assembly window and subsequently measured (see above) exceeds the true flux directly transmitted along the path direction $\psi \equiv 0$ according to

$$\Phi_{\mathrm{T}}^{\mathrm{M}}\left(\lambda, r_{\mathrm{T}}, 0, \bullet\right) = \Phi_{\mathrm{T}}\left(\lambda, r_{\mathrm{T}}, 0, \bullet\right) + 2\pi \int_{0}^{\psi_{\mathrm{FOV}}} \beta\left(\lambda, \psi, \varphi\right) \sin\psi \, d\psi \ , \tag{2.6}$$

where $\beta\left(\lambda, \psi, \varphi\right)$ is the volume scattering function (VSF) (Ch. 1, Sect. 1.5). In other words, because a transmissometer measures a portion of the forward scattered light, its measurement overestimates the transmittance $T\left(\lambda, r_{\mathrm{T}}\right)$ and underestimates the beam attenuation coefficient calculated with equation (1.6). The acceptance angle, and thus the scattering error, is dependent on the optical elements of the instrument. There is no standard specified for transmissometer acceptance angle, and each manufacturer may use a different one for each particular instrument design. Therefore, were the transmittance of a homogeneous water volume to be measured a number of perfectly calibrated beam attenuation meters from HOBILabs, WET Labs, or Sea Tech, for example, each instrument model would yield a slightly different $c\left(\lambda\right)$, because of its different acceptance angle. These differences also depend on the shape of VSF.

These considerations lead to two questions. What is the best detector acceptance angle choice for a transmissometer design? What method should be used to correct the beam attenuation measurements for scattered light acceptance?

The first question appears to have a simple answer. The above discussion and equation (2.8) would seem to imply that the smaller the acceptance angle, the better the measurement. That may not be correct. One must further consider what is being measured when choosing the acceptance angle (Pegau *et al*. 1995), and particularly at very small angles, in the presence of near-forward scattering. Density fluctuations due to natural, or instrument related, turbulence steer the beam into random fluctuations and increase the apparent beam attenuation coefficient (Bogucki *et al*. 1998) independently from ordinary molecular and particle scattering processes (Ch. 1, Sect. 1.5). How might this phenomenon affect a particular application of the measurement? Were a person interested in inverting the spectral beam attenuation coefficient to determine particle properties, they wouldn't want a beam attenuation meter that is very sensitive to scattering by turbulence. For active LIDAR imaging systems, on the other hand, it may be important to know the transmittance effects due to very near forward scattering independent of the sources that may dominate the scattering process. From another perspective, the angular resolution of radiative transfer models tends to be larger than one degree, so fine angular resolution of the volume scattering coefficient and related beam attenuation coefficient is not needed for accurate model calculations (Mobley *et al*, 1993). For many such calculations it is preferable to smooth the highly forward peaked phase function (Fig. 1.3, Ch. 2) and decrease the beam attenuation coefficient accordingly. Gordon (1993) indicates that for irradiance level radiative transfer it is possible to completely disregard scattering in the first 15°, an angle much larger than the acceptance angles of transmissometers. Finally, from an engineering perspective, it is more difficult to build a stable transmissometer with a very small acceptance angle. Based on these considerations, most transmissometers are designed with an acceptance angle $\lesssim 1^{\circ}$.

The second question has been addressed by several investigators over the years (Gumprecht and Sliepcevich, 1953; Jones and Wills, 1956; Jerlov, 1957; Duntley, 1963; Voss and Austin, 1993). Voss and Austin (1993) examined the scattering error for both collimated beam and cylindrically limited instruments designs. They found that the percent error increases with increasing acceptance angle and with increasing $c\left(\lambda\right)$. The average error for a 670 nm transmissometer with a 1.0° acceptance angle is approximately 19%. However, accurate correction of an apparent $c_{\mathrm{M}}\left(\lambda\right)$ measured by that instrument would require knowing both the VSF $\beta\left(\lambda, \psi, \varphi\right)$ over the range $0 < \psi \le \psi_{\mathrm{FOV}}$, and the single scattering albedo $\omega_{\mathrm{o}}\left(\lambda\right) = \dfrac{b\left(\lambda\right)}{c\left(\lambda\right)}$ (Vol. I, Ch. 2, Sect. 2.4). To date, very few reliable measurements have been made of $\beta\left(\lambda, \psi, \varphi\right)$ at angles less than 1°. Given the extreme rate of increase in the magnitude of the VSF for particles $\beta_{\mathrm{p}}\left(\lambda, \psi, \varphi\right)$, and for turbulence, as $\psi \to 0$ (Ch. 1, Fig. 1.3), any estimate of its integrated value over the range $0 < \psi \le 1°$ would be highly uncertain. That uncertainty would transmit directly into any $c(\lambda)$ correction algorithm attempting to account for the effects of the near-forward VSF.

The best approach to dealing with the effects of scattered light in measured beam attenuation coefficients may be that proposed by both Voss and Austin (1993) and Pegau *et al*. (1995). That is, do not try to apply any scattering corrections to the measured determination of $c(\lambda)$. Simply report the acceptance angle characteristics of the transmissometer used to make the measurements, and leave all considerations of how to handle scattering artifacts to the user of the data. Internal consistency of IOP is obtained by including light scattered up to a certain acceptance angle ψ_{FOV} in the beam attenuation coefficient, and not including it in the VSF. We may rerwrite (1.1), $c(\lambda) = a(\lambda) + b(\lambda)$, as

$$c(\lambda) = a(\lambda) + 2\pi \int_{\psi_{\mathrm{FOV}}}^{\pi} \beta(\lambda,\psi)\sin\psi d\psi + 2\pi \int_{0}^{\psi_{\mathrm{FOV}}} \beta(\lambda,\psi)\sin\psi d\psi \,,$$

or,

$$c_{\mathrm{m}}(\lambda) = c(\lambda) - 2\pi \int_{0}^{\psi_{\mathrm{FOV}}} \beta(\lambda,\psi)\sin\psi d\psi = a(\lambda) + 2\pi \int_{\psi_{\mathrm{FOV}}}^{\pi} \beta(\lambda,\psi)\sin\psi d\psi = a(\lambda) + b_{\mathrm{m}}(\lambda)$$

where $c_{\mathrm{m}}(\lambda)$ and $b_{\mathrm{m}}(\lambda)$ are the measured beam attenuation and volume scattering coefficients, respectively.

In another design variant, the beam is cylindrically limited, rather than collimated. In the cylindrically limited light arrangement, the pinhole at the source is imaged on the receiver lens, and the receiver aperture is focused on the source lens. This design illuminates a large volume of water and uses more of the source light. No currently available commercial instruments use the cylindrically limited design, although at one point in history, transmissometers of this type were manufactured by Martek. The Visibility Laboratory Spectral Transmissometer (VLST) was a laboratory-built instrument using a cylindrically limited beam in a folded path configuration (Petzold and Austin 1968). Several copies of the VLST, built in the late 1970's, continued in use to measure $c(\lambda)$ until *circa* 1990.

Pathlength Considerations

One issue that must be addressed when designing a transmissometer is what the in-water pathlength should be. Scientifically, it is important to keep the pathlength long enough that the sample volume presents a statistical average of the surrounding water, and short enough that multiply scattered light is not incorporated into the beam. In most ocean waters, multiply scattered light is not in general a problem for the commercially available transmissometers. If scattered light leaves the beam then it will take two additional scattering events to get the light back into the beam and redirected towards the detector. The addition of baffles along the light path can nearly eliminate any possibility of multiply scattered light being detected in ordinary circumstance. In extremely turbid waters, however, the single scattering albedo is very large, and the volume scattering phase function $\tilde{\beta}(\lambda,\psi,\varphi)$ is extremely biased in the near forward direction (Fig. 1.3, Ch. 1). Under such conditions, if $r_{\mathrm{T}} > 3c(\lambda)^{-1}$ m, there is a significant probability that some fraction of scattered photons will undergo 3 or more successive small angle scattering events, re-enter the transmission path, and join the flux reaching the detector. The apparent beam attenuation coefficient will be artificially reduced if this occurs.

There are also engineering concerns associated with the optical pathlength. The path must be short enough that light reaches the detector; it would do no good to have an instrument with a pathlength $r_{\mathrm{T}} \approx 10c(\lambda)^{-1}$ m, because the transmitted signal would not be detectable. On the other hand, the pathlength must be long enough for attenuation to reduce the transmitted flux enough that the difference in incident and transmitted fluxes are large enough to be measurable. Longer pathlengths also reduce the relative uncertainty in the measurement of the pathlength r_{T}.

A pathlength in the range $c(\lambda)^{-1} \le r_{\mathrm{T}} \le 3c(\lambda)^{-1}$ is generally considered close to optimal. As electronics and sources have improved, however, instruments with pathlengths $r_{\mathrm{T}} < c(\lambda)^{-1}$ m have been shown to work well over a wide range of oceanic conditions.

Ambient Light Rejection in Open and Enclosed Path Transmissometers

The basic transmissometer designs (Fig. 2.1) do not physically reject all ambient sunlight, which could add to the measured flux. Enclosed path designs that place the optical path within a cell through which the water is pumped, such as the ac-9, have more physical blocking of ambient light, but are not totally immune to its effects. Some scheme must be developed to remove ambient light artifacts. A simple approach is to measure the signal with the source on and with the source off. The ambient signal with the source off is used as the dark reference for relating output signal to transmitted flux. The current generation of instruments use a more sophisticated, but similar, approach. The light source is rapidly modulated (chopped) and the detector output is phase locked to the modulation frequency, so that the transmitted flux is proportional to the amplitude of the alternating component of detector output. The key underlying assumption is that the natural light field varies slowly and is not part of the alternating signal. This approach may have difficulties when the ambient light also varies rapidly, such as with indoor lights that have a 60 Hz fluctuation, or near the ocean surface where waves may rapidly modulate the light field. Even with good electronic rejection of ambient light, it is wise to reduce the possible influence of ambient light by using baffles and careful positioning of the instrument.

2.3 CHARACTERIZATION and CALIBRATION OF BEAM TRANSMISSOMETERS

Calibration With Pure Water

As explained above, the calibration constant C_T for a transmissometer is determined by measuring its response to a "standard" medium having a known value of $c_{\mathrm{STD}}(\lambda)$. The optical "standard" medium commonly used to calibrate oceanographic transmissometers and absorption meters (Ch. 3) is pure water, so that $c_{\mathrm{STD}}(\lambda) = c_{\mathrm{w}}(\lambda) = a_{\mathrm{w}}(\lambda) + b_{\mathrm{w}}(\lambda)$. The recommended values of $a_{\mathrm{w}}(\lambda)$ and $b_{\mathrm{w}}(\lambda)$ are taken from Table 1.2, as explained in Ch. 1, Sect. 1.2.

Pure water of optical calibration grade is freshly prepared by methods described in Chapter 3. This difficult step is critical, because residual traces of particles and/or dissolved organic material introduce serious calibration offsets and relative uncertainties between calibrations. The pure water standard is introduced into the optical path by one of two methods:

1. An open path transmissometer must be thoroughly cleaned and rinsed in purified water, and then immersed in a test tank containing the pure water standard. Care must be taken to prevent bubbles from collecting on the instrument's optical windows. It is ordinarily not practical to carry out this calibration procedure at sea.
2. To calibrate an enclosed path instrument, a volume of the pure water standard is pumped through the flow-through measurement cell, as described in detail in Chapter 3 for the ac-9, as an example. Procedures to assure bubbles do not form within, or be introduced into, the flow-through measurement cell (Ch. 3) must be followed carefully. This pure-water calibration procedure can be carried out at sea, and it is recommended to do so daily, whenever possible.

In either case, after allowing suitable time for the instrument to warm up, the instrument signal outputs in response to flux transmitted in the pure water standard and dark (ambient) background, $V_{\mathrm{D,w}}(\lambda)$ and $V_{\mathrm{D,w}}^{\mathrm{dark}}(\lambda)$ [and if appropriate, also $V_{\mathrm{R,w}}(\lambda)$ and $V_{\mathrm{R,w}}^{\mathrm{dark}}(\lambda)$], are recorded over a several minute sampling period and averaged.

For pure water, the forward scattering is sufficiently small that the acceptance angle has little effect on the calibration. From equation (1.7) (Ch. 1), the transmittance of the pure water standard is $T_{\mathrm{w}}\left(\lambda, r_{\mathrm{T}}\right)=e^{-c_{\mathrm{w}}(\lambda) r_{\mathrm{T}}}$. For an instrument with a source reference detector we substitute from (2.4) to write

$$\mathrm{C}_{\mathrm{T}}\left(\lambda\right)=T_{\mathrm{W}}\left(\lambda, r_{\mathrm{T}}\right)\frac{\left[V_{\mathrm{R,w}}\left(\lambda\right)-V_{\mathrm{R,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}, \tag{2.7}$$

or for an instrument with a constant source output we substitute from (2.5) to write

$$\mathrm{C}_{\mathrm{T}}\left(\lambda\right)=\frac{T_{\mathrm{W}}\left(\lambda, r_{\mathrm{T}}\right)}{\left[V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}, \tag{2.8}$$

as appropriate.

By straightforward combinations of (1.6), (2.4) and (2.7) it is easy to show that for a transmissometer with a source reference detector,

$$\left.\begin{aligned}
T\left(\lambda, r_{\mathrm{T}}\right)&=T_{\mathrm{W}}\left(\lambda, r_{\mathrm{T}}\right)\frac{\left[V_{\mathrm{R,w}}\left(\lambda\right)-V_{\mathrm{R,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}\frac{\left[V_{\mathrm{D}}\left(\lambda\right)-V_{\mathrm{D}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{R}}\left(\lambda\right)-V_{\mathrm{R}}^{\mathrm{dark}}\left(\lambda\right)\right]}, \text{ and}\\
c\left(\lambda\right)-c_{\mathrm{w}}\left(\lambda\right)&=\frac{1}{r_{\mathrm{T}}}\ln\left\{\frac{\left[V_{\mathrm{R,w}}\left(\lambda\right)-V_{\mathrm{R,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}\frac{\left[V_{\mathrm{D}}\left(\lambda\right)-V_{\mathrm{D}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{R}}\left(\lambda\right)-V_{\mathrm{R}}^{\mathrm{dark}}\left(\lambda\right)\right]}\right\}
\end{aligned}\right., \tag{2.9}$$

or combining (1.6), 2.(5) and (2.8) for a transmissometer with a constant source output

$$\begin{aligned}
T\left(\lambda, r_{\mathrm{T}}\right)&=T_{\mathrm{W}}\left(\lambda, r_{\mathrm{T}}\right)\frac{\left[V_{\mathrm{D}}\left(\lambda\right)-V_{\mathrm{D}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}, \text{ and}\\
c\left(\lambda\right)-c_{\mathrm{w}}\left(\lambda\right)&=\frac{-1}{r_{\mathrm{T}}}\ln\left\{\frac{\left[V_{\mathrm{D}}\left(\lambda\right)-V_{\mathrm{D}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}\right\}.
\end{aligned} \tag{2.10}$$

The essential calibration factors to be reported, therefore, are the detector response and ambient (dark) offset in pure water $V_{\mathrm{D,w}}\left(\lambda\right)$ and $V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)$, and if a source reference detector is used also its response and ambient offset $V_{\mathrm{R,w}}\left(\lambda\right)$ and $V_{\mathrm{R,w}}^{\mathrm{dark}}\left(\lambda\right)$. The total beam attenuation coefficient $c\left(\lambda\right)$ may be easily determined by adding $c_{\mathrm{w}}\left(\lambda\right)$ from Table 1.1 (Ch. 1) to the difference calculated with equation (2.9) or (2.10).

An alternative approach to determining the total beam attenuation coefficient directly from the measured voltage response is to determine, from the pure water calibration, a calculated offset reference voltage $V_{\mathrm{ref}}\left(\lambda\right)$ and dark offset $V_{\mathrm{dark}}\left(\lambda\right)$ such that the total transmittance may be calculated directly as

$$T\left(\lambda, r_{\mathrm{T}}\right)=\frac{\left[V_{\mathrm{D}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{ref}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}, \tag{2.11}$$

where it is assumed that $V_{\mathrm{D}}^{\mathrm{dark}}\left(\lambda\right)=V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)$ varies very slowly over time and may be treated as an instrument constant. This approach is only used with transmissometers assumed to have a constant source output, examples of which include the former SeaTech red transmissometers. The value of $V_{\mathrm{ref}}\left(\lambda\right)$ is calculated by combining (2.11) with the transmittance relationship (2.10) as

$$T\left(\lambda, r_{\mathrm{T}}\right)=T_{\mathrm{W}}\left(\lambda, r_{\mathrm{T}}\right)\frac{\left[V_{\mathrm{D}}\left(\lambda\right)-V_{\mathrm{D}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}=\frac{\left[V_{\mathrm{D}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]}{\left[V_{\mathrm{ref}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)\right]},$$

from which it easily follows that

$$V_{\mathrm{ref}}\left(\lambda\right)=\frac{V_{\mathrm{D,w}}\left(\lambda\right)-V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right)}{T_{\mathrm{W}}\left(\lambda,r_{\mathrm{T}}\right)}+V_{\mathrm{D,w}}^{\mathrm{dark}}\left(\lambda\right),\ \mathrm{V}. \tag{2.12}$$

The Sea Tech transmissometers were calibrated to read $c_{\mathrm{w}}\left(650\right)=0.364\ \mathrm{m}^{-1}$ in pure water. This representation and approach perhaps simplifies the determination of $c\left(\lambda\right)$ for the inexperienced user, but at the same time obscures the value of $c_{\mathrm{w}}\left(\lambda\right)$ used to determine the offset reference voltage.

Air "Calibrations"

The sensors output signal response $V_{\mathrm{D,air}}^{\mathrm{f}}$ and dark offset $V_{\mathrm{D,air}}^{\mathrm{dark,f}}$ are recorded in air by the manufacturer at the time of each factory water calibration. These values are typically reported with the calibration records, as "factory" air calibration and dark values (and thus the superscript "f"), to allow the user to periodically record "air calibration", or "air tracking" data as a check on instrument stability. Air tracking is primarily intended to be used to monitor offsets in the instrument's output due to changes in the optical system caused by shipping or mounting of the instrument to a cage or other deployment package. Air tracking can also be used to monitor instrument drift over extended periods of time. Historically, before the advent of pure water field calibrations, the air calibration was the only stability tracking method available.

Air tracking data is best obtained in the laboratory, where the environment is consistently clean and dry, preferably before and after each transmissometer deployment. Although air calibrations can be performed while in the field, it is at best, difficult to do them on a ship due to the moist environment. Readings in air may be significantly offset by small amounts of moisture either condensed on, or adsorbed in the windows.

Detailed protocols for carrying out air calibrations are provided for particular instruments by the manufacturer. In general terms, the protocols include instructions and methods for careful cleaning of optical surfaces, allowing time for exposed optical surfaces to dehydrate in a dry environment, and procedures to avoid or compensate for temperature increases when the instrument is operated in air.

User air calibration values can be used to adjust the pure water calibration and responses to correct for instrument drift as

$$V_{\mathrm{D,w}}^{\mathrm{adjusted}} = \frac{V_{\mathrm{D,air}} - V_{\mathrm{D,air}}^{\mathrm{dark}}}{V_{\mathrm{D,air}}^{\mathrm{f}} - V_{\mathrm{D,air}}^{\mathrm{dark,f}}} \left[V_{\mathrm{D,w}}^{\mathrm{f}} - V_{\mathrm{D,w}}^{\mathrm{dark,f}} \right], \tag{2.13}$$

and the adjusted pure water-response and dark values are substituted into (2.10) to calibrate field measurements. If the manufacturer instead provides a factory reference voltage for calibrating the instrument using equation (2.11), the adjusted pure water and dark values should be substituted in (2.12) to determine $V_{\mathrm{ref}}^{\mathrm{adjusted}}$. Air calibration adjustments of this type are usually recommended only for instruments with "constant" LED source output, such as the WET Labs C-Star, older SeaTech red transmissometers, and other similar instruments by different manufacturers. Field water calibrations are the recommended basis for correcting drifts in closed path, flow-through cell instrument, such as the ac-9.

Instrument Temperature Dependence

The change in a transmissometer's response and dark values are usually determined by measuring response variations, with the optical path in air, or in a dry, inert gas such as Nitrogen or Argon, as the instrument temperature is varied. The response and dark values at each internal instrument temperature (an ancillary measurement and data output needed for temperature corrections) are recorded, and reported either as a lookup table of correction factor and temperature pairs, or as the coefficients of a polynomial function of temperature that has been fit to the correction factors. Instruments that have a closed, flow-through optical cell are usually characterized in a water bath, the temperature of which is cycled over a range typically from 5 $^{\mathrm{o}}$C to 30 $^{\mathrm{o}}$C over the course of the experiment; to avoid condensation, the flow-through cell is usually filled with a dry, inert gas and sealed. The internal instrument temperatures are somewhat higher than the ambient temperature, due to heating by the electronic circuits and source. If this experiment is done with air in the optical path of an open-path transmissometer, *i.e.* in a temperature controlled chamber, some method must be used and documented to avoid artifacts due to condensation on the windows.

2.4 FIELD MEASUREMENT METHODS

The procedures for measuring *in situ* profiles, over depth *z*, of $c(z,\lambda)$ using constant output LED source transmissometers are straightforward. The instrument is connected into a data acquisition system and mounted on a profiling cage following the manufacturer's instructions. If the instrument has an analog output, the user must ensure that the external analog-to-digital converter used to digitize the readings is calibrated in absolute units of V, since that is the basis on which the instrument has been calibrated.

The windows on the beam transmissometer must be cleaned with lens cleaner, or a mild detergent solution, and a soft cloth, or tissue, rinsed with distilled water, then rinsed with isopropyl alcohol and wiped dry. An approximate air calibration reading should be made before every cast to verify that the windows are clean. A transmissometer dark voltage should also be measured at this time. These on-deck air calibrations should be logged and compared to the more careful air calibrations done under dry laboratory conditions before and after each cruise (Section 2.3). If pre- and post-cruise air calibrations are significantly different, the time history should indicate whether the change occurred suddenly (*e.g.* a scratch in the window), or as a drift over time.

Each time an open-path transmissometer is placed into the water, care must be taken to assure that bubbles do not collect on the windows, particularly if the instrument is mounted in a vertical orientation.

Protocols covering methods for making field measurements with the ac-9 instrument are described in detail in Zee *et al*. (2002). Some critical aspects of these protocols are briefly reviewed in Chapter 3 to emphasize their importance.

2.5 DATA ANALYSIS METHODS

There are several generic steps needed to process and analyze a vertical profile of measured transmissometer data:

1. ***Merge the transmissometer data*** with externally measured ***depth*** and ***temperature data***. Assuming that the transmissometer does not have an internal, high-quality depth transducer, it is usually mounted together with a CTD to provide the depth and water temperature fields. If the transmissometer output data record does not include the internal instrument temperature measured by a built-in thermistor, external water temperature provides the basis for any temperature compensation adjustments that may be required.
2. Apply ***lag corrections*** to account for the time interval between when water enters the intake port and when it enters the beam-attenuation measurement optical path in a flow-through transmissometer.
3. Subtract the ***depth offset*** between the pressure transducer used to measure package depth and either

a. the intake port of a flow-through transmissometer, or

b. the midpoint of the optical path in an open path transmissometer.

4. ***Field calibration adjustments*** should be applied by the methods specified by the manufacturer of a particular instrument. In many cases this will involve entering the changes in an instrument calibration file used by the computer software that implements and applies (2.9) or (2.10) to calibrate the data.
    a. Pure water calibration results are the preferred source of these adjustments for flow-through instruments.
    b. Air calibration for tracking drift corrections should be applied using only data from calibrations carried out under dry laboratory conditions and showing insignificant variations between replicated calibrations. When the manufacturer represents the calibration coefficients in terms of a reference signal to be applied using (2.11), the corrected air calibration factor is computed using (2.13).
5. ***Instrument Internal Temperature Compensation*** factors should be applied in the manner specified by the manufacturer of a particular instrument.
6. *Compute transmittances* $T(\lambda, r_T)$, ***and beam attenuation coefficients*** $c(\lambda) - c_w(\lambda)$ offsets, ***relative to pure water*** using the appropriate combination of equations (2.9), (2.10), or (2.11) with (1.6) for the instrument type and output data.

7. ***Add pure water*** $c_w(\lambda)$, determined from Table 1.1, to $c(\lambda)-c_w(\lambda)$ to obtain the ***total beam attenuation coefficient*** $c(\lambda)$.

Detailed procedures required to carry out each of the above steps for particular instrument are typically provided by the manufacturer. WET Labs Inc., for example, provides both a User's Manual for it's *ac-9* absorption and beam attenuation coefficient meter, and a detailed ac-9 Protocol Manual (Van Zee *et al*. 2002); additional information from the latter document, regarding absorption and beam attenuation measurements, is outlined in Chapter 3.

Many of the steps listed above apply also when a transmissometer is installed and operated on a ship as a component of an along-track measurement system. The lengthy plumbing path in such a system introduces intake-to-measurement lags of up to several minutes, while a research vessel typically advances approximately one Km in 3 min. Therefore, accurate temporal and spatial co-registration of, *e.g.*, surface water temperature, chlorophyll a fluorescence, and $c(\lambda)$ requires accurate determination of the flow rate and lag time between a water volume's intake (usually in a ship's sea chest), passage through some debubbler apparatus, and its arrival in the measurement cell of each instrument.

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