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TRANSMISSOMETRY AND NEPHELOMETRY

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Introduction

Transmissometry and nephelometry are two of the most common optical metrics used in research and monitoring of the Earth's oceans, lakes, and streams. Both of these measurements relate to what we perceive as the clarity of the water, and both provide vital information in numerous studies of natural processes and human activities' impact upon water bodies. Applications involving these measurements range from monitoring drinking water suitability to understanding how carbon is transferred into and transported within ocean waters.

Transmissometry refers to measurements made by transmissometers or beam attenuation meters. These sensors infer the total light lost from a beam of light passing through the water. These losses are caused by two primary mechanisms. Suspended particles and the molecules of the water itself scatter the light away from its original path; the water, and dissolved and particulate matter contained within, absorb the light and convert it into heat, photosynthetic activity, fluorescence, and other forms of energy. Larger concentrations of scattering and absorbing substances therefore result in greater losses in signal.

Nephelometry refers to measurements made by optical scattering sensors, often referred to as turbidity sensors or nephelometers. These sensors project a beam of light into the water and measure the radiant flux of light scattered into the direction of a receiver. Since the receiver signal increases with greater numbers of particles, the device infers the concentration of suspended particles in the water.

Scattering sensors are used more commonly in environmental monitoring applications, especially in highly turbid waters with large concentrations of particles; transmissometers see more use in general scientific studies. However, the uses for which they are employed broadly overlap. Nevertheless, transmissometers perform quite different measurements from those of scattering sensors and the quantities they measure are independent of one another and typically offer no direct comparison. In fact, while the data products they provide may covary, the relationship between the values most certainly will differ depending upon the composition of the materials in the water.

Using a transmissometer one can derive an attenuation coefficient that mathematically describes the ability of the water to transmit light. This coefficient is a fundamental optical characteristic and an absolute quantity for a given medium. The scattering sensor, on the other hand, collects a very small portion of the scattered light and is usually calibrated to some secondary standard. The units of measurement are themselves relative to that standard. Other differences also prove crucial in defining these measurements. Limitations imposed by the instruments themselves, application-specific requirements, sensor sizes, and cost all play roles in determining the possible suitability of one measurement versus another. Thus, in order to best fit these two methods to potential applications, it is necessary to understand the measurements, the design of the sensors performing them, and the products that the sensors provide.

Measurements and Fundamental Values

In the realm of water sciences, transparency and turbidity are two of the most commonly used terms in describing optical clarity. These are general terms and typically not tied to absolute physical quantities other than through the use of secondary standards. However, the set of underlying optical processes that describe the impact of water-based media upon light propagating through them are well defined, if not completely understood. In the study of the transmission of light energy through water, the inherent optical properties (IOPs) refer to the set of intrinsic optical characteristics of the water and components contained therein. The IOPs define how light propagates through the water. In comparison to apparent optical properties (AOPs), the other general class of in-water optical measurements, the IOPs are not affected by changes in the radiance distribution from sunlight or other sources. The IOPs include coefficients for the attenuation, absorption, and scattering of light as well as the volume scattering function.

The coefficients of attenuation (c), absorption (a), and scattering (b) determine radiance losses of a ray of light propagating through the water. Light is either lost to absorption by the water and material contained within or it is scattered by the same. The attenuation coefficient accounts for losses attributed to both the absorption and the scattering and is equal to the sum of these coefficients eqn [1].

$$c = a + b \qquad [1]$$

One determines the beam attenuation coefficient by comparing the radiant flux of a collimated beam of light at source (F_s) with the radiant flux of the beam at a receiver detector (F_d), a finite distance (r) away. This ratio is known as the beam transmittance (T), given by eqn [2] or equivalently by eqn [3].

$$F_d/F_s = T = e^{-cr} \qquad [2]$$

$$c = -\ln(T)/r \qquad [3]$$

Here r is the path length between the source and the receiver. This coefficient is the value ultimately determined by a transmissometer. The attenuation coefficient is expressed in units of inverse meters (m^{-1}). Thus, when one refers to water with an attenuation coefficient of $1\,m^{-1}$, the implication is that within a 1 m path the available light within a collimated beam is reduced to 1/e or approximately 37% of its original energy.

Within the visible light spectrum the scattering and absorption losses from the water itself remain effectively constant, and thus variability found in field measurements results from non-water particulate and dissolved matter. The extent of absorption-based losses compared to scattering-based losses depend both on the materials being measured and on the spectral configuration of the meters. Both the scattering and absorbing properties of water-based components are prone to variation with the wavelength of light at which measurements are conducted. Variations in the absorption depend heavily upon the amount of colored dissolved organic matter (CDOM) and chlorophyll content. CDOM absorbs very strongly in the blue wavelengths; chlorophyll absorbs heavily in the blue and in addition has a pronounced absorption peak in the deep red portion of the spectrum (676 nm). Absorption by these materials provides the appearance of color to the water. Visually, CDOM laden waters tend to appear brown, and chlorophyll-rich waters appear green. A deep blue cast to the water indicates very low levels of both of these substances. The spectral dependency of the scattering signals is largely due to the size of the particles from which the light is scattered (**Figure 1**).

In addition to the optical loss coefficients, the volume scattering function (VSF) forms another important component of the IOPs in describing the fate of light in water. The VSF describes optical scattering as a function of the angle, θ, away from the direction of propagation of the incident beam of light. The VSF coefficient, $\beta(\theta)$, defines the radiant energy lost into a given angular region of the light scattering and is expressed in terms of inverse meters per steradian. The VSF integrated over the entire spherical volume into which light is scattered provides b, the total scattering coefficient (eqn [4]).

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin(\theta)\, \mathrm{d}\theta \qquad [4]$$

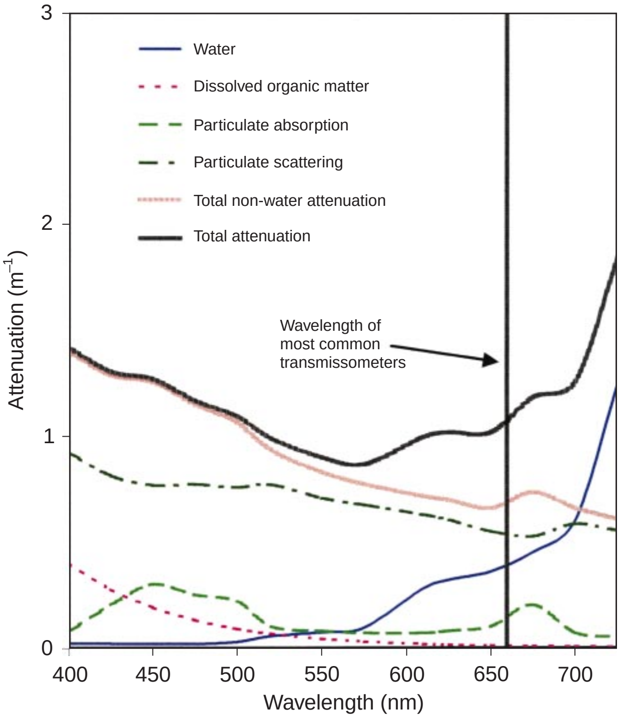

Figure 1 Relative contributions of water and non-water scattering and absorbing components are seen in formulation of the attenuation coefficient within 'typical' waters.

The actual shape of the VSF depends upon the particle field being measured. Specific properties that define this shape include the particle size and shape and the index of refraction. Particle size is probably the single most pronounced factor in defining the VSF in that it dictates the regime of light interaction with the particles themselves. Very small particles that fall within the wavelength of the light impinging upon the particles are subject to molecular or Rayleigh scattering. This interaction is relatively weak, and creates a VSF that is relatively constant with angle. While Rayleigh scatterers are by far the most prevalent in most waters, most of the scattering signal seen by sensors is attributed to particles ranging from 1 μm to > 50 μm. The scattering behavior of these particles is typically modeled using Mie theory. Mie theory uses Maxwell's equations to predict perturbations of an incident planar wave by spherical particles in its path. In general, larger particles will create a greater degree of near-forward scattering.

Most scattering sensors are not considered tools for determination of in-water optical properties, but all scattering sensors including turbidity sensors measure the VSF within a given angular region, typically somewhere in the region of 90–160° with respect to the incident direction of the light. It is perhaps ironic that while these sensors are among the most ubiquitous of in-water optical tools, the VSF is one of the least-characterized of all the IOPs. This is because no single angle measurement can account for the shape of the entire function. This in turn points to a major source of error in all turbidity-based measurements. Different materials dictate different VSFs and a single angle measurement will vary with concentration from one type of material to the next. In actual fact a diverse amalgam of organic and inorganic particulates reside within most waters. This ultimately tends to homogenize the VSFs such that the variability in the VSF of the composite is less than the variability of individual components (**Figure 2**).

Most scattering measurements are based upon some standard such as formazin, diatomaceous earth, or more recently spherical styrene bead suspensions. These standards are used because they tend to be reproducible and easy to mix into various concentrations for calibrations. Units of quantity are expressed in form of turbidity units such as NTU (nephelometric turbidity units). Because of the disparate VSFs of these standards and natural waters, total attenuation (or particle concentration) cannot be obtained from turbidity measurements without intercalibrating with transmissometers (or by filtering and weighing) in natural waters.

Sensors

Transmissometers

A basic transmissometer consists of a collimated light source projected through an in-water beam path and then refocused upon a receiver detector. Typically single-wavelength transmissometers employ a light-emitting diode coupled with an optical bandpass filter as the source. Source light is often split so that a portion of the beam impinges upon a reference or compensation detector that is either used in numerical processing of the data or integrated into a source stabilization feedback circuit. The source output is often modulated and the lamp and receiver detector samples are in phase with the source modulation. This greatly reduces ambient light detection by the receiver from the sun or other unwanted sources. Path lengths are fixed with distances typically ranging from 5 cm to 25 cm depending upon the waters in which the sensors are used (**Figure 3**).

The receiver detector converts radiant flux into current and its output is thus proportional to the radiant energy passed through the water. Electronics subsequent to the detector amplify and rectify the signal for digitization or direct output as a DC voltage level. This signal is known as the instrument transmittance (T_i) (eqn [5]).

$$T_\mathrm{i} = S \times T \qquad [5]$$

S represents the instrument transmittance scaling constant. This constant is a combined term that includes signal amplification, losses through windows and lenses, and other sensor gain factors. From eqn [5] and assuming a 25 cm pathlength, we obtain eqn [6] or equivalently eqn [7].

$$T_i/S = \mathrm{e}^{-c(0.25)} \qquad [6]$$

$$c = 4 \ln T_\mathrm{i} - Q \qquad [7]$$

The constant $Q = 4 \ln S$ is a general scaling term that is removed, or compensated for, during the calibration process.

An ideal transmissometer would reject all but the parallel incident light into its receiver. This implies that there is no error associated with near-forward scattered light getting into the receiver. However, limitations in real-world optics make this a near impossibility. Transmissometers thus provide a value for a system attenuation coefficient that has

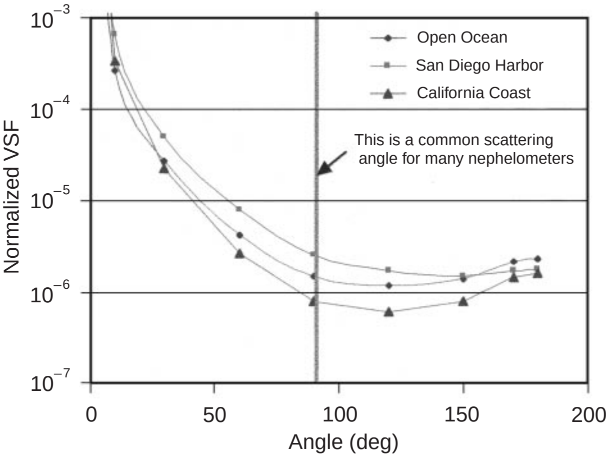

Figure 2 Normalized VSF data for three representative ocean water types. Note that at 90°, the most common nephelometer scattering angle, significant differences exist for the respective coefficients. Data collected by Theodore Petzold and Seibert Duntley of Scripps Institute of Oceanography.

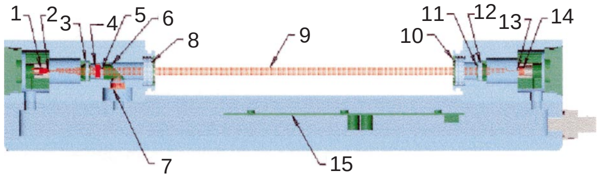

Figure 3 Cutaway view showing the primary optical components found in a modern transmissometer. A transmitter assembly and receiver assembly are mounted and aligned within a rigid frame. The transmitter assembly consists of (1) a source lamp; (2) a pinhole aperture; (3) a collimating lens; (4) field aperture; (5) an interference filter; (6) a beam splitter; (7) a reference detector; and (8) a pressure window. The beam (9) then passes through a fixed-path volume of water and enters the receiver assembly. The receiver consists of (10) a pressure window, (11) field aperture, (12) a refocus lens, (13) a pinhole aperture, and (14) the receiver detector. Signals from the detector are then fed to the electronics for processing and output (15).

a finite scattering error and is defined primarily by the acceptance angle of the receiver optics. These values range from around 0.5° to 1° in water for most commercial instruments. Because that VSF for in-water particles is highly peaked at these angles, this can result in underestimation of the attenuation coefficient and can also lead to sensor-to-sensor discrepancies in measurement. It thus becomes important to know this angle in treating data carefully. While it is possible to build sensors with narrower acceptance angles than 0.5°, scattering in the very near-forward direction becomes dominated by turbulent fluctuations in the density of the water itself. This turbulence-induced scattering is irrelevant to particulate studies and, depending upon the distances and receiver sizes involved, to most signal transmission applications.

The conceptual framework for the transmissometer measurement involves starting with a full signal and monitoring small negative deviations from it. The sensitivity of the instrument thus depends upon its ability to resolve these changes. In many oceanic and other clear water investigations, signal changes as small as $0.001\,\mathrm{m}^{-1}$ become significant. In a 25 cm instrument this implies a requirement for transmittance resolution on the order of 0.025%. At the other end of the environmental spectrum, many inland waterways and some harbor areas would render a 25 cm path instrument ineffective due to loss of all signal. Therefore, range and resolution become the two critical factors in determining a transmissometer's effectiveness in a given application. While it is easy to imagine using arbitrarily long path lengths to obtain increased sensitivity, the instrument path begins to impose other limitations upon its utility. Size and mechanical stability both reduce utility of the longer path instruments. On the other hand, shorter paths impose more demands than just high levels of precision in measurement. Cleaning of optical surfaces also becomes a major issue in maintaining sensor reproducibility and accuracy. Again using the 25 cm path length instrument as an example, maintaining signal reproducibility of $0.01\,\mathrm{m}^{-1}$ over time requires a cleaning technique that gives results that repeat within 0.25% transmittance. For a 10 cm path length instrument, repeatability would need to be within 0.10% transmittance. Likewise, internal correction mechanisms such as compensation of temperature-related drift impose stringent requirements upon the sensor's electronics as well as the subsequent characterization process. Long-term drift and general mechanical stability also must be tightly constrained for the instrument to provide accurate results over time. The requirements prove challenging in light of the forty degree (centigrade) temperature swings and the 6000 meter depth excursions to which the instruments potentially get exposed.

While the calculation of the attenuation coefficient from raw transmittance is independent of the cross-sectional area of the beam, the beam size does play an important role in the transmissometer's ability to measure. Accurate transmittance measurements rely upon the water and the materials it contains acting as a homogenous medium. This model starts to break down in two important cases: when the number concentration of particulates becomes significantly low compared to the total volume of the illuminated sample area; and when the particle sizes become significantly large in comparison to the cross-sectional area of the beam. Taken in the extreme, one can easily imagine a very narrow beam providing a binary response at the receiver depending upon whether a particle occludes its path. Practically speaking, most transmissometers need to show minimal spiking for particle sizes up to 100 μm diameter. Particles more than a few micrometers in diameter are 'seen' by the receiver at about two times their actual size as a result of diffraction. This means for a beam of 5 mm nominal width that a single 100 μm particle could reduce signal at the receiver by approximately 0.08% or on the order of $0.0032\,\mathrm{m}^{-1}$ in a 25 cm path (or $0.008\,\mathrm{m}^{-1}$ in 10 cm path). This proves acceptable for most operational conditions. On the other hand, a 1 mm particle could create an 8% deviation in sensor output, creating a noticeable spike. Fortunately, 1 mm particles are extremely rare except in active erosion zones.

There are presently two primary methods used in calibrating transmissometers. The first uses fundamental principles of beam optics and knowledge of the index of refraction difference between air and water to directly estimate the sensor output. Electro-optical linearity in response to signal changes is assumed or verified. The sensor's gain level is set near full scale for transmission in air and the sensor is checked to ensure that if the source output is completely blocked it provides a real zero output. Accounting for the differences in reflection and transmission of the air–glass interfaces compared to the water–glass interfaces, one can then assume that, upon immersion, any further deviations in signal are due to the attenuation of the water and materials contained therein. This measurement is then verified by immersion in clean water and subsequent comparison to clean water values. Error terms in this method usually include deviations of the modeled optics from the real world. These errors include lens-induced focusing aberrations, alignment issues, spectral content of the source, and any dust or film on any of the optical components. The primary advantages of this method are that the calibration process relies only upon the air value measured by the meter, and that the attenuation due to the water is included in the water-based measurements.

The second method involves blanking the meter directly with clean water. More akin to calibration approaches used in spectrophotometry, this method involves immersion of the instrument into optically clean water, measuring the value, and setting that value as full-scale transmittance or, conversely, $0.000\,\mathrm{m}^{-1}$ attenuation (clean water values for the attenuation can then be added back in accordance with published values). The chief disadvantage of this method lies in the difficulty of creating and verifying optically clean water. While various levels of filtering can remove most of the particulates from the water, filters can also introduce bubbles. These bubbles are seen as particles by the sensor. Assuming that one achieves filtration without introducing any bubbles, bubble creation is still a concern in that any partial pressure imbalances between the gases contained within the water and the surrounding environment will result in subsequent bubble formation. Added to that is the possibility that the containers and the sensors themselves may also act as sources of particulate contamination. The chief advantage of this method is that it accommodates for small deviations in the real instrument with respect to the ideal.

The overriding issue with calibration of transmissometers is the same as in the discussion of the need for and difficulty of proper cleaning. In order to calibrate an instrument to operate accurately in cleaner waters, the calibrations must achieve accuracy to within 0.25% of full-scale measurement. Ultimately, reproducibility of results becomes the best check for calibration. That said, this level of accuracy is really only required in conditions where particle concentrations are approaching minimal levels. Relative changes of transmittance will still be precisely reflected in the instrument's measurements.

Scattering Sensors

A simple scattering sensor consists of a source element projecting a beam of light in the water and a receiver detector positioned at a fixed angle with respect to the source. The source beam is sometimes stabilized by inclusion of a second receiver that receives a portion of the light coming directly out of the lamp. This signal is then fed back into the lamp driver circuitry to compensate for fluctuations in the source with time and temperature. The source beam has a defined primary projection angle and a distribution of light about that angle. Conversely, the receiver is placed at a specific angle and maintains a defined field of view about that angle. These factors combine to form the distribution of angular response for the scattered light (**Figure 4**).

As with transmissometers, it is necessary to reject ambient light from the sun and other non-sensor sources during measurement. With scattering sensors this is achieved both through the use of synchronously modulated light and detector amplification and also through the use of direct optical rejection. Direct optical rejection is employed at the source through the use of relatively narrow spectral band sources that emit light in the infrared away from the water-penetrating wavelengths of sunlight. Accordingly the receiver incorporates narrowband optical filters that reject wavelengths away from the primary emission bands of the source.

Specific angular configurations used in modern scattering sensors vary widely. Some sensors are designed to operate within a highly constrained, narrowband, angular relationship, and some are designed to collect as much scattered light as possible and thus encompass a very wide angular range. In general two truths hold for all the designs: they will all provide a roughly linear response that is proportional to the particle concentration (at least in low to moderate concentrations); and different optical configurations will demonstrate different absolute response curves with respect to each other even when calibrated with the same standard (**Figure 5**).

A scattering sensor works by the simple principle that when particles are present they will scatter light

Figure 4 Typical scatter sensors and transmissometers.

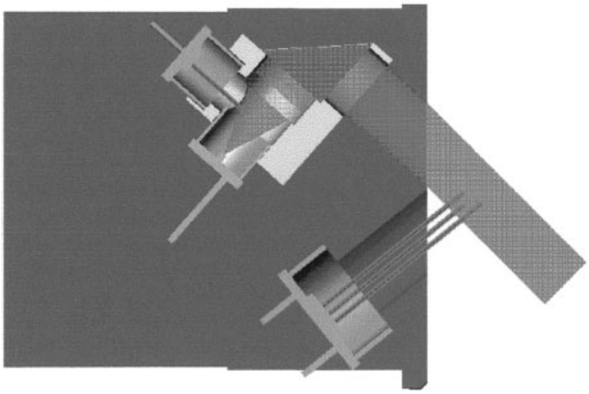

Figure 5 One of many possible optical configurations for a scattering sensor. A source assembly consisting of a LED lamp, reference detector, lens, and right angle prism projects light into the water. The receiver is placed to receive light at 90° with respect to projected source beam.

and the receiver will collect some of that light. Using Beer's law, which states that increasing concentrations will result in a linear increase in output signal, the sensor's output varies from a zero value in clean water to a full-scale value at the upper end of its range. While it is convenient to assume a linear response with concentration, this is not strictly true. Light reaching the volume of interaction and the light scattered back into the detector is subject to secondary losses due to attenuation. As the concentration of scattering components in the water increases, so does the attenuation. This produces a nonlinearity in the output signal. In sensors with large interaction volumes and a wide angular response, this becomes a particularly messy analytical problem in that the light is subject to a large range of effective path lengths in propagation from the source and back to the receiver. In the extreme case, sensors exist that position a near-isotropic source next to a wide-angle detector such that they both project out, perpendicular to the same plane. In these sensors the effective volume of interaction is strictly a function the attenuation coefficient in that it is infinite other than for induced losses of light. As with transmissometers, the volume of interaction also affects a scattering sensor's sensitivity and the effect of larger particles upon the signal. Small volumes show less sensitivity and measure larger particles as signal spikes. The combined issues of long-path attenuation coupling and volumetric sensitivity point to the preference of designs incorporating larger beams with greater interaction volumes for measurements of cleaner waters and narrower beams with interaction volumes close to the sensor surface for use in highly turbid waters.

The response of a given scattering sensor is very highly dependent upon its specific optical configuration. Angle of interaction, angular distribution, wavelength at which the source emits, and the relative path distance from the source and back to the receiver are all factors in how a sensor will behave. As mentioned earlier, it should be expected that two different designs will provide two different responses. In studies in which researchers require only relative responses with space or time, this is not a major issue. A twofold change in a given concentration of particles will generate an associated response in the instrument output. However, many studies require some form of reproducible results. It is not enough that two sensors are calibrated to the same medium. They must also respond in the same way to any other medium that they might mutually measure. Standards such as ISO 7027 have been published. These standards impose constraints on the angle of interaction between the source and the receiver (90°), the angular distribution of the source, and its wavelength of operation, as well as other design parameters. The goal is to ensure that all sensors built within the constraints imposed by the standard will provide similar results in similar waters. This is a very important step toward achieving consistent results amenable to intercomparison.

Straightforward in concept, sensor calibration employing a standard suspension, provides several pitfalls in practice. First and foremost, no calibration can be achieved to better accuracy than the standard solutions themselves. Secondly, it is critical to ensure that the container in which the calibration takes place is not a cause of secondary reflections of light that can get back to the receiver. Care must also be taken to ensure that the suspension is not settling or flocculating during the measurement. Finally, one variation of this technique is to use arbitrary concentration of the calibration media and calibrate against another 'standard' precalibrated sensor. Great care should be applied when using this method. Standard sensors often already incorporate compensation schemes for linearizing the data. These schemes in turn are developed for use with a specific type of suspension. This can create dramatic and surprising results when using another suspension.

While scattering sensors are predominantly used to determine relative concentrations of particulates, another very important set of applications involve characterization of the volume scattering function itself. One of the important goals in observational oceanography involves the use of remotely sensed data from satellites and other airborne platforms to rapidly characterize large areas of surface and near surface waters. Of particular interest are the emerging methodologies associated with using ocean color data captured from airborne and space-borne platforms to provide information about the biology and chemistry of waters. In the United States, NASA projects such as the Coastal Zone Color Scanner and the more recent SeaWiFs satellite program stimulated this interest, and in the case of SeaWiFs continue to contribute a growing body of information. The light that these platforms receive is a function of the sea surface state and the resultant reflections and the water-leaving radiance. This radiance in turn is defined by the absorption and scattering characteristics of the water. Scattering in the region of 90–180° is specifically important because it represents incoming light from the sun that is scattered back into the atmosphere. To quantify this, a class of sensors called optical backscattering sensors have been developed and calibrated specifically for this purpose. In many respects these sensors are very similar to other scattering sensors in that they use the same basic optical configurations and respond similarly to variations in the particle field. The major differences involve design constraints upon the wavelengths of the source emitters and the angles of interaction. Equally importantly, the calibration of these sensors involves tying the sensor response directly to the volume scattering function.

Calibration of scattering sensors for radiometric measurements involves detailed knowledge of the sensor optics geometry and some known scattering agent. The prevalent method for single-angle measurements incorporates a sheet of highly reflective diffuse material and maps the sensor response as a function of the distance between the target and the sensor. This information is then applied to derive the angular weighting function of the interaction volume. Finally, this weighting function is applied to a typical ocean water VSF. More recently, researchers have begun to apply a calibration technique that incorporates known concentrations of scattering agents with well-defined VSFs. These two techniques address different elements of a sensor calibration and may well find optimum effectiveness when used in conjunction with one another (**Figure** 5).

Applications

Domains of Use

The use of transmissometers and nephelometers falls broadly into two categories. We want to study the water's optical properties and how they might relate to ongoing processes occurring in the water, and we want to determine how much foreign matter is in it. While, ultimately, both thrusts of study lead to measurement of the same media within a given body of water, the products that the instruments provide differ, and the requirements surrounding the given areas of study tend to drive the development of the different technologies. The factors ultimately determining the appropriateness of one sensor versus another do not always pertain to the data products provided. Size, cost, ease of deployment, ease of maintenance, and researcher's experiences all contribute to decisions on which type of sensor is the best to use.

Optical oceanographic research motivated much of the development of modern transmissometers. This arena also stimulated development of scattering sensors that are specifically designed and calibrated for providing coefficients related to the VSF. Much of this work in the United States revolves around Naval research needs, and primary development of sensors now available commercially was in large part funded through Naval research dollars. Naval applications include mine hunting, underwater tactical assessment for diving operations, and sea truthing for laser communications and imaging research. The US National Aeronautics and Space Administration (NASA) has also played a major role in developing underwater tools for optical characterization. These tools help calibrate the airborne sensors. Similarly, numerous other governments foster the development and use of these tools through their respective Naval, space and other scientific agencies. While not engaged in the study of ocean optical properties *per se*, many other ocean scientists working under aegis of funds supplied by these agencies use transmissometers and optical backscattering sensors in ongoing efforts to understand physical, biological, and chemical distributions and processes in the water.

Scattering sensors remain the dominant optical tools used by environmental researchers. These sensors' size and cost make them widely affordable and easily used, and the newer sensors incorporate fouling-retardant features such as shutters and biocidal exposed surfaces. As such they are becoming increasingly subscribed to as the sensor of choice in compliance-driven monitoring applications developed by various governmental agencies throughout the world. Naturally, the more attractive size and costs of scattering sensors also make them favorable choices in many larger-scale applications.

It is likely that remote sensing will to some degree change preferences for sensors among fresh water researchers over the next ten years. Presently there is relatively little airborne color data available for fresh water bodies, and thus many limnology researchers have not yet been compelled to measure optical properties of lakes directly. With the next generation color airborne sensors and new governmental mandates driving more effective broader-scale sampling strategies, the need and desire for transmissometer measurements and scattering measurements for VSF determination will undoubtedly grow.

How Sensors are Deployed

One major constraint in an underwater sampling is how to use the instrumentation effectively in the environment for which it is intended. Researchers often want to measure the water in places they cannot easily get to, or over timescales that make personal attendance of equipment an unappealing proposition. To these considerations must be added the requirement that the data gathered must truly reflect changes at the time and space scales of the governing processes within the water column, and the constraint imposed by doing this sampling at a reasonable cost. The sampling challenge becomes formidable. As a result, the development of effective sampling platforms has become as challenging and competitive a discipline of research as instrumentation design itself.

Transmissometers and scattering sensors are typically integrated into multiparameter sampling packages for acquiring and storing data (CTDs, data sondes, loggers). The packages are then deployed from boats or other platforms and lowered through the water column, travel on or are towed by a vessel, or are placed on buoys or mooring lines in order to log measurements over an extended period. Many variations of these basic methods exist but virtually all entail these basic concepts.

A new class of autonomous deployment platforms will serve to revolutionize underwater sampling. These range from miniature programmable underwater vehicles, to freely drifting ocean profilers that can continuously move through the water column, and to rapidly deployable profiling moorings. Many flavors of these various platforms are now emerging. Some will find important niches for acquisition of data over space and time.

Some Current Applications

There are many different applications engaging the use of transmissometers and scattering sensors. **Table 1** represents only a sampling across numerous disciplines.

Extending Capabilities

As mankind's need to understand and monitor the Earth's waters has increased, they have driven the development of more rugged, more reliable, smaller, and cost-effective technologies for transmissometry and nephelometry as measurement techniques. These resultant technologies have not only carved greater roles for optical measurement methods but have also proved seminal in the development of entirely new sensors. Recently, a new generation of IOP tools has been made available to the oceanographic community. They include sensors for the determination of the in-water absorption coefficient, multiangle scattering sensors, and a set of IOP tools with spectral capabilities. Transmissometers and simple scattering sensors have laid the foundation for the optical techniques and data methods of these new devices. In turn, these new sensors promise to significantly enhance the role of IOP measurements in modern observing platforms.

One of the more significant recent breakthroughs in optical measurement techniques lies in the development of the absorption meter. This sensor uses a measurement method and optical geometry similar to a transmissometer except that it encompasses the sensor's beam path with a reflective tube and incorporates a large-area detector at the receiver end of the path. The reflective tube and large-area detector combine to collect the bulk of the light scattered from the source beam. Thus the light not detected is primarily due to absorption by the water and its constituents.

The wide-band spectral nature of sunlight coupled with the selective filtering capabilities of water and the absorption characteristics of phytoplankton and dissolved organic material make spectral optical characterization of the water highly desirable. Likewise, the spectral information from the scattering of particles provides more direct correlation with remote color data as well as a more complete description of the type of particles scattering. New tools encompassing spectral attenuation, absorption, and scattering are now commercially available. These tools are playing increasingly important roles in various applications.

Despite the plethora of scattering sensor data available, very little information exists concerning the range of variability of the VSF, and how it relates to different water masses and the processes within them. One of the chief constraints in fully characterizing the VSF is that it requires a multi-angle scattering measurement encompassing in excess of 4 orders of magnitude of scattered light intensity. After some seminal work performed by researchers at the Scripps Institute of Oceanography during the late 1960s and early 1970s, very little has since been done to add to this body of data. In fact, VSF functions measured then remain *de facto* calibration standards for instruments being built today. In recent years researchers in Europe and the United States have refocused attention upon this issue. As a result, a new set of multiangle scattering sensors is now coming into commercial availability.

Other development efforts and new instrumentation incorporate scattering and transmittance measurements in unique ways to obtain specific underwater chemical and biological components. One example of these includes an underwater transmissometer that uses polarized light to determine concentrations of particulate inorganic carbon. These instruments promise to fill a vital niche in understanding the fate of carbon in the seas. Another example in development are underwater flow cytometers. While the prevalence of IOP measurements look at bulk phase phenomena, new instruments are now available as ship-board and dock mounted units that couple scattering and fluorescence measurements of individual cells and organisms to provide identifying signatures. Patterned after laboratory flow-cytometers, the in water devices will offer break-through capability in typing specific organisms in their natural environment.

One of the most exciting aspects of the recent advancements in IOP-related technologies lies in the opportunities offered by their combined use. One marked example lies in the characterization of particle aggregations in the water. While the attenuation

Table 1 Applications of transmissometry and nephelometry

Application	*Description*
Monitoring terrestrial runoff and impact of industrial inflows on water quality	Scattering sensors stationed in rivers and streams allow researchers to determine impacts of inflows upon water quality. Inflows might be created by logging, agriculture, mining, land development, controlled and uncontrolled outflows from water treatment plants, natural runoff and other events that introduce new matter into the monitored bodies.
Compliance monitoring	United States' compliance monitoring of fresh water bodies is soon likely to include turbidity as a required parameter for ongoing measurement.
Determining biological distribution in the water	Both transmissometers and scattering sensors are deployed in viewing the biological variability in space and time through the water column.
Radiative transfer studies – optical closure	In verifying the optical relationships between the inherent and apparent optical properties, researchers seek to test the relationships through direct measure and comparison of values from the disparate instrument types. Scientists also seek to reconcile measurements of the inherent properties among themselves in validation of IOP theory.
Remote sensing validation	Satellite and other airborne remote imaging systems require in-water transmissometry, scattering, and absorption measurements to calibrate these sensors to water-borne optical properties.
Studying the benthic layer processes	In understanding the processes effecting the settling and re-suspension of particles near the bottom of the water column both scattering sensors and transmissometers can provide relative indications of particle flux.
Frazil ice formation	Transmissometers have been shown to 'see' signal fluctuations associated with the formation of frazil or supercooled ice. These studies are imperative in understanding how polar ice sheets are formed.
Diver visibility	Navies require better tactical assessment of waters for determining operational risk for divers and other visibility-related operations.
Small-scale structure in the water column	In coastal regimes many physical and ecological processes take place on smaller time and space scales than previously thought. The speed of acquisition and sensitivity of modern scattering sensors and transmissometers allow accurate particulate mapping within the water column, which in turn serves as a tracer for these processes.
Tracking particulate organic carbon	Data from transmissometers has been shown to accurately reflect total particulate organic carbon within the water column. Understanding in-water carbon transport processes is, in turn, vital to understanding carbon flux between the water and atmosphere through the uptake and output of CO_2.
Tracking bloom cycles	Transmissometers on moorings located both in open ocean and in coastal areas track seasonal bloom cycles as well as event-driven changes from major storms or other potential system disturbances.
Monitoring activity around thermal vents and underwater volcanoes	Scattering sensors on moorings and underwater vehicles track plumes from underwater vents and eruptions.

or scattering at one wavelength will provide data about relative concentrations of particles within the water column, spectral data from these sensors combined with absorption measurements can move us a long way toward characterizing the aggregation into various biological and inorganic components.

Summary

Transmissometry and nephelometry provide increasingly valuable information relating to the light-transmitting characteristics of water as well as an idea of the relative concentration of suspended material within lakes and oceans. While sometimes viewed as near-synonymous techniques, these methods use different measurement methods, provide different products, and have different strengths and weaknesses in considering the applications to which they are applied. Applications vary widely and across numerous disciplines, but tend to be divided into two major classes: those that attempt to characterize the fundamental optical properties of the water; and those that seek the relative concentrations of foreign particulate matter in the water. In general, nephelometry is the preferred technique in environmental and fresh water applications and transmissometry is more common in oceanographic research. Although transmissometry and nephelometry differ as measurement techniques, in their application domains, and in subsequent calibration and handling, all of these sensors are capable of providing outputs in terms of absolute coefficients that describe the fate of light passing through water. These coefficients of light transfer are collectively known as the inherent optical properties or IOPs. Their values are related through the volume scattering function that describes scattering as a function of angle into which light is deflected. While these sensors play an increasing role in observing in water processes, they also provide a technological foundation for a new generation of sensors that extend IOP capabilities. These new sensors hold the ability to determine absorption coefficients, to determine coefficients as a function of wavelength, and to characterize the volume scattering function at more than one angle. These improvements not only allow more complete characterization of natural waters but also provide a tangible means of relating remotely sensed data from air and space to in-water processes.

See also

Optical Particle Characterization. Radiative Transfer in the Ocean. Satellite Remote Sensing Microwave Scatterometers. Turbulence Sensors.

Further Reading

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TRAPPED PARTICULATE FLUX

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The transportation of biogenic and lithogenic particles from the upper ocean to the deeper ocean layers and to the ocean floor by vertical settling is one of the key processes to understand the