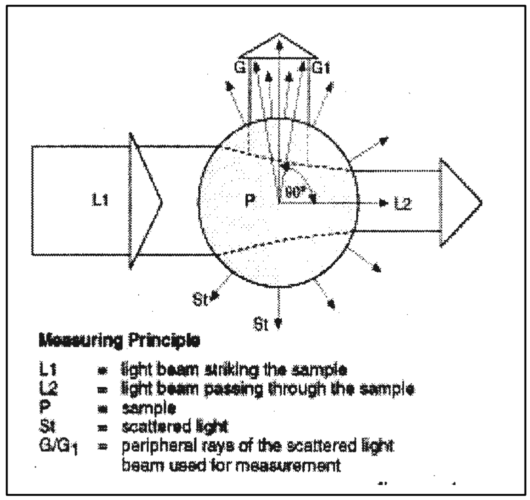
11. BASIC TURBIDIMETER DESIGN AND CONCEPTS

11.1 Introduction

Turbidity is described in the *Standard Methods for the Examination of Water and Wastewater* Method 2130B (EPA Method 180.1) for turbidity measurement as, "an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample" (Standard Methods, 1995). This chapter includes a detailed summary of the various types of instruments used to measure turbidity and includes descriptions of the physical properties associated with the measurements of turbidity and design configurations.

As shown in Figure 11-1, modern turbidimeters use the technique of nephelometry, which measures the amount of light scattered at right angels to an incident light beam by particles present in a fluid sample. In general, all modern turbidimeters utilize the nephelometric measurement principals, but instrument manufacturers have developed several different meter designs and measurement configurations.



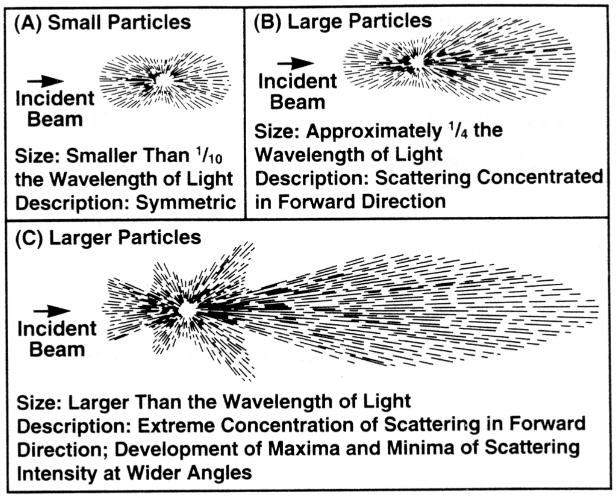
Source: GLI, undated.

Figure 11-1. Scattered Light at 90°

11.2 Turbidimeter Measuring Principles

As light passes through 'absolutely pure' water, the light beams travel along relatively undisturbed paths. However, some distortion occurs as light is scattered by molecules present in the pure fluid. As shown in Figure 11-1, when light passes through a fluid containing suspended solids, the light beam interacts with the particles, and the particles absorb the light energy and re-radiate light in all directions.

Particle size, configuration, color, and refractive index determine the spatial distribution of the scattered light intensity around the particle. As shown in Figure 11-2, particles much smaller than the wavelength of the incident light, which is typically expressed in nanometers (nm), scatter light of approximately equal intensity in all directions. However, particles larger than the wavelength of the incident light, form a spectral pattern that results in greater light scattering in the forward direction (away from the incident light) than in the other directions. This scattering pattern and intensity of the light beam transmitted through the sample can also be affected by the particles absorbing certain wavelengths of the transmitted light (Sadar, 1996).



Source: Sadar, 1996.

Figure 11-2. Angular Patterns of Scattered Light from Particles of Different Sizes

Since the light scattered in the forward direction is variable depending on particle size, the measurement of the light transmitted through the sample yields variable results. In addition, the change in transmitted light is very slight and difficult to distinguish from electronic noise when measuring low turbidities. High turbidity samples are also difficult to measure using transmitted light due to multiple scatter of the light by many particles in the fluid. To solve these problems, turbidimeters primarily measure the scatter of light at a 90 degree angle to the incident beam and relate this reading to turbidity. This angle is considered very sensitive to light scatter by particles in the sample. As described later in this chapter, additional light sensors are also sometimes added to detect light scattered at other angles in order to improve the instrument range and remove errors introduced by natural colors and lamp variability.

11.2.1 Light Source

The basic turbidimeter instrument contains a light source, sample container or cell, and photodetectors to sense the scattered light. The most common light source used is the tungsten filament lamp. The spectral output (band of wavelength light produced) of these lamps is generally characterized by “color temperature,” which is the temperature that a black body radiator must be operated to produce a certain color. The tungsten filament lamps are incandescent lamps and are termed “polychromatic,” since they have a fairly wide spectral band that includes many different wavelengths of light, or colors. The presence of the various wavelengths can cause interference in the turbidity measurements as natural color and natural organic matter in the sample can absorb some specific wavelengths of light and reduce the intensity of the scattered light (King, 1991).

The tungsten filament lamp is also highly dependent on the voltage of the lamp power supply. The voltage applied to the lamp determines the spectral output characteristics produced, making a stable power supplies a necessity. In addition, as with any incandescent lamp, the output from the lamp decays with time as the lamp slowly “burns out,” making recalibration of the instrument a frequent and necessary requirement.

To overcome some of the incandescent lamp limitations, some turbidimeter designs utilize monochromatic light sources, such as light emitting diodes (LEDs), lasers, mercury lamps, and various lamp filter combinations. Monochromatic light has a very narrow band of light wavelengths (only a few colors). By selecting light wavelengths that are not normally absorbed by organic matter, the monochromatic light source can be less susceptible to interference by sample color. However, some of these alternate light sources respond differently to particle size, and are not as sensitive to small sized particles as the tungsten filament lamp.

11.2.2 Sample Volume

Grab samples are typically introduced into bench top turbidimeter instruments through a transparent sample cell made of glass. These samples cells, or cuvettes, are usually about 30 milliliters in capacity. Some on-line turbidimeters utilize the glass sample cell, but most designs use a flow-through chamber with the light source located outside the sample. Sample chambers in on-line instruments range from 30 milliliters to over two liters.

11.2.3 Photodetector

In turbidimeters, photodetectors detect the light produced from the interaction of the incident light and the sample volume and produce an electronic signal that is then converted to a turbidity value. These detectors can be located in a variety of configurations depending on the design of the instrument. The four types of detectors commonly used include photomultiplier tubes, vacuum photodiodes, silicon photodiodes, and cadmium sulfide photoconductors (Sadar, 1992).

Each of the four types of detectors vary in their response to certain wavelengths of light. Therefore, if a polychromatic light source is used, the spectral output of the light source has a direct bearing on the type and design of photodetector selected for an instrument. The specification of the photodector is not nearly as critical when a monochromatic light source is used. In general, with the polychromatic tungsten filament lamp as a light source, the photomultiplier tube and the vacuum photodiode are more sensitive to the shorter wavelength light in the source, making them more sensitive to the detection of smaller particles. Conversely, the silicon photodiode is more sensitive to longer wavelengths in the light source, making it more suited for sensing larger particles. The sensitivity of the cadmium sulfide photoconductor is between the sensitivity of the photomultiplier tube and the silicon photodiode.

11.3 Turbidimeter Design Configurations

Several instrument design standards have been developed by various organizations to attempt to standardize instrument designs and achieve test results that are accurate and repeatable. These standards govern the design of the various turbidimeter configurations available today, which include the single beam design, modulated four beam design, surface scatter design, and transmittance design. Only the single beam design, ratio design, and modulated four beam design are approved by EPA.

11.3.1 Design Standards

The requirements stated in *Standard Methods* 2130B (see Appendix D) are similar to the requirements of EPA Method 180.1 (see Appendix C) for turbidity measurement. The EPA Method 180.1 lists the following design requirements for turbidimeters:

- "Light Source: Tungsten-filament lamp operated at a color temperature between 2200 and 3000 degree K.
- Distance traversed by incident light and scattered light within the sample tube not to exceed 10 cm.
- Angle of light acceptance by detector: Centered at 90 degrees to the incident light path and not to exceed +/- 30 degrees from 90 degrees. The detector, and filter system if used, shall have a spectral property between 400 and 600 nm (Standard Methods, 1995)."

EPA has recognized one additional standard for turbidimeter design called GLI Method 2. Like EPA Method 180.1, this standard is applicable for turbidities in the 0 to 40 NTU range, but may be used for higher turbidities by diluting the sample. The GLI Method 2 standard requires that instruments utilize basic nephelometric concepts, but requires the use of two light sources with a photodetector located at 90-degrees from each source. This concept, which is often called a modulated four beam design, pulses the two light sources on and off and utilizes a portion of the scattered light as a reference signal to arithmetically cancel errors. A full description of the modulated four beam design is included later in this Chapter.

The specific apparatus requirements listed in the GLI Method 2 standard are as follows:

- The wavelength of the incident radiation shall be 860 nanometers.
- The spectral bandwidth of the incident radiation shall be less than or equal to 60 nanometers.
- There shall be no divergence from parallelism of the incident radiation and any convergence shall not exceed 1.5 degrees.
- There shall be two light sources and two detectors.
- The measuring angle between the optical axis of the incident radiation and that of the diffused radiation for light pulsed through the sample by either light source shall be 90 +\- 2.5 degrees.

An additional turbidimeter design standard was developed by the International Organization for Standardization. ISO 7027 defines the requirements for a turbidimeter light source with stricter requirements attempting to produce instruments that have good repeatability and compare well with other instruments. The specification reads:

"Any apparatus may be used provided that it complies with the following requirements:

- The wavelength , λ, of the incident radiation shall be 860 nm;
- The spectral bandwidth , $\Delta\lambda$, of the incident radiation shall be less than or equal to 60 nm;
- There shall be no divergence from parallelism of the incident radiation and any convergence shall not exceed 2.5 degrees;

- The measuring angle (tolerance on deviation of the optical axis) shall be o +/- 2.5 degrees
- The aperture angle, Ω_θ, should be between 10 and 20 degrees in the water sample (ISO, 1990)."

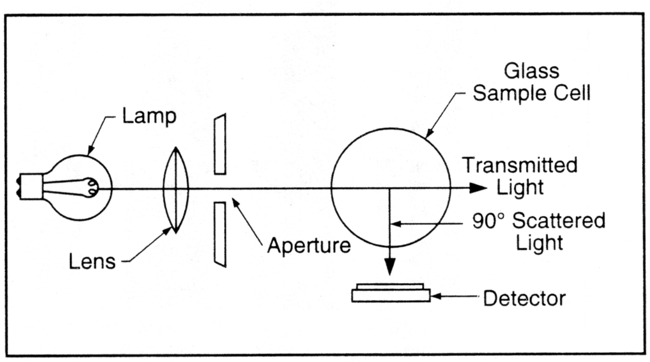
ISO 7027 requires the use of monochromatic light sources such as tungsten lamps fitted with monochromators and filters, diodes, or lasers. However, the standard recognizes that many older instruments have polychromatic light sources, and allows their use for water treatment monitoring and control, but not for comparison to readings from other turbidimeters.

The tighter definition of the light source in ISO 7027 eliminates many of the variables inherent to the polychromatic sources used in the other standards. However, ISO 7027 does not eliminate the effects of light source decay or electronic gains and drifts inherent in monochromatic sources such as LEDs (Lex, 1994). **ISO 7027 is not accepted by EPA for turbidity analysis for compliance with the IESWTR.**

11.3.2 Single Beam Design

The single beam design configuration, shown in Figure 11-3, is the most basic turbidimeter design using only one light source and one photodetector located at 90 degrees from the incident light. The single beam design is the oldest of the modern nephelometers and typically is used with a polychromatic tungsten filament lamp. The design is still in wide used today and yields accurate results for turbidity under 40 NTU, provided that samples have little natural color. In fact, many on-line instruments in use today still utilize the single beam design.

The single beam design does, however, have limited accuracy at higher turbidities. As turbidity increases and the amount of scattered light increases, multiple scattering can occur when light strikes more than one particle as it reacts with the sample fluid. The resulting scattered light intensity reaching the 90 degree detector can diminish as the instrument effectively "goes blind." For this reason, a single beam design conforming strictly to EPA 180.1 does not typically demonstrate stable measurement capability at high turbidities and is generally only applicable for turbidity readings from 0 to 40 NTU.



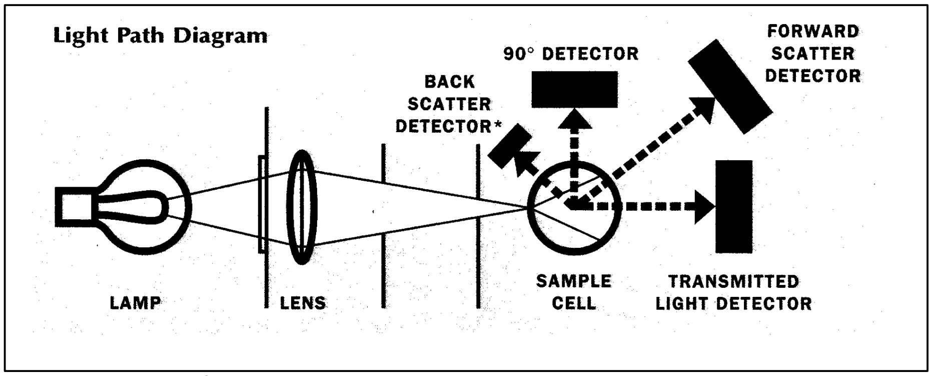
Source: Sadar, 1996.

Figure 11-3. Basic Nephelometer

The design of the single beam instrument is also limited by the need for frequent recalibration of the instrument due to the decay of the incandescent light source. Because of the polychromatic nature of the light source, these instruments also can demonstrate poor performance with samples containing natural color. Since most treated water samples have low or no color, use of the single beam design is appropriate.

11.3.3 Ratio Design

The ratio turbidimeter design expands upon the single beam concept, but includes additional photodetectors located at other angles than 90 degrees from the incident light. As shown in Figure 11-4, the ratio design utilizes a forward scatter detector, a transmitted light detector, and for very high turbidity applications, a back scatter detector. The signals



Source: Sadar, 1996.

Figure 11-4. Ratio Turbidimeter

from each of these detectors are mathematically combined to calculate the turbidity of the sample. A typical ratio mathematical algorithm is as follows (Standard Methods, 1995):

$$T = I_{90} / (d_0 * I_t + d_1 * I_{fs} + d_2 * I_{bs} + d_3 * I_{90})$$

Where:

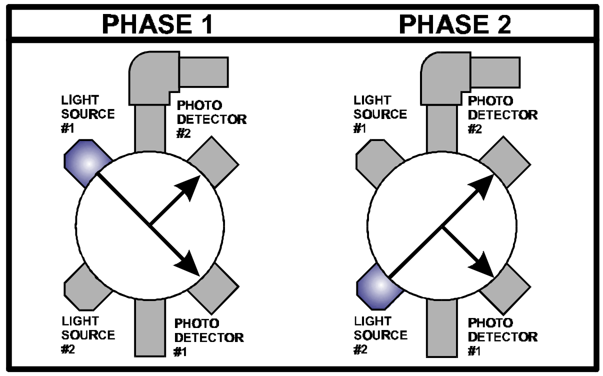
T = Turbidity in NTU
d_0, d_1, d_2, d_3 = Calibration Coefficients
I_{90} = 90 Degree Detector Current
I_t = Transmitted Detector Current
I_{fs} = Forward Scatter Detector Current
I_{bs} = Back Scatter Detector Current

The use of multiple photodetectors and the ratio algorithm gives the instrument much better performance with colored samples. The transmitted light and the 90-degree scattered light are affected almost equally by the color of the sample because they travel nearly the same distance through the sample volume. When the ratio of the two readings is taken, the effects of color absorption on the two readings tend to cancel mathematically.

11.3.4 Modulated Four Beam Design

Unlike the single beam and ratio turbidimeters, the modulated four-beam instrument design utilizes two light sources and two photo detectors. The two sources and the two detectors are used to the implement theory of ratio measurements to cancel errors. As shown in Figure 11-5, the light sources and detectors are located at 90 degrees around the sample volume (Great Lakes Instruments, undated).

This design takes two measurements every 0.5 seconds. In the first phase, light from source #1 is pulsed directly into photodetector #2. Simultaneously, photodetector #1 measures the light scattered from this pulse at a 90 degree angle. In the second phase, light from source #2 is pulsed directly into photodetector #1. Simultaneously, photodetector #2 measures the light scattered from this pulse at a 90 degree angle. In both phases, the signal from the photodetector receiving the direct light signal is the active signal, while the signal from photodetector measuring scattered light is called the reference signal. The two phase measurements provide four measurements from two light sources: two reference signals and two active signals.



Source: GLI, undated.

Figure 11-5. Modulated Four-Beam Turbidimeter

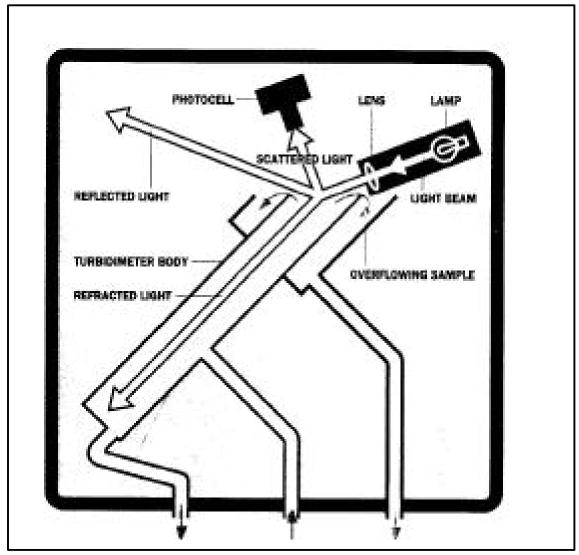
The turbidity of the sample is calculated from the four independent measurements taken from the two light sources using a mathematical algorithm similar to the algorithm used by the ratio instrument design. The result is that errors resulting from sample color appear in both the numerator and denominator of the mathematical algorithm, and the errors are mathematically canceled.

Like the ratio design, the mathematical algorithm used in the four beam design allows for more sensitivity in highly turbid samples and extends the range of the instrument to about 100 NTU. The error cancellation achieved by the ratio algorithm also makes the instrument very accurate in the 0 to 1 NTU range.

11.3.5 Surface Scatter Design

As turbidity increases, light scattering intensifies and multiple scattering can occur as light strikes more than one particle as it interacts with the fluid. Light absorption by particles can also significantly increase. When particle concentration exceeds a certain point, the amount of transmitted and scattered light decreases significantly due to multiple scattering and absorption. This point is known as the optical limit of an instrument.

The surface scatter design utilizes a light beam focused on the sample surface at an acute angle. As shown in Figure 11-6, light strikes particles in the sample and is scattered toward a photodetector that is also located above the sample surface. As turbidity increases, the light beam penetrates less of the sample, thus shortening the light path and compensating for interference from multiple scattering. The reported range of surface scatter instruments is about 0 to 9999 NTU, although these instruments are best suited for measuring high turbidities such as are present in raw water and recycle streams (Hach Corporation, 1995). These designs are not approved by EPA.



Source: Hach Corporation, 1995.

Figure 11-6. Surface Scatter Turbidimeter

11.3.6 Transmittance Design

Instruments utilizing a transmittance design are often referred to as turbidimeters, but these instruments do not measure true turbidity of water in NTUs. These instruments are better termed "absorptometers" as they measure the amount of light transmitted through a sample rather than the amount of light scattered by a sample. Light transmittance is measured by introducing a light source to a sample volume and measuring the relative amount of light transmitted through the sample volume to a photodetector located opposite the light source. Transmittance values are reported as 0 to 100 percent of the incident light source transmitted through the sample. The use of absorptometers in water treatment has generally been restricted to monitoring spent filter backwash water to determine relative cleanliness of the filter media (Hach Corporation, 1995). These designs are not approved by EPA.

11.4 Types of Turbidimeters

There are three common types of turbidimeters employed today. These are referred to as bench top, portable, and on-line instruments. Bench top and portable turbidimeters are used to analyze grab samples. Bench top units are typically used as stationary laboratory instruments and are not intended to be portable. On-line instruments are typically installed in the field and continuously analyze a sample stream spilt off from a unit process. Measurement with these units requires strict adherence to the manufacturer's sampling procedure to reduce errors from dirty glassware, air bubbles in the sample, and particle settling.

11.4.1 Bench Top Turbidimeters

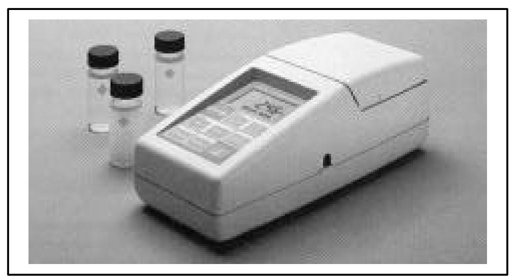
Most bench top turbidimeters are designed for broad applications and have the capability to measure highly colored samples as well as samples with high turbidities. The most popular bench top turbidimeters used today utilize the ratio design, but may have options for back scatter detectors or monochromatic light sources. Many ratio bench top instruments also have the capability to turn off the ratio calculation so that measurements can be made using the single beam design. Older bench top instruments may be of the single beam design, and some have analog rather than digital displays. Bench top units are used exclusively for grab samples and require the use of glass cuvettes for holding the sample volume.

Source: Hach Corporation, 1995.

Figure 11-7. Bench Top Turbidimeter

11.4.2 Portable Turbidimeters

Portable turbidimeters are similar to the bench top units, except that they are designed for portable use and are battery operated. Portable turbidimeters are available in a variety of designs, including the single beam and ratio designs. The accuracy of portable instruments is comparable to the bench top units, but the resolution of low turbidity reading may only be 0.01 NTU as compared to the 0.001 NTU resolution of bench top units (Hach Corporation, 1995).



Source: Hach Corporation, 1995.

Figure 11-8. Portable Turbidimeter

Portable turbidimeters are designed for use in the field with grab samples. These instruments are designed to be rugged and capable of withstanding the affects of moving the instrument as well as variable field conditions. However, since these instruments are inherently susceptible to damage or disturbance from dropping, abuse, or environmental conditions such as dust, these units are not appropriate for the process monitoring and reporting tasks normally accomplished by bench top units or on-line turbidimeters.

However, portable instruments are useful for measuring turbidity at remote locations such as at sampling points in the watershed upstream of a water treatment plant, or at a remote raw water intake location. Portable instruments are also useful for conducting special process studies, such as backwash recycle characterization or distribution system analysis that may be accomplished more readily and accurately in the field rather than conducting analysis after transporting a sample to a laboratory.

11.4.2 On-Line Turbidimeters

The on-line instruments used in the water treatment industry typically utilize the single beam or modulated four beam design. On-line ratio turbidimeters are also available, but their use has not been as extensive as the single beam and modulated four beam designs. On-line surface scatter turbidimeters are often used for raw water monitoring and transmittance-type absorptometers have been used for filter backwash monitoring.

Source: GLI, undated.

Figure 11-9. On-Line Turbidimeter

On-line instruments typically sample a side stream split off from the treatment process. The sample flows through the on-line instrument for measurement and then is wasted to a drain or recycled through the treatment process. Supervisory Control and Data Acquisition (SCADA) instrumentation and remote telemetry can also be connected to on-line instruments to collect data for trending analysis or to control automated treatment actions based on the turbidities measured. The use of SCADA with turbidity measurement is discussed in Chapter 4.

Typical sample flow rates through on-line instruments range from about 0.1 to 1.0 liter per minute. Some single beam on-line turbidimeters do not contain a glass sample container. The light source is located above the sample volume, which has an optically flat surface as it flows over a weir. The photodetector is submerged within the sample volume and requires frequent cleaning to prevent fouling. Most on-line four beam instruments used in the water industry contain a sealed flow-through sample volume with windows at each of the light sources and photodetectors. These surfaces must also be cleaned frequently to prevent fouling.

Most on-line instruments contain bubble traps to eliminate air bubbles from the sample that might interfere with the turbidity readings. Bubble traps are typically baffled chambers that allow air bubbles to rise to the sample surface prior to the sample entering the measurement chamber. The volume of the sample chamber varies significantly between the single beam and four beam design due mostly to the design of the bubble trap. Single beam devices typically include a bubble trap within the sample chamber, making the sample volume in excess of two liters. Several other on-line instruments use sample volumes as small as 30 milliliters.

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LIST OF FIGURES (manually completed)