Standard Guide for The Use of Various Turbidimeter Technologies for Measurement of Turbidity in Water[1]

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ε1 NOTE—Editorial corrections were made throughout in November 2016.

1. Scope

1.1 This guide covers the best practices for use of various turbidimeter designs for measurement of turbidity in waters including: drinking water, wastewater, industrial waters, and for regulatory and environmental monitoring. This guide covers both continuous and static measurements.

1.1.1 In principle there are three basic applications for on-line measurement set ups. The first is the bypass or slipstream technique; a portion of sample is transported from the process or sample stream and to the turbidimeter for analysis. It is then either transported back to the sample stream or to waste. The second is the in-line measurement; the sensor is submerged directly into the sample or process stream, which is typically contained in a pipe. The third is in-situ where the sensor is directly inserted into the sample stream. The in-situ principle is intended for the monitoring of water during any step within a processing train, including immediately before or after the process itself.

1.1.2 Static covers both benchtop and portable designs for the measurement of water samples that are captured into a cell and then measured.

1.2 Depending on the monitoring goals and desired data requirements, certain technologies will deliver more desirable results for a given application. This guide will help the user align a technology to a given application with respect to best practices for data collection.

1.3 Some designs are applicable for either a lower or upper measurement range. This guide will help provide guidance to the best-suited technologies based given range of turbidity.

1.4 Modern electronic turbidimeters are comprised of many parts that can cause them to produce different results on samples. The wavelength of incident light used, detector type, detector angle, number of detectors (and angles), and optical pathlength are all design criteria that may be different among instruments. When these sensors are all calibrated with the sample turbidity standards, they will all read the standards the same. However, samples comprise of completely different matrices and may measure quite differently among these different technologies.

1.4.1 This guide does not provide calibration information but rather will defer the user to the appropriate ASTM turbidity method and its calibration protocols. When calibrated on traceable primary turbidity standards, the assigned turbidity units such as those used in Table 1 are equivalent. For example, a 1 NTU formazin standard is also equivalent in measurement magnitude to a 1 FNU, a 1 FAU, and a 1 BU standard and so forth.

1.4.2 Improved traceability beyond the scope of this guide may be practiced and would include the listing of the make and model number of the instrument used to determine the turbidity values.

1.5 This guide does not purport to cover all available technologies for high-level turbidity measurement.

1.6 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

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limitations prior to use. Refer to the MSDSs for all chemicals used in this procedure.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1129 Terminology Relating to Water

D3977 Test Methods for Determining Sediment Concentration in Water Samples

D6698 Test Method for On-Line Measurement of Turbidity Below 5 NTU in Water

D6855 Test Method for Determination of Turbidity Below 5 NTU in Static Mode

D7315 Test Method for Determination of Turbidity Above 1 Turbidity Unit (TU) in Static Mode

2.2 *Other References:*

USGS National Field Manual for the Collection of Water Quality Data[3]

Wagner's Field Manual Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting[4]

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms used in this standard, refer to Terminology D1129.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *calibration drift, n*—the error that is the result of drift in the sensor reading from the last time the sensor was calibrated and is determined by the difference between cleaned-sensor readings in calibration standards and the true, temperature-compensated value of the calibration standards.

3.2.2 *calibration turbidity standard, n*—a turbidity standard that is traceable and equivalent to the reference turbidity standard to within statistical errors; calibration turbidity standards include commercially prepared 4000 NTU Formazin, stabilized formazin, and styrenedivinylbenzene (SDVB).

3.2.2.1 *Discussion*—These standards may be used to calibrate the instrument.

3.2.3 *calibration-verification standards, n*—defined standards used to verify the accuracy of a calibration in the measurement range of interest.

3.2.3.1 *Discussion*—These standards may not be used to perform calibrations, only calibration verifications. Included verification standards are opto-mechanical light-scatter devices, gel-like standards, or any other type of stable-liquid standard.

3.2.4 *continuous, adj*—the type of automated measurement at a defined-time interval, where no human interaction is required to collect and log measurements.

3.2.4.1 *Discussion*—Measurement intervals range from seconds to months, depending on monitoring goals of a given site.

3.2.5 *design, n*—a more detailed technology description that will encompass all of the elements making up a technology, plus any inherent criteria used to generate a specific turbidity value.

3.2.5.1 *Discussion*—The design will typically translate into a specific make or model of an instrument.

3.2.6 *detection angle, n*—the angle formed with its apex at the center of the analysis volume of the sample, and such that one vector coincides with the centerline of the incident light source's emitted radiation and the second vector projects to the center of the primary detector's view.

3.2.6.1 *Discussion*—This angle is used for the differentiation of turbidity-measurement technologies that are used in this guide.

3.2.6.2 *attenuation-detection angle, n*—the angle that is formed between the incident light source and the primary detector, and that is at exactly 0 degrees.

(1) Discussion—This is typically a transmission measurement.

3.2.6.3 *backscatter-detection angle, n*—the angle that is formed between the incident light source and the primary detector, and that is greater than 90 degrees and up to 180 degrees.

3.2.6.4 *nephelometric-detection angle, n*—the angle that is formed between the incident light source and the detector, and that is at 90 degrees.

3.2.6.5 *forward-scatter-detection angle, n*—the angle that is formed between the incident light source and the primary detector, and that is greater than 0 degrees but less than 90 degrees.

(1) Discussion—Most designs will have an angle between 135 degrees and 180 degrees.

3.2.6.6 *surface-scatter detection, n*—a turbidity measurement that is determined through the detection of light scatter caused by particles within a defined volume beneath the surface of a sample.

(1) Discussion—Both the light source and detector are positioned above the surface of the sample. The angle formed between the centerline of the light source and detector is typically at 90 degrees. Particles at the surface and in a volume below the surface of the sample contribute to the turbidity reading.

3.2.7 *fouling, v*—the measurement error that can result from a variety of sources and is determined by the difference between sensor measurements in the environment before and after the sensors are cleaned.

3.2.8 *in-situ nephelometer, n*—a turbidimeter that determines the turbidity of a sample using a sensor that is placed directly in the sample.

3.2.8.1 *Discussion*—This turbidimeter does not require transport of the sample to or from the sensor.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from United States Geological Survey (USGS), USGS Headquarters, 12201 Sunrise Valley Drive, Reston, VA 20192, http://www.usgs.gov/FieldManual/Chapters6/6.7.htm.

[4] Wagner, R. J., et al, *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting*, USGS Enterprise Publishing Network, 2005, available from: http://pubs.usgs.gov/tm/2006/tm1D3.

3.2.9 *metadata, n*—the ancillary descriptive information that describes instrument, sample, and ambient conditions under which data were collected.

3.2.9.1 *Discussion*—Metadata provide information about data sets. An example is the useful background information regarding the sampling site, instrument setup, and calibration and verification results for a given set of turbidity data (especially when data are critically reviewed or compared against another data set).

3.2.10 *nephelometric-turbidity measurement, n*—the measurement of light scatter from a sample in a direction that is at 90° with respect to the centerline of the incident-light path.

3.2.10.1 *Discussion*—Units are NTU (Nephelometric Turbidity Units). When ISO 7027 technology is employed units are FNU (Formazin Nephelometric Units).

3.2.11 *pathlength, n*—The greatest distance that the sum of the incident light and scattered light can travel within a sample volume (cell or view volume).

3.2.11.1 *Discussion*—The pathlength is typically measured along the centerline of the incident-light beam plus the scattered light. The pathlength includes only the distance the light and scattered light travel within the sample itself.

3.2.12 *ratio-turbidity measurement, n*—the measurement derived through the use of a nephelometric detector that serves as the primary detector, and one or more other detectors used to compensate for variation in incidentlight fluctuation, stray light, instrument noise, or sample color.

3.2.13 *reference-turbidity standard, n*—a standard that is synthesized reproducibly from traceable raw materials by the user.

3.2.13.1 *Discussion*—All other standards are traced back to this standard. The reference standard for turbidity is formazin.

3.2.14 *seasoning, v*—the process of conditioning labware with the standard that will be diluted to a lower value to reduce contamination and dilution errors.

3.2.15 *slipstream, n*—an on-line technique for analysis of a sample as it flows through a measurement chamber of an instrument.

3.2.15.1 *Discussion*—The sample is transported from the source into the instrument (for example, a turbidimeter), analyzed, and then transported to drain or back to the process stream. The term is synonymous with the terms "on-line instrument" or "continuous monitoring instrument."

3.2.16 *sonde, n*—a monitoring instrument that contains two or more measurement sensors that share common power, transmitting, and data logging.

3.2.16.1 *Discussion*—A sonde usually has one end that contains the measurement sensors, which are in close proximity to each other and together are submerged in a sample.

3.2.17 *stray light, n*—all light reaching the detector other than that contributed by the sample.

3.2.18 *technology, n*—a general classification of a turbidimeter design that incorporates the type and wavelength of the incident-light source, detection angles, and the number of detectors used to generate a turbidity measurement and its defined reporting unit.

3.2.18.1 *Discussion*—In ASTM turbidity test methods, the technology is based on type and number of light sources, and their respective wavelength, detector angle(s), and number of detectors used in the technology to generate the turbidity value.

3.2.19 *turbidimeter, n*—an instrument that measures light scatter caused by particulates within a sample and converts the measurement to a turbidity value.

3.2.19.1 *Discussion*—The detected light is quantitatively converted to a numeric value that is traced to a light-scatter standard. See Test Method D7315.

3.2.20 *turbidity, n*—an expression of the optical properties of a sample that causes light rays to be scattered and absorbed rather than transmitted in straight lines through the sample.

3.2.20.1 *Discussion*—Turbidity of water is caused by the presence of matter such as clay, silt, finely divided organic matter, plankton, other microscopic organisms, organic acids, and dyes.

4. Summary of Practice

4.1 This guide is to assist the user in meeting and understanding the following criteria with respect to turbidity measurements:

4.1.1 The selection of the appropriate technology for measurement of a given sample with implied characteristics.

4.1.2 Help in the selection of a measurement technology that will help meet the scope of requirements (goals) for use of the data.

4.1.3 Assist in the selection of a technology that is best suited to withstand the expected environmental and sample deviations over the course of data collection. Examples of deviations would be expected measurement range and interferences.

4.1.4 Understand both the general strengths and limitations for a given type (design) of technology in relation to overcoming known interferences in turbidity measurement.

4.1.5 Provide general procedures that can be used to determine whether a given technology is suitable for use in a given sample or a given application.

4.1.6 Understand the need for the user to include critical metadata related to turbidity measurement.

4.1.7 This guide will help the user select the appropriate technology for regulatory purposes.

5. Significance and Use

5.1 Turbidity is a measure of scattered light that results from the interaction between a beam of light and particulate material in a liquid sample. Particulate material is typically undesirable in water from a health perspective and its removal is often required when the water is intended for consumption. Thus, turbidity has been used as a key indicator for water quality to assess the health and quality of environmental water sources. Higher turbidity values are typically associated with poorer water quality.

5.1.1 Turbidity is also used in environmental monitoring to assess the health and stability of water-based ecosystems such as in lakes, rivers and streams. In general, the lower the turbidity, the healthier the ecosystem.

5.2 Turbidity measurement is a qualitative parameter for water but its traceability to a primary light scatter standard allows the measurement to be applied as a quantitative measurement. When used as a quantative measurement, turbidity is typically reported generically in turbidity units (TUs).

5.2.1 Turbidity measurements are based on the instruments' calibration with primary standard reference materials. These reference standards are traceable to formazin concentrate (normally at a value of 4000 TU). The reference concentrate is linearly diluted to provide calibration standard values. Alternative standard reference materials, such as SDVB co-polymer or stabilized formazin, are manufactured to match the formazin polymer dilutions and provide highly consistent and stable values for which to calibrate turbidity sensors.

5.2.1.1 When used for regulatory compliance reporting, specific turbidity calibration standards may be required. The user of this guide should check with regulatory entities regarding specifics of allowable calibration standard materials.

5.2.2 The traceability to calibrations from different technologies (and other calibration standards) to primary formazin standards provides for a basis for defined turbidity units. This provides equivalence in the magnitude of the turbidity unit between the different measurement technologies when they are all calibrated on standards that are traced to primary formazin. This means that a TU is equivalent in its magnitude to a nephelometric turbidity unit (NTU), and all other units as described in this guide. See Table 1.

5.2.3 Turbidity is not an inherent property of the sample, such as temperature, but in part is dependent on the technology used to derive the value. Even though the magnitude of turbidity units are equivalent and are based on turbidity standards, the units do not maintain this equivalence when measurement of samples is practiced. Turbidity standards are generally free of interferences and samples are not. Depending on the type of technology employed for measurement, the magnitude of the different interferences on a given sample can differ significantly with respect to the different measurement technologies. The user of a turbidity technology should expect to observe a lack of measurement equivalence across different turbidity measurement designs when common samples are analyzed. See Section 6 on interferences.

5.2.4 Depending on the application, some instruments are calibrated on a sample that has been characterized (or defined) by some independent means. The calibration may include one or more samples that have been characterized with respect to the application of its use. See Test Methods D3977.

5.3 Turbidity is not a quantative measure of any chemical or physical property of water. Different expected interactions between a given measurement technology and a given sample with a unique combination of interferences can significantly impact the final turbidity result. As stated in 5.3, depending on the technology used, the result will differ. It is imperative to provide a linkage of metadata that is reflective of the design type (that is, technology) used to generate the turbidity values. In all ASTM standards, the measurement units are reflective of the design criteria and the information is presented in Table 1.

5.3.1 The actual reporting units, signified by a two to four-letter code, are based upon distinguishing design criteria for each of the common measurement technologies. The intent of attaching the measurement unit to the determined turbidity value is to indicate the type of technology used.

5.3.2 Even though various instrument designs may be grouped by technology type (that is, FNU, NTU, FBU, etc., and refer to Table 1), instruments within a group should not be considered to be identical nor it is proposed that sample values obtained will be alike. Instruments within each technology may still have other design differences whereby samples give different results. For example, pathlength differences between two instruments with the same reporting units can impact measurements and the relative difference in results.

5.4 *Discussion of* Table 1*:*

5.4.1 Table 1 provides a summary of technologies and their respective reporting units that are in the different ASTM test methods. The reporting unit is a two to four letter-code that has been assigned to a unique type of technology. The reporting unit follows every reported turbidity measurement and serves as metadata to the respective measurement.

5.4.2 The key design features are based on three criteria: (*1*) type of light source used, (*2*) primary detector angle with respect to the incident light beam, and (*3*) number of detectors used.

5.4.2.1 If the measurement unit begins with an "F" then the light source is a near-IR wavelength. Most designs will encompass a light source that is in the 860 ± 60 nm range. The strength of this wavelength is that most natural colors do not absorb at this level, which reduces or eliminates color interference. Two things that interfere at the near-IR are carbon black and copper sulfate. Second, the incident light beams are easily collimated, which extends the overall operational range. Third, the output of the light source can be regulated to provide a stable output over time. The weakness is that longer wavelengths are less sensitive to smaller particles with respect to response at very low turbidities.

5.4.2.2 If the measurement unit either begins with an "N" or is a two-letter unit (for example, BU, AU), the incident light source will be in the 400–680-nm range. The strength of this wavelength range is increased sensitivity to smaller particles when compared to longer wavelengths (such as those in the near infared (IR) range). The weakness of this wavelength range is that color that absorbs at the same wavelengths, as those that are emitted by light source will cause a negative interference. Second, if the source is an incandescent light source, additional optics is required to maintain collimation and stability over time. The light source will typically need to periodic replacement over the life of an instrument.

5.4.2.3 If the measurement unit includes an "R" it is a nephelometric method that utilizes a 90-degree detector plus one other detector. This is referred to as a ratio metric technique and helps to compensate for color interference, regardless of the wavelength of the incident light source. The technique also helps to linearize the response to turbidity at higher levels and can provide an extended measurement range. The technique can also help to stabilize measurement outputs. The technique is the most flexible across different applications because of the combination of sensitivity to low turbidity ranges and the ability can measure very high turbidity levels.

5.4.2.4 If the measurement unit has a "B" it indicates a backscatter technique. These techniques typically have a wide range, but are not sensitive at low turbidities. They are also more susceptible to color and particulate absorbance interferences.

5.4.2.5 If the measurement unit has an "A" it indicates an attenuation or absorbance measurement. The measurement is a combination of light that is attenuated and absorbed, in combination. Color is a significant interference, except for applications that require color to be considered part of the overall turbidity measurement. The method is very sensitive to wavelength and thus, the reporting unit should also include the wavelength of the incident light beam.

5.4.2.6 If the measurement unit contains an "M" it indicates a technology in which at least two incident light beams and two detectors are employed. The method also encompasses a ratio technique. These designs are very similar to ratio techniques as are the advantages and limitations.

5.4.2.7 *Other Units:*

(a) mNTU—The technology indicates a monochromatic incident light source in visible wavelength range and a nephelometric technique. The technology design allows for an improved limit of detection over conventional light sources. Its primary use for low turbidity measurements, such the monitoring for membrane breaches and ultra-purification processes.

(b) SSU—The "SS" portion of the unit indicates a surface scatter technique is being used. The technique positions both the light source and detector that are in the same horizontal plane above the sample. Light that is scattered by particles at or very near the surface and detected at an angle that is at 90 degrees to the centerline of the incident light beam. The system has a high detection range, but low sensitivity. It is also susceptible to color interferences, but to a lesser degree than techniques that pass light completely through the sample. The technique is valuable for applications where it is desirable for the sample not to touch the optics of the instrument.

5.4.3 The table provides information regarding to the most prominent applications and discusses interference concerns. This information is based on technologies that are in the field at the time this guide was written, but does not constitute endorsement to any given manufacture of a given technology. In some cases, a design can be successfully used outside of the stated applications in Table 1. The user should perform testing to ensure the technology meets limit of detection, sensitivity, and range requirements that insure representative data can be acquired.

TABLE 1 Summary of Known Commercialized Technologies, Key Design Features, Prominent Sample Applications, Ranges, and Reporting Units for Turbidity Measurements

Turbidity Reporting Unit Used in ASTM Test Methods	Turbidity Reporting Unit Used in ASTM Test Methods	Prominent Application and Major Interference Concerns	Suggested Application and Operating Range Ranges
Nephelometric Non-Ratio (NTU)	The detector is centered at 90º relative to the incident light beam. The incident light source is a tungsten filament lamp that is operated at a color temperature between 2200 and 3000 K.	White light turbidimeters. These designs comply with EPA 180.1 for low level turbidity monitoring. Color is a major negativeinterference and optical variations cannot be compensated with this technique.	Regulatory for drinking water. The optimal operating range is 0.0 to 40 units if the sample has no color. Best comparability will be at turbidities below 5 TU.
Ratio White LightTurbidimeters (NTRU)	This technology applies the same light source as the EPA 180.1 design but uses several detectors in the measurement. A primary detector centered at 90° relative to the incident beam plus other detectors located at other angles. An instrument algorithm uses a combination of detector readings to generate the turbidity reading.	Complies with the USEPA Interim Enhanced Surface Water Treatment Rule regulations and Standard Methods 2130B. Can be used for both low and high level measurement. Color interference (negative) is reduced and lamp variations are compensated for with this technique.	Regulatory for drinking water and wastewater (0–40 units). The technology can potentially measure up to 10 000 units.
Nephelometric, Near- IR Turbidimeters, Nonratiometric (FNU)	This technology uses a light source in the near IR range (860 ± 60 nm). The detector is centered at 90º relative to the incident light beam.	The instrument design is compliant with ISO 7027. The wavelength is less susceptible to color interferences. The light source is very stable over time because its output can be highly controlled. This technique is applicable for samples with color and for low level monitoring. Only highly samples that absorb light above 800 nm can result in negative interference.	Regulatory compliance in Europe for drinking water and wastewater (0–40 units). The technology can measure up to 1000 units or more, depending on pathlength.
Nephelometric Near-IR Turbidimeters, Ratio Metric (FNRU)	This technology applies the same light source that is required by ISO 7027. The design uses several detectors in the measurement. A primary detector is centered at 90° relative to the incident beam and other detectors are located at other angles. An instrument algorithm uses the combination of detector readings to generate the turbidity value.	Complies with ISO 7027. This technique is applicable for samples with high levels of color and for monitoring to high turbidity levels. Samples that absorb light above 800 nm will result in some negative interference.	Regulatory compliance monitoring in Europe for drinking water and wastewater (0–40 units). The technology can potentially measure up to 10000 units.

TABLE 1 *Continued*

Turbidity Reporting Unit Used in ASTM Test Methods	Turbidity Reporting Unit Used in ASTM Test Methods	Prominent Application and Major Interference Concerns	Suggested Application and Operating Range Ranges
Surface Scatter Turbidimeters (SSU)	The technology uses the same white light source as in EPA 180.1. The detector centered at 90º relative to the incident light beam. Both the detector an incident light source is mounted in a fixed position in the same plane that is immediately above the sample.	Turbidity is determined through light scatter from a defined volume of sample beneath the surface of a sample. Negative color interferences are reduced when compared to the non-ratio nephelometric method.	Sample flows through the instrument. This is a good watershed monitoring instrument and can measure from 0.5 to 10,000 units.
Formazin Back Scatter (FBU)	This design applies a near-IR monochromatic light source in the (860 ± 60 nm) nm range as the incident light source. The scattered light detector is typically positioned at 30 ± 15° relative to the incident light beam. However, some designs may have a detection angle that is approximately 0° relative to the incident light beam.	This technology is not applicable for most regulatory purposes. It is best applied to samples with high turbidity and is commonly used in trending applications. Absorbance and color above 800 nm will result in negative interference	This technology is best suited for in-situ measurement, in which a probe is placed in a sample for continuous monitoring purposes. It is best applied to turbidities in the range of 100–10 000+ unit range.
Backscatter Unit (BU)	The design applies a white light spectral source (400–680 nm range). The detector geometry is between 90 and 180° relative to the incident light beam.	This technology is not applicable for most regulatory purposes. It is best applied to samples with high turbidity. The measurement will be susceptible to any visible color and particle absorbance that will result in a negative interference.	This technology is best suited for in-situ measurements in which sample color is part of the turbidity measurement. It is best applied to turbidities in the 100–10 000+ unit range.
Formazin Attenuation Unit (FAU)	The incident light beam is at a wavelength of (860 ± 60 nm) nm. The detector is geometrically centered at 0° relative to the incident light beam. This is typically an attenuation measurement.	The design may be applicable for some regulatory purposes. The measurement is commonly performed with spectrophotometers. It is best suited for samples with high-level turbidity. Particle absorption is a prominent interference.	This measurement is part of the ISO 7027 regulation. The optimal turbidity range is between 20 and 1000 units.
Light Attenuation Unit (AU)	The wavelength of the incident light is in the 400–680 nm range. The light scatter detector is geometrically centered at 0º relative to incident beam. This is an transmission measurement.	This design is not applicable for some regulatory applications. This is commonly performed with spectrophotometers. Color and absorption are prominent interferences if their respective absorptive spectrum is the same as the output spectrum of the incident light.	This is best applied to samples in which color is part of the turbidity measurement. The best application is to samples in the turbidity range of 20 to 1000 units.
Nephelometric Turbidity Multibeam Unit (FNMU)	The technology consists of two light sources and two detectors. The light sources comply with ISO 7027. The detectors are geometrically centered at 90° relative to each incident light beam. The instrument measures in two phases in which the detectors are either at 90 or 180º relative to the incident light beam, depending on the phase. An instrument algorithm uses a combination of detector readings to calculate the reported value.	This technology is compliant to the EPA Regulatory Method GLI Method 2 and ISO 7027. It is applicable to regulatory monitoring for drinking water, wastewater, and industrial monitoring applications. The technology is very stable. This technology will be immune to color absorbance below 800 nm. Above 800 nm, color and particle absorbance interferences will be reduced.	Regulatory monitoring at low turbidity levels in the 0.02 to 40 unit range. The technology can measure up to 4000 units.
Laser Turbidity Units (mNTU)	The technology consists of an incident laser light source at 660 nm and a detector that is a high-sensitivity PMT design. The detector is centered at 90º relative to the incident light beam.	This technique complies with the EPA-approved Hach Method 10133. The application is for the monitoring of filter performance and breakthrough. Color interference can occur it absorbs the same wavelength of light that is emitted by the incident light source. However, color is typically significant in filtered samples.	Regulatory monitoring of drinking water effluent and membrane systems. The range is about 7 to 5000 mNTU. 1 NTU = 1000 mNTU.
Forward Scatter Ratio Unit (FSRU)	The technology encompasses a single light source and two detectors. Light sources can vary from single wavelength to polychromatic sources. The detection angle for the forward scatter detector is between 0 and 90º relative to the centerline of the incident light beam. More commonly, the forward scatter detection angle will be between 15 and 45º. The second detector is at exactly 0º.	The technology is sensitive to turbidities as low as 1 TU. The ratio technology helps to compensate for color interference and fouling.	The measurement of ambient waters such as streams, lakes, rivers. The range is typically from about 1–800 FSRU, depending on the manufacturer.

TABLE 2 Typical Interferences Associated with Turbidity Measurement

Typical Interferences that Originate from the Sample and their Impact on the Turbidity Measurement	
Absorbing Particles (Colored)	Negative bias (reported measurement is lower than actual turbidity)
Color in the Matrix	Negative bias if the incident light wavelengths overlap the absorptive spectra of a sample
Bubbles	Positive or negative bias (reported measurement is higher than the actual turbidity) and can impact measurement accuracy at all turbidity levels. Depending on the location of bubbles with respect to the optical elements and the technology being employed, the interferences can be either.
Particle Size Distribution	Particle size distribution can be considered a interference but is typically considered an inherent part of the sample. The particle-size distribution in a sample, and operating spectrum will affect the relative sensitivity of turbidimeters. The intensity of light scattered from a water sample depends, among other factors, on the ratio of particle diameter to light wavelength. Since the operating wavelength of a turbidimeter is fixed, particle size is the controlling variable.
Particle Density	Negative bias (reported measurement is lower than the actual turbidity)
Temperature	Sample temperatures can cause fogging of optical windows or of the sample cell. Depending on which component in a given design becomes fogged, the resultant interference can be either positive or negative. Some systems have features that can compensate for fogging, which include the use of desiccants, wipers, or anti-fogging materials. Such features must be demonstrated to perform as expected as they can otherwise result in measurement error.Changes in sample temperature can also impact the inherent turbidity of the sample. A sample that increases in temperature after collection can impact particulate solubility or increase microbiological activity, thereby impacting the turbidity of the sample.
Instrument Based Interferences and their Impact on Turbidity Measurement	
Optical Variation	Degradation of instrument optical components can have both positive and negative impacts on measurement, but bias is usually negative.
Sample Cell Variations	Either positive or negative bias. This can be minimized through the use of matching and indexing techniques and the application of silicone oils to reduce reflections due to scratches. The impact of this interference is most severe at turbidity values below 0.1 turbidity units.
Particle Settling	Positive or negative bias can result due to the rapid settling of particles and depending on the length of time to perform a measurement. This is typically associated with grab sample, and laboratory/portable benchtop measurements.
Stray Light	Positive bias (reported measurement is slightly higher than the actual turbidity). Stray light has the most significant impact at turbidity levels below 0.1 turbidity units.
Temperature	The stability of certain instrument components can change with temperature. Most modern instruments have internal compensation features for changes in ambient temperature over a defined range. Check with instrument manufacturers to determine the temperature for the operational range their respective technology.
Contamination	Positive bias (reported measurement is higher than actual turbidity). This is caused by dust contamination on optical surfaces that cannot be easily cleaned. This is most prominent on laboratory and portable turbidimeters.

5.4.4 *Range of Measurement*—Table 1 provides guidance on the estimated range of use for the different measurement technologies. A key design criterion is the pathlength of measurement. This is the actual distance that light travels through a sample to generate the scatter that ultimately becomes detected. It encompasses both the incident light distance and the receive angles for the scattered light detectors. The longer the pathlength, the lower the measurement ranges, but the better the sensitivity. Shorter pathlengths may provide a greater range, but a poorer sensitivity and a poorer the limit of detection.

6. Interferences in Turbidity

6.1 The measurement of turbidity is subject to a combination of different interferences. Some interferences are inherent with the sample itself and others are instrument-based. Table 2 summarizes these interferences.

6.2 Turbidity interferences will either cause positive or negative bias. Negative bias results in a measurement being below the true turbidity and is typically associated with measurements greater than 1 TU and can become more significant as the turbidity of a sample increases. Positive bias interferences are typically associated with extremely low turbidity measurements, where stray light becomes a factor in measurement. Stray light and particulate contamination on optical surfaces can cause positive interferences and is most prevalent at levels below 0.1 TU. These levels are representative in applications involving in highly pure waters.

6.3 Color is sometimes considered an interference, and other times it is not. It is dependent upon the application. For example, when performing compliance monitoring for drinking water, color is considered an interference and certain measurement techniques will help to reduce its effects. An application where color is not considered interference would be the monitoring of a natural water to determine the effectiveness on the underwater vision for aquatic predators and prey. In this application color is considered to be part of turbidity because the application relates the effectiveness of underwater vision for the aquatic species. The majority of applications however, color is considered an interference and typically causes false negative bias.

6.4 *Summary*—The minimization of interferences will improve measurement reliability. Several different turbidity measurement methods (that is, instrument designs or technologies) have evolved to address one or a combination of interferences

TABLE 3 Prework Prior to Technology Selection

Measurement Considerations	Questions to Consider
The purpose for the turbidity measurement	Process Control? Regulatory Compliance or Assessment, or both? Natural event monitoring?
The physical location of the instrumentation	Outdoors versus indoors? Remote versus a local site?
Frequency of site attendance	Does the monitoring require a specific level of attentiveness? What is the necessary level of frequency?
The measurement sensor application and location	Is the measurement in the environment, in situ, in-line, or in process (on-line)?
Additional desired measurement parameters	What other parameters are required? For example, pH, DO, temperature, flow, etc. Will a sonde be used?
Sample disposal	How will the sample be disposed? Sanitary drain? Run the sample back to the source? Sample treatment prior to disposal? Secondary processing?
Special considerations	What are those considerations that should be addressed to insure accurate and reliable measurement?
Ambient light considerations	Will ambient light interfere? Will sunlight/moonlight impact the site? Will reflections cause interference? What is the direction of the interference (positive or negative)?
Biological activity	Will my sample be prone to biological activity? What will the impacts of the biology in the sample be on the sensor? Will a sensor with compensating features (for example, a wiper) be needed?
Temperature	What are the expected sample and ambient temperature changes? Will the technology meet the ambient and sample temperature ranges?
Regulatory compliance	Is the measurement subject to regulatory reporting? And if so, to what regulatory reporting method?

and to meet specific monitoring criteria for a particular application. For example, some designs are intended to maximize sensitivity to turbidity on the cleanest of waters. Other designs minimize the effects of an interference such as color. Many designs have features such as bubble traps or bubble rejection software to minimize bubble interference. Other methods have been developed to function in a specific type of application or over a discreet turbidity range. Depending on the characteristics within a sample and the measurement technology that was applied, the various components of the turbidity measurement and the inherent interferences within the sample can impact the reported value. Different technologies often produce different turbidity values on the same sample.

6.5 The combination of a sample's respective characteristics, its inherent interferences, and these interactions with a given measurement technology can have a significant impact on resultant turbidity values that are generated. A sample may contain an interference that will have a strong bias on a certain technology and weak to no bias on a different technology. For example, many of the more modern technologies, such as those that utilize near IR light sources with ratioing will not be biased by color when compared to mature technologies such as those that utilize the incandescent light sources and single detection systems. However, these same technologies may have limited operating ranges that may or may not be acceptable for the required application. Thus, it is important to understand the type of sample and the application of the measurement in order to optimize the performance and consistency of the measurements.

7. Sample Assessment

7.1 Prior to selection of a measurement technology, several questions concerning the sample, sampling site and monitoring goals should be considered. Table 3 includes the questions that should be considered. In this guide, sample is defined as that portion in view of the optical detectors for a given technology, which is measured to generate a result. For a static measurement, is that portion of a sample stream or process that is collected for measurement.

7.2 *Empirical Sample Assessment*—Whenever possible, the sample should be assessed to help determine the best technology fit for monitoring a sample. Empirical characterization helps to identify interferences that may be reduced or eliminated. Table 4 provides a general list of questions that focus on potential interferences from a sample. Table 4 also provides general guidance on the type of technology that may or may not be suitable for a given interference.

8. Equipment Technologies

8.1 Table 1 provides a summary of availably technology configurations. This section provides figures for each general design type and discusses best use applications.

8.2 The descriptions are based on field knowledge provided by both users and manufacturers of the technologies. These descriptions are an expansion of Table 1.

8.3 *Turbidity Technologies:*

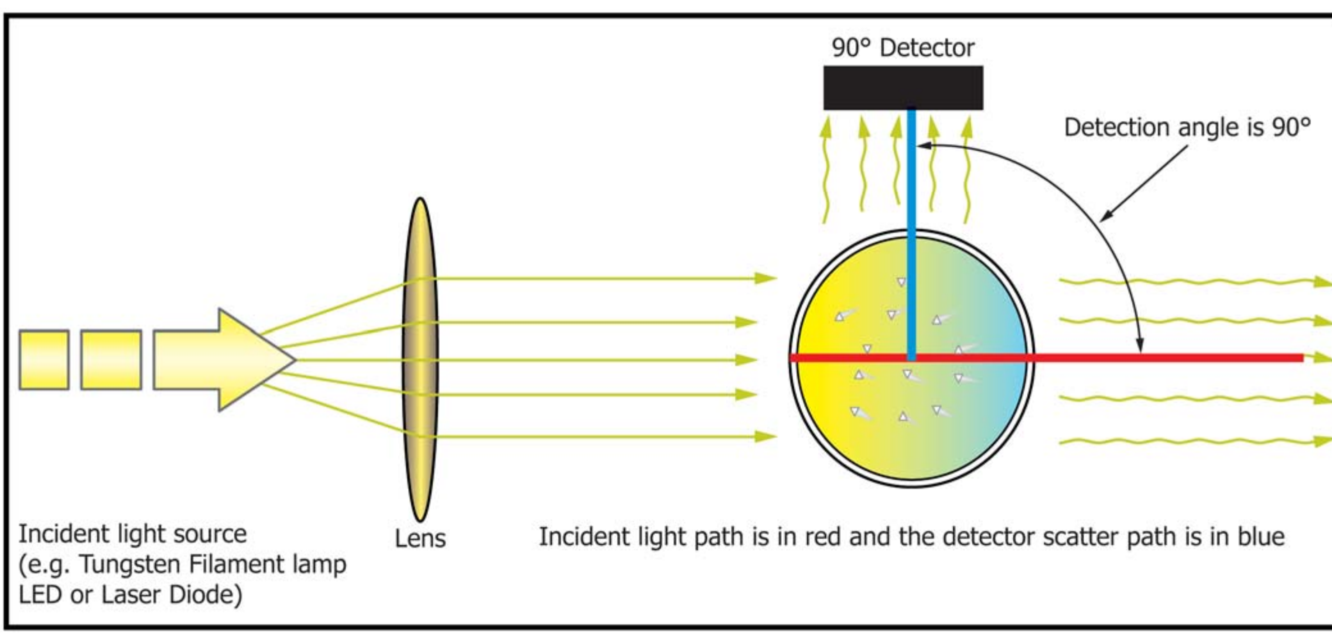
8.3.1 *Nephelometric Non-Ratio Technologies:*

8.3.1.1 *Description*—This is a single detector technology with a single light source. The angle between the centerline of the light source and the centerline of the view angle of the detector is 90 degrees. See Fig. 1.

8.3.1.2 *Sample Applications*—Samples of low turbidity and no color most frequently use this configuration. If samples have some color, then a light source with a wavelength greater than 800 nm is typically used. Bubbles are an interference and

TABLE 4 Empirical Sample Assessment

Sample Description	Impact on Technology	Best Case Scenario for Technology
Expected sample range through the duration of the study	Few technologies can measure accurately across all ranges. It is very important to understand primary range of measurement for the sample.	For low-level samples, use a technology that incorporates a 90° detection angle and a longer pathlength. One-inch pathlengths are typically suitable for measurements below 5 TU. For high level samples, a ratio technology and technologies with backscatter detection will provide better high range sensitivity.
Does the sample have any apparent color other than white	White samples are highly reflective and are most easily measured. Non-transparent samples with dark colors can interfere significantly if the absorbance spectra of the sample overlap that of the incident light source.	Samples with no color that appear to be clear or white can be measured with single detector systems that measure at 90°. If any color is suspected, then a ratio technique should be incorporated, or a light source that is not absorbed by the interference can be considered. Light sources that emit wavelengths in excess of 800 nm are often suitable.
Does the sample have black absorbing particles	The sample will absorb nearly all wavelengths of light, which will cause readings to bias negative.	Select a technology that is both a ratio technique and incorporates an incident wavelength that exceeds 800 nm.
Does the sample have excessive outgassing	Are bubbles expected to be present?	A technology that incorporates a bubble trap may be necessary for process applications. If the sample is pressurized, it should be run through the instrument prior to degasification takes place. For in-situ measurements, the position of the sensor is critical to insure bubbles do not form on the measurement face of the instrument. For these applications, the activation of any signal averaging and bubble reject software will help reduce the impact of bubble interferences on the measurement.
Does the sample require pumping?	Pumping can be a source of bubble formation.	Insure the pump does not cavitate. If cavitation takes place, a bubble trap device may be needed to condition the sample prior to measurement.
Will the environmental challenges include large temperature swings and humidity	Temperature and humidity can result in the fouling of optical surfaces.	Be sure the instrument can operate within the expected sample and ambient ranges. If a technology cannot, then additional effort, such as a protective enclosure may be necessary to meet the monitoring goals of the study.



NOTE 1—The pathlength through the sample is shown in red and the shortest scattered light path is in blue. The longer this distance, the better the measurement sensitivity.

FIG. 1 Technology Diagram of a Nephelometric Non-Ratio Technology

must be removed for most accurate measurements. Longer sample pathlengths (between 2.0 and 10 cm) are common typically meet the sensitivity criteria for low-level measurements.

8.3.1.3 *Common Uses*—Regulatory compliance reporting for U.S. EPA or ISO requirements in drinking water. Sample measurement accuracy and sensitivity is necessary to measure turbidities at least down to 0.1 units. It is common to match to static measurements and matching technologies are common for laboratory, portable and process configurations.

8.3.1.4 *Technology Configurations*—To achieve compliance uses as stated in 8.3.1.3, process (on-line) technologies are typically used. This is necessary to reduce stray light interferences and bubble removal of samples. in-situ and in-line

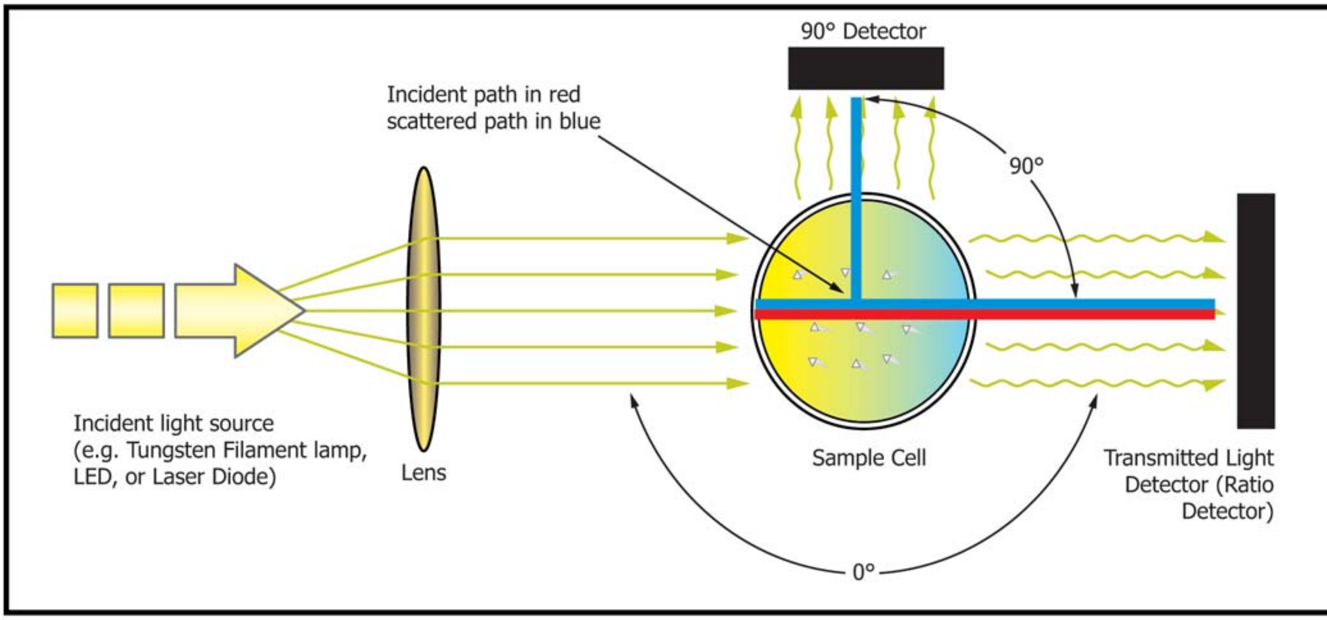


FIG. 2 Technology Diagram of a Nephelometric Ratio Technology

sensors are also available, but typically have shorter pathlength that prevents high performance at the turbidity levels mentioned in 8.3.1.3.

8.3.1.5 *ASTM Reference Documents*—For low-level turbidity, please refer to Test Methods D6698 and D6855.

8.3.1.6 *Reporting Units*—NTU, FNU, mNTU.

8.3.2 *Ratio Nephelometric Technologies:*

8.3.2.1 *Description*—The technology encompasses a single light source and at least two detectors. One detector is positioned at the 90 degrees relative to the centerline of the incident light beam. The sum of light scatter from all of the detectors is ratioed against the light scatter of the 90-degree detector to generate the turbidity value. See Fig. 2.

8.3.2.2 *Sample Applications*—Samples of a wide range of turbidity and with color most frequently use this configuration. The ratio technique still utilizes the nephelometric detection angle that can detect low level turbidities as described in 8.3.1.3, but can also detect turbidity up to a very high range. Some instruments read as high as 10 000 TU. The ratio technology allows for an array of different light sources to be used. Bubbles are an interference and must be removed for most accurate measurements. Longer sample path lengths between 2.0 and 10 cm are common for laboratory and portable applications, which is necessary to obtain low-level sensitivity.

8.3.2.3 *Common Uses*—The ratio technique helps to stabilize optical systems and is commonly used for regulatory compliance reporting for U.S. EPA or ISO methods for drinking water. Sample measurement accuracy and sensitivity is necessary to measure turbidities at least down to 0.1 units. Most configurations are in a laboratory or portable design, but process designs are available. The range of application is broad with this technique.

8.3.2.4 *Technology Configurations*—The most common configurations are for benchtop and portable designs. For on-line designs, configurations are available that incorporate solid-state incident light sources, with most of these being at or above the 800-nm wavelength range.

8.3.2.5 *ASTM Reference Documents*—For low-level turbidity, please refer to Test Methods D6698 and D6855. For high-level turbidity, please refer to Test Method D7315.

8.3.2.6 *Reporting Units*—NTRU, and FNRU.

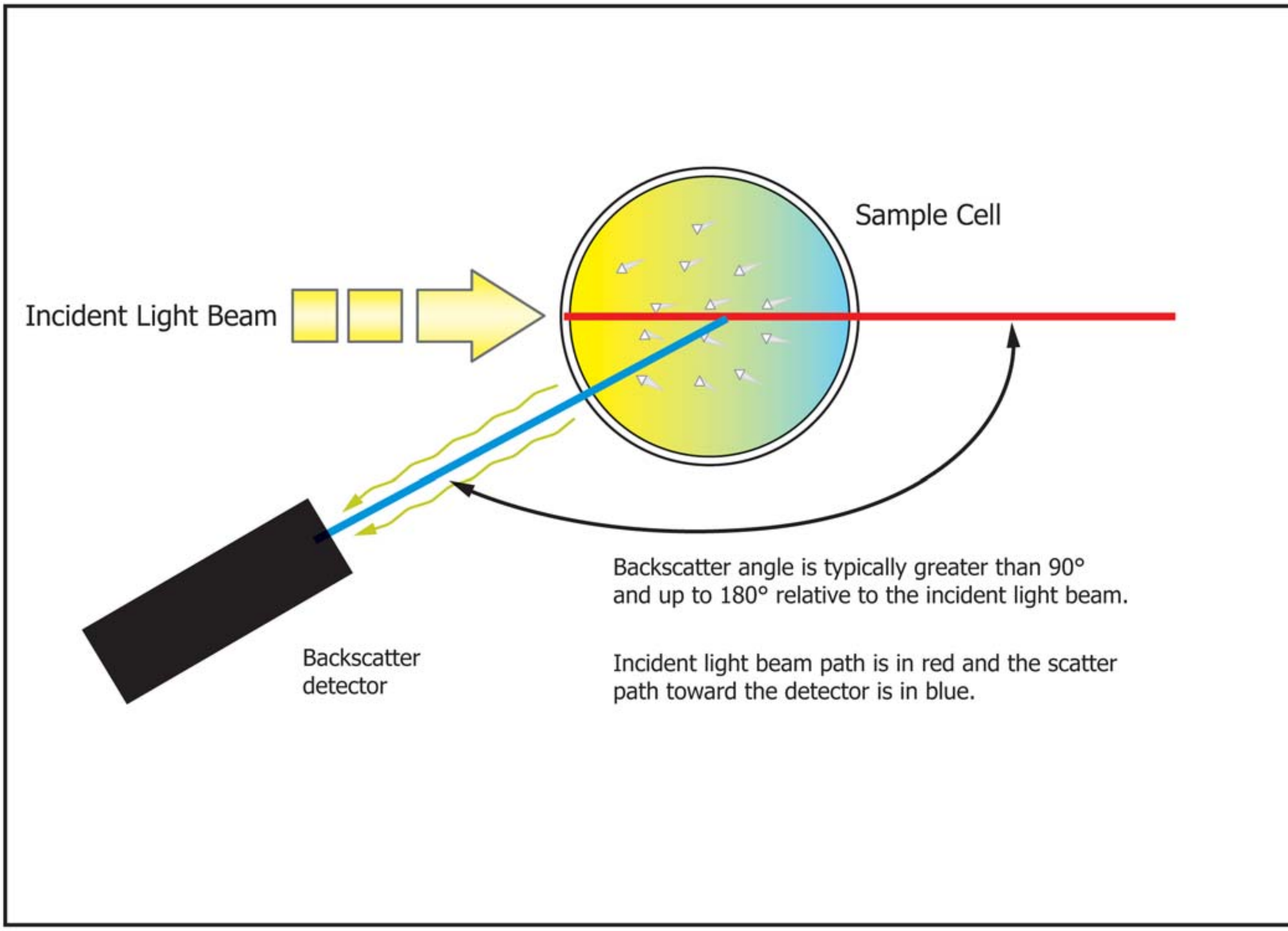
8.3.3 *Backscatter Technologies:*

8.3.3.1 *Description*—The technology encompasses a single light source and a single detector. The detector is positioned at an angle that is between 90 and 180 degrees relative to the centerline of the incident light beam. The most common designs incorporate a solid-state light source and are of a probe design. See Fig. 3.

8.3.3.2 *Sample Applications*—The measurement technique requires that the sample be able to scatter light back to the detector. This requires higher minimum sample turbidities, which usually needs to exceed 100 TU. Most path lengths are typically small which may further raise the minimum turbidity limit. The techniques typically have range that can exceed 10 000 TU. Color can interfere and is best remedied through the use of a long-wavelength light source that is greater than 800 nm. Bubbles will interfere in the measurement, especially in applications where significant outgassing of air is prevalent.

8.3.3.3 *Common Uses*—The backscatter technique can typically detect a change in turbidity for high-level samples, but lacks the sensitivity at low turbidity levels. Thus, they are typically not used in regulatory applications. The techniques are typically easy to install, but must be monitored for fouling on any optical surfaces. Measurements typically will not compare closely to other techniques because of its different design. Thus, calibration or verification against a bench or portable instrument of a different design is not recommended.

8.3.3.4 *Technology Configurations*—The most common configurations are for in-situ or in-line designs. This technology can also be found as a probe design. The most common



NOTE 1—In the design shown, pathlength varies depending on the turbidity of the sample.

FIG. 3 Technology Diagram of a Backscatter Technology

designs will incorporate an incident solidstate incident light source, with most of these being at or above the 800-nm wavelength range.

8.3.3.5 *ASTM Reference Documents*—Refer to the ASTM high-level turbidity methods, which include Test Method D7315.

8.3.3.6 *Reporting Units*—BU and FBU. FBU is most common.

8.3.4 *Attenuation Technologies:*

8.3.4.1 *Description*—The technology encompasses a single light source and a single detector. The detector is positioned at 0 degrees relative to the centerline of the incident light beam. See Fig. 4.

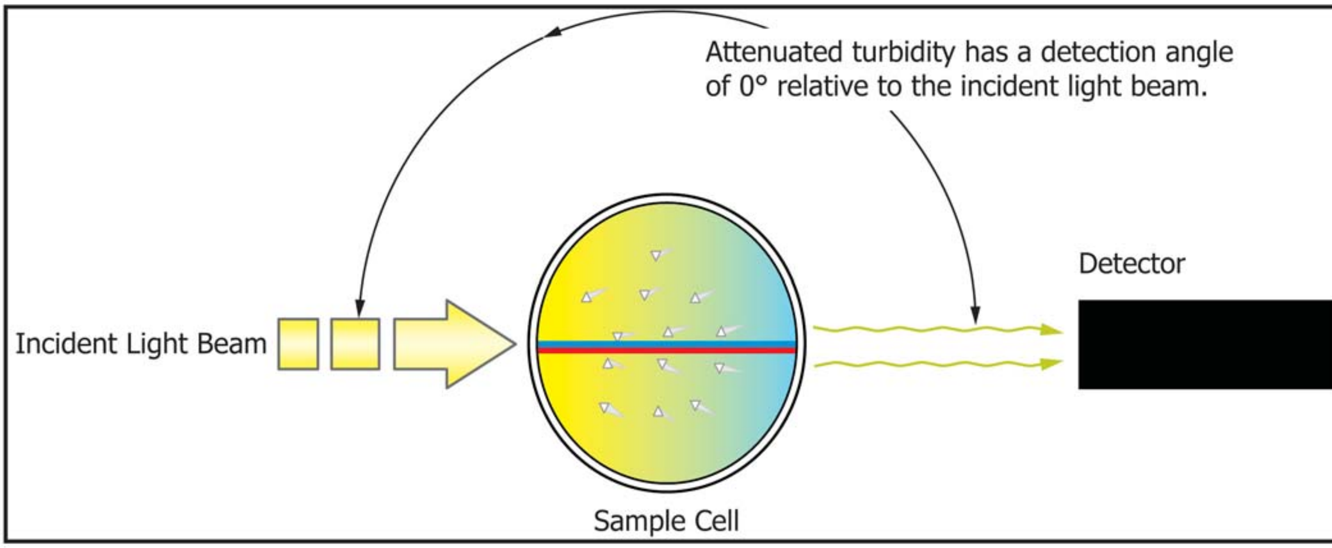
8.3.4.2 *Sample Applications*—The measurement technique is very susceptible to both light scatter and light attenuation. Color and absorbance interferences are most significant when using this technique. The technique is most useful if the user of the application requires that color to be part of the turbidity measurement.

8.3.4.3 *Common Uses*—The attenuation is used when both color and light scatter are to be combined into a single measurement. The technique is to higher levels, typically above 40 units. The measurement range can be modified through using a shorter or longer pathlength. These sensors are used in some regulatory compliance applications. The technique is very susceptible to fouling and bubble interferences and steps must be taken to insure that these are removed. For samples with color, this technology is commonly found to deviate significantly when compared to traditional 90-degree scatter technologies

8.3.4.4 *Technology Configurations*—The most common configurations are for in-situ designs and are sometimes referred to as a transparency measurement. Similar configurations can be made on benchtop and portable configurations through the use of spectrophotometers and colorimeters. This technology can also be found as a probe design. The most common designs will incorporate an incident solid-state incident light source, with most of these being at or above the 800-nm wavelength range. There are no known on-line, benchtop, or portable designs.

8.3.4.5 *ASTM Reference Documents*—Refer to the ASTM high-level turbidity methods, which include Test Method D7315.

8.3.4.6 *Reporting Units*—AU and FAU. When using AU, it is recommended that the wavelength of the measurement also be reported.



NOTE 1—The scatter path is the same as the incident light path

FIG. 4 Technology Diagram of an Attenuation Technology

8.3.5 *Surface Scatter Technologies:*

8.3.5.1 *Description*—The detector centered at 90 degrees relative to the incident light beam. Both the detector and the incident light source are mounted in a fixed position that is in the same plane and immediately above the sample. The incident light beam is projected upon the sample at approximately a 45-degree angle and is both scattered and reflected by particles to a detector. The view volume is beneath the surface of the sample. The detector is positioned at the complementary angle to the surface to provide an overall 90-degree angle relative to the incident light beam. Both the detector and light source are positioned above the horizontal surface of the sample. Pathlength does change as the turbidity of the sample changes, with the pathlength shrinking with increasing turbidity. This technology allows the pathlength to self adjust, which provides a wide range of measurement. See Fig. 5.

8.3.5.2 *Sample Applications*—The measurement technique based on the ability to detect light that is scattered by particles at or near the surface of a sample. The technique has a broad range of use, from about 0.5 to 10 000 TU. The technique requires a flowing sample to generate a horizontal surface, where turbidity is measured. Only flow-through designs are available. Color will interfere, but not to the same degree as a non-ratio technique that requires the light to pass through the sample. Turbidity samples that require continuous monitoring without directly contacting any optical components with the sample are most suited for this technique. Bubbles and flow-cell fouling can interfere in measurements and need to be addressed.

8.3.5.3 *Common Uses*—The surface scatter technique can typically detect a change in turbidity across a wide range of sample types. It is commonly used in process applications where optical fouling needs to be eliminated. The technique of often used for regulatory reporting, usually on wastewater effluents. The technology is typically used in the assessment of raw waters and on corrosive samples such as in pulp and paper applications. Since there are no matching benchtop or portable designs, the calibration or verification of this technology to a laboratory or portable instrument is not recommended.

8.3.5.4 *ASTM Reference Documents*—Refer to the ASTM high-level turbidity methods, which include Test Method D7315.

8.3.5.5 *Reporting Units*—SSU.

8.3.6 *Multi-Beam Ratio Technologies:*

8.3.6.1 *Description*—The technology consists of two light sources and two detectors. The light sources comply with ISO 7027. The detectors are geometrically centered at 0 and 90 degrees relative to each incident light beam. The instrument measures in two phases in which the detectors are either at 0 or 90 degrees relative to the incident light beam, depending on the phase. An instrument algorithm uses a combination of detector readings that are ratioed to deliver the turbidity value. See Fig. 6.

8.3.6.2 *Sample Applications*—Samples of low turbidity commonly favor this configuration. The combination of the long wavelength light source and the ratio technique provide for color interference minimization. The technique is primarily process or in-situ based. It is commonly used for regulatory compliance. Bubbles are an interference and must be removed for most accurate measurements. Longer sample pathlengths are available (between 2.0 and 10 cm) and provide for low-level sensitivity.

8.3.6.3 *Common Uses*—This incorporates a ratio technique that provides for a stable optical system and is commonly used for regulatory compliance reporting for U.S. EPA or ISO methods. Sample measurement accuracy and sensitivity is necessary to measure turbidities below 0.1 units. All configurations are either to an on-line or in-situ design. Currently, there are no laboratory or portable designs. The design is very close to a ratio technique with a similar light source and can provide good comparability for uses in verification.

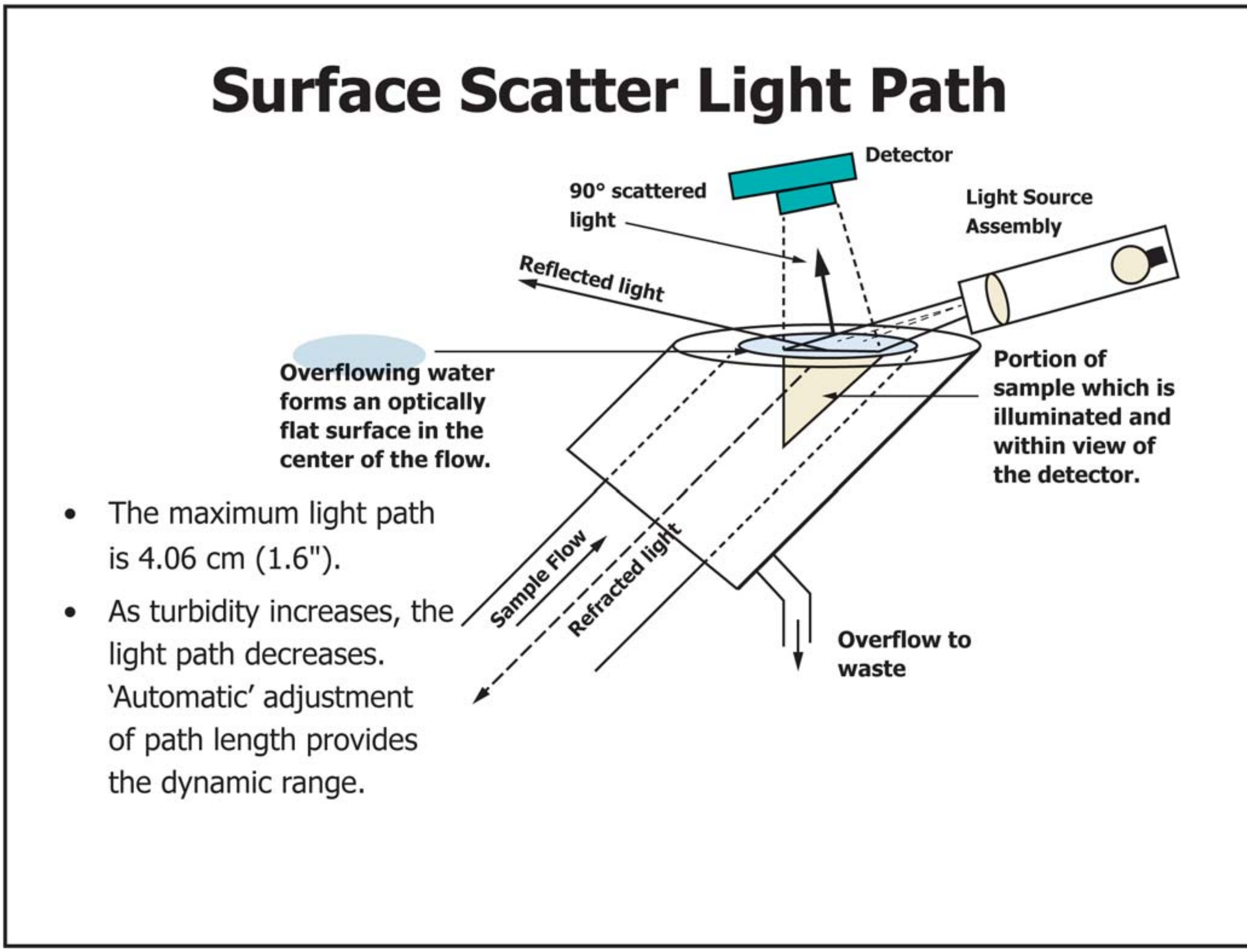
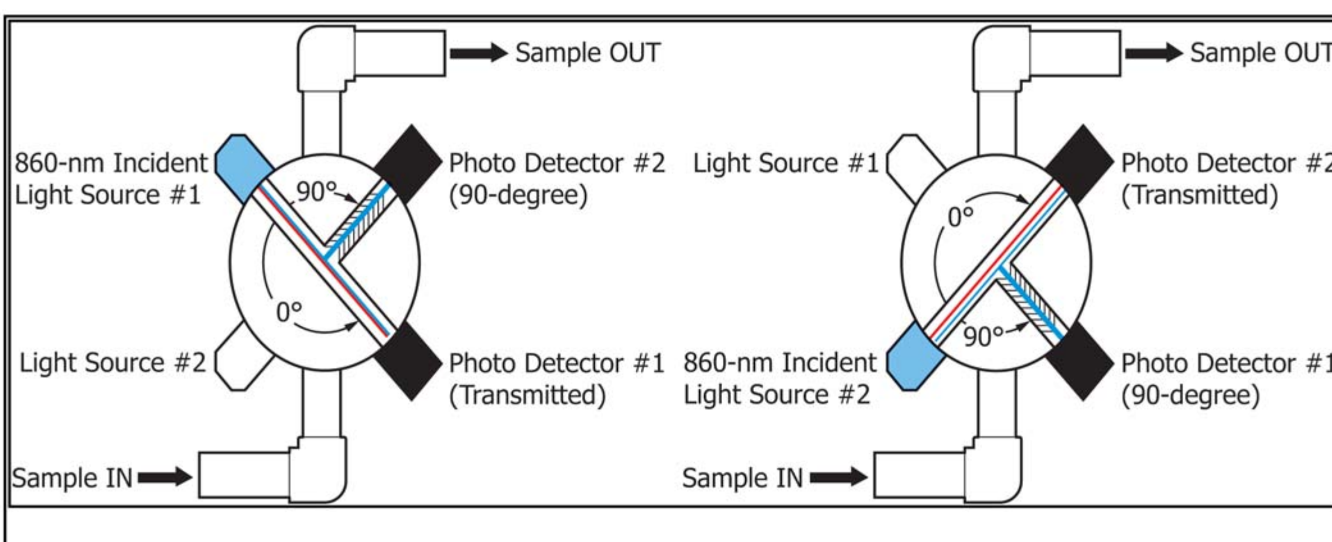


FIG. 5 Technology Diagram of a Surface Scatter Technology



NOTE 1—The blue traces show the paths of the scattered light.

FIG. 6 Diagram of a Multi-Beam Ratio Technology

8.3.6.4 *Technology Configurations*—The most common configurations are for on-line and in-situ designs. Both applications use a solid-state light sources in the 860 ± 60-nm range. There are no known laboratory or portable designs.

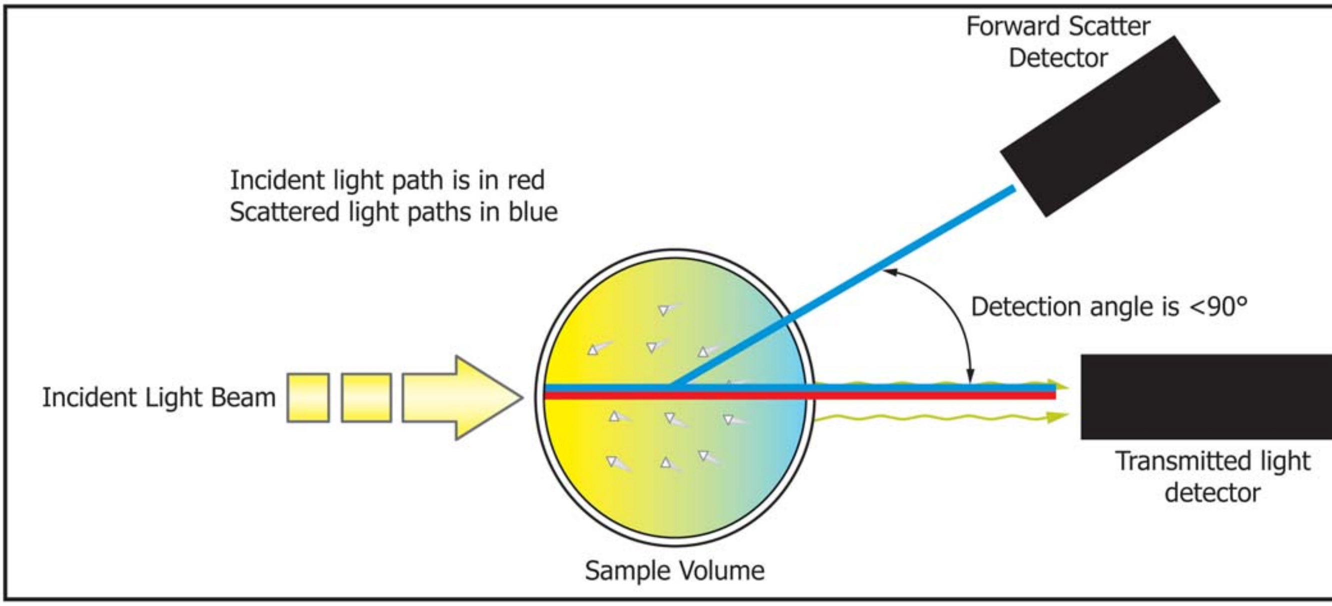


FIG. 7 Diagram of a Forward Scatter Ratio Technology

8.3.6.5 *ASTM Reference Documents*—For low-level turbidity, please refer to Test Methods D6698 and D6855.

8.3.6.6 *Reporting Units*—FNMU.

8.3.7 *Forward Scatter Technologies:*

8.3.7.1 *Description*—The technology encompasses a single, solid-state light source and either a single detector or multiple detectors (ratio). The detection angle for the forward scatter detector is between 0 and 90 degrees relative to the centerline of the incident light beam. See Fig. 7. A second ratioing detector is typically used and will have a detection angle exactly at 0 degrees.

8.3.7.2 *Sample Applications.*

8.3.7.3 *Common Uses*—Drinking water, lakes, rivers, groundwater, oceans.

8.3.7.4 *Technology Configurations*—Portable and in-line designs that use flow cell are available. In-line designs are typically submersed in the sample for water quality measurements.

8.3.7.5 *Reporting Units*—FSU for non-ratio and FSRU for ratio.

9. Turbidimeter Specifications

9.1 The basis for performance specifications:

9.1.1 *Definition*—Performance specifications are those specifications that assess the instrument for analytical measurement capabilities. The four important performance specifications for turbidity include: accuracy, repeatability, sensitivity, and limit of detection (LOD). These performance specifications are typically determined using standard materials that can be reproducibly prepared and introduced into the measurement scheme of the instrument.

9.1.2 Performance specifications are typically derived under controlled conditions using standard calibration materials. These calibration materials typically have low color and absorbance interferences, which distinguishes them from most samples. Because of this difference, it is difficult to assess how an instrument will perform in the field when based solely upon performance specifications. Further, performance specifications are normally derived under a given set of standardized conditions. These conditions typically include temperature and humidity. These standardized conditions will often differ from the actual field conditions for a given instrument and it should not be assumed that they will transfer to any set of ambient or sample conditions in the field.

9.1.2.1 It should never be expected for a given technology that has specifications determined on calibration standards to perform equally well on real world samples. Interferences such as those described in this practice will typically impact measurement technologies to some level.

9.1.3 This guide recommends that testing be conducted as close to field conditions as possible. This guide also recommends that the technology be evaluated using a range of real world samples that are expected from a given site. From this field evaluation, a more realistic assessment of instrument performance can be determined. It may be impractical to derive many of the specifications in the field, but two key criteria should be considered for most practical purposes in the field. These include sensitivity and stability.

9.1.4 *Sensitivity*—In turbidity, sensitivity is the ability for a given technology to detect a change in turbidity in a given sample that is indeed due to turbidity. It is the turbidity change is that observed above all instrument noise, and beyond all interference that may be present in the given sample. At low-level turbidities, sensitivity is often tested through a limit of detection test (LOD) or method detection limit test (MDL). This provides information on the bottom end of the measurement range, where turbidity detectability actually begins. For measurements above the LOD, sensitivity is very important to determine if an instrument will adequately respond to a change in turbidity over an extended measurement range. This guide presents one common test that can be used to determine if a given sensor's responsiveness to changes for a given sample is

TABLE 5 Preparation of Dilutions to Determine Measurement Sensitivity for a Given Sample Type

Percent of Sample	mL of Sample (to make 1 L)	mL of Dilution Water (to make 1 L)
10	100	900
20	200	800
40	400	600
60	600	400
80	800	200
100	1000	0

adequate. The test is to prepare different dilutions of the sample under assessment and determine if instrument response correlates to the different dilutions.

9.1.4.1 The sample dilutions technique determines a given sensor's responsiveness to changes in given sample. Several dilutions of the sample, that range from full strength (100 percent concentrated) down to a dilution that meets or exceeds the low end turbidity that would be expected. Each dilution is prepared with low turbidity water. Each dilution starting with the lowest expected turbidity (lowest percent of sample in a dilution) is then measured. Table 5 provides an example of the dilutions to be prepared in quantities of 1-liter. Record several measurements for each dilution, and then generate an average turbidity the dilution.

9.1.4.2 A plot between the concentrations of the sample (usually as a percentage of the most concentrated form of the sample) on the x-axis (horizontal) versus the measured turbidity of each concentrate y-axis (vertical) is prepared. See Fig. 8. Areas with a positive slope will indicate instrument sensitivity and areas with a zero slope or negative slope will indicate poor, no sensitivity, or negative sensitivity (see Fig. 9).

(1) Fig. 8 displays three different sensor responses to dilutions of a sample. After the data was plotted (as instructed in 9.1.4.2) the slope of each sensor can be calculated. The sensor with the highest slope (the blue trace) is the most sensitive and would be the most appropriate technology to measure the turbidity of the sample. The sensor that represents a more moderate slope (the pink trace) represents a positive correlation and may or may not be adequate for sample measurement, depending on the performance goals of the application. The third sensor response (the red trace) shows poor sensitivity and virtually no sensitivity at the higher concentrations of the sample. This sensor would likely fail to meet the performance objectives for this sample.

(2) Fig. 9 represents a generic response curve that is observed with turbidity sensors with a single detector system, the most common of which are nephelometric detectors. In this figure, the response is typically linear at lower turbidity levels. The linearity continues until incident light penetration through the entire view volume of the sample begins to decrease, thereby reducing available light scatter. This results in non-linearity though the correlation between turbidity and light scatter is still positive. This positive response will eventually diminish at a critical turbidity level when either the detector becomes saturated or light penetration into the sample begins to decrease. At turbidity levels above this critical no response level (the peak of the curve), the response may even begin to decrease as light penetration into the sample continues to diminish. The graphs shows that a sensor that has a similar profile will have an upper working limit, that can only be identified through a series of dilutions as described in 9.1.3.

(3) The procedure provided to determine sensor sensitivity is intended to provide the user with an early assessment of a sensor's performance for a given sample. In most cases, it would be expected that each assessment would need to be tailored to the respective application so it is in alignment with its monitoring goals. The procedure is not intended to deliver highly accurate results nor is it intended to deliver a correlation that would be expected to translate to other samples or sites.

9.1.5 *System and Measurement Stability*—Stability can refer to several conditions that include a sensor's exposure to different sample and ambient temperatures, sample flow variations, and environmental conditions.

9.1.5.1 Ambient temperature stability generally infers that a given measurement system (the sensor and supporting technology not vary in measurement (to within a given set of limits) over a given operational temperature range. The user should consult the manufacturer for best practices to insure expected performance criteria will be met. These best practices typically cover calibration, installation, and maintenance to minimize the impact of changing ambient temperatures. If extreme ambient temperatures are expected to exceed the manufacturer's specifications, the user should take appropriate actions to remedy the situation. An example would be to provide an external enclosure for the necessary components of a system that would be exposed to the temperature extremes.

9.1.5.2 Sample flow stability can impact measurements and is highly dependent on the application and is most critical in on-line or slipstream instruments. In theory, a specified range of sample flow should be independent of the measurement for a given sensor. However, excessive flow through a sensor can impact the efficiency of bubble removal systems these turbidimeters. Conversely, too low of a flow could result in particle settling within the sensor body, thereby compromising results. For in-line or in-situ applications, the position and depth of a sensor into a sample stream (or sample line) can impact measurements as well.

(1) The tolerance to variations in flow rate on a given sample should be evaluated when using an on-line or slipstream turbidimeters. The instrument should be installed with a flow control valve that can be used to change the flow as necessary. Some instruments require control of the flow prior to the sample reaching the instrument and others control the flow after the sample passes through the instrument, the selection of which is dependent upon the sensor design. Select the middle of the published flow range a given instrument to establish a measurement baseline. Then change the flow rate, by no more than 10 percent increments in either the positive or negative direction, monitoring the baseline after each change. Continue until a change in the baseline is observed that contributes to unacceptable measurement error.

9.1.5.3 Particulate stability is the ability for a sample to remain homogeneous as it passes through an instrument. At lower flow rates particles will may settle and cause a sample to stratify. At high flow rates, bubbles may become a significant interference.

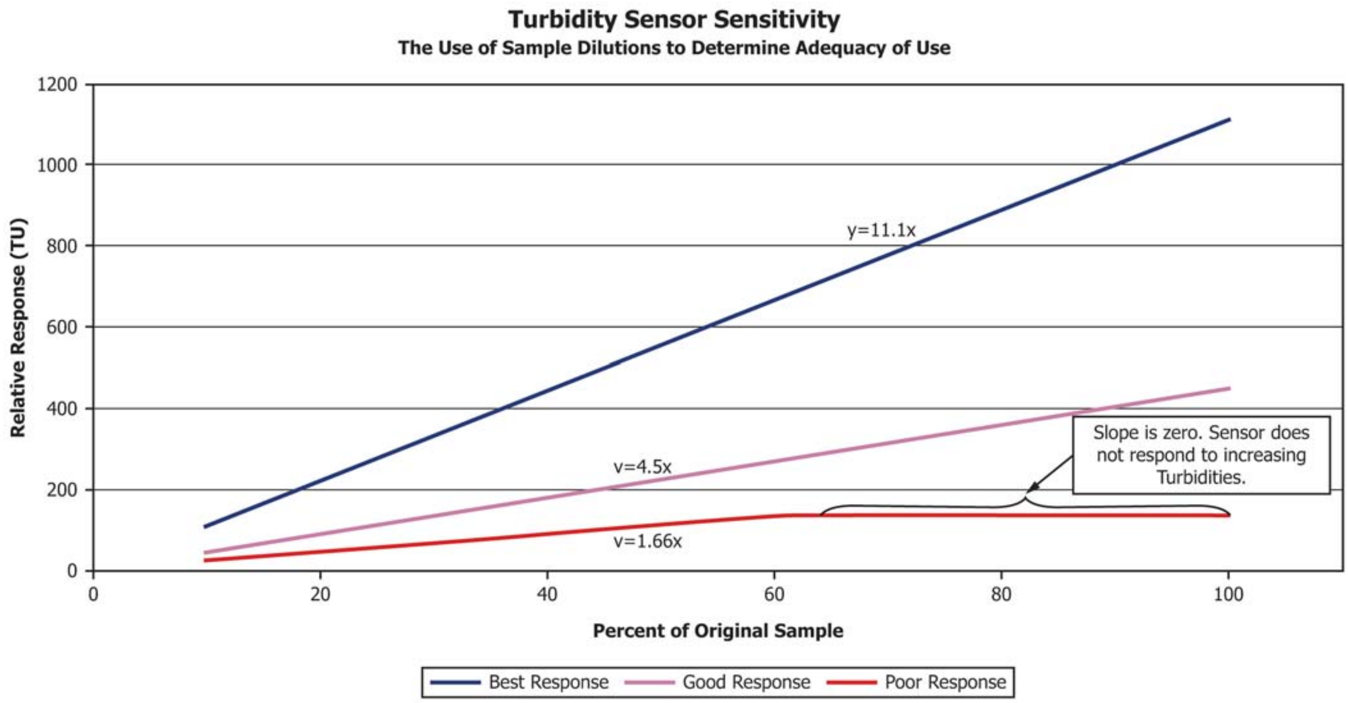


FIG. 8 Scenarios for Turbidity Sensor Sensitivity

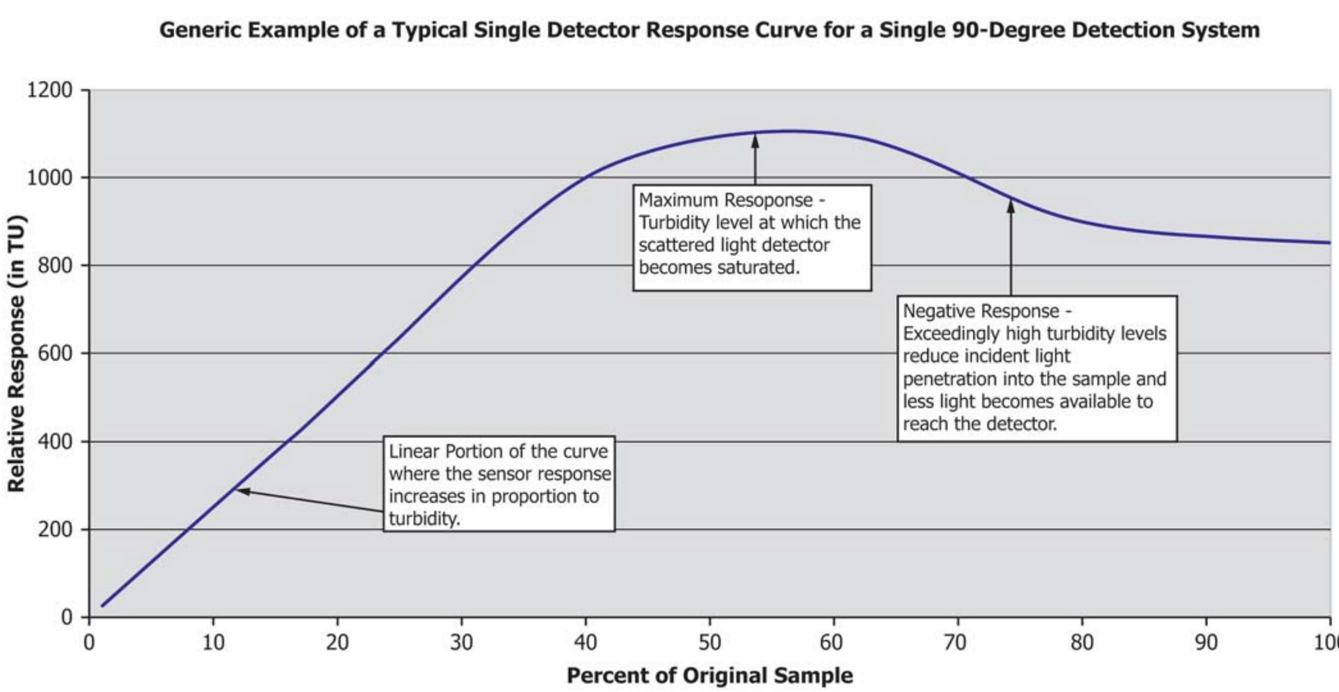


FIG. 9 Generic Response Curve for a Single Detector Turbidimeter System

(1) Particulate settling can cause critical measurement errors for on-line or slipstream sensors. Inspect the flow-cells for any evidence of settling. If settling is observed, clean the flow cell and return sample flow to the sensor. Continue to incrementally increase the sample flow until particulate settling no longer observed.

9.1.6 *Summary*—The user should not expect any technology to perform equally over all temperatures and flow conditions. It is important to identify the optimal boundaries that will yield consistent and meaningful results. Manufacturers typically offer guidance on optimal operational conditions that can serve as a basis for evaluating sensor performance across expected monitoring conditions.

10. Calibration and Verification

10.1 Depending on the application and monitoring goals the frequency of calibration and verification for a given technology may differ. It is important to consult the manufacturer's recommendations for calibration and verification practices and protocols.

10.2 In the absence of manufacturer recommendations, refer to the respective ASTM turbidity procedure for details on the calibration and verification procedures.

10.3 Comparative calibration and verification. It is common to compare measurements from a continuous or in-situ turbidimeter to a portable or bench turbidimeter for the purpose of either calibration or to verify operational performance of the continuous monitoring turbidimeter. If this practice is conducted, several precautions are warranted.

10.3.1 The bench or portable instrument that is used to verify the continuous monitoring instrument should use a similar measurement technology. Ideally, the technologies have the same reporting units, as are those that are derived and described Table 1 and Section 7.

10.3.2 For continuous monitoring technologies that do not have a technology laboratory or portable equivalent, the light source should be matched first, followed by the detection angle. Ratio designs will typically read higher because they compensate more effectively for interferences.

10.3.3 *Calibration of Continuous Field Monitors:*

10.3.3.1 Consult manufacturer's recommendations and instructions for performing calibrations on any turbidimeter. Any deviations from these procedures should be under consultation with the manufacturer. When a laboratory or portable instrument is used to verify a continuous monitoring instrument, measurement variability will be used when calibration is performed using the same type of calibration materials.

10.3.3.2 Calibration of continuous instrumentation is can be performed using the same make and models of the instruments in the laboratory. Verification should then follow calibration. After the verification step is complete, the instruments are placed in their respective field sites. Once they are set up and operational, re-verification of the deployed instruments should also be performed to confirm the instrumental performance remained integral throughout the transportation to the site and subsequent installation. Once verification is confirmed, the instrument can be expected to perform as expected from this point forward.

(1) Refer to Wagner's Field Manual for more information regarding this type of calibration.

(2) A site maintenance schedule should be established for each monitoring site that is in accordance with monitoring goals. The schedule should include the tasks for verification and maintenance if deemed necessary. If maintenance was performed which could impact the measurement performance, then a final verification should be performed on the sensor prior to ending the visit.

10.3.4 The technologies should be calibrated using the same type of standards, if possible.

10.3.5 In many cases, the portable instrument may not have the range of the continuous monitoring instrument. If this is the case the range of verification is limited to the range of the portable instrument.

10.3.6 If possible, analyze samples in the field where numerous aliquots are possible if necessary.

10.4 *Field Calibration of Sensors*—If field calibration of a sensor is performed, refer to the manufacturer's instructions for feasibility and recommendations. In addition, see ASTM SSC Method, Test Methods D3977, Chapter 6.7 of the USGS National Field Manual, and Wagner's Field Manual.

11. Record Keeping

11.1 *Introduction*—Metadata is very important when conducting a study. Metadata should be to the level of detail that a post project review of a monitoring site or study could be conducted to a level to confirm data integrity. Metadata can help ensure a comprehensive overview of the history of the site and can help explain data deviations that were unexpected.

11.2 At a minimum, the metadata should contain site notes, instrument logs, calibration logs, verification logs, and records of maintenance. Any unexpected observations with the site, the sensors, or the ancillary support systems should also be longed. The person performing the log entries should also be recorded.

11.2.1 Legible, detailed, and in-depth field notes and instrument logs are essential for accurate and efficient record processing. Metadata is essential when examining old data and assessing an unexpected change in measurement.

11.2.2 A dedicated, bound instrument log book or electronic document should be maintained for each instrument used and should document the use, calibration, and maintenance of all equipment used in the collection of the optical readings. Consideration should be made to insure the integrity of the logged information is maintained.

11.2.3 Calibration information can be recorded initially on field forms or in field notebooks, but the information then must be copied into the instrument logbook. Repair or replacement of sensors, meters, or modification to the software must be recorded in the instrument logbook. The instrument logbook should contain a complete record of all maintenance in the field, the laboratory, or by the manufacturer. Permanent instrument logs contain critical calibration and maintenance information that documents instrument performance throughout the service life of the instrument. Calibration information that is important to log for record processing includes:

- Sensor repair or replacement;
- Calibration dates, times, time datum, and temperatures;
- Calibration standard values, expiration dates, and lot numbers;
- Initial and final monitor-calibration data; and
- Field meter calibration values.

12. Precision and Bias

12.1 *General Comments:*

12.1.1 For a specific application, refer to Section 5. Estimate the expected range of measurement (high versus low turbidity) and whether the application requires static or continuous monitoring. From this information, refer to the referenced ASTM turbidity methods' respective P&B.

12.1.2 Refer to ASTM research reports for details regarding sample descriptions to determine if a comparable matrix was tested. Note: research reports are available from ASTM headquarters upon request.

12.1.3 It is important to note that many of the ASTM P&B studies may not be sorted by measurement technology. However, the existing data is still helpful in estimating the performance for a given application.

12.1.4 The high-level and low-level static and in-situ methods have more comprehensive round robin P&B and this may be helpful in ascertaining an appropriate technology.

13. Keywords

13.1 back-scatter; benchtop turbidity; continuous monitoring turbidity; in-situ turbidity; light-scattering; nephelometer; on-line turbidity; portable turbidity; ratio turbidity; sediments; turbidimeter; turbidity; turbidity application; turbidity interferences; turbidity meter; turbidity technology; turbidity units; water monitoring