Making Sense of Turbidity Measurements – Advantages In Establishing Traceability Between Measurements and Technology

Mike Sadar

Hach Company, 5600 Lindbergh Drive, Loveland, Colorado 80539-0389

Biographical Sketch of Author

Mr. Sadar has over 14 years experience in the research, development, and application of turbidity and particle analysis technologies as applied to environmental waters. He is a well-known authority on turbidity and membrane technology, has authored several papers on the science of turbidity and its applications, and serves on several American Society for the Testing of Materials (ASTM) sub-committees related to turbidity and suspended sediments measurement. Mr. Sadar received his Bachelor of Science degree in analytical chemistry from Colorado State University in 1988.

Abstract

While turbidity is well recognized as a key indicator of water quality in stream and watershed monitoring, the platforms employed to detect and quantify turbidity yields diverging results. The measurement of turbidity is highly influenced by the instrument's use of radiant incident-light and scattered light detection angle. Further, the accuracy of measurement is subject to particle shape and size, its distribution in a water sample, morphology, and color. As a consequence, interpretation of turbidity values can be perplexing, leading to under- or overstating of measurement values.

Historically, the collection of turbidity data is logged and interpreted without knowledge or trace to the type of platform used and its bias to the measurement. To reconcile this problem, the USGS and ASTM D-19 technical subcommittees on high-level turbidity have begun re-structuring turbidity reporting to lend traceability to the type of platform used in performing the measurement.

The purpose of this paper is to present an overview as to the variety of turbidity measuring platforms used in stream monitoring and to categorize them into equivalent or like measuring units. The value of understanding the difference and bias for each measuring platform should lead to a better interpretation of turbidity as it is related to water quality. The traceability to the technology will provide for better data comparability from a historical perspective.

Introduction:

Turbidity is the measurement of scattered light that results from the interaction of incident light with particulate material in a liquid sample. It is 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[1]. Turbidity of water is often caused by the presence of suspended and dissolved matter such as clay, silt, finely divided organic matter, plankton, other microscopic organisms, organic acids, and dyes. 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 water quality monitoring parameter to assess the health and quality of environmental water sources. Higher turbidity values are associated with poorer water quality.

Turbidity measurement is a qualitative parameter for water but its traceability to a primary 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 (TU's) or nephelometric turbidity units (NTU's). The primary standard for this parameter is a polymer compound known as formazin and this standard provides the traceable means for all other standards and is used to calibrate all types of turbidimeters. The polymer, when developed, was matched to a gravimetric mass of kaolin clay and 1 NTU approximately equals 1 mg/l Kaolin, when the clay is milled to a defined particle distribution[2]. For the more than 30 years, formazin has been used as the traceable primary standard for turbidity. This means that a TU is equivalent to a NTU, which are equivalent to all other turbidity units in which the calibration standard was formazin (or an alternative calibration standard that was traced to match formazin). Thus, all turbidimeter values have the same magnitude relative to this primary traceable standard.

The traceability of turbidity measurement to a common primary standard has allowed the application of this parameter to be used as a regulatory compliance tool for insuring a specific level of quality for water as it is applied to various uses. Turbidity is also used in environmental monitoring to assess the health of water-based ecosystems such as in watersheds, rivers, lakes, and streams.

Interferences in Turbidity Measurement:

The measurement of turbidity is suspect to a broad array of interferences. The most prevalent of interferences are summarized in Table 1. Turbidity interferences will either cause positive or negative bias. Negative bias results in a measurement being below the true reading and is typically associated with measurements greater than 1 NTU and can become more significant as the value increases. Positive turbidity interferences are typically associated with extremely low turbidity measurements, which are values below 0.1 NTU, which are significant in highly pure waters such as filtered drinking water.

Table 1 – Typical Interferences Associated with Turbidity Measurement[3]

Interference	Effect on the 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 within the sample matrix.
Particle Size	Either positive or negative bias (wavelength dependent) a) Large particles scatter long wavelengths of light more readily than will small particles. b) Small particles scatter short wavelengths of light more efficiently than long wavelengths
Bubbles	Positive bias and can impact measurement accuracy at all turbidity levels.
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 low turbidity values.
Stray light	Positive bias (reported measurement is slightly higher than the actual turbidity)
Particle Density	Negative bias (reported measurement is lower than the actual turbidity)
Particle Settling	Positive or negative bias can result from 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.
Instrument Based	Degradation of instrument optical components can have both positive and negative impacts on measurement, but bias is usually negative.
Contamination	Positive bias (reported measurement is higher than actual turbidity)

In Table 1, color is listed as an interference. However, depending on the application, color may be treated as part of the turbidity measurement and may not be considered as interference. Many instrument designs have been developed to reduce the impact of this variable (color absorbance) on the light scattering components of turbidity.

In an attempt to minimize interferences and improve measurement reliability, several different turbidity measurement methods (I. e. instrument designs or technologies) have evolved. Some of these designs are intended to maximize sensitivity to turbidity on the cleanest of waters. Other designs minimize the effects of interferences such as color. And, yet 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 measurement values on the same sample.

Common Turbidity Technologies:

The vast number of different technologies can be categorized by three different variables. One variable is the type of incident light source that is used. The second variable is the detection angle for the scattered light. The third variable is the application of multiple detectors, a technique known as ratioing. These components are discussed in more detail below:

Incident light sources: Light sources can be divided into three different categories: incandescent light sources, LED light sources, and laser light sources.

- Incandescent light sources are typically a polychromatic light source that requires a specific color temperature range. Most commonly, the temperature range is specified to be in the 2200 to 3000º Kelvin range. Under this operating condition, the source will emit energy that includes wavelengths in the 400 to 600 nm range. These shorter wavelengths will be more effectively scattered by smaller particles.
- Light emitting diode (LED) light sources. These sources commonly apply LED illumination technologies, with the most common wavelength range (that is used in turbidity measurement) between 830-to 890 nm (near IR). These light sources are typically not absorbed (interfered) by visible color in the sample.
- Laser light sources. A small portion of incident light sources will include laser-based light sources that emit energy at a discrete wavelength that is typically in the 400-700-nm range. Laser-based light sources are very sensitive to small changes in turbidity and are often used to monitor filtration performance for clean waters.

Detection Angle: Detection angle can have a significant impact on the detection of particles from a size perspective and on the turbidity range of the instrument. Also, the number of the detectors and their relative angle to the incident light beam can help reduce the impact of interferences such as color and changes in the instrument components. The different angles and the impact of multiple detectors are summarized below:

- 90-degree detection angle. This is often referred to as the nephelometric detection angle and the angle formed between the centerline of the incident light beam and the centerline of the receive angle forms an angle of 90 degrees. This is the most common detection angle because of its sensitivity to a broad range of particle sizes. Figure 1 provides an illustration of a nephelometric detection angle that can utilize any of the light sources discussed above.

- Attenuated detection angle. This detection angle is geometrically oriented at an angle that is 180-degrees relative to the incident light beam. This detection angle measures the attenuation of the incident light beam due to light scatter and absorption. Figure 2 provides an example of an attenuated detection angle. This angle has the greatest susceptibility to absorbance and color interferences.

- Backscatter Detection Angle. The backscatter detection angle has a detector that is geometrically centered at an angle of between 30 and 40 degrees relative to the incident light beam. This angle will be sensitive to light scatter that is reflected back in the direction of the incident light source, which is characteristic with extremely high turbidity samples. Figure 3 provides an example of the geometry of a backscatter detection system for turbidity.

Ratioing: This turbidity technology involves the use of two or more detectors to determine the turbidity value within a sample. A second technology uses the combination of two incident light sources and two detectors.

- Multiple Detection Angles. This approach will utilize one primary detector, which is typically oriented at a 90-degree angle relative to the incident light beam, and it is often referred to as the primary nephelometric detector. Other detectors will be at various angles including an attenuated; backscatter, and forward scatter angles. A software algorithm is often used to produce the turbidity measurement from the combination of detectors. These detectors can help compensate for color interference and in optical changes such as lamp degradation. Figure 4 provides an illustration of the geometric arrangement of detectors that constitute a ratio measurement. Figure 5 provides an illustration on how a ratio technique can be applied to an in-situ turbidimeter probe.

- Dual light source dual detector. This unique approach uses a combination of light sources that are geometrically oriented at 90-degree angles to each other. The detectors are also oriented at 90-degrees to each other and at 90 and 180-degrees to each of the light sources. In one phase of measurement, a detector will be the nephelometric (90-degree) detector and the other detector will be at 180-degrees to the light source that is powered. In the second phase of the measurement, the second light source will be powered and the detector positions from phase one are reversed. A software algorithm is then used to generate the turbidity value from different measurement phases. The combination of the two phases provides a turbidity measurement that is corrected for color absorption, fouling of the optics, and any optical changes that can occur. An illustration of the dual light source dual detector is provided in Figure 6.

The combination of the sample, its respective characteristics and the selected 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 certain technologies and weak to no bias on other technologies. For example, many of the newer technologies, such as those that utilize near IR light sources with ratioing will not be biased by color when compared to some of the older technologies that utilize the incondescent light sources. 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.

Summary of Technologies:

Turbidity measurements of a common sample are often not consistent across a wide variety of measurement technologies. This also holds true with higher turbidity samples such as environmental waters or water that can change significantly over the course of time. Historically, turbidity measurement has attached a generic turbidity unit, such as the NTU or FTU to any reported value with little attention paid to the type of measurement technology that was used. This results in lost traceability to the measurement technology and it often invalidates any type of comparability that was drawn across different samples.

- For example, consider two different stream waters that were measured using two different instrument technologies. One technology reported a value from stream 1 that was twice the turbidity value of stream 2. Unless there is knowledge that stream 1 and 2 turbidity measurements were performed with identical measurement technologies, there is no means of validating that stream 2 was actually twice the turbidity of stream 1.

The scenario provided in the above example is common when comparing data from a historical perspective. Without the knowledge of the technology used to perform the measurement, there is no discreet means to compare data from different sources. If traceability to the instrument were provided, critical insight will be available when performing data interpretations.

The American Society Testing and Materials (ASTM) turbidity subcommittees and United States Geological Survey (USGS) recognized the lack of traceability of turbidity measurements in historical databases. In an attempt to improve data quality and collection, distinct turbidity reporting units were developed that are now based on the instrument technology. Each technology is traced to a unique turbidity unit. Table 2 provides a summary of the different known turbidity technologies that are available and the respective reporting units. In addition, Table 2 provides application information for each of these technologies.

Table 2: Summary of Known Instrument Designs, Applications, Ranges, and Reporting Units.

Design and the Proposed Reporting Unit[4]	Prominent Application and Major Interference Concerns	Key Design Features	Suggested Application and operating range Ranges
Nephelometric non-ratio (NTU)	White light turbidimeters. These designs comply with EPA 180.1 for low level turbidity monitoring.[5] Color is a major negative interference and optical variations cannot be compensated with this technique.	The detector is centered at 90 degrees 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.[5]	Regulatory for drinking water. The optimal operating range is 0.0 to 40 units.
Ratio White Light turbidimeters (NTRU)	Complies with the USEPA Interim Enhanced Surface Water Treatment Rule regulations and Standard Methods 2130B.[6] Can be used for both low and high level measurement. Color interference (negative) is reduced and lamp variations are compensated for with this technique.	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.	Regulatory for drinking water and wastewater (0-40 units). The technology can potentially measure up to 10,000 units.
Nephelometric, near- IR turbidimeters, non-ratiometric (FNU)	The instrument design is compliant with ISO 7027.[7] 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.	This technology uses a light source in the near IR range (830-890 nm). The detector is centered at 90° degrees relative to the incident light beam.	Regulatory compliance in Europe for drinking water and wastewater(0 - 40 units). The technology can measure up to 1000 units.
Nephelometric	Complies with ISO 7027. This	This technology applies the same light	Regulatory compliance

near-IR turbidimeters, ratio metric(FNRU)	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.	source that is required by ISO7027. The design uses several detectors in the measurement. A primary detector is centered at 90^o 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.	monitoring in Europe for drinking water and wastewater (0 - 40 units). The technology can potentially measure up to 10000 units.
Surface Scatter Turbidimeters (NTU)	Turbidity is determined through light scatter at or near the surface of a sample. Negative color interferences are reduced when compared to the non-ratio nephelometric method.	The technology uses the same light source as in EPA180.1. The detector centered at 90 degrees relative to the incident light beam. Both the detector an incident light source are mounted in a defined position immediately above the sample.	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 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 design applies a near-IR monochromatic light source in the 780-900 nm range as the incident light source. The scattered light detector is positioned at 30±15 ^{o} relative to the incident light beam.	This technology is best suited for insitu 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)	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.	The design applies a white light spectral source (400-680 nm range). The detector geometry is 30±15 ^{o} relative to the incident light beam.	This technology is best suited for insitu 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 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.	The incident light beam is at a wavelength of 860±30 nm. The detector is geometrically centered at 180^o relative to the incident light beam. This is typically an attenuation measurement	This measurement is part of the ISO 7027 regulation. The optimal turbidity range is between 20 and 1000 units.
Light attenuation unit (AU)	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.	The wavelength of the incident light is in the 400-680 nm range. The light scatter detector is geometrically centered at 180^o relative to incident beam. This is an attenuation measurement.	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 1,000 units.
Nephelometric Turbidity Multibeam Unit (FTMU)	This technology is compliant to the EPA regulatory method GLI Method 2[8] and ISO 7027. It is applicable to regulatory monitoring for drinking	The technology consists of two light sources and two detectors. The light sources comply with ISO7027. The detectors are geometrically centered at	Regulaotry monitoring at low turbidity levels in the 0.02 to 40 unit range. The technogy

	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.	90° relative to each incident light beam. The instrument measures in two phases in which the detectors are either at 90° or 180° relative to the incident light beam, depending on the phase. An instrument algorithm uses a combination of detector readings to calculate the reported value.	can measure up to 4000 units.
Laser Turbidity Units (mNTU)	This technique complies with the EPA approved Hach Method 10133[9]. 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.	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 90 degrees relative to the incident light beam	Regulatory monitoring of drinking water effluent and membrane systems. The range is 0.007 to 5 units. Reports in mNTU where 1 NTU = 1000 mNTU.

Conclusions:

Currently, the units for reporting turbidity values are commonly the same and independent of the instrument design being used. Depending on the interferences present (especially in high level reporting), the instrument design can have a sizeable impact effect on the bias of the reported result. For example, if a sample with a high-level turbidity value is measured with a white light non-ratio instrument, the results will likely be biased negative and a reading obtained using a 4-beam, IR ratio method will have little to no negative bias. The solution to this problem is to apply measurement units that are traceable to the type of technology used. This will help to better qualify data into databases and effectively help in results interpretation.

The logic behind the proposed unit traceability assignment was based on the different design criteria that were discussed earlier in this paper. These criteria can be separated by light source, detector orientation, and the number of detectors used to make the measurement. Generally (but not always), the following criteria were chosen for the traceability units. Any unit that begins with the letter "N" will designate an incandescent light source. Any unit that begins with the letter "F" will designate the use of a near-IR light source. The second letter in the unit will provide traceability to the detection angle, with the letter "B" representing backscatter, and the letter "A" indicating attenuation. The use of the letter "R" indicates a ratio method and the use of the letter "M" indicates a multi-light source/multi-detector technology. Last, units of mNTU will provide traceability to laser based methods.

The ability to accurately trace the turbidity measurement to an instrument design technology is necessary to effectively qualify and quantify the turbidity measurement. Attaching more specific technology-traceable units to the results will help to clarify the turbidity value and will allow the user to determine when it is appropriate to directly compare results obtained with different instruments. This proposed traceability has been developed as a joint effort between the ASTM high-level turbidity subcommittees, the USGS, and the instrument manufacturers. The method is currently under development with the ASTM D-19 technical sub-committees.

Figures:

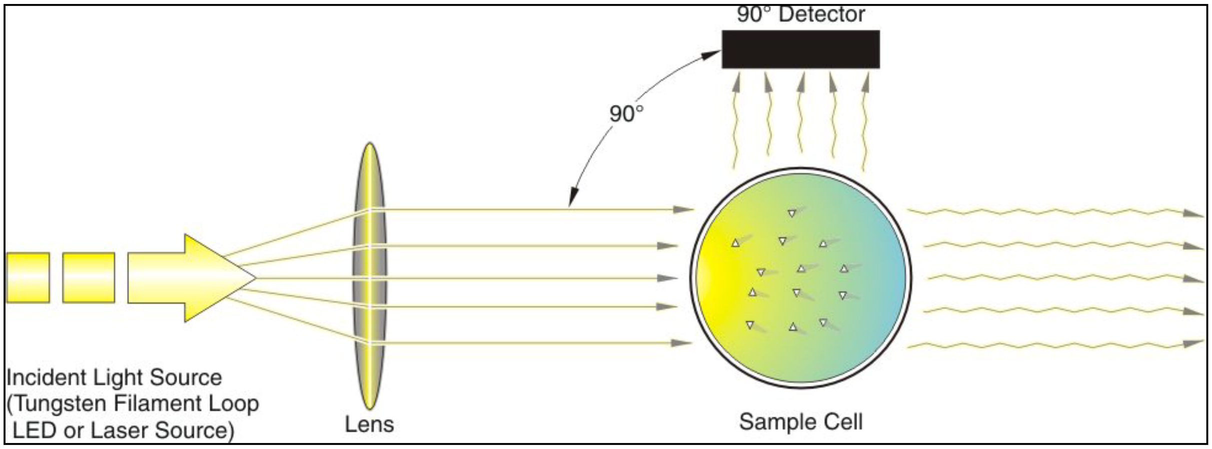

Figure 1 - Optical geometry required for a basic nephelometric turbidity measurement.

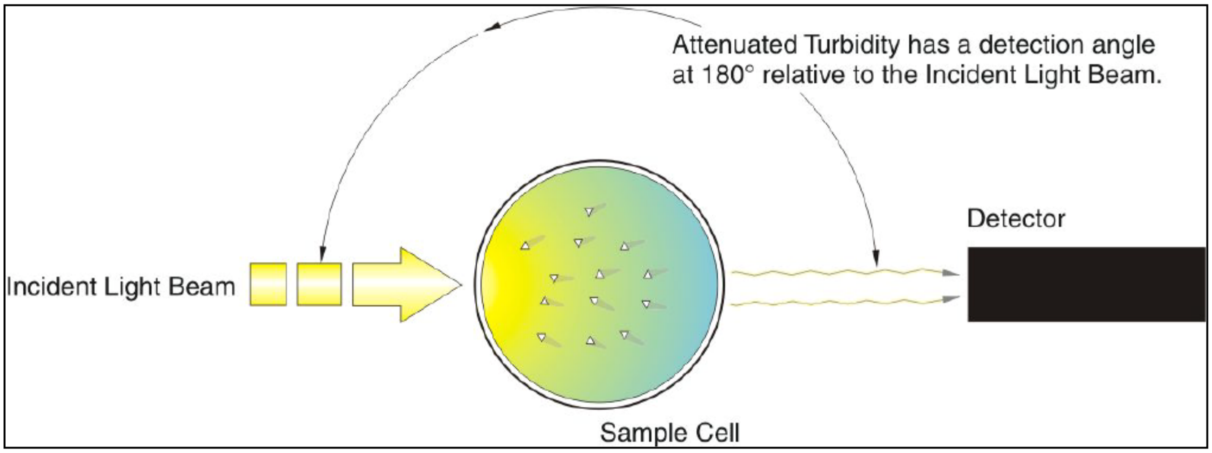

Figure 2 - Optical geometry for an attenuated turbidity measurement.

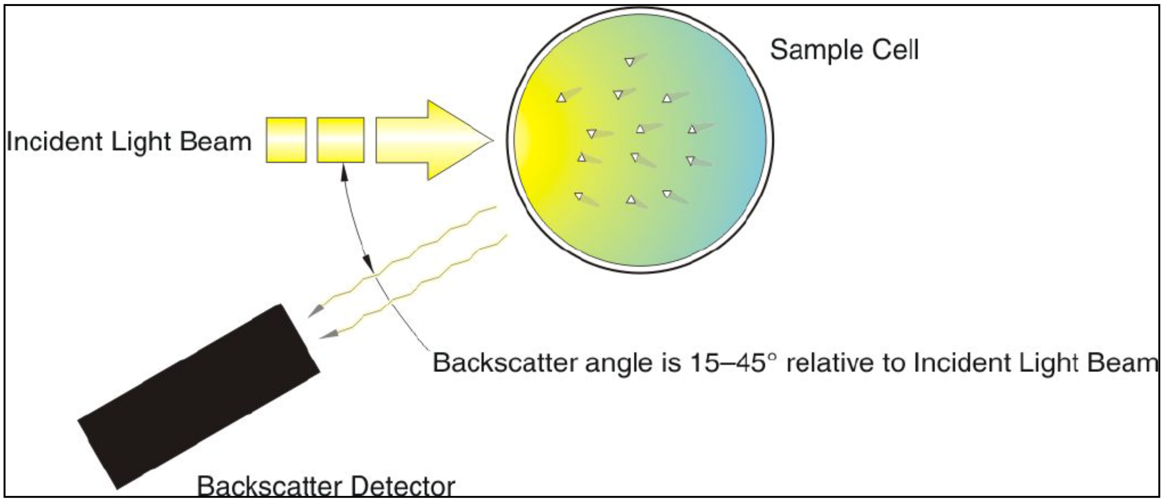

Figure 3 – The optical geometry for a backscatter turbidity measurement design that can be applied to high turbidity measurements.

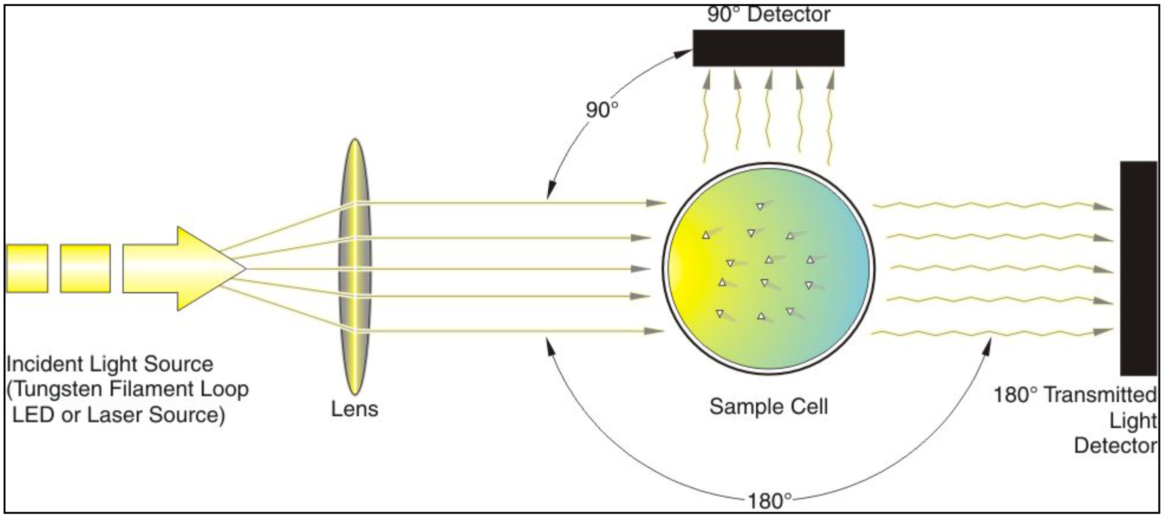

Figure 4 – Optical geometry for a basic ratio system involving two detectors. More detectors may be present in different designs to help reduce various interferences or extend the measurement range of the instrument.

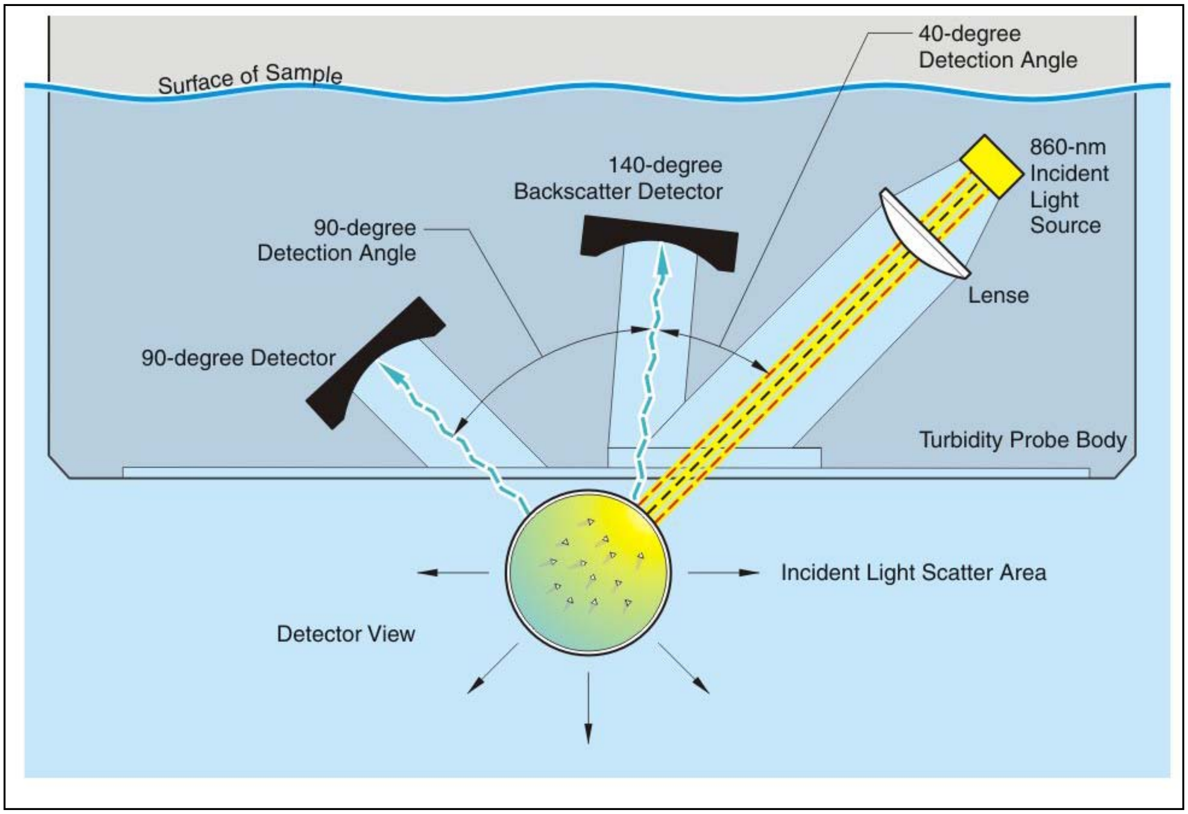

Figure 5 - Optical geometry for a turbidimeter probe design that utilizes a ratioing technology. The 90-degree detection angle is formed between the incident light beam and this detector.

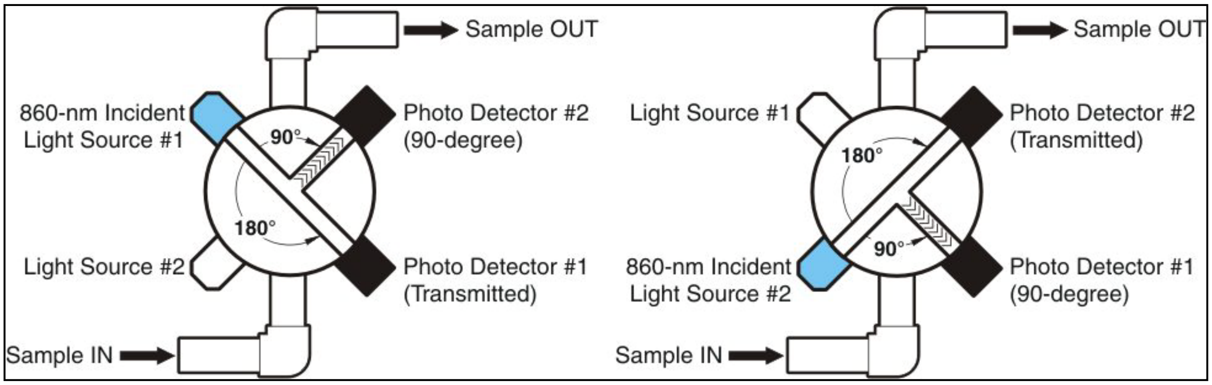

Figure 6 - The optical design for a multi-beam, multi-detector turbidimeter. Both phases of the measurement are displayed to demonstrate how the pairs of light sources and detectors combine to generate the turbidity measurement.

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