Turbidimeter Instrument Comparison: Low-level Sample Measurements

Technical Information Series

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In memory of

Clifford C. Hach

(1919-1990)

inventor, mentor, leader and, foremost,
dedicated chemist

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SECTION 1 INTRODUCTION

Turbidity has been used as an effective indicator of water quality for nearly 100 years. Today, turbidity is a regulated parameter in the drinking water industry, used to assess the quality of effluent water in drinking water plants.
Accurate turbidity measurements require robust turbidity instrumentation and careful sample preparation and measurement techniques, particularly at low turbidity levels.

Currently, very little data have been gathered on low-level samples using modern instrumentation and refined turbidity measurement techniques. As regulations become more stringent, instrument performance at low turbidity levels must improve. Past turbidity studies have typically evaluated instrument performance at levels greater than one Nephelometric Turbidity Unit (NTU). However, new regulations require accurate, reliable measurements below 0.50 NTU.

This paper describes the effects of instrument design on low-level turbidity measurements, controlling for sample preparation and measurement techniques. It also examines the relationship between a wavelength of incident light and the resulting light scatter caused by fine particles.

1.1 Methods Used

The instruments evaluated in this study use one of two methods to measure turbidity:

- International Standardization Organization Method 7027 (ISO Method 7027)

  or

- Standard Methods for the Examination of Water and Wastewater, Method 2130B. (The United States Environmental Protection Agency Method 180.1 for turbidity is very similar to this method in terms of the design criteria for compliant instrumentation.)

These methods are based on the turbidity methods used most frequently by regulatory agencies. All instrumentation used in this study meets or exceeds the design criteria set forth in these two methods. These methods, based on pure nephelometry (90° scatter only) and ratio nephelometry, are described in more detail in *SECTION 3 OVERVIEW OF REGULATORY METHODS*.

1.2 Samples Used

Samples measured in this instrument comparison study include USEPA WS040 and WS041 performance samples, low-level turbidity standards, and effluent samples. In addition, sediments potentially found in effluent samples such as clay and silica were spiked into low-level water samples and measured. All samples ranged from 0.012 to 1.00 NTU.

1.3 Study Goals

The study goals included:

- Comparing the laboratory, process, and portable instrumentation designs of low-level turbidity measurements. All instrumentation met either of the two most common regulatory methods worldwide: USEPA Method 180.1 and ISO Method 7027.
- Comparing measurements of low-level samples made on instruments designed to meet USEPA Method 180.1. Within this comparison, differences between ratio and non-ratio measurements were evaluated.
- Comparing measurements of low-level samples made on instruments designed to meet ISO Method 7027. Within this comparison, differences between ratio and non-ratio measurements were evaluated.
- Comparing the performance of ISO Method 7027 and USEPA Method 180.1.

SECTION 2 GENERAL OVERVIEW OF TURBIDITY

2.1 Theory of Light Scattering

In simplest terms, turbidity is the optical property that results when light interacts with suspended particles in solution (most commonly water). Suspended solids such as silt, clay, algae, organic matter, and other microorganisms scatter and absorb light passing through a sample. This light scatter results in turbidity. The measurement of this scattering is a very simple indicator of water quality. More light scattering results in greater turbidity.

Light also interacts with molecules to produce very low-levels of scattering. Therefore, even the purest solutions will never have zero turbidity, due to molecular scattering. In low-level measurements, a small portion of the measured turbidity results from molecular scatter. Using current technologies specified by regulatory agencies, particle-free water has an estimated turbidity of 0.010 and 0.012 nephelometric turbidity units (NTU).

Turbidity is not directly related to particular types of particles or their respective shapes. The measured value results from all the material present in a sample and does not indicate that specific types of material are present. Turbidity is a highly qualitative measurement but, through the use of standards and standardization methods, this method has the potential to become more quantitative.

The direction and intensity of light scatter from particles depends on the size, shape, color, refractive index, and concentration of the particles in solution. The wavelength of transmitted light and the color of the suspending media also influence light scatter. When these factors are considered, the most consistent light scatter angle is a right angle from the centerline path of the incident light.

In order to correlate the relationship between light scatter and turbidity (making the method quantitative), light scatter measurements are made at right angles to the incident light. Such measurements are called “nephelometric” and have the units NTU. Between 0 and 40 NTU light scatter and turbidity have a linear relationship. Any non-linearity detected below 0.1 NTU is attributed to stray light from the instrumentation and/or irregularities in the sample cells. Zero NTU is defined as zero nephelometric light detected by the measuring system.

The main benefits of nephelometric measurement are its consistency and sensitivity to particles with a wide size range. These benefits allow for comparability and consistency between nephelometric turbidimeters.

2.2 Interferences

Light scattering in all water samples is affected by: 1) the absorbance and refractive index of the particles and/or the sample matrix, and 2) the size, shape, orientation, and absorption qualities of the particles being measured. These interferences depend on whether the wavelength of transmitted light passing through the sample is absorbed or scattered. The following generalizations regarding interferences apply to most samples:

1. Samples containing particles that strongly absorb incident light will prevent a significant portion of this light from reaching the detection system. This will result in an artificially low turbidity value.

2. Samples with a matrix that strongly absorbs incident light will prevent a significant portion of this light from reaching the detection system. This will result in an artificially low turbidity value.

3. Light scatter depends on the size of the particle and the wavelength of light interacting with that particle. Therefore:

  a. Large particles scatter long wavelengths of light more effectively than they scatter short wavelengths.

  b. Small particles scatter short wavelengths of light more effectively than large particles but have less effect on the scatter of longer wavelengths.

The amount light scatter depends greatly on the wavelength of the source. This relationship can be expressed by the following:

$$\text{Scatter} = \frac{1}{\lambda^4}$$

The strength of this relationship makes defining the wavelength of light used to measure turbidity very important. If the wavelength of light doubles, the scatter efficiency decreases by a factor of 16. Thus, 450-nm wavelength will scatter 16 times more than 900-nm wavelength interacting with the same particle.

To minimize these potential interferences, several methods of turbidity measurement have been developed. These methods have been designed to maximize sensitivity to particulate matter present in a sample and minimize the effect of interferences present in samples. Fortunately, low-level water samples such as effluent from a water treatment plant have little or no inherent color, making the interference from the matrix nominal. However, light absorbance by the particles may cause interferences.

2.2.1 Eliminating Color Interference

Color, expressed as Platinum-Cobalt color units, has a minimal effect on the turbidity measurements of effluent water samples. Studies have shown that color spiked into effluent water samples with turbidities less than 1.0 NTU do not interfere up to approximately 100 Pt-Co color units. However, color at far lower Pt-Co values will result in greater measurement interference as the turbidity levels increase above 1.0 NTU. The use of an alternate incident light system or ratio techniques can reduce or eliminate color interference.

Alternate Incident Light Systems

Alternate incident light systems use an incident light source with a spectral output that does not interfere with the sample. The most common alternate source is the light emitting diode (LED) with an spectral output in the 850 to 880 nm range. Since few naturally occurring materials absorb light at this wavelength, the incident light will not interfere with inherent color present in most natural samples. Unfortunately, this long wavelength is less sensitive to small particle systems than a spectra containing shorter wavelengths of light. Theoretically, this lower sensitivity can be amplified using modern electronic systems.

Ratio Detection Systems

Ratio detection systems will significantly reduce color interference and correct for lamp fluctuations. Ratio detection systems use the nephelometric measurement (I_{90}) as the primary light scatter detector, but contain other detectors that compensate for incident light loss to color absorbance (*Figure 1*). The other detectors typically measure transmitted or forward scatter light. The transmitted detector (I_T) determines if light has been lost due color absorbance or lamp fluctuations. The forward scatter detector (I_{FS}) determines if light has been overscattering in the forward direction from larger or non-spherical particles. The ratio algorithm defined by the following:

$$T_{Ratio} = \frac{I_{90}}{a_1 I_{FS} + a_2 I_T}$$

Where:

I_{90} = nephelometric scatter detected light

a_1 = constant, forward scatter light (determined from calibration)

I_{FS} = forward scatter detected light

a_2 = constant, transmitted light (determined from calibration)

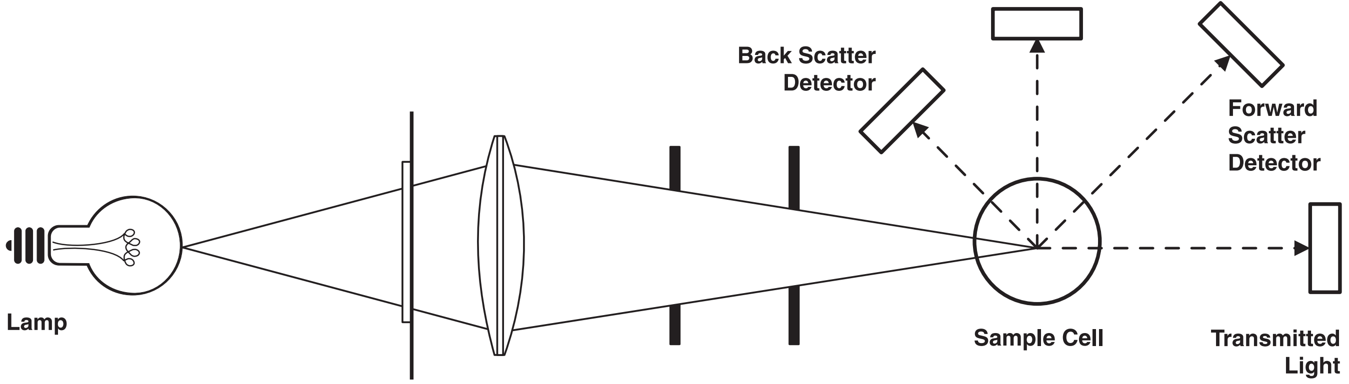
I_T = transmitted detected light

When light is lost due to color or lamp fluctuations, the level of transmitted detected light decreases in proportion to the amount of primary scatter signal light (I_{90}) lost. This decrease in the denominator (the bottom term) results in a correlated decrease in the numerator (the top term). Thus the value is corrected.

Similarly, when light is lost due to non-symmetrical scatter in the forward direction, the level of forward scatter detected light changes in proportion to the amount of primary scatter signal light (I_{90}) lost to the 90° detector. This change in the denominator (the bottom term) results in a corresponding change in the numerator (the top term). This value is also corrected.

Forward scatter effects occur most frequently in samples greater than 40 NTU and do not need to be considered when measuring samples below 1.0 NTU. Similarly, the back scatter detector is used only in samples greater than 1000 NTU.

Figure 1 Typical optical design of ratio turbidimeters



2.2.2 Stray Light

Stray light is defined as that light that reaches the nephelometric detector, not a result of scatter from the sample. Stray light is always a positive interference. Sources of stray light include: imperfections in and scratches on sample cells, internal reflections of the optical system, contamination of the optics or sample cell chamber with dust, and electronic noise. Stray light should be minimized by keeping instrumentation clean, and using highly-polished, matched, defect-free sample cells. Instrument design can also affect stray light.

2.3 Calibration and Standards

2.3.1 Formazin Standards

The NTU is directly traceable to the primary standard known as formazin. Formazin is the only primary turbidity standard that can be reproducibly prepared from traceable raw materials. The reaction to generate the formazin polymer is an aldol-condensation organic reaction between hydrazine and hexamethylenetetramine. The polymer in solution consists of random shapes and sizes. In addition, the highly reflective polymer absorbs minimal light.

The particle size distribution of formazin ranges from 0.01 to 10 µm, similar to the particle distribution found in natural water samples. This statistical reproduction of the standard is good. The synthesis is reproducible to better than 1% under carefully controlled conditions. All other turbidity standards have at some time been traced to primary formazin. For these reasons, most instrument manufacturers use formazin as a basis for developing calibration algorithms for instrumentation and specifications of instrument performance.

Other units of turbidity measurement include the FTU (formazin turbidity unit), FNU (formazin nephelometric unit), FAU (formazin attenuation unit), Absolute turbidity (TE/F), and mg/L Kaolin. All of these units are derived from and/or traceable to formazin. Specifically, the formazin units (NTU, FNU, FAU, FTU) are defined by the primary formulation for formazin and the instrumental method of measurement.

2.3.2 Types of Calibration Standards

Other standards used for calibration include stabilized formazin, styrene divinylbenze (SDVB), and instrument specific optomechanical devices. Of these, formazin, stabilized formazin, and SDVB are the only standards allowed for regulatory reporting purposes. See *Table 1*.

Stabilized formazin is the formazin polymer stabilized in a non-light-scattering matrix. The performance of this standard is exactly the same as formazin. The advantage of stabilized formazin is its long-term stability. Stabilized formazin standards prepared at specific values remain stable for at least two years. This allows standards to be produced under strict conditions and eliminates the need for the user to prepare these standards. As a result, stabilized formazin standards can be applied to any turbidimeter while maintaining long-term stability.

SDVB standards are microscopic beads with a narrow size distribution. These standards have been demonstrated to perform well at low turbidity levels, but due to the mono-dispersed nature of the size distribution, incident light may overscatter into the forward direction and result in inaccurate calibration.

Therefore, these standards are instrument specific and cannot be used universally. Many manufactures may not recommend SDVB standards as a general calibration standard on their respective instruments. Users should refer to the manufacturer's calibration instructions to determine if this is an acceptable calibration standard.

Finally, several types of opto-mechanical devices are being developed to mimic the scatter of light onto the detector apparatus of certain turbidimeters. The devices are instrument specific and usually traced to formazin polymer. The devices are used to either monitor calibrations of turbidimeters or calibrate instruments not used for regulatory reporting.

Table 1 Comparison of calibration and calibration verification standards

Standard	Type	Particle Size Range	Use on Hach Instruments
User prepared formazin (4000 NTU)	Calibration	0.01 to 10.0 µm	Yes. Lower dilution limit is 2 NTU.
Commercially prepared formazin (4000 NTU)	Calibration	0.01 to 10.0 µm	Yes. Lower dilution limit is 2 NTU.
Stabilized formazin (StablCal®)	Calibration or verification	0.01 to 10.0 µm	Yes. Standards ready-to-use down to 0.10 NTU.
SDVB	Calibration or verification	0.1 to 1 µm	Not recommended for calibration. Can be used for verification below 1.0 NTU. Instrument specific
ICE-PIC opto-mechanical secondary standard	Non-reporting calibration or verification	NA	Calibration of 1720C, 1720D, or 1720D/L at 20 NTU. Verification down to 0.5 NTU. Standards are instrument specific.
Gelex	Verification	0.01 to 50 µm	Instrument specific.

2.4 Calibration of Hach Turbidimeters for Low-level Measurement

Instrument calibrations differ from traditional analytical measurements because the range of calibration points is typically much greater than the range of measured points. Explanation for these differences is provided below.

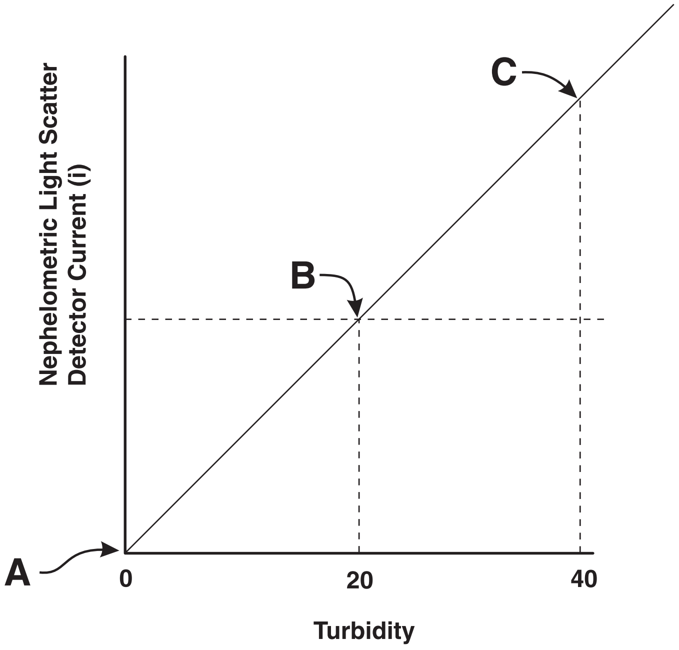
1. The relationship of nephelometric detector response to turbidity is highly linear in the range of 0 to 40 NTU, if no color interferences exist. This linearity requires only two points to accurately define the calibration over this range. See *Figure 2*.
2. The 20 NTU calibration point is set using a 20 NTU formazin standard. The standard was selected because of several criteria:
   - **a.** Twenty NTU is the midpoint of the linear range of 0 to 40 NTU.
   - **b.** The standard is easily prepared with a high degree of accuracy.
   - **c.** Calibration accuracy is maintained from the standard to the lowest measurement levels because the relationship between nephelometric light scatter and turbidity is linear.
   - **d.** Errors due to stray light and sample cell variation are negligible at 20 NTU and do not affect the low-level accuracy of the calibration curve.
3. The low end of the measurement range is 0.000 NTU. This value is defined as zero light scattered to the nephelometric detector. This point is determined

when the incident light source is turned off and the sample cell compartment is tightly closed. This measurement is only performed when the instrument power is cycled. See *Figure 2*.

4. The deionized water standard is only measured to determine the turbidity of the dilution water used to prepare the high end calibration standard. This value is measured and then stored in the software of the turbidimeter. The value is then subtracted from the measured value of the other turbidity standards used to perform a calibration. In subtracting this value from the measured value of the calibration standards, the absolute value of the standard is calculated, maximizing the accuracy of the calibration points.

Low-level standards prepared for calibration can propagate several types of error. These errors come from apparatus, molecular turbidity, and instrument stray light. Below 1.0 NTU, these errors become large enough to produce results with significantly larger error than would result from calibration using a higher turbidity standard.

Figure 2 Light Scattering Correlated to Turbidity



A = Bottom calibration point (0 scatter to nephelometric detector)
B = Defined calibration point (typically at 20 NTU)
C = Top end of linear calibration range for nepholometric measurement

SECTION 3 OVERVIEW OF REGULATORY METHODS

One of the primary goals of having a global method is to gain measurement consistency when using different turbidimeters. Two sets of design criteria have been generally accepted for performing turbidity measurement. These methods, USEPA Method 180.1 and ISO Method 7027, have been used as part of the measurement requirement guidelines for regulatory compliance. The similarities and differences of these methods are briefly discussed below:

3.1 USEPA Method 180.1

USEPA Method 180.1 is the most common regulatory method used in the world. It is referenced to Standard Methods for the Examination of Water and Wastewater Method 2130B. The following design criteria are required with USEPA Method180.1:

- The primary detector must be for nephelometric (90 degree) measurement ±30 degrees.
- The light source must be a tungsten filament lamp with a color temperature between 2200 and 3000 K.
- The spectral response peak for the detector must be between 400 and 600 nm, the primary wavelengths of light.
- The measurement range is from 0 to 40 NTU. Any sample above this range must be diluted until it is within this range.

Method 180.1 has several advantages:

- The method uses short wavelengths of light that are more sensitive to scattering by small particles.
- Tungsten lamps emit light that is nine times more effectively scattered by small particles than the 860 nm light source.
- The method is most applicable in clean water samples, below 1.0 NTU.
- Tungsten lamps are readily available and inexpensive.
- The method is well-documented and widely understood.

Two drawbacks to this method exist. First, it is sensitive to interference from color that absorbs light in the wavelength range of 400-600 nm. Second, the tungsten light sources require lengthy warm-up times in order to achieve short term stability and must be calibrated frequently.

Compliance with the drinking water regulations using USEPA Method 180.1 require only the measurement of low turbidity levels. In the past, the final effluent water in drinking water plants must have a turbidity less than 0.5 NTU 95% of the time, with a maximum level of 2 NTU. In 1998, this regulation tightened to a turbidity of 0.3 NTU 95% of the time, with a 1.0 NTU maximum turbidity level. Many water treatment plants have subscribed to the Partnership for Safe Drinking Water, which imposes a maximum turbidity level of 0.1 NTU. At these levels, instruments must measure accurately, and discrepancies between instruments should be known.

3.2 ISO Method 7027

ISO Method 7027 originated in the brewing industry and is commonly used in Europe. The method has been accepted for regulatory reporting in water since the 1980s. The following design criteria are required with ISO Method 7027:

- The primary detector must be for nephelometric (90 degree) measurement, ±1.5 degrees.
- The light source must be at a wavelength of 860 nm. An LED or a combination of tungsten filament lamps with filters can be used to achieve this wavelength.
- The spectral bandwidth of the light must be within 860 nm ±30 nm.
- The measurement range is from 0 to 40 NTU. Any sample above 40 NTU must be diluted until the measurement is within this range.

The strengths of ISO Method 7027 include the use of a near-monochromatic light source that is stable, has low absorbance interference with samples, and results in low stray light. The major drawback of using the long wavelength source is its reduced sensitivity to small particle sizes. The reduced sensitivity can be amplified but this will result in increased measurement noise at low turbidity levels. At the low end of the measurement range, instruments using this method tend to read slightly lower than those using USEPA Method 180.1. Regulatory compliance for water treatment plants requires accurate measurements at the very low turbidity range.

3.3 Overview of Instrumentation Used

The instruments used to perform low-level measurements and the methods they comply with are listed *Table 2*. See *SECTION 5 INSTRUMENTATION OVERVIEW* for additional information.

Table 2 Instrumentation Used to Perform Low-level Turbidity Measurements

Instrument	Compliance Method	Type
2100A	USEPA 180.1	Laboratory
2100N/AN*	USEPA 180.1	Laboratory
2100AN IS/N IS	ISO 7027	Laboratory
2100P	USEPA 180.1	Portable
1720C	USEPA 180.1	On-line (Process)
1720D	USEPA 180.1	On-line (Process)
1720D/L	ISO 7027	On-line (Process)

* The 2100AN light source can be filtered to emit at a wavelength of 860 nm, allowing this instrument to meet ISO 7027 compliance.

To accurately assess if an instrument is designed to perform low-level measurements, the accuracy specifications must be understood. *Table 3* describes performance specifications of each instrument used in this study.

The following definitions apply to the instrumentation used in this study:

Accuracy: The difference between the measured value and that of a known value. Hach expresses all accuracy as percent relative error of reading. Below 0.1 NTU, the estimated stray light is a positive error and becomes the limiting factor for accuracy. At such levels, the estimated stray light becomes the accuracy of the measurement.

Linearity: The relationship between light scatter and measured turbidity. At the low end of the nephelometric range, instrument linearity will be very high if stray light interference has been minimized. Linearity is related to accuracy in that it will statistically define the trending and the linearity of the accuracy curve in an instrument.

Precision: How reproducible a measurement is with a given instrument. As sample turbidity decreases, precision also decreases. Typically precision is expressed as a relative standard deviation based on at least seven replicable measurements.

Resolution: The ability of an instrument to measure a sample accurately. For low-level analysis, the instrument resolution should measure to the nearest 0.01 NTU, preferably to the nearest 0.001 NTU. The resolution can often help describe other sample characteristics. For example, noise in the least significant digit often indicates bubbles or a greater than normal distribution of large particles. Samples that show little fluctuation in the resolution digit tend to be of very high quality and have very few, if any large particles.

Stray light: An estimate of the turbidity caused by factors such as light leaks, glass cells, etc., rather than the sample. Should be estimated in order to allow the user to gain an accurate estimate of the instrument performance at low turbidity levels. Stray light should be no greater than 0.020 NTU. If the amount of stray light is greater, the instrument should be cleaned or serviced to reduce this effect.

Table 3 Hach Turbidimeter Specifications for Low-level Measurement*

Instrument	Accuracy[1]	Linearity	Precision (NTU)	Resolution (NTU)[2]	Stray light (NTU)
2100A	±5 percent	±1 percent	±1 percent or 0.02	0.01	<0.04
2100AN	±2 percent	±1 percent	0.010	0.001	<0.010
2100AN IS/NIS	±2 percent	±1 percent	0.010	0.001	<0.005
2100P	±2 percent	±1 percent	0.01	0.001	<0.02
1720C	±2 percent	±1 percent	±0.002	0.001	<0.01
1720D	±2 percent	±1 percent	±0.002	0.001	<0.010
1720 D/L	±2 percent	±1 percent	±0.002	0.001	<0.005

[1] Accuracy is expressed as a percent of reading plus the stray light of the system.
[2] Resolution is for the lowest measurement range of the instrument.

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* All specifications are with respect to the lowest measurement range of the instrument. Specifications may be different for higher ranges.

SECTION 5 INSTRUMENTATION OVERVIEW

5.1 2100AN/2100N Optical Design

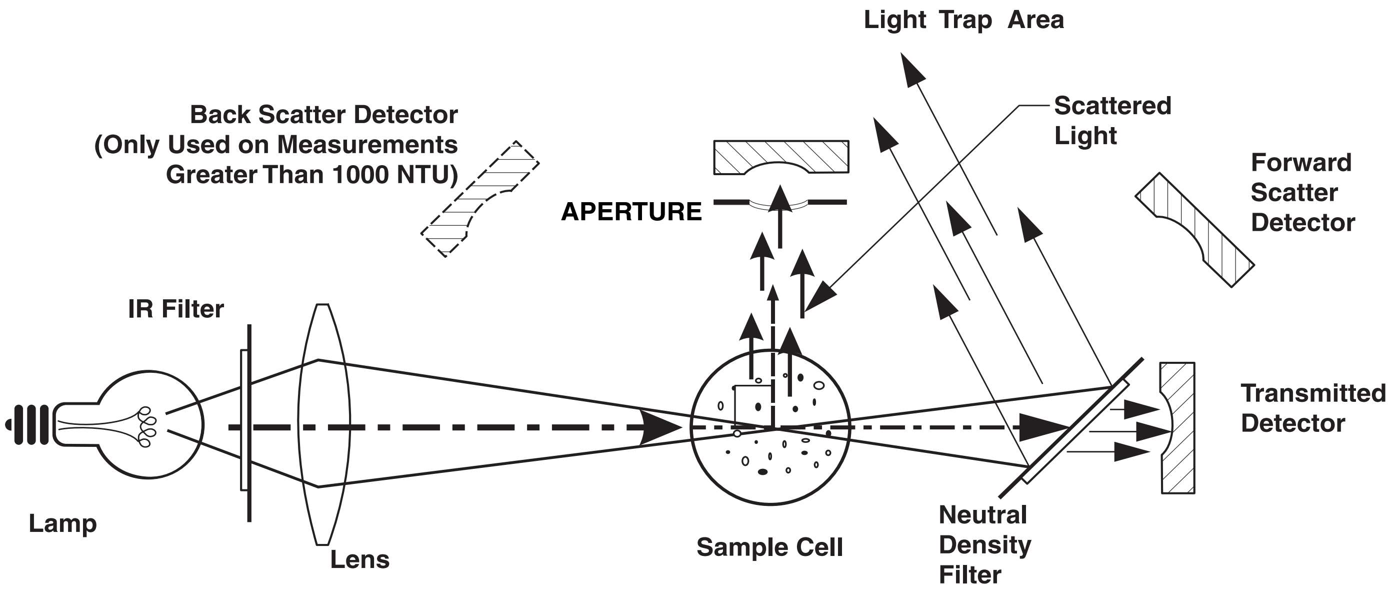
The Model 2100N/AN Laboratory Turbidimeters meet the design criteria of the USEPA Method 181.1, and is acceptable for compliance reporting. The instrument is a nephelometer capable of measuring in either RATIO ON or RATIO OFF (non-ratio) mode.

The optical system, shown in *Figure 3*, is comprised of a tungsten-filament lamp, lenses and apertures to focus the light, a 90° detector to monitor scattered light, a forward-scatter light detector, a transmitted-light detector, and a back-scatter light detector. The stray light of these instruments is typically lower than in older instruments because it contains a complex optical system used to help collimate and reduce the divergence of the polychromatic incident light. A significant portion of the stray light present will come from the sample cell.

Light with a spectral output of between 400 and 600 nm can be used if a filter is in the instrument. Small particles will scatter these shorter wavelengths more effectively than longer wavelengths. However, shorter wavelengths are very susceptible to color interferences.

The instrument measures turbidity at less than 40 NTU using only the 90° scattered-light detector (RATIO OFF) or using the complete set of detectors (ratio). In the RATIO ON mode, the instrument's microprocessor uses a mathematical calculation to ratio signals from each detector. For low-level measurements below 1.00 NTU, the transmitted detector will primarily compensate for lamp degradation.

Figure 3 2100N/AN Light Path Diagram for Low-Level Measurement



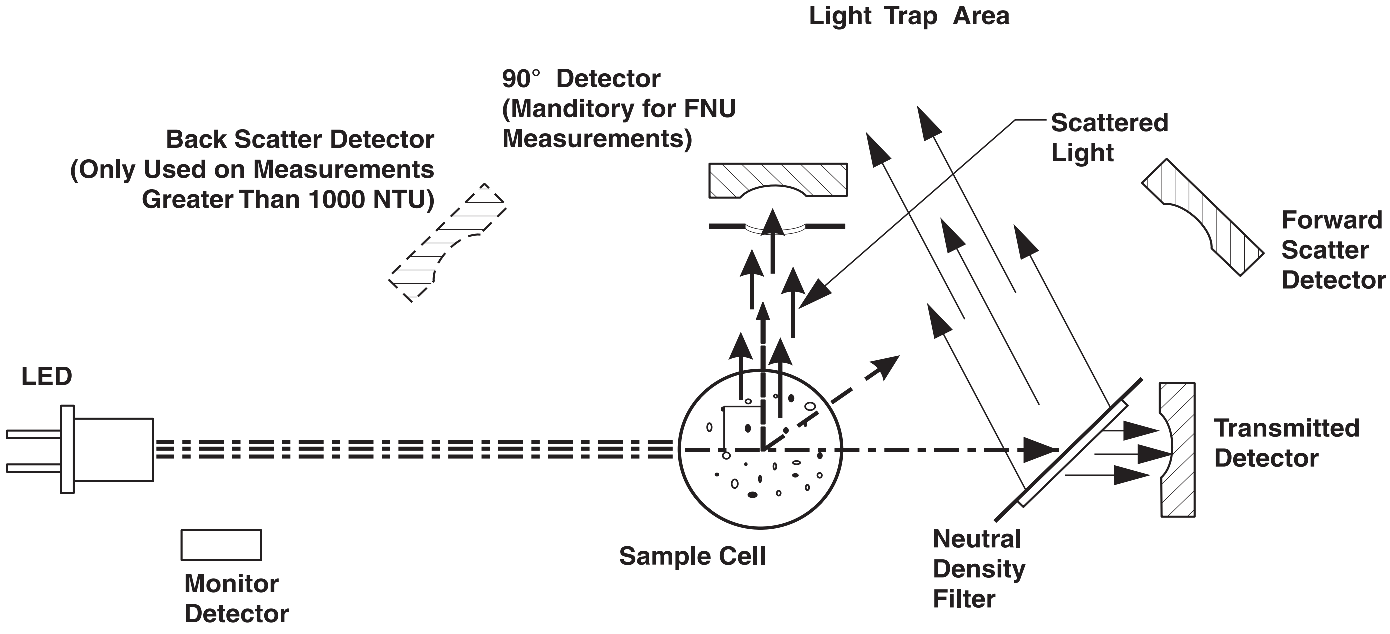
5.2 2100AN IS/2100NIS Optical Design

The Model 2100N/AN IS Laboratory Turbidimeters are nephelometers capable of measuring scattered or attenuated light. Calibration with formazin provides the capability for direct readout in FNU and FAU units. The instrument meets design criteria specified in DIN 38 404, NF EN 27027, and ISO 7027 turbidimeter measurement standards.

The optical system, shown in *Figure 4*, includes an 870 ±30 nm light emitting diode (LED) assembly, a 90° detector, a transmitted-light detector, and a back-scatter detector. This design provides for a highly collimated incident light source with monochromatic characteristics. This results in very low stray light for this system. As in the 2100AN and 2100N, the majority of the residual stray light will come from the sample cell. Small particles will not scatter the longer wavelength as efficiently as shorter wavelengths, but this longer wavelength of light is less susceptible to color interferences.

The instrument measures turbidity at less than 40 NTU using only the 90° scattered-light detector or using the complete set of detectors (ratio). In the RATIO ON mode, the instrument's microprocessor uses a mathematical calculation to ratio signals from each detector.

Figure 4 2100NIS/ANIS Light Path Diagram for Low-Level Measurement

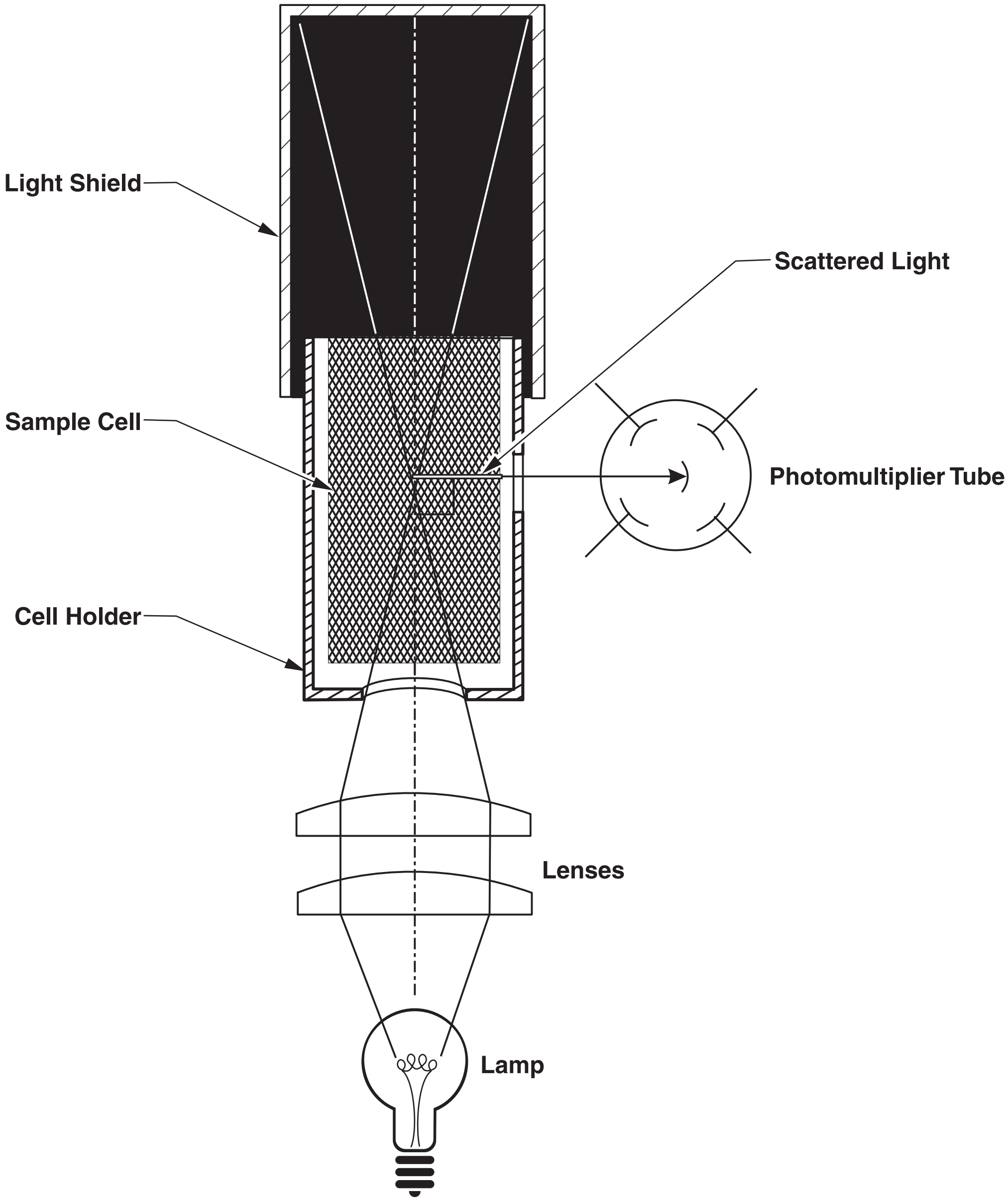


5.3 2100A Optical Design

The Hach Model 2100A Turbidimeter is a laboratory nephelometer calibrated for measuring turbidity in colorless liquids. It is suitable for a broad range of turbidity measurement with ranges of 0-0.2, 0-1.0, 0-10, 0-100, and 0-1,000 NTU. The 2100A turbidimeter was the first nephelometer that could provide accurate turbidity measurements below 1.0 NTU. Many regulatory design criteria are based on this instrument.

In the optical system shown in *Figure 5*, an intense beam of polychromatic light is directed up through the bottom of a glass cell containing the test sample. Light scattered by particles in the sample is detected by a sensitive photomultiplier tube at a 90° angle from the incident light beam. Since this design forces light to pass through many surfaces in order to perform a measurement, stray light is higher in this instrument than more modern turbidimeters.

Figure 5 2100A Turbidimeter Light Path Diagram

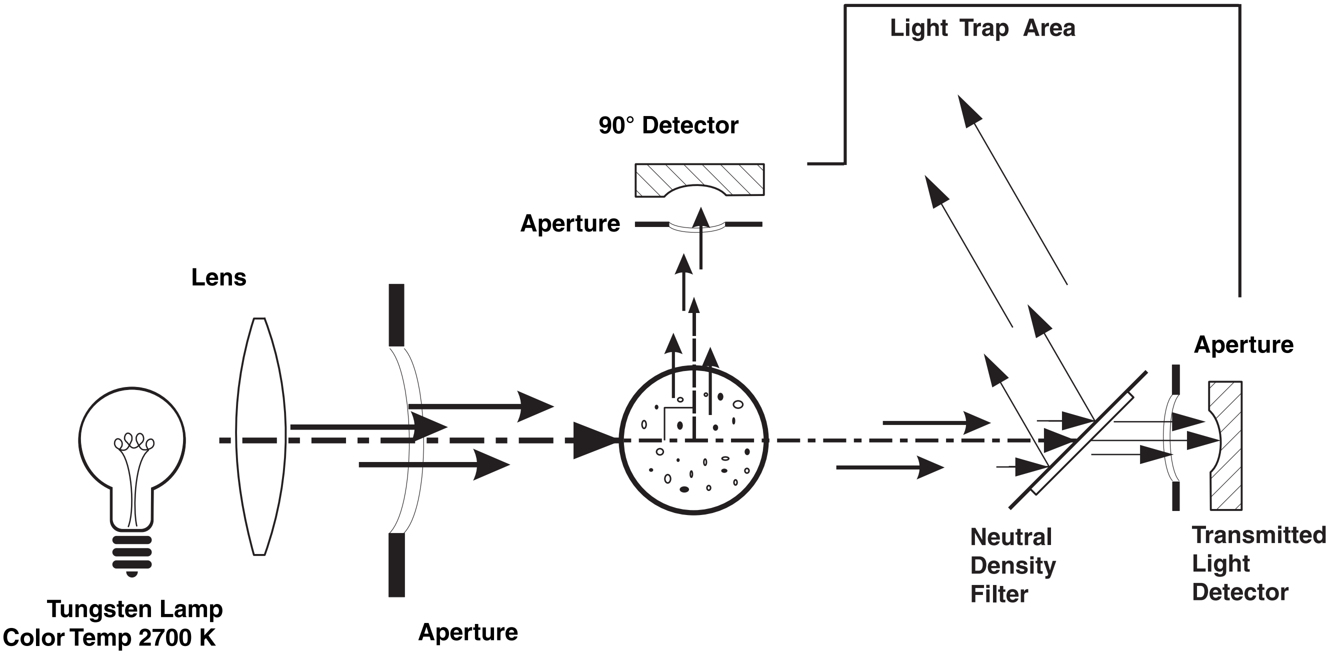


5.4 Portable Turbidimeter (2100P) Optical Design

The Model 2100P Portable Turbidimeter operates on the nephelometric principle of turbidity measurement. This instrument meets the design criteria specified by the United States Environmental Protection Agency, Method 180.1.

The optical system (*Figure 6*) includes a tungsten-filament lamp, a 90° detector to monitor scattered light and a transmitted light detector. The instrument's microprocessor calculates the ratio of the signals from the 90° and transmitted light detectors. This ratio technique corrects for interferences from color and/or light absorbing materials (such as activated carbon) and compensates for fluctuations in lamp intensity, providing long-term calibration stability. The optical design also minimizes stray light, increasing measurement accuracy.

Figure 6 2100P Optical System



5.5 1720D and 1720C Optical Design

Turbidity is measured in the 1720 C or 1720D Turbidimeter by directing a strong beam of incandescent light from the sensor head assembly down into the sample in the turbidimeter body. Light scattered at 90° by suspended particles in the sample is detected by the submerged photocell. Both the 1720C and 1720D instruments have the light scatter detector submerged in the sample itself, thus eliminating the need for a sample cell. This dramatically reduces the stray light that would otherwise would come from a sample cell. However, the 1720C typically has slightly higher stray light due to the bubble trap located inside the measurement chamber (turbidimeter body). By removing the bubble trap from the measurement chamber and the reshaping the internal measurement chamber in the 1720D series turbidimeters, stray light levels have been reduced to the lowest levels ever. Both instruments are compliant to USEPA Method 180.1

The 1720D turbidimeter body was designed to reduce stray light error even more than the 1720C turbidimeter. The 1720D body was shaped to match the shape of the lamp filament projection after it passes through the optical lens. As a result, the 1720D turbidimeter gives slightly lower turbidity measurements.

The amount of light scattered is proportional to the turbidity of the sample. If the turbidity of the sample is negligible, little light will be scattered and detected by the photocell and the turbidity reading will be low. High turbidity, on the other hand, will cause a high level of light scattering and result in a high reading.

Sample enters the turbidimeter body and flows through the baffle network of the bubble trap. The flow allows bubbles to either cling to surfaces of the baffle system or rise to the surface and vent to atmosphere. After traveling through the bubble trap, sample enters the sample measurement chamber in the turbidimeter body. The sample spills over the weir into the drain port. *Figure 7* presents a diagram of the 1720D turbidimeter.

5.6 1720D/L Optical Design

The 1720D/L turbidimeter incorporates the design criteria of ISO 1720 into the optical configuration of the 1720D turbidimeter. Specifically, the 1720D/L contains an LED that emits at a wavelength of 860 ±30 nm that is the incident light scattered by the sample. In addition, a monitor detector is installed to regulate the output of the LED and provide a very stable light source. The incident light is highly collimated, resulting in reduced stray light over a tungsten light source. This turbidimeter also uses the same sample measurement chamber as the 1720D, further reducing the stray light in the measuring system. This produces the most accurate low-range measuring turbidimeter available. *Figure 8* presents a diagram of the 1720D turbidimeter.

5.7 Bubble Rejection and Flow Rates

When measuring samples on-line using process instruments, accurate measurements depend on the efficient removal of bubbles from the sample. Using bubble traps and maintaining a steady, controlled flow rate up to and through the process turbidimeters helps achieve accurate measurements. Typically, slower flow rates will result in better bubble removal and more accurate measurements.

Figure 7 Section View of the 1720D Low Range Turbidimeter

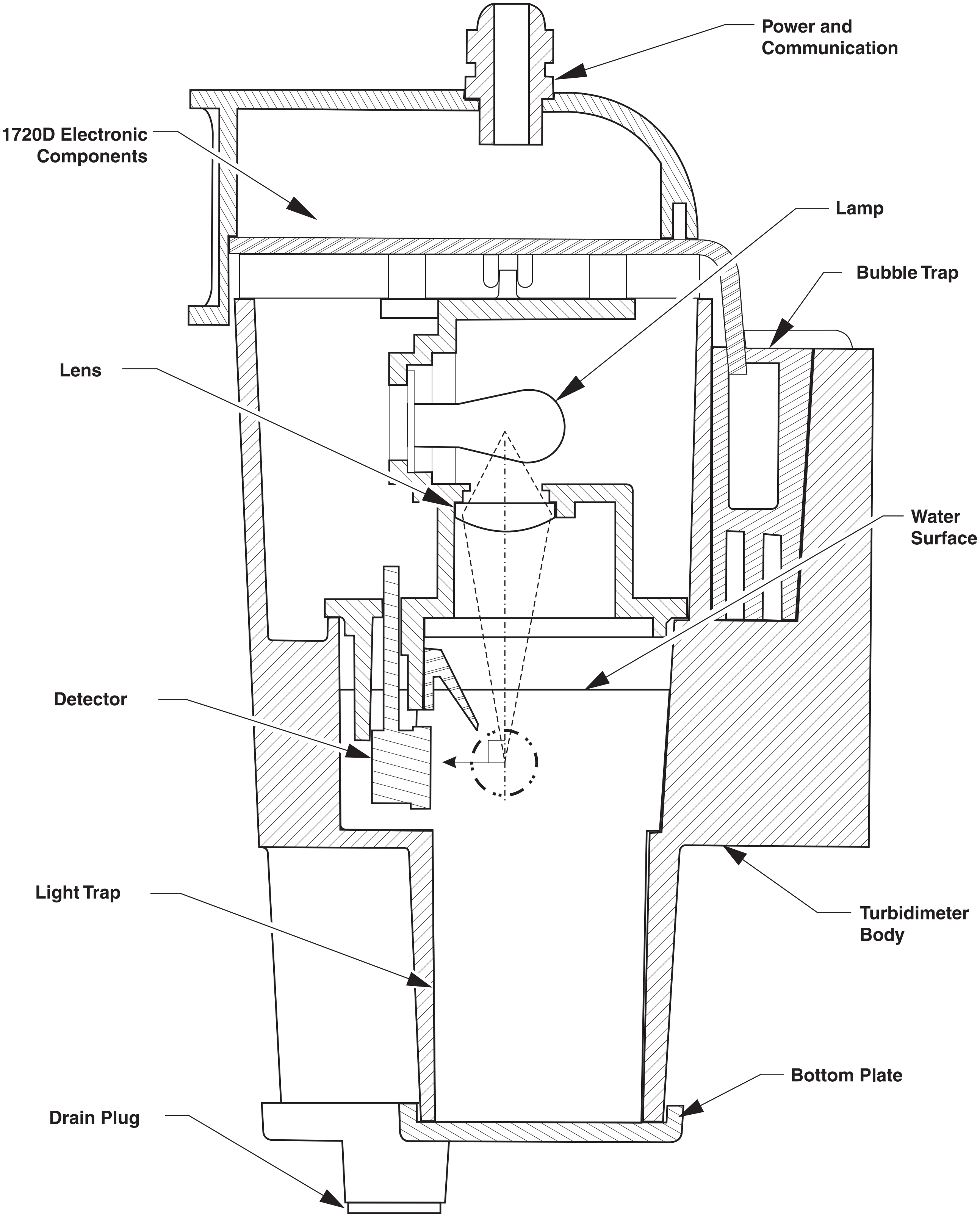
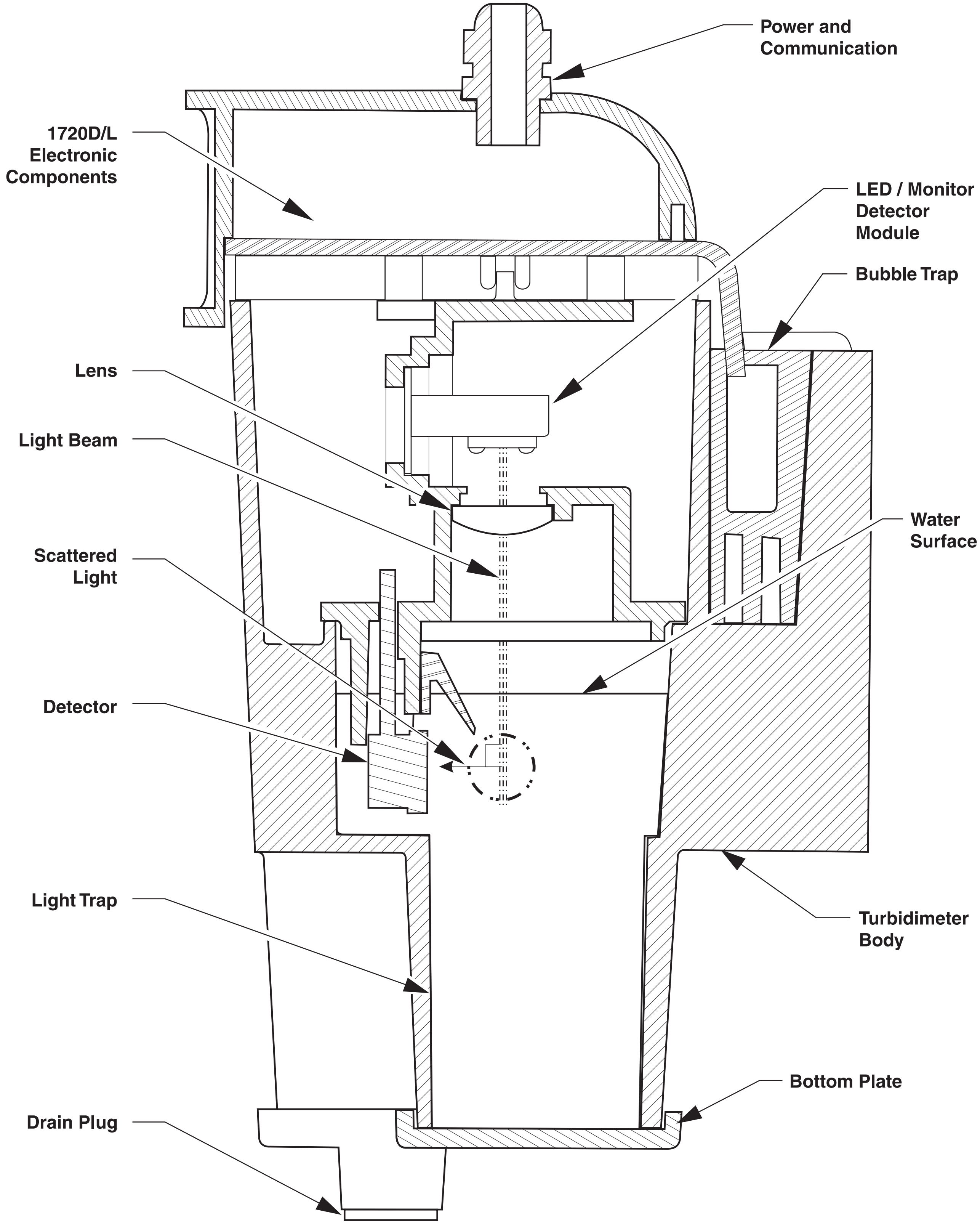


Figure 8 Section View of the 1720D/L Low Range Turbidimeter



SECTION 6 MEASUREMENT TECHNIQUES

Achieving the most accurate and reproducible data possible requires: 1) consistent sample preparation and measurement, and 2) consistent instrument preparation and setup throughout the entire study. The sections below describe the steps used in setting up the instrumentation for measurement, verifying the calibrations of each instrument, preparing the sample, and measuring the sample.

6.1 Instrument Preparation and Measurement

6.1.1 Preparation of Laboratory and Portable Turbidimeters

The following steps were completed prior to measuring all low-level samples:

1. Ensured all instrumentation was clean and emitted low stray light. Stray light was determined by measuring reverse osmosis filtered deionized (RO/DI) water. If the turbidity exceeded 0.030 NTU, the instrument's optical system was cleaned. In addition, the area surrounding the instrumentation was cleaned to minimize dust contamination.

2. Calibrated the instrumentation using fresh standards prepared from primary stock formazin 4000 NTU solution. Prepared all standards using clean Class A glassware and volumetric techniques. Prepared RO/DI dilution water.

3. Acid washed all sample cells used for calibration and rinsed repeatedly with RO/DI water.

4. Matched all clean sample cells so they read no greater than 0.003 NTU from each other when using RO/DI water as the sample. The 2100P and 2100A instruments required special sample cells. The number of cells used was kept to a minimum.

5. After calibration, verified all instrument calibrations using StablCal® verification standards ranging from 0.1 to 0.5 NTU. The instruments must read within the accuracy specification for each standard. These standards will also serve as surrogate samples to help distinguish measurement differences between instruments.

6.1.2 Instrument Preparation for Process Turbidimeters

1. Ensured all instrumentation was cleaned and emitted low stray light. Stray light was determined by measuring reverse osmosis filtered deionized (RO/DI) water. If the turbidity exceeded 0.030 NTU, the instrument's optical system was considered clean.

   a. The turbidimeter body was cleaned as described in the instrument manual. The body was thoroughly rinsed with RO/DI water. In addition, bubble traps and detection apparatus were also cleaned. The surrounding area was cleaned.

   b. The turbidimeter optics were visually examined to ensure that they were clean. Water droplets or dust on the turbidimeter lens was wiped away. The optics were thoroughly rinsed with RO/DI water.

   c. The instruments were calibrated using a fresh 20 NTU formazin standard made from primary formazin 4000 NTU stock standard. The standard was prepared using clean Class A glassware and was diluted with RO/DI water.

   d. After calibration, instrument calibrations were verified using StablCal verification standards ranging from 0.1 to 0.5 NTU. The instruments had to read within the accuracy specification for each verification standard. These standards also served as surrogate samples to help distinguish measurement differences between instruments.

6.2 Sample Collection and Measurement

6.2.1 Sample Collection

Several samples were measured, including samples from ultra-filtration processes, water treatment plant effluent samples, kaolin spiked samples, and silica spiked samples. In addition, several surrogate samples were measured. These included StablCal® Stabilized Formazin Standards and regulatory performance samples. All analyzed samples are summarized in *APPENDIX A* on page *49*.

1. Enough sample was collected in a single container to allow for adequate rinsing of all turbidimeters (on-line, laboratory, and portable) involved in this study.

2. The sample containers were polyethylene bottles that had been meticulously cleaned with 1:1 HCl acid wash, followed by 10 rinses with reverse osmosis filtered, deionized water.

3. When collecting a sample, the containers were first rinsed with sample and then filled.

4. Samples were analyzed as soon as possible, but some samples were stored for up to 24 hours before analysis. During analysis, all measurements were taken with all instruments as quickly as possible to reduce the possibility of the turbidity changing. In most cases, a sample was analyzed from start to finish in less than 30 minutes.

6.2.2 Sample Measurement Using the 1720C and 1720D Turbidimeters.

1. All measurement parameters were set the same. For the 1720C and 1720D Turbidimeters, the minimum response time (signal averaging) was 30 seconds.
2. The amount of sample collected was at least the volume that required to perform a measurement with the turbidimeter. For example, if the instrument held one liter of sample, at least two liters of sample were needed to rinse the instrument and measure the sample. The aliquots of sample needed for laboratory and portable measurement were taken from the same container holding the same sample.
3. The sample was mixed thoroughly immediately prior to transferring it by gently inverting the container.
4. The turbidimeter body was rinsed at least once with the sample.
5. The turbidimeter body was carefully and slowly filled with sample to minimize the creation of bubbles. The sample was introduced though the sample inlet port. Internal bubble traps degassed the sample. The turbidimeter was filled until the sample began to drain out the sample outlet.
6. The turbidimeter head was carefully placed on the turbidimeter body. The body was then gently tapped to release bubbles adhered to the detector.
7. One to five minutes was allowed for the reading to stabilize. The stable values were recorded over a 30-second period. The average value was entered as a data point.
8. After measurement, the turbidimeter bodies were drained and immediately flushed with RO/DI water. The bodies were covered to prevent dust contamination.

6.2.3 Sample Measurement Using Laboratory and Portable Turbidimeters

In low-level turbidity measurements, sample contamination before and during measurement is one of the greatest potential sources of error. Careful and rigorous sample preparation procedures are described below:

1. All cells were cleaned again, rinsed repeatedly with RO/DI water, and capped immediately prior to collecting a sample.
2. A single sample cell was used on all laboratory instruments.
3. Samples were collected and prepared using the same techniques throughout the study.
    - **a.** The sample was thoroughly mixed immediately prior to measurement.
    - **b.** The cell was rinsed twice with sample.
    - **c.** The cell was filled at least 80% full of sample and immediately capped.
    - **d.** Allowed the cell to stand for 1–5 minutes so bubbles could dissipate.
    - **e.** The outside of the cell was cleaned and oiled as instructed in the laboratory and portable instrument manuals.
    - **f.** The cell was very gently inverted once to resuspend any particles that may have settled.
    - **g.** The cell was placed in the instrument. After 1–3 minutes the reading became stable and repeatable.
    - **h.** The lowest stable and repeatable reading was recorded.
    - **i.** *Steps f* and *g* were repeated for each instrument.

SECTION 7 RESULTS AND DISCUSSION

7.1 Data

Data were collected from February 1998 through February 1999. For any specific sample, all measurements were made at the same time on all available instruments. Samples were not stored for future analysis. Whenever possible, measurements were made on at least two instruments of the same model, in the same measurement mode (ratio or non-ratio). These measurements were then averaged and represent a specific data point. Throughout this study, the ratio and non-ratio measurement modes were kept separate.

The measurement of the USEPA WS040 and WS041 samples involved performing six replicate analyses of each sample. The average of these six replicate measurements was then calculated and used as the data point for the specific measured value on each instrument. *APPENDIX B* lists the number of measurements of each sample.

The data generated from each sample across all instruments was then averaged to yield an overall intra-instrument average. This average value can be compared to each individual instrument value. The difference between the average value and the individual instrument value can be used for comparison purposes. This is the difference that appears in each of *Tables 4*, *5*, *6*, and *7*. Thus, the lower the value in a table, the lower the instrument read relative to the other instruments that were used to measure a specific sample.

A total of 24 samples are displayed in *Tables 4* through *7*. The arrangement of data in these tables was based on the common set of instruments used to take measurements at the time the samples were analyzed. If a sample was not measured on a specific instrument listed in a table, the letters “n/m” (not measured) are entered. *Tables 4*, *5*, *6*, and *7* are categorized as follows:

- *Table 4* contains data related to all real world samples and four low-range StablCal® standards. This table contains the largest number of instruments and the largest number of samples.
- *Table 5* contains data for all the USEPA WS040 and WS041 samples.
- *Table 6* contains data from kaolin standards prepared according to the Japanese standard for measuring the turbidity of water, JIS K0101. A total of five standards ranging from 0 to 1 degrees turbidity (one degree turbidity equals one NTU) are shown.
- *Table 7* contains data from five water samples spiked with known amounts of silica dioxide (SiO_2). Samples ranged from 0.5 to 10.0 mg/L silica dioxide.

7.2 Results

7.2.1 Intra-instrument Comparison Using Water Samples and StablCal Standards

Table 4 contains the bulk of the low-level measurements taken with the largest array of instruments. The measured differences between instruments are presented in NTUs.

Table 4 Intra-instrument Deviation Using Water Samples <0.1 NTU and StablCal Standards

Instrument	RO/DI #2*	RO/DI #1	WTP #2	Dist Tap #1*	WTP #1	0.139 NTU	0.30 NTU	0.50 NTU	1.0 NTU	Rank
Avg. Value	**0.0241**	**0.0257**	**0.0478**	**0.0644**	**0.1552**	**0.1367**	**0.3056**	**0.5064**	**1.0335**	
2100AN Ratio	0.001	0.001	-0.002	0.004	0.006	0.002	0.007	0.005	-0.009	6
2100AN Non-ratio	0.001	0.001	-0.002	0.005	0.002	0.000	0.003	0.005	0.017	5
2100P Ratio	0.006	0.004	0.002	0.006	0.010	0.008	-0.001	-0.001	-0.034	7
2100A Non-ratio	0.016	0.019	0.012	0.016	-0.005	0.023	0.019	0.014	-0.024	9
2100AN IS Ratio	-0.015	-0.013	-0.013	-0.012	0.004	-0.015	-0.020	-0.009	-0.014	1
2100AN IS Non-ratio	-0.016	-0.012	-0.015	-0.012	0.006	-0.016	-0.017	-0.008	0.001	2
1720D Non-ratio	0.002	-0.000	-0.002	-0.002	-0.015	-0.004	0.008	-0.013	0.002	4
1720D/L Non-ratio	-0.003	-0.008	-0.003	-0.007	-0.018	-0.009	-0.005	-0.011	0.013	3
1720C Non-ratio	0.008	0.006	0.023	0.005	0.010	0.011	0.003	0.021	0.045	8
Avg. 180.1	**0.0298**	**0.0311**	**0.0530**	**0.0698**	**0.1565**	**0.1435**	**0.3124**	**0.5113**	**1.0333**	
Avg. 7027	**0.0128**	**0.0148**	**0.0375**	**0.0538**	**0.1525**	**0.1235**	**0.2920**	**0.4968**	**1.0338**	

* These two samples were measured on-line using the recommended minimum flow rate.

When evaluating all the samples in *Table 4*, we can see definite measurement trends between instruments. Of the seven types of instruments, performing nine different measurements on each sample (two instruments recorded both ratio and non-ratio readings of the same sample), they can be ranked from reading the lowest to the highest as follows:

2100ANIS < 1720D/L < 1720D < 2100AN < 2100P < 1720C < 2100A

The range of readings on any specific sample was between 0.028 and 0.039 NTU. Of these instruments, the 2100A trended much higher than the other instruments, reading an average of between 0.010 and 0.015 NTU higher than modern laboratory turbidimeters. Last, the newer process turbidimeters (1720D and 1720D/L), read between 0.010 and 0.015 NTU lower than the older process instrument (1720C).

When recording the process measurements, two samples, “RO/DI #2” and “Dist Tap #1” were measured on-line. No differences were observed in measurements between a static and process measurement as long as the flow rate was minimized in order to reduce bubble interference. However, increasing the flow rate can dramatically increase the readings.

Figure 9 displays results obtained from the reverse osmosis filtered deionized water (RO/DI), the lowest turbidity sample that can be reliably reproduced. Typically, these samples have few, if any, particles. Any particles present will be very small. Thus, the readings are generally very quiet once these samples have been degassed.

RO/DI Sample #2 ran through the process turbidimeters at the lowest permissible recommended flow rate. As long as the flow rate was slow enough to thoroughly degas the sample, the difference between on-line and static measurements using process instruments was minimal (0.002 NTU or less).

Since the RO/DI samples are essentially particle free, colorless, and fully degassed, differences between instrument measurements can be most easily observed using these samples. The newer instruments, with designs that further reduce stray light (2100AN, 2100AN IS and 1720D series of turbidimeters), read lower than the older instruments that have higher stray light (2100A, 1720C and 2100P turbidimeters). When comparing measurements taken using USEPA 180.1 and ISO 7027, the ISO 7027 instruments consistently read lower (0.015 NTU).

This lower trend seen in the ISO 7027 instruments can be attributed to the combination of lower stray light in the optical systems and lower sensitivity to small particles. The LED light source is more easily collimated than the traditional tungsten light sources, significantly reducing the stray light. Also, the longer wavelength emitted by the ISO 7027 instruments will be scattered by small particles less effectively than the shorter wavelengths of light generated by tungsten light sources.

Finally, ratio and non-ratio measurements of the samples are compared. The 2100AN and 2100AN IS turbidimeters can perform both ratio or non-ratio measurements simultaneously without disturbing the sample. Virtually no differences exist between the ratio and non-ratio measurements. The greatest difference between a ratio and non-ratio 2100AN or 2100AN IS measurement of RO/DI samples was 0.001 NTU.

Figure 9 Instrument Comparison at Low Turbidity Levels–Reverse Osmosis Water Samples

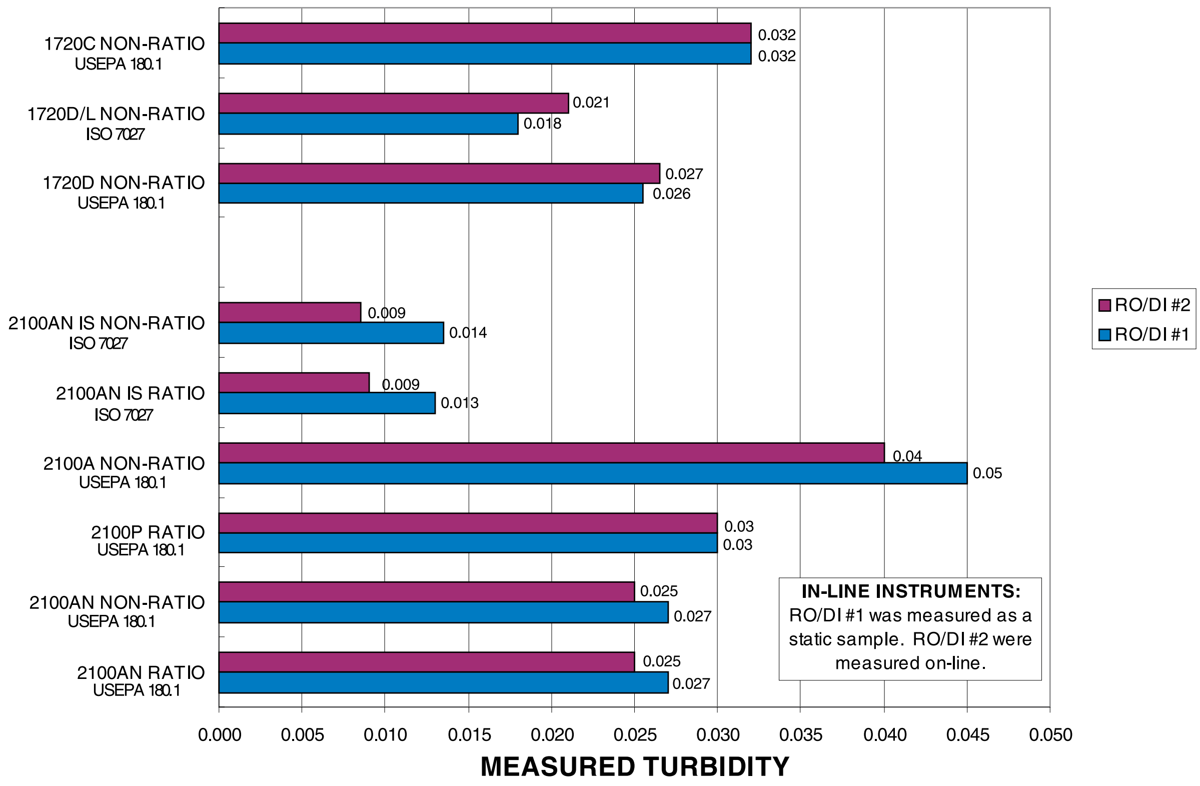


Figure 10 illustrates measurements made on two effluent samples from local water treatment plants (WTP) and a third sample from a local distribution system (tap water). The tap water, measured on-line with the process turbidimeters, are comparable to the static measurements taken on the laboratory turbidimeters. These samples are of relatively low turbidity and will generally have only very small particles. As with the RO/DI samples, these samples are relatively quiet. WTP Sample #1 was measured approximately 48 hours after collection, and WTP Sample #2 was measured approximately 6 hours after collection. Sample #2 had much higher turbidity and variance than the other turbidity samples. The increase in variance was due to the broader distribution of particles and a higher concentration of larger particles that make the readings less consistent.

The instrument trends with these samples are very similar to the RO/DI measurements. ISO 7027 instruments trend lower than USEPA 180.1 instruments by an average of 0.016 NTU. In addition, newer instruments read lower than the older instruments, indicating stray light is the major cause for this trend. Again, the difference between ratio and non-ratio measurements is negligible. The difference between ratio and non-ratio readings on either the 2100AN or 2100AN IS instruments was 0.003 NTU or less.

Figure 10 Instrument Comparison on Low Turbidity Samples from Water Treatment Plants and Distribution

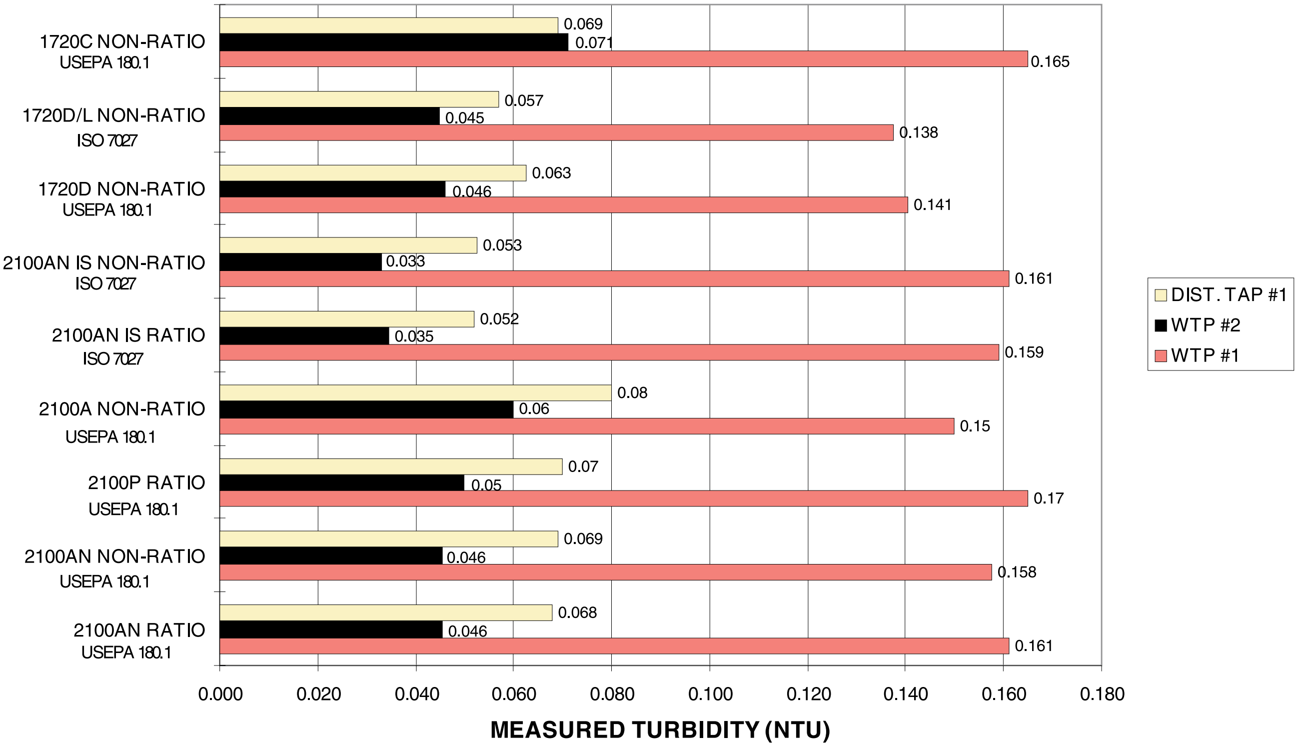


Figure 11 illustrates measurements made on StablCal Stabilized formazin standards. These standards ranged from 0.0 to 1.0 NTU. It is important to use defined standards for low-level comparison studies because instrument performance specifications are based on formazin standards. It is important to validate that the instruments measure accurately at low-levels because calibration is performed using significantly more turbid standard (20.0 NTU). Accurate measurement of low-level standards validates the linearity of the correlation between light scatter and turbidity.

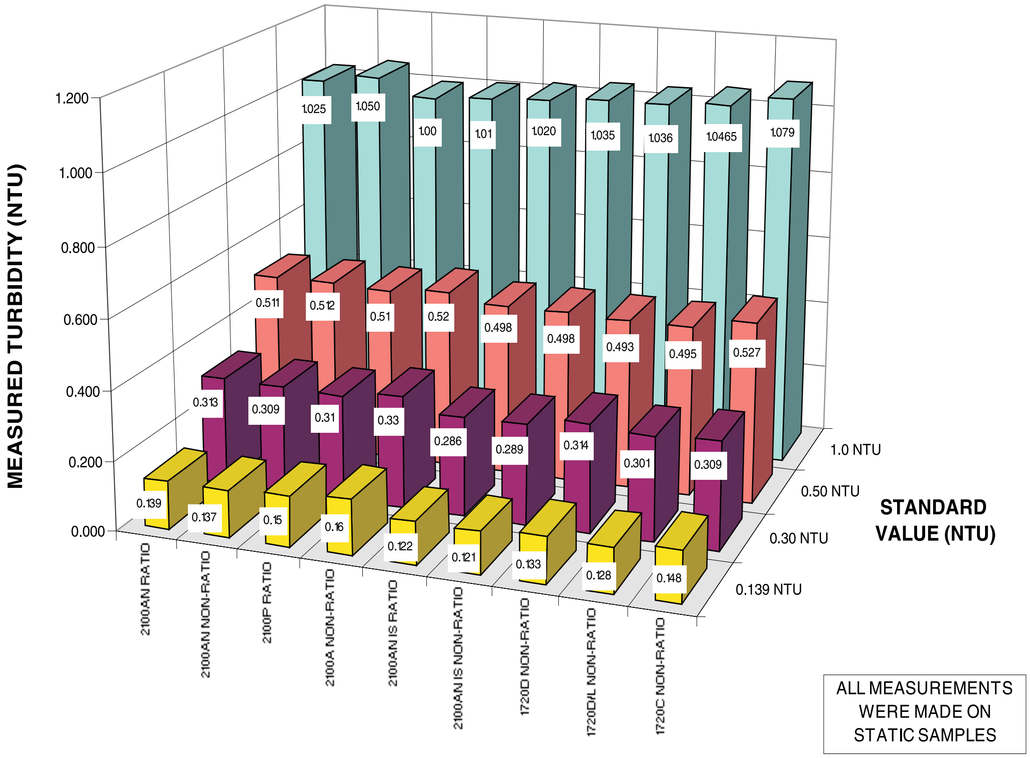
The accuracy specification for the 0.30, 0.50, and 1.00 NTU StablCal standards are 0.05 NTU. The 0.139 standard is specified using a RSD value of < 5 percent, or a numerical standard deviation of 0.007 NTU.

These standards are also beneficial because they most closely mimic real world samples. Size distributions approximate the $^{1}/_{d^{3}}$ relationship. (As the particle size decreases by a factor of 10, the number of particles increases by a factor of 1000.) The highly reflective standards efficiently scatter incident light. Light absorption by the formazin polymer is minimal. Further, the formazin polymer has a density similar to that of water. This results in a stable turbidity suspension that produces stable measurements over time.

In *Figure 11*, the differences between the ISO 7027 and USEPA 180.1 are instrument dependent as the turbidity of the standards approaches 1.0 NTU. For example, at 1.0 NTU, the 2100AN reading is lower than the 2100AN IS. As the value of the standards decreases to 0.139 NTU, the differences between ISO 7027 and USEPA 180.1 methods become more apparent, with the ISO 7027 instruments trending lower. In addition *Figure 11* shows that the older instruments with higher stray light trend higher throughout the measurement of these standards.

With the exception of one measurement (1720C with the 1.0 NTU standard), all the measurements are within their specifications and the specifications placed on the standards. Therefore, instrument calibrations produce valid and accurate turbidity measurements at very low turbidity levels.

Figure 11 **Instrument Comparison at Low Turbidity Values StablCal Stabilized Formazin Standards**



ALL MEASUREMENTS WERE MADE ON STATIC SAMPLES

7.2.2 Intra-instrument Comparison Using WS040 and WS041 Samples

Table 5 contains the results from the USEPA WS040 and WS041 samples. Three samples were measured only on laboratory and portable instruments. Two samples were measured on laboratory, portable, and process turbidimeters. The samples evaluated ranged from 0.16 to 0.35 NTU.

Table 5 Intra-instrument Deviation Using WS040 and WS041 Samples

Instrument	WS40 #2	WS40 #3	WS41 #2	WS 41 #3	WS41 #4	Rank
Avg. Value	**0.3321**	**0.3295**	**0.2067**	**0.2035**	**0.1794**	
2100AN IS Ratio	-0.023	-0.029	-0.014	-0.008	-0.007	1
2100AN IS Non-ratio	-0.011	-0.018	-0.012	-0.017	-0.006	2
2100AN Ratio	0.002	-0.006	0.007	0.007	0.006	3
2100AN Non-ratio	0.013	0.007	0.007	0.007	0.007	5
2100A Non-ratio	0.006	0.030	0.023	0.008	0.034	7
Ratio XR Ratio	-0.002	-0.005	n/m	n/m	n/m	n/a
2100P Ratio	0.015	0.015	0.008	0.015	0.011	6
1720D Non-ratio	-0.002	n/m	0.012	n/m	n/m	4
Avg. 180.1	**0.3276**	**0.3384**	**0.2146**	**0.2102**	**0.1881**	
Avg. 7027	**0.3056**	**0.3072**	**0.1870**	**0.1903**	**0.1622**	

Again, the measurements made using the ISO 7027 method read lower, with the average reading being 0.021 NTU less than a corresponding measurement made using USEPA 180.1. The range of readings on any specific sample was between 0.013 and 0.058 NTU, depending on the sample. Ratio and non-ratio measurements of the WS041 samples differed by less than 0.005 NTU.

When looking at all the data in *Table 5*, the instruments were ranked from reading lowest to highest are as follows:

2100ANIS < 2100AN < 1720D < 2100P < 2100A

Of these instruments, the 2100AN IS trended lowest and the 2100A trended highest.

Figure 12 was prepared from measurements performed on several sets of turbidity samples from the USEPA Water Supply Performance Evaluation Study #40. Two turbidity samples, Sample #2 and Sample #3, are shown in *Figure 12*. These samples are turbidity surrogates comprised of styrenedivinylbenzene (SDVB) beads with a relatively narrow size distribution ranging between 0.1 and 0.5 µm. The “true value” assigned by the USEPA to each of these standards was 0.26 NTU.

The results displayed in *Figure 12* show significantly higher readings than the true value of these standards across all instrumentation. The results from the USEPA WS040 report also show higher trending. The suspected cause of this trending is contamination.

The ISO 7027 instruments trended slightly lower than the USEPA 180.1 instruments, though the magnitude of the change is smaller than those differences associated with the lower turbidity samples. There is also a larger difference between ratio and non-ratio readings. The differences between ratio and non-ratio measurements on a single instrument range as high as 0.013 NTU. This may be due to the narrow size distribution of these standards that can result in non-symmetrical light scatter. Non-symmetrical light scatter can result in increased differences between ratio and non-ratio measurements. Generally, this narrow size distribution error will become more prominent as turbidity levels exceed 1.0 NTU.

Figure 12 Instrument Comparison on Low Turbidity Samples USEPA WS040 Study

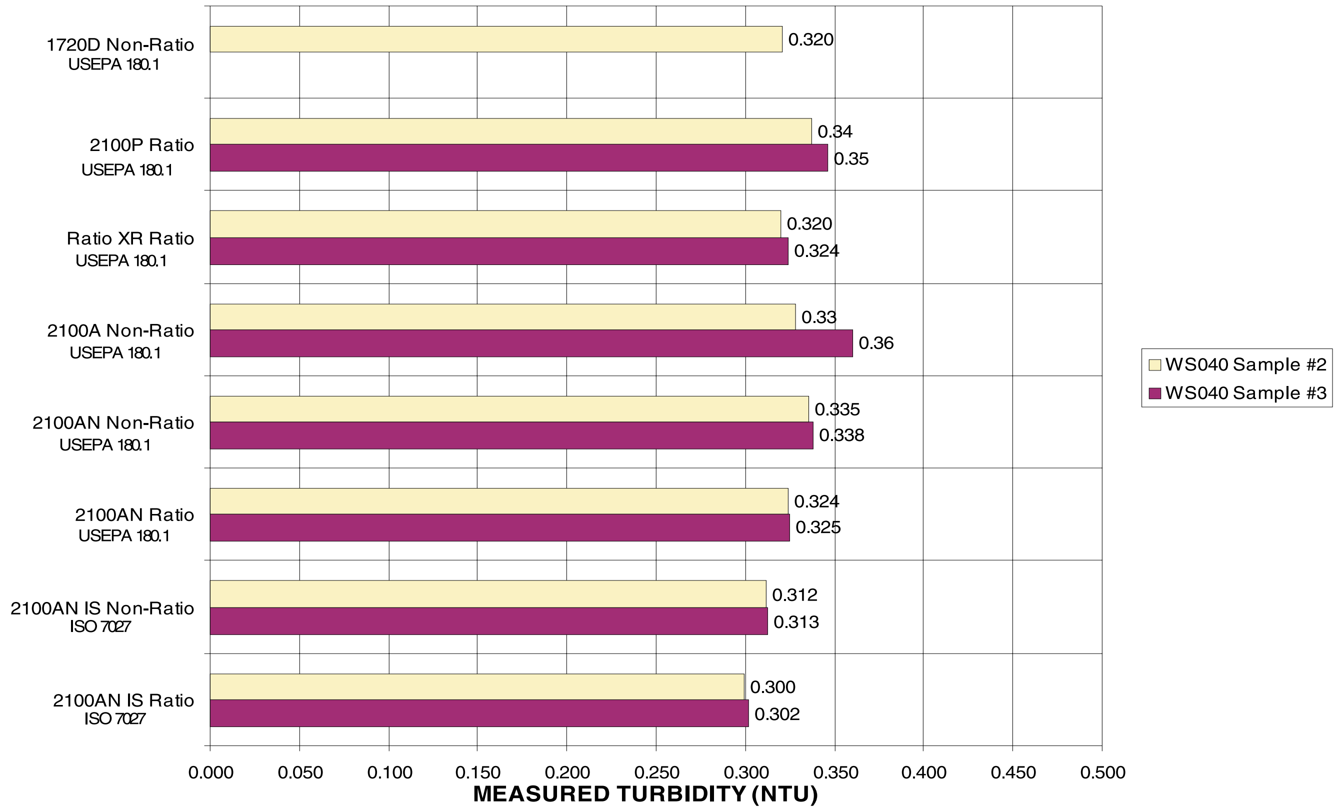
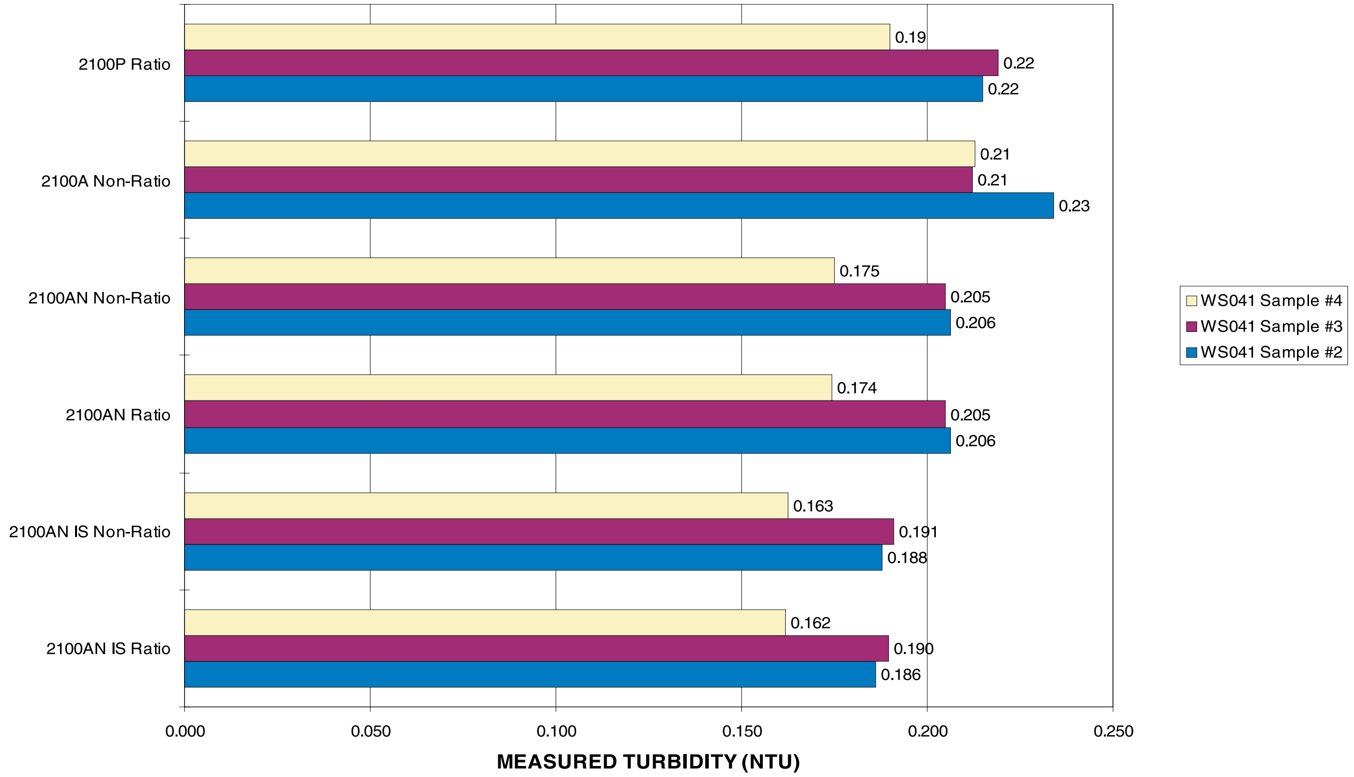


Figure 13 shows three WS041 samples, Sample #2, Sample #3, and Sample #4. Samples #2 and #3 are composed of SDVB material. Sample #4 is a stabilized formazin standard. Only laboratory and portable turbidimeters were used to measure these standards. Again, the WS041 results trend higher when compared to the true values, but the difference is much smaller than was the WS040 results.

ISO 7027 instrumentation continued to trend lower than USEPA 180.1 instruments on each of these samples. Further, older instrument models such as the 2100A, trend higher than new instrument models (2100AN). The differences between ratio and non-ratio readings were very minimal. In most cases, the difference between these readings on a single instrument (2100AN or 2100AN IS) was <0.002 NTU.

Figure 13 Instrument Comparison on Low-level Turbidity Samples USEPA WS041 Study



7.2.3 Intra-instrument Comparison Using Kaolin Turbidity Standards

The data in *Table 6* describes samples spiked with a known quantity of kaolin. The kaolin material is light colored.

Table 6 Intra-instrument Deviation Using Kaolin Spiked Water Samples

Instrument	0.1 mg/L Kaolin	0.3 mg/L Kaolin	0.5 mg/L Kaolin	0.7 mg/L Kaolin	1.0 mg/L Kaolin	Rank
Avg. Value	**0.121**	**0.298**	**0.417**	**0.561**	**0.866**	
2100AN IS R	-0.003	0.016	0.051	0.044	0.086	4
2100AN R	0.006	-0.007	-0.011	0.038	0.136	3
2100P R	0.009	-0.008	0.003	0.009	-0.011	2
2100A NR	-0.021	-0.038	-0.117	-0.191	-0.266	1
1720D NR	0.010	0.038	0.073	0.100	0.055	5
Avg. 180.1	**0.122**	**0.294**	**0.404**	**0.550**	**0.844**	
Avg. 7027	**0.118**	**0.314**	**0.467**	**0.605**	**0.952**	

Kaolin clay is a common material in water samples. Kaolin is also used as a turbidity standard in the Japanese water industry. Several kaolin standards were prepared according to the method JIS K0101. Kaolin turbidity is recorded in units of degrees, indicating the use of kaolin. For this study, turbidity standards ranging between 0.1 and 1.0 degrees were prepared.

A correlation between degrees turbidity and NTU was drawn using several different instruments. Most instruments have a 1:1 correlation, but the correlation begins to weaken above 10 degrees (10 NTU).

Kaolin standards have some unique characteristics that result in different trends between instruments. First, the material is much denser than water and settles quickly. Thus, when reading these standards, several readings were taken over a defined time period and averaged. Second, the readings are very noisy, and signal averaging was necessary to achieve measurement consistency. Finally, the kaolin particles have a slight tan color that absorbs specific wavelengths of incident light in incandescent turbidimeters (USEPA 180.1).

As shown in *Figure 14*, kaolin standards produce different results with different methods. Unlike the samples described previously, the ISO 7027 instruments read higher than the USEPA 180.1 instruments. These differences become more prominent as the turbidity values increase. At 0.1 NTU, the 2100A readings were slightly low. As the standards approach 1.0 NTU, the 2100A response is greatly diminished*. However, as the turbidity of the kaolin standard increases, newer USEPA 180.1 instruments in ratio mode responded better to the additional kaolin.

The best linearity was achieved with ISO 7027 instrumentation and the 1720D turbidimeter. Both instruments displayed excellent correlation up to 1 degree.

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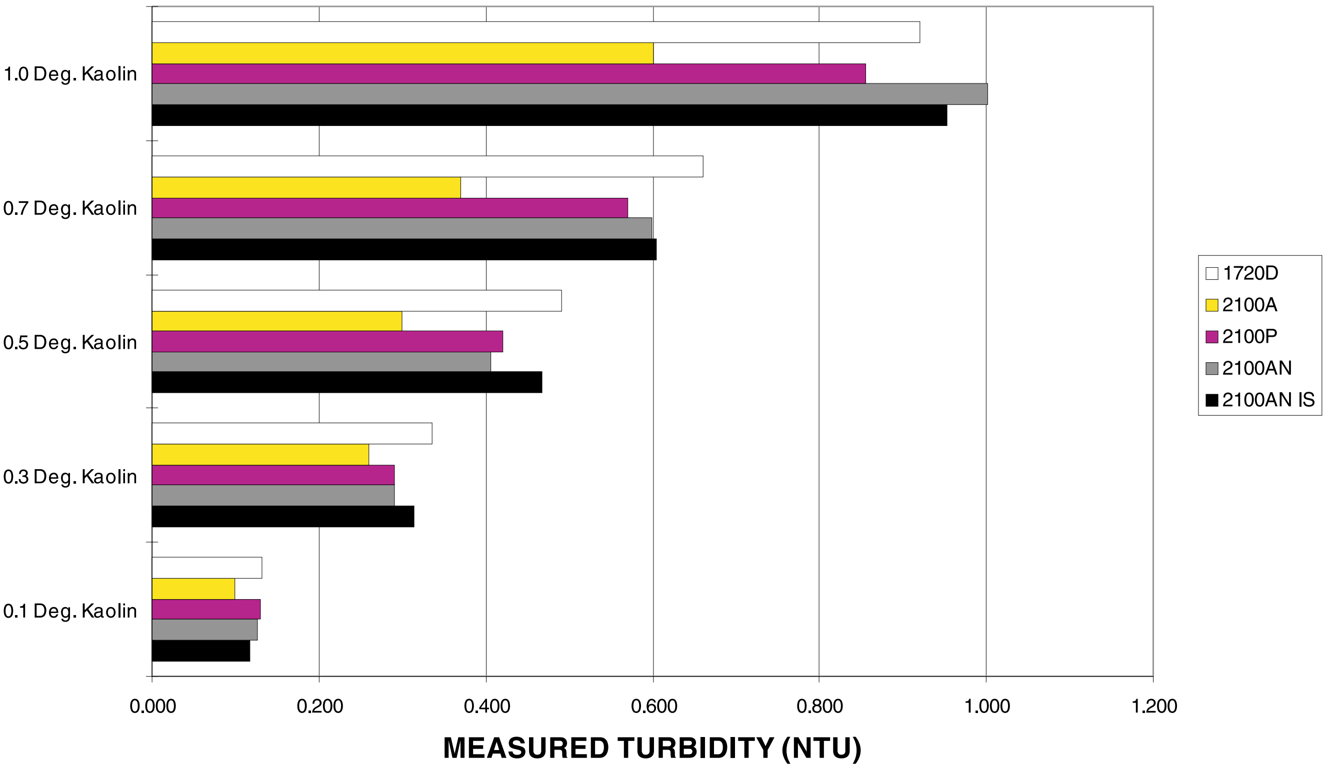
* The 2100A reads lower than other USEPA 180.1 instruments because it has a photomultiplier tube with a very narrow response curve in the 400 to 600 nm range. This narrow range makes the instrument more sensitive to color than detectors that have a wider response curve.

Figure 14 Instrument Comparison at Low Turbidity Levels Kaolin Turbidity Standards JIS K0101



7.2.4 Intra-instrument Comparison Using Silica Spiked into Water Samples

The data in *Table 7* describes samples spiked with a known quantity of silica. The silica material appeared to be highly reflective. These samples displayed very unusual measurement characteristics. The samples have a narrow size distribution in which non-symmetric scatter in the forward direction occurs.

The two method designs continued to exhibit the same instrument trends, with the ISO 7027 measurements reading lower by 0.010 to 0.020 NTU. No other instrument trends were easily defined.

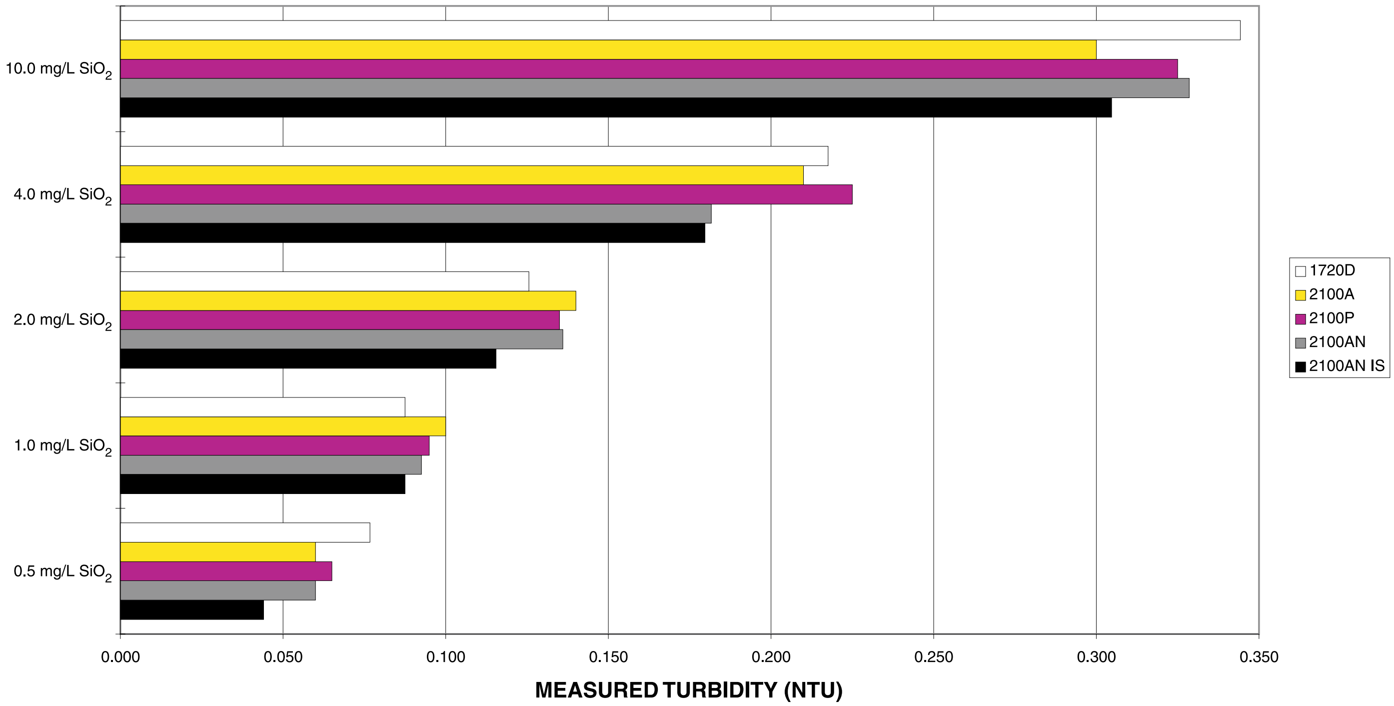
Table 7 Intra-instrument Deviation Using Silica Spiked Water Samples

Instrument	**0.5 mg/L SiO_2**	**1.0 mg/L SiO_2**	**2.0 mg/L SiO_2**	**4.0 mg/L SiO_2**	**10.0 mg/L SiO_2**	**Rank**
Avg. Value	**0.061**	**0.092**	**0.130**	**0.203**	**0.320**	
2100AN IS Ratio	-0.017	-0.005	-0.015	-0.023	-0.016	1
2100AN Ratio	-0.001	0.000	0.006	-0.021	0.008	2
2100P Ratio	0.016	-0.005	0.005	0.022	0.005	5
2100A Non-ratio	0.004	0.003	0.010	0.007	-0.020	3
1720D Non-ratio	-0.001	0.008	-0.005	0.015	0.024	4
Avg. 180.1	**0.065**	**0.094**	**0.134**	**0.209**	**0.324**	
Avg. 7027	**0.044**	**0.088**	**0.116**	**0.180**	**0.305**	

Figure 15 shows instrument comparisons on the RO/DI water samples that were spiked with different amounts of silica dioxide. The spike consisted primarily of particles ranging from 0.1 to 2.0 µm. Silica dioxide is very effective at scattering light and absorbs little incident light.

The 2100AN IS readings trended low using all of the lower turbidity standards, up to a spike of 4.0 mg/L silica. In comparison to other low-level standards (those measuring <0.1 NTU), the trend is consistent with instrument stray light being the determining factor resulting in the differences between instruments. Above 0.1 NTU, stray light becomes less important and instrument trends become less defined. Trends between instruments become more difficult to define. Scatter between instruments increases among instruments compliant to USEPA 180.1.

Figure 15 Instrument Comparison at Low Turbidity Levels RO/DI Water Spiked with Silica



7.2.5 Beta Site Instrument Comparison

Figure 16 displays the results from a turbidimeter beta site study using low-level stabilized formazin standards. The water plant that participated in this study is highly recognized for having very high quality standards in performing consistent and accurate turbidity measurements. The discussion of this study will cover those variables that will result when these types of studies are conducted in the industry.

The standard used in this study had a turbidity of 0.113 NTU. Only 2100N turbidimeters were used. Major variables in this study were calibration, sample cells, and the standard. Several measurement variables are shown in *Figure 16*. An explanation of the legend is below:

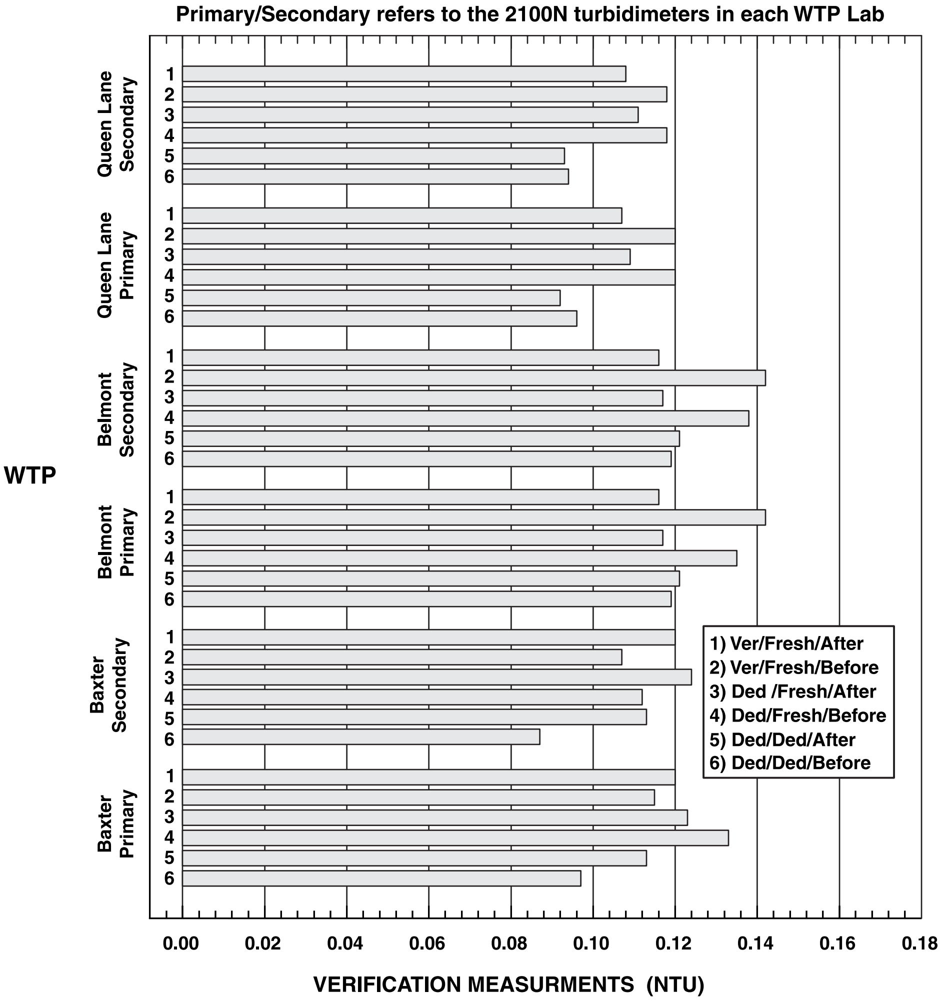
1. **Ver/Fresh/After:** The sample cells were varied and fresh standard was obtained immediately before each sample measurement. *Figure 16* shows data taken after calibration.
2. **Ver/Fresh/Before:** The sample cells were varied and fresh standard was obtained immediately before each sample measurement. *Figure 16* shows data taken before calibration.
3. **Ded/Fresh/After:** A single sample cell was used to perform all measurements and the standard solution was fresh before each measurement. *Figure 16* shows data taken before calibration.
4. **Ded/Fresh/Before:** A single sample cell was used to perform all measurements and the standard solution was fresh before each measurement. *Figure 16* shows data taken before calibration.
5. **Ded/Ded/After:** A single sample cell was used to perform all measurements and the standard solution remained in this sample cell for the duration of the study. *Figure 16* shows for data taken after calibration.
6. **Ded/Ded/Before:** A single sample cell was used to perform all measurements and the standard solution remained in this sample cell for the duration of the study. *Figure 16* shows data taken before calibration.

All measurements were taken on 2100N turbidimeters located at three different analysis laboratories. The primary instruments were used on a daily basis and the secondary instruments served as the backups. Note that calibration had a strong effect on the performance of the instrumentation. The error in measurement relative to the value of the stabilized formazin standard was an order of magnitude lower after calibration. Thus, the age of the instrument will affect measurements.

In comparing the sample cell and measurement conditions, the strictest conditions were 5 and 6 and the highest variability involved conditions 1 and 2. In addition, even though the sample cells were varied, they were matched to within 0.010 NTU. As expected, the largest deviation occurred when both the sample cells and standards were varied on a daily basis. In addition, the measurements trended higher under these conditions. As measurement conditions varied less, the variability and average value decreased.

Overall, *Figure 16* displays the variability between sample cells, samples, calibrations, and laboratories. Even though there is a wide array of variables, the measurement variation is generally low. Accurate comparisons will require frequent and accurate instrument calibration. This, coupled with care and consistency during sample preparation and measurement over time, will result in realistic, meaningful comparisons.

Figure 16 Beta Site Measurements of StablCal 0.113 NTU Verification Standards



AVERAGES
Percent Error Before Calibration = 3.83%
Percent Error After Calibration = 0.34%

7.2.6 Low-Level Comparison of Hach Process Turbidimeters:

Three different models of the Hach 1720 series of turbidimeters were compared on-line with the same water sample. The instrumentation included two 1720D turbidimeters, two 1720D/L turbidimeters, and one 1720C turbidimeter. Over 1440 measurements were taken over the 24 hour measurement period. All instruments were new and calibrated immediately before the comparison.

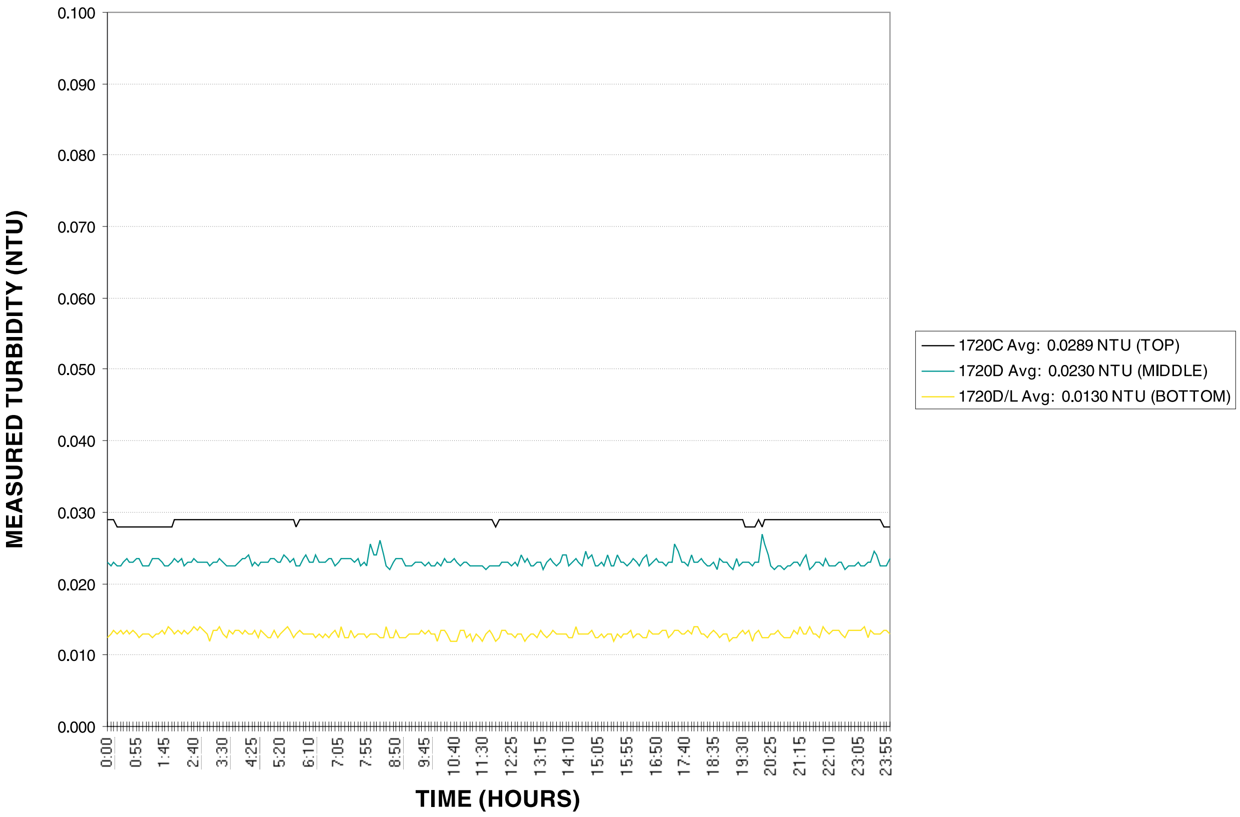
The instruments analyzed the sample for a 24-hour period. All measurement conditions were set the same:

- Signal averaging was set at 30 seconds.
- Flow rates were within specification, but at the low end of the recommended flow for each instrument (approximately 250 mL per minute).
- Data from each instrument was logged at one minute intervals.

Figure 17 displays the results of this comparison. The two 1720D and two 1720D/L measurements were averaged. In the legend, the averaged measured value for each instrument type is listed.

The same instrument trends observed in static observations occurred in the continuous measurements. The ISO 7027 instrument, the 1720D/L, read approximately 0.015 NTU lower than the USEPA 180.1 instruments. Comparing the USEPA 180.1 instruments, the 1720D with the lower stray light body read lower than the 1720C by approximately 0.006 NTU.

Figure 17 On-line Low-level Turbidimeter Comparison Using RO/DI



SECTION 8 CONCLUSIONS

Data collection in this study was subject to very stringent conditions. The turbidimeters were in top working order and had minimal stray light. The instruments were calibrated immediately prior to taking comparison data, minimizing intra-instrument variability. In addition, the sample cells were used repeatedly to minimize variations in measurement.

Differences between the two regulatory methods were observed at low turbidity levels. USEPA Method 180.1 uses a light source far more sensitive to small particles than ISO Method 7027. As a result, the ISO Method 7027 measurements read slightly lower than USEPA Method 180.1.

Most of the other differences between instruments result from stray light. Newer instruments and instruments without sample cells (process turbidimeters), tend to have slightly lower stray light and trend lower than older instruments or laboratory instruments.

Overall, net differences between the ISO Method 7027 and USEPA Method 180.1 methods result in trade-offs that the plant operator must evaluate based on plant needs. Modern turbidimeter design has improved significantly over the years, as shown below:

1720D/L ≤ 2100AN IS < 1720D < 2100AN < 2100P ≤ 1720C < 2100A

Current turbidimeters based on ISO Method 7027 or USEPA Method 180.1 clearly surpass earlier designs. Turbidimeters based on either method will provide an excellent investment for the conscientious plant operator.

The keys to making accurate low-level measurements can be summarized with a few points:

1. Use newer instrumentation that has low stray light characteristics and is designed for low-level use.
2. Keep instrumentation and sample cells clean and well maintained.
3. Calibrate the instrumentation in strict accordance to the manufacturer’s instructions.
4. Verify the instruments are measuring accurately at low-levels.
5. Do not use offset values in any of the instrumentation.
6. Measure samples using consistent, meticulous preparation techniques.
7. Keep the general area where these instruments are located clean and dust-free.

SECTION 9 REFERENCES

[1] *Standard Methods for the Examination of Water and Wastewater*, 19th ed.; Method 2130B, 1995, 2-8–2-11.

[2] *Methods for the Determination of Inorganic Substances in Environmental Samples*; EPA-600/R-93-100, Method 180.1. USEPA, 1993.

[3] *International Organization for Standardization*, Method ISO 7027. 1990.

[4] *Water Supply Performance Evaluation Study*, #40. USEPA. March 1998.

[5] *Water Supply Performance Evaluation Study*, #41. USEPA. October 1998.

APPENDIX A RAW DATA

Table 8 StablCal® Standards and Low-level Water Samples

INSTRUMENT	RO/DI #1	RO/DI #2	WTP #2	DIST. TAP #1	WTP #1	0.139 NTU	0.30 NTU	0.50 NTU	1.0 NTU
2100AN ratio	0.027	0.025	0.046	0.068	0.161	0.139	0.313	0.511	1.025
2100AN non-ratio	0.027	0.025	0.046	0.069	0.158	0.137	0.309	0.512	1.050
2100P ratio	0.03	0.03	0.05	0.07	0.17	0.15	0.31	0.51	1.00
2100A non-ratio	0.05	0.04	0.06	0.08	0.15	0.16	0.33	0.52	1.01
2100AN IS ratio	0.013	0.009	0.035	0.052	0.159	0.122	0.286	0.498	1.020
2100AN IS non-ratio	0.014	0.009	0.033	0.053	0.161	0.121	0.289	0.498	1.035
1720D non-ratio	0.0255	0.0265	0.046	0.0625	0.1405	0.133	0.3135	0.493	1.036
1720D/L non-ratio	0.018	0.021	0.045	0.057	0.1375	0.128	0.301	0.495	1.0465
1720C non-ratio	0.032	0.032	0.071	0.069	0.165	0.148	0.309	0.527	1.079
Average all turbidimeters	0.0257	0.0241	0.0478	0.0644	0.1552	0.1368	0.3056	0.5064	1.0335
Minimum	0.013	0.0085	0.033	0.052	0.1375	0.121	0.286	0.493	1.00
Maximum	0.045	0.04	0.071	0.08	0.165	0.16	0.325	0.527	1.079
Range	0.032	0.0315	0.038	0.028	0.0275	0.039	0.039	0.034	0.079
Average USEPA turbidimeters	0.0311	0.0298	0.0530	0.0698	0.1565	0.1435	0.3124	0.5113	1.0333
Average ISO 7027 turbidimeters	0.0148	0.0128	0.0375	0.0538	0.1525	0.1235	0.2920	0.4968	1.0338
Number of measurements	48	48	48	48	48	48	48	48	48

Table 9 USEPA WS040 and WS041 Samples

Instruments	WS040 Sample #2	WS041 Sample #3	WS041 Sample #2	WS041 Sample #3	WS040 Sample #4
2100AN IS ratio	0.300	0.302	0.186	0.190	0.162
2100AN IS non-ratio	0.312	0.313	0.188	0.191	0.163
2100AN ratio	0.324	0.325	0.206	0.205	0.174
2100AN non-ratio	0.335	0.338	0.206	0.205	0.175
2100A non-ratio	0.33	0.36	0.23	0.21	0.21
Ratio XR ratio	0.320	0.324	n/a	n/a	n/a
2100P ratio	0.34	0.35	0.22	0.22	0.19
1720D non-ratio	0.320	n/a	0.211	n/a	n/a
Average all turbidimeters	0.3221	0.3295	0.2067	0.2035	0.1794
Minimum	0.302	0.302	0.186	0.190	0.162
Maximum	0.338	0.360	0.234	0.219	0.213
Range	0.036	0.058	0.048	0.029	0.051
Average USEPA turbidimeters	0.3276	0.3384	0.2146	0.2102	0.1881
Average ISO 7027 turbidimeters	0.3056	0.3072	0.1870	0.1903	0.1622
Number of measurements	90	72	100	66	66

Table 10 Silica Spiked Into RO/DI Water (values reported as mg/L SiO_2 Spiked)

Instrument	0.5 mg/L SiO_2	1.0 mg/L SiO_2	2.0 mg/L SiO_2	4.0 mg/L SiO_2	10.0 mg/L SiO_2
2100AN IS	0.044	0.088	0.116	0.180	0.305
2100AN	0.060	0.093	0.136	0.182	0.329
2100P	0.07	0.10	0.14	0.23	0.33
2100A	0.06	0.10	0.14	0.21	0.30
1720D	0.077	0.087	0.126	0.218	0.344
Average all turbidimeters	0.061	0.092	0.130	0.203	0.320
Minimum	0.044	0.087	0.116	0.180	0.300
Maximum	0.077	0.100	0.140	0.225	0.344
Range	0.033	0.013	0.025	0.045	0.044
Average USEPA turbidimeters	0.065	0.094	0.134	0.209	0.324
Average ISO 7027 turbidimeters	0.044	0.088	0.116	0.180	0.305
Number of measurements	28	28	28	28	28

Table 11 Kaolin Turbidity Standards (values reported as Degrees Kaolin)

Instrument	0.1 Deg. Kaolin	0.3 Deg. Kaolin	0.5 Deg. Kaolin	0.7 Deg. Kaolin	1.0 Deg. Kaolin
2100AN IS	0.118	0.314	0.467	0.605	0.952
2100AN	0.127	0.291	0.406	0.599	1.002
2100P	0.13	0.29	0.42	0.57	0.86
2100A	0.10	0.26	0.30	0.37	0.60
1720D	0.132	0.336	0.490	0.661	0.921
Average all turbidimeters	0.121	0.298	0.417	0.561	0.866
Minimum	0.100	0.260	0.300	0.370	0.600
Maximum	0.132	0.336	0.490	0.661	1.002
Range	0.032	0.076	0.190	0.291	0.402
Average USEPA turbidimeters	0.122	0.294	0.404	0.550	0.844
Average ISO 7027 turbidimeters	0.118	0.314	0.467	0.605	0.952
Number of measurements	28	28	28	28	28

APPENDIX A, continued

Table 12 Statistical Summary of all Samples Measured

Sample	Number of Measurements	Total Number of Instruments	Average Value NTU	Measurement Range	Minimum Value	Maximum Value	EPA 180.1 Average	EPA 180.1 Ratio Average	EPA 180.1 Non-Ratio Average	ISO 7027 Average	ISO 7027 Ratio Average	ISO 7027 Non-Ratio Average
RO/DI #1	48	12	0.0257	0.032	0.013	0.045	0.0310	0.0290	0.0320	0.0150	0.0130	0.0160
RO/DI #2	48	12	0.0241	0.032	0.009	0.040	0.0300	0.0280	0.0310	0.0130	0.0090	0.0150
WTP #2	48	12	0.0478	0.038	0.033	0.071	0.0530	0.0480	0.0560	0.0380	0.0350	0.0390
DIST. TAP #1	48	12	0.0644	0.028	0.052	0.080	0.0700	0.0690	0.0700	0.0540	0.0520	0.0550
WTP #1	48	12	0.1552	0.027	0.138	0.165	0.1570	0.1630	0.1530	0.1530	0.1590	0.1490
0.139 NTU	48	12	0.1368	0.039	0.121	0.160	0.1440	0.1420	0.1440	0.1240	0.1220	0.1250
0.30 NTU	48	12	0.3056	0.039	0.286	0.325	0.2146	0.3090	0.3140	0.2920	0.2860	0.2950
0.50 NTU	48	12	0.5064	0.034	0.493	0.527	0.2102	0.5080	0.5129	0.4968	0.4975	0.4965
1.00 NTU	48	12	1.0335	0.079	1.000	1.079	0.1881	1.0125	1.0438	1.0338	1.0200	1.0408
WS040 Sample #2	90	11	0.3224	0.032	0.100	0.132	0.3290	0.3310	0.3280	0.3060	0.3000	0.3120
WS040 Sample #3	72	9	0.3304	0.058	0.302	0.360	0.3420	0.3350	0.3490	0.3070	0.3020	0.3130
WS041 Sample #2	100	10	0.2067	0.048	0.186	0.234	0.2080	0.2107	0.2171	0.1870	0.1860	0.1880
WS041 Sample #3	66	7	0.2035	0.029	0.190	0.219	0.2050	0.2119	0.2085	0.1903	0.1897	0.1910
WS041 Sample #4	66	7	0.1794	0.051	0.162	0.213	0.1750	0.1821	0.1940	0.1622	0.1617	0.1630
0.1 mg/L Kaolin	28	10	0.1210	0.032	0.100	0.132	0.1220	n/a	n/a	0.1180	n/a	n/a
0.3 mg/L Kaolin	28	10	0.2980	0.076	0.260	0.336	0.2940	n/a	n/a	0.3140	n/a	n/a
0.5 mg/L Kaolin	28	10	0.4170	0.190	0.300	0.490	0.4040	n/a	n/a	0.4670	n/a	n/a
0.7 mg/L Kaolin	28	10	0.5610	0.291	0.370	0.661	0.5500	n/a	n/a	0.6050	n/a	n/a
1.0 mg/L Kaolin	28	10	0.8660	0.402	0.600	1.002	0.8440	n/a	n/a	0.9520	n/a	n/a
0.5 mg/L SiO_2	28	10	0.0611	0.033	0.044	0.077	0.0654	n/a	n/a	0.0440	n/a	n/a
1.0 mg/L SiO_2	28	10	0.0925	0.013	0.087	0.100	0.0937	n/a	n/a	0.0875	n/a	n/a
2.0 mg/L SiO_2	28	10	0.1304	0.025	0.116	0.140	0.1341	n/a	n/a	0.1155	n/a	n/a
4.0 mg/L SiO_2	28	10	0.2028	0.045	0.180	0.225	0.2086	n/a	n/a	0.1797	n/a	n/a
10.0 mg/L SiO_2	28	10	0.3205	0.044	0.300	0.344	0.3244	n/a	n/a	0.3047	n/a	n/a

APPENDIX B MEASUREMENT BREAKDOWN

Measurement Breakdown for StablCal® Standards and Low-level Water Samples

Three measurements on each instrument in each measurement mode. The exception is the 2100A, in which only one measurement was made on this instrument. Process turbidimeter measurements were made with 30 second signal average, with three readings taken over a 1-3 minute period.

Table 13 Number of Measurements with StablCal® Standards and Low-level Water Samples

Instrument	RO/DI #1	RO/DI #2	WTP #2	DIST. TAP #1	WTP #1	0.139 NTU	0.30 NTU	0.50 NTU	1.0 NTU
2100AN ratio	6	6	6	6	6	6	6	6	6
2100AN non-ratio	6	6	6	6	6	6	6	6	6
2100P ratio	6	6	6	6	6	6	6	6	6
2100A non-ratio	1	1	1	1	1	1	1	1	1
2100AN IS ratio	6	6	6	6	6	6	6	6	6
2100AN IS non-ratio	6	6	6	6	6	6	6	6	6
1720D non-ratio	6	6	6	6	6	6	6	6	6
1720D/L non-ratio	6	6	6	6	6	6	6	6	6
1720C non-ratio	3	3	3	3	3	3	3	3	3
Total	46	46	46	46	46	46	46	46	46

Measurement Breakdown for USEPA WS040 and WS041 Samples

Six replicates of each sample were measured on each type of instrument. For the 2100AN, 2100AN IS, 2100P, two instruments were used and measurements were made in both the ratio and non-ratio mode. The 1720D values represent a total of three instruments to measure each sample. The 2100A and Ratio XR entries are for a single instrument of each type respectively.

Table 14 Number of Measurements with USEPA WS040 and WS041 Samples

Instruments	WS040 Sample #2	WS040 Sample #3	WS041 Sample #2	WS041 Sample #3	WS041 Sample #4
2100AN IS ratio	12	12	12	12	12
2100AN IS non-ratio	12	12	12	12	12
2100AN ratio	12	12	12	12	12
2100AN non-ratio	12	12	12	12	12
2100A non-ratio	6	6	6	6	6
Ratio XR ratio	6	6	n/a	n/a	n/a
2100P ratio	12	12	12	12	12
1720D non-ratio	18	n/a	34	n/a	n/a
Total	90	72	100	66	66

Measurement Breakdown for Silica Spiked Into RO/DI Water

Three measurements were made on each instrument. Two 2100AN IS, 2100AN, and 2100P instruments were used. Only one 2100A was available for use. Three 1720D instruments were used to represent the process instruments. Measurements were made only in the ratio modes only on the 2100AN and 2100AN IS instruments. Only one reading of each sample was taken on a single 2100A instrument.

Table 15 Number of Measurements Silica Spiked Into RO/DI Water

Instrument	0.5 mg/L SiO_2	1.0 mg/L SiO_2	2.0 mg/L SiO_2	4.0 mg/L SiO_2	10.0 mg/L SiO_2
2100AN IS	6	6	6	6	6
2100AN	6	6	6	6	6
2100P	6	6	6	6	6
2100A	1	1	1	1	1
1720D	9	9	9	9	9
Total	28	28	28	28	28

Measurement Breakdown for Kaolin Turbidity Standards

Three measurements were made on each instrument. Two 2100AN IS, 2100AN, and 2100P instruments were used. Only one 2100A was available for use. Three 1720D turbidimeters were used to represent the process instruments. Measurements were made only in the ratio modes only on the 2100AN and 2100AN IS instruments. Only one reading of each sample was taken on a single 2100A instrument.

Table 16 Number of Measurements Kaolin Turbidity Standards

Instrument	0.1 Deg. Kaolin	0.3 Deg. Kaolin	0.5 Deg. Kaolin	0.7 Deg. Kaolin	1.0 Deg. Kaolin
2100AN IS	6	6	6	6	6
2100AN	6	6	6	6	6
2100P	6	6	6	6	6
2100A	1	1	1	1	1
1720D	9	9	9	9	9
Total	28	28	28	28	28

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