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Hydrometry — Suspended sediment in streams and canals — Determination of concentration by surrogate techniques

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National foreword

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A list of organizations represented on this committee can be obtained on request to its secretary.

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Hydrometry — Suspended sediment in streams and canals — Determination of concentration by surrogate techniques

Hydrométrie — Sédiments en suspension dans les cours d'eau et dans les canaux — Détermination de la concentration par des techniques de substitution

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Foreword

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

The committee responsible for this document is ISO/TC 113, *Hydrometry*, Subcommittee SC 6, *Sediment transport*.

Introduction

Sedimentation and sediment transport in streams, rivers, reservoirs and estuaries are key parameters in many scientific, environmental, engineering, and agricultural problems. Success in managing and solving sedimentation problems requires comprehensive knowledge of sediment movement. This requires reliable methods of estimation of sediment load with high-quality data. The amount of sediment transport data being collected, however, has steadily declined in recent decades largely due to difficulty and costs associated with field methods used for data collection. High temporal resolution data of high quality are needed to better understand and more adequately describe many sedimentation processes.

The bed load and suspended load broadly constitute total sediment load. However, the scope of this International Standard is confined to the measurement of suspended sediment. Conventional methods for measurement of suspended sediment concentrations in streams rely on the principle of collecting samples of water-sediment mixture at various points in time and space using suitable sampling equipment and deployment methods and analysing the samples in laboratory for estimating the sediment concentration. These methods are labour intensive, expensive and can be hazardous. Moreover, the accuracy of these methods in estimating the sediment concentration of rivers and streams over a period of time may not be dependable due to the large spatial and temporal variability associated with the transport of suspended sediment.

Continuous and accurate estimation of suspended sediment concentration is essential in certain situations such as:

a) in hydropower projects for the safety of the turbines and other machinery, reservoir silting and flushing;

b) water-supply projects for monitoring water quality;

c) storm water run-off from urban areas;

d) silting of wetlands; and

e) long-term monitoring of sediment transport in rivers and streams, in order to obtain reliable base lines that can be used for decision making.

In such situations, automatic and cost-effective techniques are essential to collect high-quality data on suspended sediment concentrations and particle sizes.

Recent technological advances in the fields of optics and acoustics have provided new sediment-surrogate technologies and methods to determine suspended sediment fluxes and characteristics. Some of these methods can be used to measure suspended sediment concentration at higher resolution, with greater automation and potentially lower cost than traditional methods. These methods involve surrogate technologies that derive the suspended sediment concentration from measurements of optical backscatter, laser diffraction and acoustic backscatter.

The measurement of suspended sediment concentration (SSC) in the water samples can be carried out with the help of nephelometry, transmission, laser diffraction and acoustic back scatter techniques. The working principles, applications, advantages and disadvantages, limitations and usable instruments of the above techniques are elaborated in this International Standard. The optical backscatter technique is readily available and relatively inexpensive. Optical backscatter sensor sensitivity depends on grain size, colour and composition. The advantages are small size and small sample volume, linear and high frequency response, insensitive to ambient light, large measuring range and low cost. The laser diffraction (LD) technique is also readily available and cost effective. The acoustic backscatter is another technique for measurement of SSC in the aquatic ecosystems. Measurements are possible for a range of sediment sizes that is dependent on the acoustic frequency. The available maximum sampling depth will be limited at high concentrations.

Hydrometry — Suspended sediment in streams and canals — Determination of concentration by surrogate techniques

1 Scope

This International Standard specifies methods for determination of the concentrations and particle-size distributions of suspended sediment in streams and canals by surrogate techniques. Methods based on bulk-optical principle of water such as transmission and nephelometry are the most commonly used surrogates for determining suspended sediment concentrations (SSC). Instruments and techniques based on acoustic attenuation and/or acoustic backscatter principles are also in use for measurement of suspended sediment concentration. Instrumentation based on the laser diffraction principle is also used for the measurement of particle size distribution. This International Standard covers brief description of the operating principle of each method and details of some of the instruments available.

The detailed method and principle of optical and acoustical transmission, nephelometry, and optical back scatter (OBS), laser diffraction technique (LD) and acoustic back scatter technique (ABS) with their limitations are described in Annex A, Annex B and Annex C respectively.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

ISO 4363, *Measurement of liquid flow in open channels — Methods for measurement of characteristics of suspended sediment*

ISO 13320, *Particle size analysis — Laser diffraction methods*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772, ISO 4363 and ISO 13320 and the following apply.

3.1
surrogate technique
indirect method in which a substitute object or property is used for measurement in place of the original object or property

Note 1 to entry: Optical and acoustic properties of water-sediment mixture such as optical transmission, acoustic scattering and laser diffraction are some of the surrogates for measurement of suspended sediment concentration.

3.2
nephelometry
any method for estimating the concentration of particles in suspension by measuring the intensity of scattered light

Note 1 to entry: Light scattering depends upon number, size distribution, colour, composition (as manifested in the complex index of refraction) and shape characteristics of the particles.

4 Measuring principles

Optical and acoustical methods can be used for continuous measurement of sediment concentration. The measuring principles for the above surrogate techniques are similar and can be classified in three categories as described in 4.1 to 4.4 (see Figure 1).

4.1 Transmission

The source and detector are placed opposite to each other at a distance l as shown in Figure 1 A. The source emits a collimated light beam with intensity l_o. The sediment particles in the measuring volume reduce the beam intensity by absorption and scattering resulting in a reduced detector signal. The relationship between the detector signal (l_t) and the sediment concentration (c) is described by Beer's Law[43] and is given by Formula (1):

$$l_t = l_o e^{-kcl} \tag{1}$$

where

l_t is the transmitted light through a sample of length l in water of sediment concentration c;

l_o is the incident intensity of the emitter source;

k is a constant depending on the sediment, water, and instrument characteristics.

4.2 Scattering

The source and detector are placed at an angle φ relative to each other shown in Figure 1 B. The detector receives a part of the radiation scattered by the sediment particles in the measuring volume. The relationship between detector signal (l_s) and sediment concentration (c) is given by Formula (2):

$$l_s = k_3 l_o c e^{-k_2 c} \tag{2}$$

where

l_o is the incident intensity of the emitter source;

k_2 is a constant depending on the sediment, water, and instrument characteristics;

k_3 is a calibration coefficient depending on instrument geometry, particle properties (size distribution, shape, index of refraction or composition), optical /acoustic wave length and travel distance (l).

NOTE   Often, the distance l cannot be defined in optical backscatter type systems.

An important limitation of the scattering method is the strong nonlinearity of the relation between the detector signal and sediment concentration for large concentrations. Even in low concentrations where the response is linear, the output depends strongly on grain size and colour. For instance, colour alone may change the calibration by a factor of 10 for higher concentration[37] and the grain size may cause an additional change in calibration. For example, the calibration is shown to change by a factor of 20 between a white 5 µm sediment and a grey 10 µm sediment. As such, changes in sediment properties are not uncommon in nature, which are generally not known during the course of monitoring. Spot calibration from samples is likely to be contaminated by unknown errors when sediment properties change in space/time. The errors can reach several hundred percent and greater. However, the use of laser sensors is able to overcome these errors to great extent.

4.3   Transmission — Scattering

This method is based on the combination of transmission and scattering, as shown in Figure 1 C.
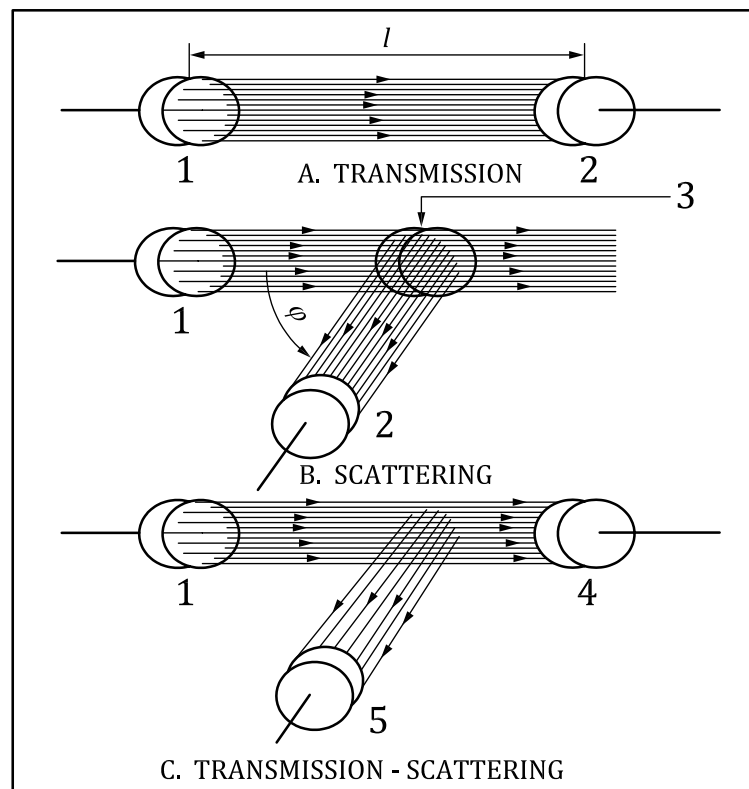
Key

1	source	4	detector
2	detector	5	detector
3	measuring volume		

Figure 1 — Basic principles of optical and acoustic methods

4.4   Diffraction

The phenomenon of bending of light from its straight line path around the corners of an obstacle or slit is known as diffraction. Diffracted light can produce fringes of light, dark or coloured bands. This property is used for measuring suspended sediment concentration in laser diffraction instruments.

Laser diffraction measures suspended sediment concentration by measuring the angular variation in intensity of light scattered as a laser beam passes through a dispersed particulate sample. Large particles scatter light at small angles relative to the laser beam and small particles scatter light at large angles. The angular scattering intensity data are then analysed to calculate the size of the particles responsible for creating the scattering pattern, using the Mie theory of light scattering.

5   Properties of sediment of importance for sediment surrogate techniques

5.1   General

The transport of sediment is based on hydraulic characteristics and physical properties of the sediment. Some of these properties are of importance for evaluating the accuracy and precision with which the sediment surrogate technologies described in this International Standard can determine SSC.

5.2   Particle size

Suspended sediment size is of importance for bulk optical and acoustical methods as these fundamentally respond to the surface area of the particles. If the surface area changes but the concentration remains constant these sensors will report a change in concentration that is proportional to the change in surface area[37]. The concentration output from LD sensors does not change with particle size.

5.3   Particle colour

The output of single-parameter bulk optical sensors depends strongly on particle colour. Sediment colour changes alone may change the calibration by a factor of 10 for higher concentration.[37] Combined with changes in grain size this may cause an additional change in calibration. For example, the calibration can be shown to change by a factor of 20 between a white 5 µm sediment and black 10 µm sediment[37]. The concentration output from LD or acoustical sensors is not influenced by particle colour.

6   Methods for determination of suspended sediment concentration by surrogate techniques

6.1   General

The surrogate methods employ *in situ* measurement using sensors that measure either

a)   the bulk optical properties of the water-sediment mixture, including transmission, nephelometry and optical backscatter (OBS) sensors, or

b)   laser diffraction (LD) sensors.

The methods also include sensors that measure the acoustical properties of the water-sediment mixture such as acoustic backscatter (ABS).

6.2   Bulk optics

Measurements of the bulk-optical properties of water-sediment mixture are the most common means for determining turbidity (water clarity) and estimating SSC in rivers. A number of optical instruments are commercially available. Bulk-optic instruments can be categorized as follows.

a)   Transmissometers, which employ a light source beamed directly at the sensor. The instrument measures the light transmission, i.e. the part of the light not scattered by the suspended particles.

b)   Nephelometers, which measure light scattered by suspended particles (rather than light transmission). The light reaching the detector is directly proportional to the amount of sediment particles scattering the source beam if their size, shape, colour and composition do not change. Nephelometers can be divided into two general categories:

   1)   Turbidity meters generally measure 90° or forward scattering. Nephelometric measurements typically are expressed in turbidity units defined by the light source, detection angle, and whether the sensor has single or multiple detectors. The units of turbidity from a calibrated nephelometer are called nephelometric turbidity units (NTU).

   2)   Optical backscatter (OBS) instruments measure backscattered infrared light, usually at 165° from the emitter, in a small (concentration dependent) volume.

These instruments provide an estimate of the suspended sediment concentration from a single point. Both transmission and scattering are functions of the number, size, colour, index of refraction, and shape of suspended particles. Particles of all sizes can be measured in this way. However, the sensitivity of these bulk optics methods depends on bulk particle area concentration, i.e. C/d, or $\Sigma_I C_i/d_i$ where C is volume concentration [when particles are smaller than the wavelength of light λ, the summation includes a weight factor corresponding to the scattering efficiency of particles, which for such small particles is other than 2 (the value for particles > λ)] and d is particle size. In other words, the method

is progressively less sensitive to increasing particle size. It also follows that the maximum working concentration depends linearly on particle size. The details of the method are given in Annex A.

These bulk-optical instruments are generally inexpensive, do not have moving parts unless a wiper for the optical window is used, and provide rapid sampling capability. The instruments rely on empirical calibrations to convert measurements to estimates of SSC. No generic calibration that can be used to calibrate the output from a transmissometer or nephelometer to SSC is possible.

There are several drawbacks associated with use of bulk-optic instruments that include:

a)   lack of consistency in instrument measurement characteristics;

b)   variable instrument response to grain size, composition, colour, shape, and coating;

c)   biological fouling or damage to optical windows;

d)   nonlinear and censored responses of sensors at high sediment concentration; and

e)   variable response with dissolved constituents causing colour.

Maximum concentration limits for these instruments depend in part on particle-size distributions. An optical backscatter (OBS) sensor has a generally linear response at concentrations less than about 2 g/l for clay and silt, and 10 g/l for sand although the exact concentrations at which the response becomes nonlinear is size dependent. The upper concentration limit for transmissometers additionally depends on the optical path length [see Formula (1)].

Transmissometers are more sensitive at low concentrations but nephelometers and OBS sensors have a broader operating range of concentrations. Because of the relation between calibration to particle size and particle colour, nephelometers and OBS sensors are best suited for application at sites with relatively stable particle-size distributions and colour.

6.3   Laser diffraction (LD)

The LD principle is described briefly in this subclause (for details see ISO 13320).

A laser beam is directed into the sample volume where particles in suspension scatter, absorb, and reflect light. Scattered laser light is received by an array of detectors that allow measurement of the scattering at multiple angles from the original direction of the beam. This yields a vector of light scattering intensities with one numerical value for each detector. Using a suitable mathematical procedure and optical model the scattering intensities are converted into a volumetric size distribution in discrete size classes defined by the scattering angles covered by the detectors. By summing the individual elements of the particle size distribution the total volume concentration for the size range covered by the instrument is obtained.

The name laser diffraction derives from the original application of this method where light scattering at multiple very small forward angles was measured. At these small forward angles (about < 10°), the scattering is dominated by diffraction, rendering particle composition (i.e. refractive index) of only secondary importance.

The LD method offers a fundamentally different basis for *in situ* measurement of the concentration (as well as sizes) of suspended sediment particles at a point in the water column. Unlike bulk optical or acoustic methods, the LD method does not suffer from a significant change in calibration with changing sediment colour, composition or size for sediment sizes within the instrument measurement limits and it does not require any calibration by the user. This property has led to the broad acceptance of the method in applications ranging from measurements of biological specimens to ceramics and particles of all types.

6.4   Acoustic back scatter (ABS)

Characterization of SSC using backscatter and attenuation of acoustic signals in water has been described and developed for several decades. The basic principles are that acoustic waves passing through a

water-sediment mixture will scatter and attenuate as a function of sediment, fluid, and instrument characteristics. The acoustic metrics of backscatter and attenuation relate functionally to sediment characteristics (concentration, size, shape and density) within an ensonified volume after adjusting for the influence of fluid and instrument characteristics. Specific formulae have been developed to correct for the non-sediment (instrument and water) factors affecting acoustic metrics. A significant limitation of single-frequency systems is that the metrics of acoustic attenuation and backscatter amplitude may change due to changes in sediment concentration and/or sediment size. The amplitude of acoustic backscatter from sediment may increase with increased concentration at a fixed size distribution or with increased sediment size at a fixed concentration; and acoustic attenuation also varies with size and particle density. Multi-frequency acoustic systems, however, have been successfully used to estimate both sediment concentration and size characteristics. The optimal frequency(ies) for measuring sediment characteristics will depend on the sediment sizes and the channel depth and/or width of measurement. Acoustics have been successfully used at concentrations up to 30 g/l, with very short acoustical path lengths. The relation of acoustics to sediment generally performs poorly at concentrations less than about 20 mg/l. Measurements can be made from fixed acoustic instruments in side- or down-looking configurations; or from mobile acoustic Doppler current profilers.

7 Calibration and validation

7.1 For the bulk optical and acoustic methods, *in situ* calibration between SSC, obtained from water samples, and the signal measured by the sensor is necessary. The purpose of the calibration is to account for the variability in the constants k, k_2, and k_3 in Formulae (1) and (2). For LD, *in situ* calibration is not necessary in order to obtain the volumetric concentration of the suspended sediment. However, in order to convert the volume concentration from a LD measurement to SSC the bulk density of the particles must be applied. The bulk density can be assumed, modelled, or derived from water samples.

The *in situ* calibration should be done under flow conditions that cover the entire range of velocities, SSC and measuring positions (close to bed and water surface). For bulk optical or acoustic methods, regular calibrations over a range of flows and sedimentary conditions are required because the constants k, k_2, and k_3 may change in time due to temporal variations in grain size, shape, colour or composition. In practice, the bulk optical and acoustical sampling methods can only be used in combination with a mechanical sampling method to collect water-sediment samples for calibration. LD instruments measure particles between a minimum and maximum size that is a function of the instrument scattering angle measurement. If the size of the suspended sediment is within the size range of the LD instrument, then LD does not require recalibration except for changes in particle bulk density, which is necessary in order to convert the volume concentration to mass concentration. If some sediment is outside of the size range of the LD instrument, consult the manufacturers' manual for information about how the overall concentration, accuracy and precision are affected.

In rivers most of the suspended sediments are transported during floods. Therefore it is recommended to take water samples for calibration especially during floods.

7.2 The accuracy and precision of data produced by a sediment surrogate technology depends on the quality of the calibration except possibly for LD. For LD, the measurement can be directly validated at any time using standards with traceability within instrument measurement limits. Validation procedures specified in ISO 13320 and the manufacturer's manual shall be followed. The accuracy of the SSC derived from a LD measurement is dependent on the accuracy of the volume concentration and the estimate of the particle density. Consult the manufacturer's manual for accuracies of the volume concentration measurement and propagate the errors when computing the SSC. For the bulk optics and acoustic methods only *in situ* calibrations of the instruments should be applied to account for sediment properties that cannot be mimicked in the laboratory, e.g. flocculated particle size at the time of the measurement.

NOTE   Traceable standards may be available from national laboratories or institutes, such as the National Institute of Standards and Technology (NIST).

7.2.1 The best way to calibrate an OBS or turbidity sensor for measuring SSC is to take water samples immediately adjacent to the sensor and develop a numerical relationship between the instrument

output and the SSC values of the samples. The SSC values should be obtained using standard methods as appropriate. Standard turbidity data in NTU or other suitable units may then be calibrated to SSC using SSC data determined from the filtration of water samples. Standard concentration units should be calibrated to SSC determined from a coincident sampling programme. A typical calibration curve is shown in Figure 2. Users of this International Standard should remain cautious at all times that calibrations can change readily with change in grain size distribution, colour, or composition so that calibration from one regime may not carry over to the other.
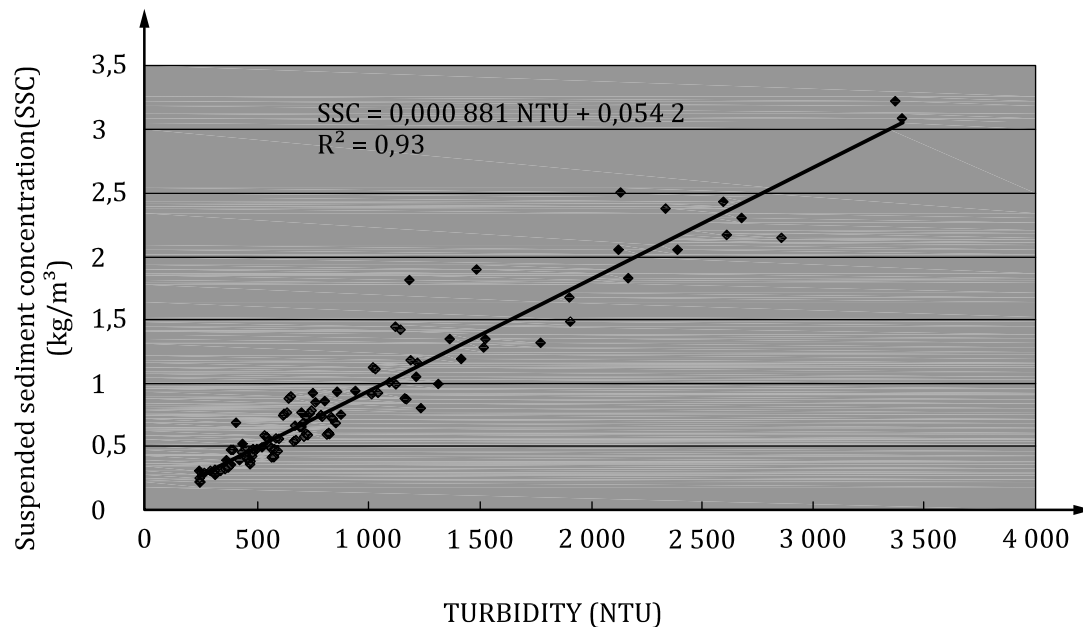
NOTE   Data courtesy of Cun tan hydrometric station, Upper Yangtze River, China.

Figure 2 — Calibration of OBS concentration with bottle samples

7.2.2   The most meaningful measure of a surrogate technology's reliability is derived from calibrations performed within the instrument measurement realm. Hence, criteria to evaluate sediment surrogate technologies should be based solely on instrument calibrations in the instrument measurement realm, if possible. However, the ultimate measure of the efficacy of a surrogate technology to monitor suspended sediments in rivers is its ability to quantify adequately the sedimentary characteristics of interest over the entire cross section. A schematic view of sample collection for calibration is shown in Figure 3.
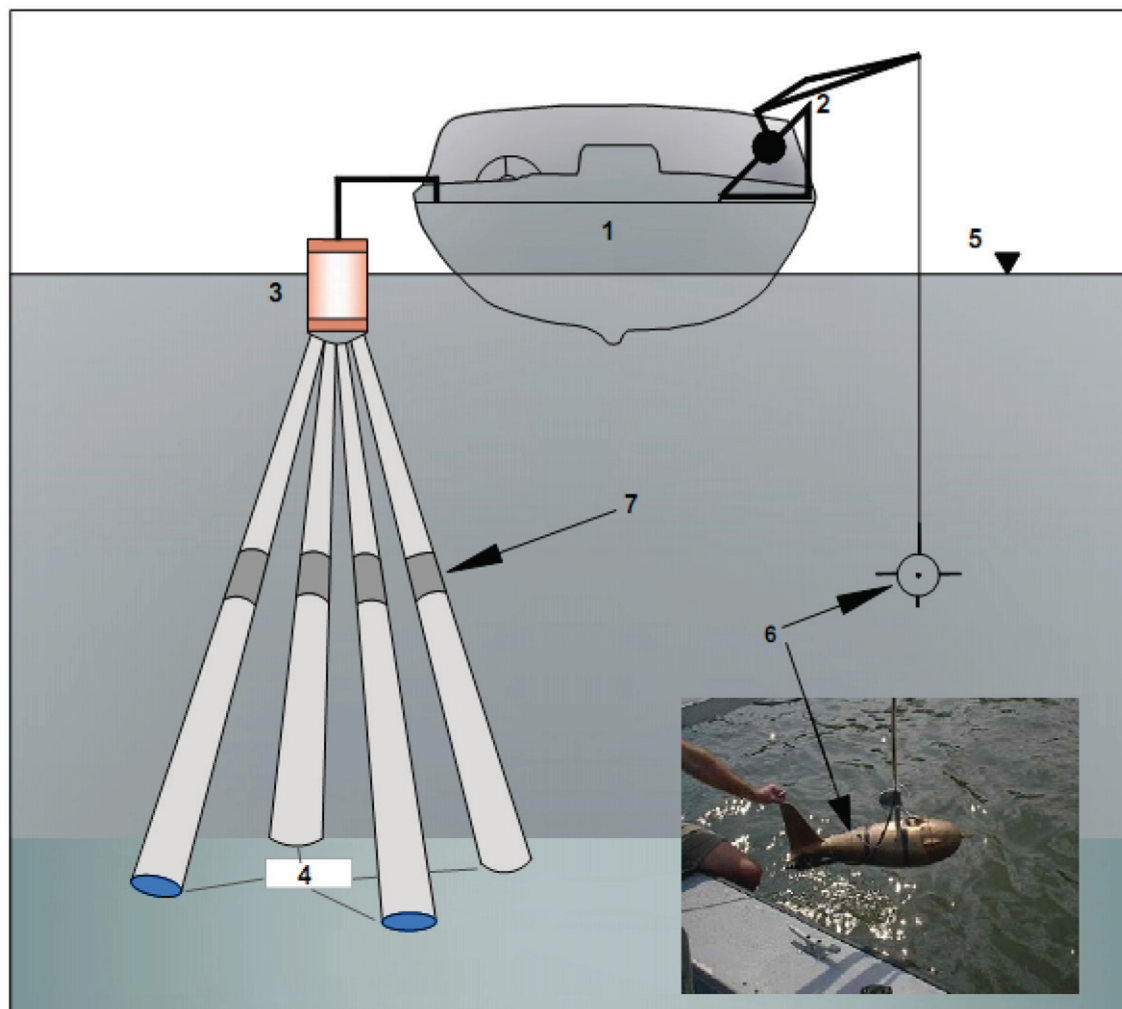
Key

1	boat	**5**	water surface
2	crane	**6**	point integrating water sampler (P-61)
3	ADCP	**7**	acoustic data collected from bins at the same depth as the water sampler
4	beams		

NOTE   Reproduced with permission from Wall and others, 2006 (see Reference [18]).

Figure 3 — Schematic view of sample collection for calibration

Annex A
(informative)

Determination of the concentration of suspended sediment by optical techniques

A.1 Transmission

A.1.1 Principle

A light source and detector are positioned at a set distance. Light is directed into the sample volume. Sediment present in the sample volume will absorb and scatter a portion of the light. A detector located opposite the light source allows determination of the degree of attenuation of the light beam. This can be related to turbidity.

A.1.2 Operational ranges

Sensors based on the transmission principle are more often used for monitoring lower turbidities and SSC (often < 1 000 mg/l) than sensors based on the scattering principle.

A.2 Scattering

A.2.1 Principle

This method is based on measuring the scattered light by positioning the light detector at an angle to the incident light. Measurements close to 90° is termed as turbidity, which reflect the collective optical properties of the water-sediment mixture that cause light to be scattered or attenuated rather than transmitted through the solution. Measurement at an angle less than 90° is termed as optical backscatter (OBS), which is used to determine the turbidity of the solution. The larger the amount of scatter or attenuation of light, the larger the value measured by the nephelometric turbidity meter. Nephelometric measurements typically are expressed in turbidity units defined by the light source, detection angle, and whether the sensor has single or multiple detectors.

A.2.2 Instrumentation

An OBS sensor is typically a cylinder utilizing an optical window from which light is both emitted and received. A pulse of either white or near-infrared light is transmitted through the optical window and is scattered or reflected by particles in front of the window in a 165° conical zone within some distance. Some of this scattered or reflected light is returned to the optical window where a receiver converts the backscattered light to a proportional voltage output.

Output from turbidity meters is in mV and data loggers usually store this data at suitable time intervals. Recorded data should be regularly downloaded from the data logger onto a computer or storage module. The voltage output from the sensor is converted to standard nephelometric turbidity units (NTU). It is recommended that calibrations are undertaken using certified polymer bead solutions. Calibration to standard units allows sensor drift to be identified and compensated. Sensors may drift significantly due to aging of electronic components and lens scratching. Calibrations should be undertaken on a three monthly basis. This calibration can be performed by the manufacturer or the user. If the calibrations are performed by the user it is important that they follow the same procedures as the manufacturer. The standard turbidity data are then quality controlled to remove erroneous data. These data usually result from debris trapped on the sensor head or algal growth on the sensor lens. They may be identified as very high constant values, highly variable values, or steadily increasing values not related to changes in

river stage. If there is evidence of linear drift in the output between cleaning intervals a linear correction may be used.

A.2.3   Operational Ranges

This method is commonly used to accurately measure turbidities ranging from 0 NTU to 3 000 NTU. Probes specifically designed for measuring higher turbidities (up to 30 000 NTU) are also available.

A.3   Calibration

Standard turbidity data in NTU values may finally be calibrated to SSC (mg/l) using SSC data determined from the filtration of water samples. The standard turbidity units are to be calibrated to SSC values determined from a coincident sampling programme. This is extremely important, as turbidity is very sensitive to variations in the properties of suspended sediment such as the size, colour and composition. Furthermore, as the sediment properties may change in time it may be necessary to calibrate the turbidity record using sediment samples that relate to specific periods of time (e.g. a seasonal calibration may be appropriate). Many samples are needed for an accurate calibration. For a reliable calibration, sediment concentration samples need to be collected over the full range of monitored turbidities; no extrapolation should be done from the calibrations. A simple linear regression model between turbidity units and measured SSC can be used for calibration. If the model standard percentage error (MSPE) of simple linear regression model meets an established minimum criterion, this model can be used to compute a time series of SSC. If the simple regression model does not meet the acceptability criterion, a multiple linear regression model using paired instantaneous turbidity and stream flow data are to be developed. If the addition of stream flow is statistically significant and the uncertainty associated with the multiple regression model results in an improvement over that for the simple linear model and is ultimately acceptable, it is used as the basis for computing a time series of SSC. The computed SSC time series can subsequently be used with its paired stream flow time series to compute a time series of suspended sediment load (SSL) by standard techniques.
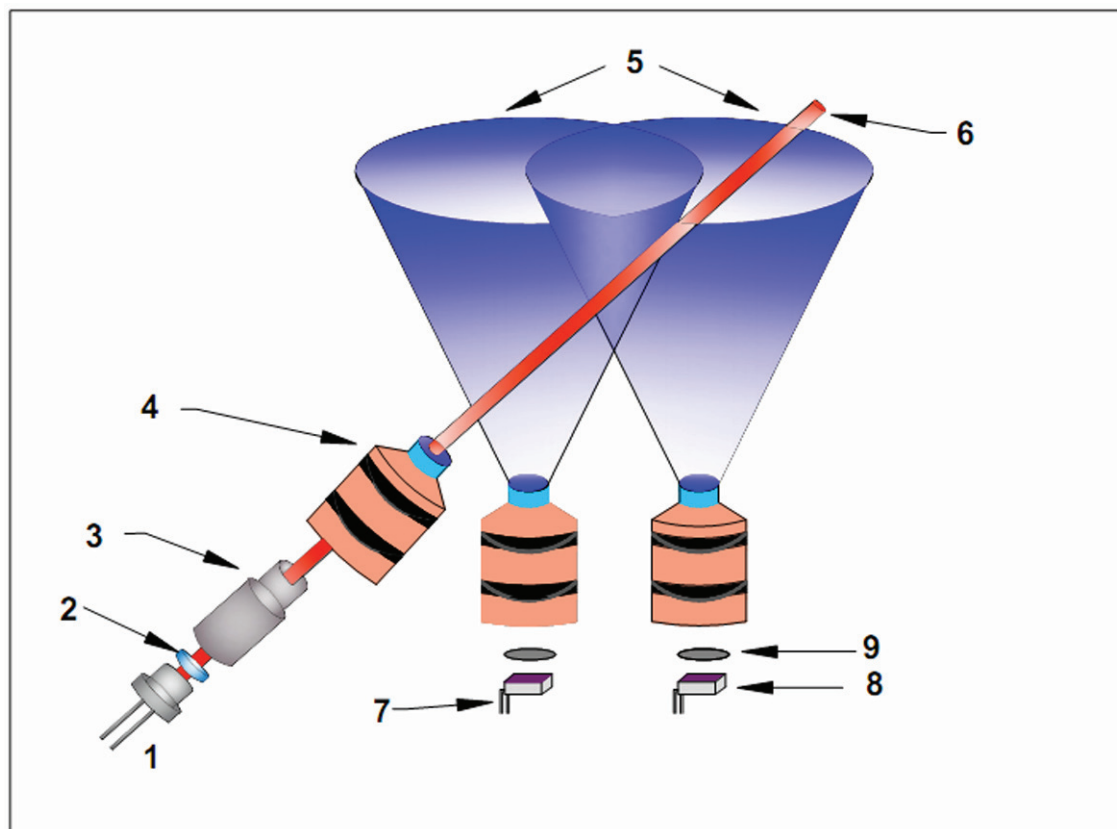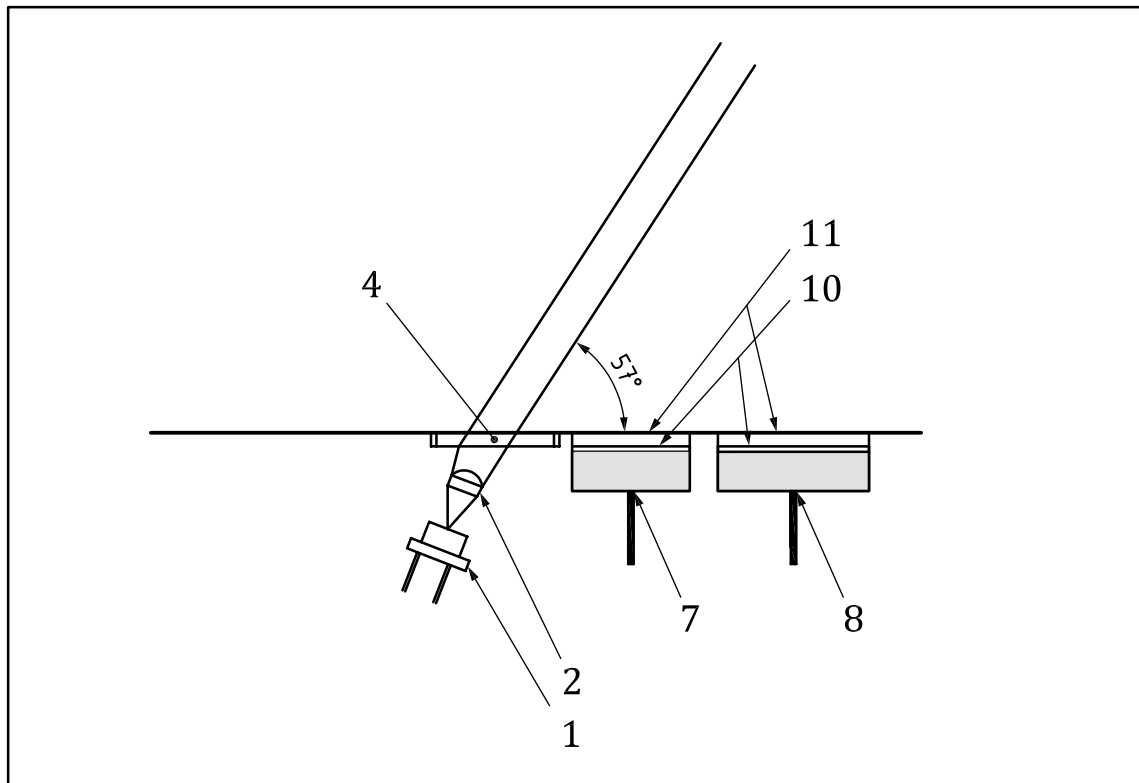
Key

1	laser diode	7	near detector (ND)
2	lens	8	far detector (FD)
3	focusing tube	9	Wratten filters (2)
4	sapphire windows (3)	10	Wratten window
5	acceptance cones 57°	11	epoxy window
6	NIR beam		

NOTE   Reproduced with permission from Campbell Scientific (see Reference [30]).

Figure A.1 — Schematic of the optical backscatter (OBS) technique

A.4   Limitations

The limitations of optical techniques can be described as follows:

a)   strongly dependent on particle size and sediment colour, regular calibration required;

b)   strongly dependent on water colour from dissolved constituents;

c)   can be affected by biological fouling and ambient light;

d)   performs well for measuring concentrations where particle size is constant or remains in 0,2 mm to 0,4 mm range; and

e)   highly susceptible for air bubbles.

Annex B
(informative)

Determination of the concentration of suspended sediment by laser diffraction technique

B.1 Principle

Laser diffraction is a technique based on the principle of small-angle laser light scattering (Mie theory). At small forward-scattering angles, laser diffraction by spherical particles is essentially identical to diffraction by an aperture of equal size. A simplified conceptual explanation is shown in Figure B1. A particle blocks light waves. Some are transmitted through the particle; others are diffracted *around* the particle. The diffracted rays appear in the small-angle region. The rays that enter the particle are scattered over the full π angle range, so that their contribution to the small-angle region is minimal. As a result, diffraction dominates the small-angle forward scattering. Particle composition and colour, which are represented by the refractive index as a function of light wavelength, became irrelevant. From the diffraction signature, which has a characteristic shape termed the Airy function, particle size and concentration can be determined by inversion of the small-angle light scattering data. In other words, if the small-angle scattering signature is observed, it leads via inversion to the size-distribution. The size-distribution is summed, to get the total concentration. By measuring the scattering signature over a wide dynamic range of angles, the concentration of particles within a size range covered by this angle range can be obtained.
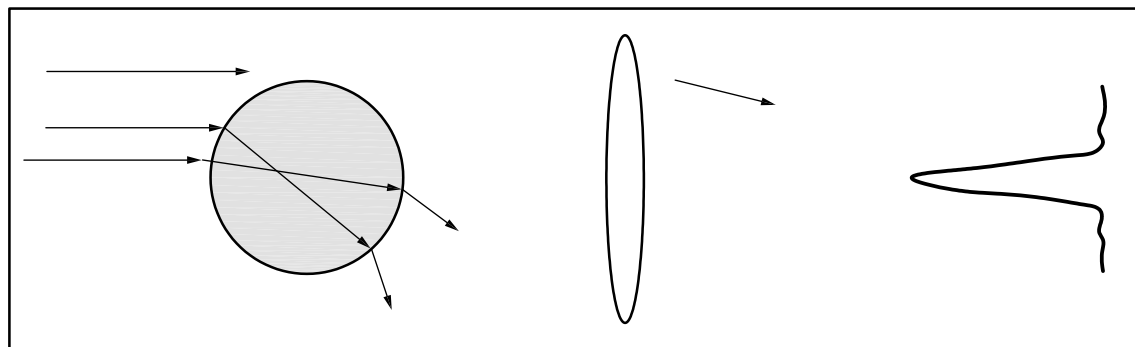

Figure B.1 — Sketch showing a parallel beam of light striking a spherical particle

B.2 Instruments

Various laser diffraction instruments are commercially available to measure the volume concentration of suspended sediments. These instruments determine the concentration of suspended sediment particles from the measurement of the laser beam scattered at different angles.
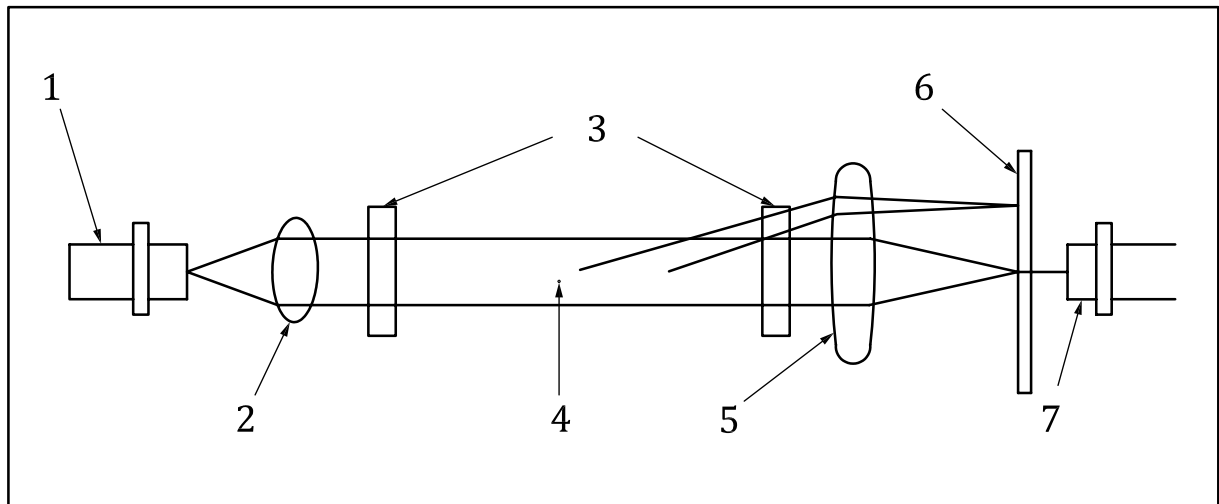
Key

1	laser diode source	5	receiving lens
2	companion focusing optic	6	connecting photographer rings
3	pressure window	7	transmission detector
4	sampler volume		

Figure B.2 — Schematic of the laser diffraction technique

B.3 Limitations

The limitations of the method can be described as follows.

a) The method is limited in the range of concentrations that can be measured. Multiple scattering effects (re-scattering of scattered light) begin to appear when the optical transmission is less than 30 %. The lower the transmission, the stronger the effects of multiple scattering will be. Maximum concentration sediments depend on the path length of the instrument. An optical transmission in the range of 40 % - 60 % is generally recommended to avoid issues with low sensitivity at high optical transmissions (low concentrations). Upper concentration limit can be extended by reducing the optical path length; however, a very short path length may produce a relatively large shear within the measuring volume disrupting the *in situ* size distribution.

b) The instruments are highly susceptible to biological fouling.

 NOTE Use of anti fouling devices may be considered to overcome this limitation.

c) The instruments measure a limited range of scattering angles, and thus a limited range of sediment sizes. Sediments less than the minimum, and greater than the maximum size range have little to no affect on the measured value. Thus, the method would require calibration for the unmeasured sediment; and recalibration for changes in the unmeasured fraction changes[8].

d) The technique is highly susceptible for air bubbles.

Annex C
(informative)

Determination of the concentration of suspended sediment by acoustic back scatter

C.1 Principle

Characterization of suspended sediment using backscatter and attenuation of acoustic signals in water has been described and developed for several decades[42][16][38][23][34]. The basic principles are that acoustic waves passing through a water-sediment mixture will scatter and attenuate as a function of sediment, fluid, and instrument characteristics, including frequency and transducer diameter. The acoustic metrics of backscatter and attenuation relate functionally to sediment characteristics (concentration, size, and shape) within an ensonified volume after adjusting for the influence of fluid and instrument characteristics. Early investigations of acoustic surrogates relied on instruments with a separate sound source and receiver, rather than a combined source and receiver such as modern transceivers (referred to here and typically as transducers). The transducer emits an acoustic pulse and then, after an interval just long enough to stop 'ringing', it receives the echoes backscattered from particles suspended in the acoustic path, as illustrated in the simplified Figure C.1. Acoustic Doppler velocity meters measure the Doppler shift in the frequency of the backscattered signal to determine the velocity of the particles scattering the signal (the assumed water velocity) relative to the transducer. The backscattered signal amplitude and attenuation provide measures of SSC.

Methods to estimate SSC from acoustic metrics have been developed by researchers working in marine environments[38]; and fluvial environments[34]. The methods are approximately equivalent. This International Standard describes methods[42], developed primarily for simplicity.

An expression relating acoustic surrogates to sediment concentration begins with sonar equation[42]. The sonar equation is written in logarithmic units of decibels in Formula (C.1) as:

$$RL = SL - 2\,TL + TS \tag{C.1}$$

where

$$2\,TL = 20\log_{10}(\Psi r) + 2\,r\,(\alpha_s + \alpha_w) \tag{C.2}$$

In this method RL is the reverberation level (measured backscatter intensity) of the received signal and is equal to $10\log_{10}(P_{rms}^2)$, P_{rms} is the average (root mean square) backscatter amplitude (as pressure) from an ensemble of measurements for a specific ensonified volume, SL is the source level of the emitted signal (generally not evaluated in this method), $2\,TL$ is the two-way transmission loss equal to the sum of the spherical spreading and attenuation, and TS is the intensity of the signal echoed by the particles in the ensonified volume, equal to $10\log_{10}(SSC)$. In Formula (C.2), α_s is the coefficient of attenuation of acoustic energy by sediment, α_w is the coefficient of attenuation of acoustic energy by water, r is the range from the transducer to the ensonified volume, and Ψ accounts for non-uniform energy spreading

in the transducer near field, r_n, which is also known as the Rayleigh distance. formulae to estimate Ψ are presented[34][38] as:

$$\Psi(r) = 1 + \frac{1}{\left(1{,}35r/r_n\right) + \left(2{,}5r/r_n\right)^{3,2}}$$ (C.3)

Water absorption α_w is a function of water temperature, salinity, and pressure and can be obtained by Formula (C.4)[7][15]:

$$\alpha_w = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2$$ (C.4)

where α_w is the coefficient of absorption in sea water.

The first term in Formula (C.4) represents the sound absorption due to the boric acid. The second term gives the sound absorption due to magnesium sulfate. The third term indicates the absorption due to pure water. The contribution of sound absorption due to other chemical ingredients has been found to be negligible. The third term provides sound absorption because of pure water. Constants P_1, P_2 and P_3 indicate effect of pressure. Frequency dependence is shown by frequencies f_1 and f_2. These are relaxation frequencies of boric acid and magnesium sulfate; f is the frequency of sound. Values of A_1, A_2 and A_3 depend on water properties such as temperature, salinity and pH.

For most freshwater fluvial environments (at depths less than 100 m), only temperature will significantly affect α_w. Some use Formula (C.2) and assume α_s to be negligible; others use Formula (C.5)[34][38] to estimate α_s:

$$\alpha_s = SSC_v\left[k(\gamma-1)^2\left\{\frac{s}{s^2+(\gamma+\tau)^2}\right\} + \frac{1}{6}\left(k^4 a_s^3\right)\right]4{,}34$$ (C.5)

where

SSC_v	is the dimensionless volumetric sediment concentration (SSC divided by sediment density);
k	is the wave number, $2\pi/\lambda$, λ being the wavelength in cm;
γ	is the specific gravity of the sediment;
a_s	is the mean sediment radius in cm;
s	is equal to $[9/(4\beta a_s)][1+1/(\beta a_s)]$;
τ	is equal to $[0{,}5+9/(4\beta a_s)]$, in which β is equal to $[\omega/2\upsilon]^{0,5}$ and ω is $2\pi f$;
f	is frequency in hertz (Hz);
υ	is the kinematic viscosity of the water, in stokes;
4,34	is the conversion from nepers to decibels for the attenuation.

The first term of the sum within the brackets is the acoustic attenuation due to viscous losses and the second is the acoustic attenuation due to scattering losses.

An important improvement to estimating α_s can be obtained from profiling using acoustic velocity meters[39].

The relative backscatter (*RB*) is computed as follows:

$$RB = RL + 2TL \tag{C.6}$$

which is equivalent to the total scattering by suspended particles. Then, $\log_{10}(SSC)$ is a function of *RB* and

$$SSC = 10^{(A+B\times RB)} \tag{C.7}$$

The coefficients *A* and *B* are evaluated using regression for paired physical *SSC* and acoustic measurements.

C.2 Instruments

Acoustic Doppler velocity meters and current profilers are commercially available and broadly used to measure velocity profiles in laboratory and environmental applications. A fixed array of multiple transducers measures axial velocities that are used to obtain a 2- or 3-dimensional current velocity vector. A transducer is a (typically piezoelectric) device that transfers voltage to a sound-wave producing pulse, and vice versa.

The return voltage signals are digitized and sliced by time interval into ranges or bins so that a velocity profile can be computed. As a velocity measuring instrument, the ADCP records the backscatter amplitude as a data-quality indicator. Velocity measurement requires the magnitude of the measured backscatter to be greater than that of ambient acoustic noise. The maximum range of an ADCP, if it does not intersect a boundary, is dependent on the signal attenuation, which is a function of water, sediment, and instrument characteristics. Acoustic meters specifically built for sediment characterization using multiple frequencies may be used.

C.3 Limitations

The limitations of the methods can be described as follows.

a) Acoustic metrics are affected by changes in particle size distribution.

b) Methods are more complex and less generalized than for bulk optics or LD at this time.

c) Accuracy is limited for low concentrations, less than about 10 mg/l.

d) Depending on method use, signal attenuation due to sediment may be difficult to determine.

e) The technique is highly susceptible for air bubbles.
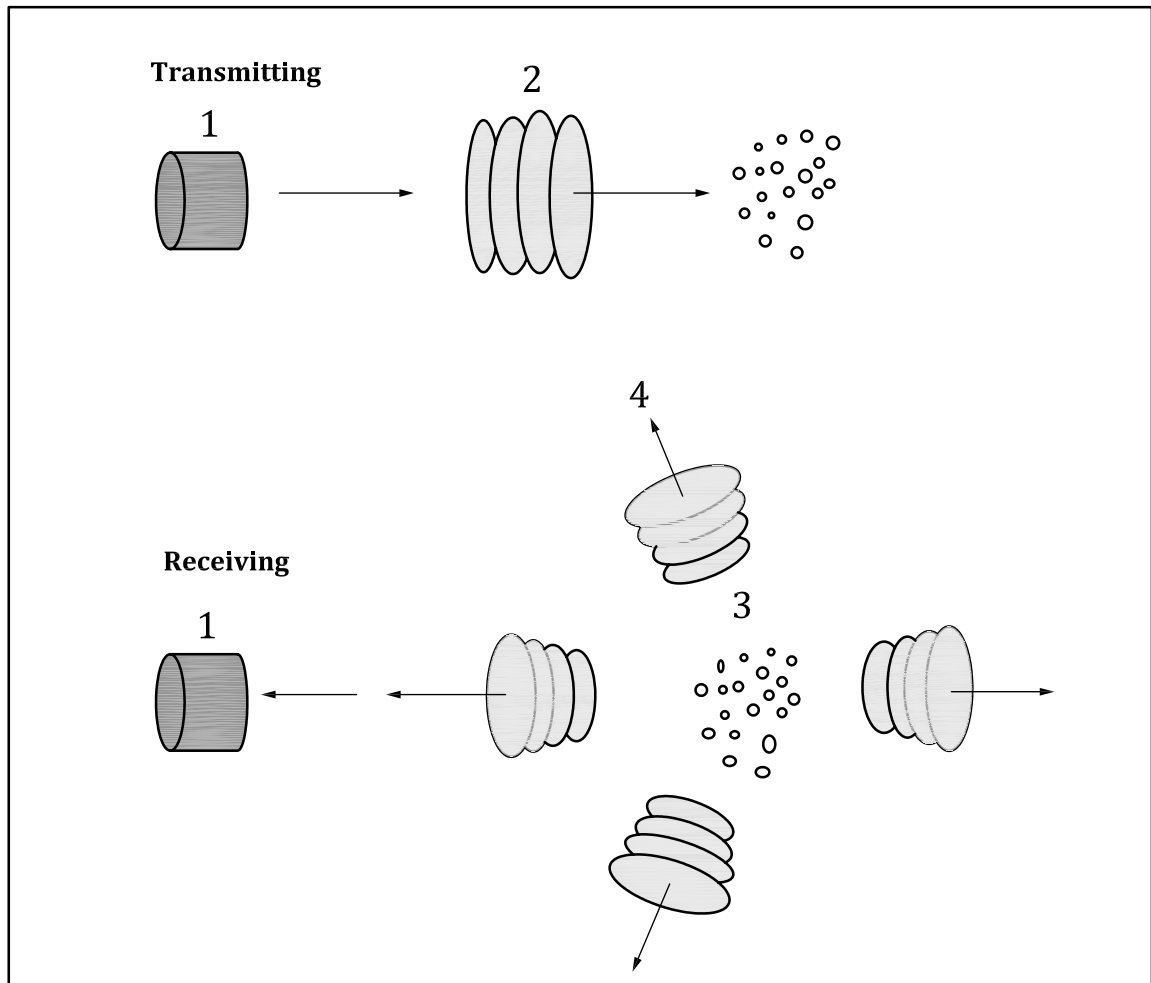
Key
1   transducer
2   transmitted acoustic ping
3   scatterers
4   reflected acoustic energy

NOTE   Reproduced with permission from Simpson, 2001 (see Reference [36]).

Figure C.1 — Acoustic backscatter from suspended particles

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