# Unique Flow Measurement Challenges for Large UV Systems

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A key element in successful implementation of an ultraviolet (UV) disinfection system is proper control and operation of the UV lamps. The intensity and operational period of a lamp bank is typically a function of the specified disinfection requirements and flowrate. Meeting the disinfection requirements while maximizing the efficiency of the UV system is predicated upon accurate and repeatable flow measurement. The complex piping of a large UV system (large being defined herein as 30 inches or greater in pipe diameter or channel width) provides very challenging hydraulic conditions that can impact the accuracy and repeatability of a flowmeter. It is critical to install a flow measurement technology that can operate as specified under these difficult hydraulic conditions in order to achieve the desired UV system performance.

## Increased Popularity of UV Disinfection Systems

UV disinfection systems are becoming more prevalent in the water and wastewater industries for a variety of reasons. Chlorine gas disinfection had been a popular method, but safety concerns and regulatory changes have led to a decrease in chlorine gas use. For example, new regulatory requirements regarding allowable concentrations of residual chlorine present in a wastewater treatment plant’s effluent required the implementation of dechlorination methods which usually involved the introduction of sulfur dioxide. As populations grew and homes were built closer and closer to wastewater treatment plants, the hazards, and associated liabilities, of storing chlorine and sulfur dioxide in bulk became increasingly unacceptable.

Chlorine, in the form of sodium hypochlorite, is far less hazardous to handle and store, effectively addressing the safety concerns associated with chlorine gas. The same discharge regulatory requirements, however, still define that a wastewater treatment plant’s effluent must be dechlorinated before being discharged into the receiving water. Sodium bisulfite is typically used in this application. Both sodium hypochlorite and sodium bisulfite add to the Total Dissolved Solids (TDS) of the plant discharge. Most National Pollutant Discharge Elimination System (NPDES) permits impose a TDS goal or limit on the plant discharge. In some areas, where the background TDS (the TDS that is found in the drinking water supply) is already high, adding more to the discharged effluent could cause that goal or limit to be exceeded.

Ozone can be used as an effective disinfectant that does not add TDS and leaves no residual in the effluent stream. It is a superior oxidant to chlorine. It has advantages for use in the destruction of endocrine disrupting compounds such as pharmaceuticals and personal care products that are typically found in domestic wastewater. There are some disadvantages to ozone disinfection systems, such as on-site generation and potential higher costs that may make that choice unappealing to some wastewater plants.

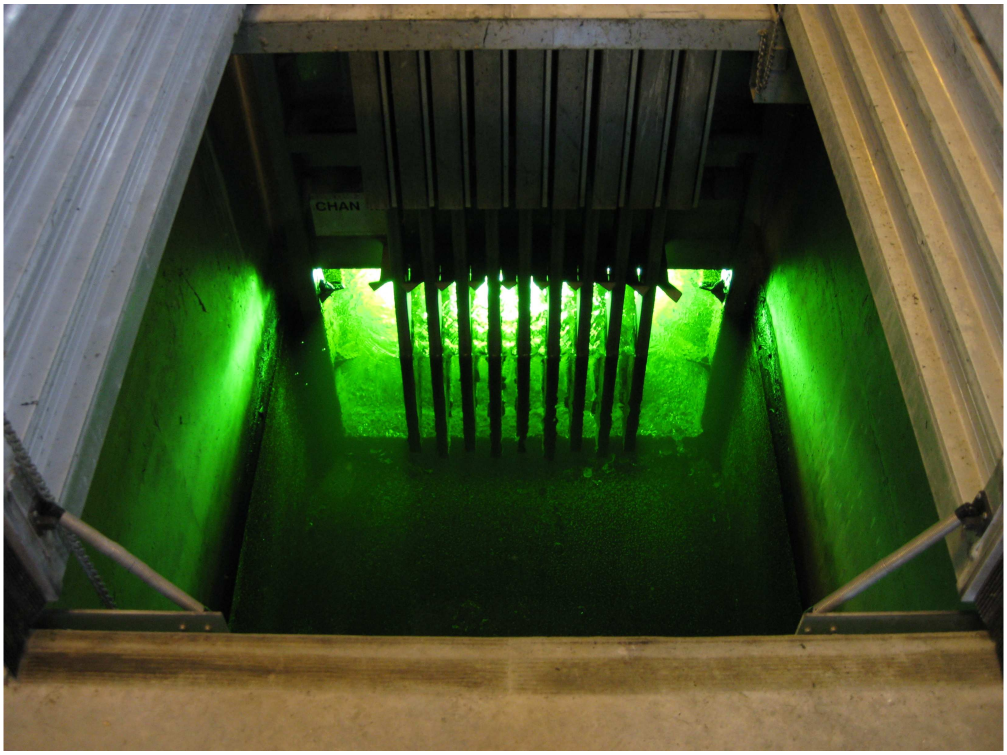

**Photo 1. UV Installation at Clark County Water Reclamation District**

Given the considerations mentioned above, many water and wastewater treatment plants are choosing UV as a disinfection method. UV systems have only minor chemical hazards (chemicals used for cleaning) associated with them, leave no residual, and add no TDS to the wastewater. UV systems disinfect by exposing the stream to intense UV light for a specified period of time. The UV spectrum is from 100 to 400 nanometers. The wavelength effective for disinfection is from 200 to 300 nm, 254 nm is most ideal. UV dose is expressed in milliwatt seconds per square centimeter ($mWs/cm^2$). For wastewater discharge, a dose in the area of $25 mWs/cm^2$ is usually adequate to meet NPDES disinfection requirements. As the water passes across the UV lamps, which are oriented parallel to the flow, it must be exposed to UV radiation for the time specified to achieve adequate dosing.

The challenge in using a UV system for disinfection is to always achieve adequate dosing without overdosing. Overdosing does not hurt the water in any way, but it uses more electricity than necessary and wears out the components of the UV system prematurely. This challenge is complicated by constantly changing flow rates. Typical municipal wastewater treatment plants receive flow in a diurnal pattern. The diurnal flowrate is typically low in the early hours of the morning while most of the population is sleeping, peaks in the late morning as the flows from morning showers and toilet use arrive, tapers off during the afternoon as water use decreases, increases to a lesser peak in the evening after people arrive home, and slowly declines to a low rate in the early hours, again. Typical potable water systems also exhibit a similar flow diurnal pattern. This variation in flowrate makes it more difficult for the optimization of a UV system without accurate and repeatable flow measurement.

## Difficulties for Traditional Flowmeters on Large UV Systems

Traditional flow measurement technologies are generally not suitable for the unique challenges presented by large UV disinfection systems. Beyond the requirement of an accurate and repeatable measurement in the presence of severely distorted flow profiles due to the complex piping of the system, the limited available space to install a flowmeter becomes the overriding factor. The end-to-end laying length of traditional flowmeters, such as magnetic and venturi flowmeters for full pipe installations and flumes for open channel installations, can exceed the limited space available for the flowmeter installation.

UV systems require highly accurate and repeatable flow measurement in the presence of complex hydraulic conditions. For such critical installations, it is essential to evaluate a potential flowmeter technology on the performance the flowmeter will provide under the actual installation conditions and not the accuracy such a flowmeter will provide in the benign conditions of a flow calibration facility. The stated accuracy for most flow measurement technologies is based on testing performed in flow calibration laboratories under ideal, or close to ideal, conditions. Those ideal conditions are rarely present in the real world environment most water or wastewater treatment plants operate in. The ultimate performance for any flowmeter is far more dependent on the actual installation conditions than on the flowmeter’s inherent accuracy. All potential uncertainties should be evaluated, chief among them being the negative effect of the flow profile distortion present at the installation location, when deciding on the proper flow measurement technology for a given requirement.

Ultimately, the accuracy (uncertainty) of a flowmeter is dependent upon all the potential uncertainties throughout its flow measurement process. For critical applications, such as large UV disinfection systems, a thorough uncertainty analysis should be performed based on the final installation dimensions as defined by the actual as-built drawings. An uncertainty analysis should be performed for each installed flowmeter, not just one as a “typical” for similar installations as too many installations aspects may vary from one installation to the next for a “typical” to be valid.

## A Viable Flowmeter Solution for Large UV Systems

Multiple ***chordal-path*** transit-time flowmeters are generally not well known to flowmeter users in the water and wastewater industries. While this type of transit-time flowmeter has been in use in these industries for many years, the application range is generally limited to the most difficult installations with complex hydraulics and the need for high performance. ***Diametrical-path*** transit-time flowmeters (clamp-on or wetted transducers) are more commonly known in the water and wastewater industries but possess certain limiting factors precluding them from consideration for many UV disinfection system installations. These limiting factors include the inability to measure flow in open-channel and partially full pipe installations, and limited performance capability in the presence of highly distorted flow profiles.

The transducer path arrangement and the numerical integration techniques utilized by multiple ***chordal-path*** transit-time flowmeters allow for much greater velocity profile resolution and is neither Reynolds Number (Rn) nor sonic velocity dependent, which are the primary performance limiting factors of the diametrical-path transit-time flowmeters. Unlike magnetic and venturi flowmeters, chordal-path transit-time flowmeters require relatively short end-to-end distance for installation addressing a critical issue for large UV systems. The chordal-path method also allows the flowmeter to measure flows in open channels as well as full pipes making it well suited for the various installation requirements of UV systems.

Multiple chordal-path transit-time flowmeter installations can include both internally mounted and feedthrough (through-wall) transducers depending on the access to the measurement section. A typical multiple chordal-path transit-time flowmeter consists of two or four chordal elevations depending on the accuracy that is required. A typical two elevation chordal transit-time flowmeter flowing full will have a system uncertainty of ± 1.5-2.0% and a typical four elevation chordal transit-time flowmeter flowing full will have a system uncertainty of ± 0.5-1.0%. It is important to note that these are anticipated ***installed accuracies***, not accuracies achieved in a laboratory under ideal flow conditions. Figure 1 shows the general configuration of a multiple chordal-path transit-time flowmeter in both a closed full pipe installation and a variable depth open channel installation.

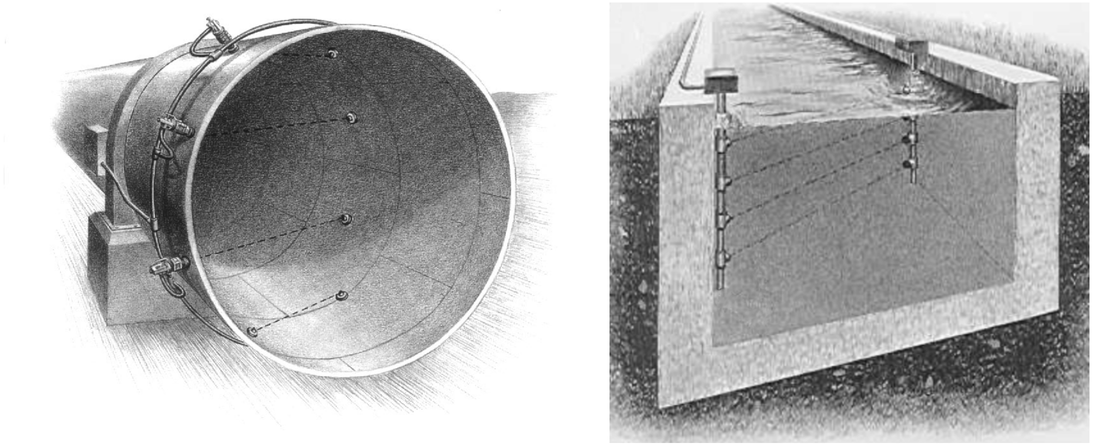

***Figure 1. Typical Multiple Chordal-Path Transit-Time Installation***

**Photo 2. UV - Open Channel Multiple Path Transit-Time Flowmeter Installation**

## Multiple Chordal-Path Transit-Time Flow Measurement Principle

In Figure 1, the upstream transducer is offset at a 45 degree angle across the pipe or channel to its downstream mating transducer. This angle can be changed to 65 degrees if external access is limited (reducing the overall end-to-end distance even further). In an installation where there is a limited upstream straight approach to the flow measurement section, crossed-paths can be installed at each elevation to correct for the effects of cross-flow. Cross-flow occurs due to an upstream disturbance in the piping configuration (elbow, bifurcation, etc.) where the main flow component is no longer axial (not parallel to the pipe wall). When cross paths are installed in the presence of cross-flow, one plane will be bias high and the opposite plane will bias low by the same magnitude of its crossed plane. The two acoustic paths installed at the same chordal elevation are averaged with a resulting net bias of zero.

$$\text{Tdown} = \frac{L}{C - (V \times \cos\theta)} \qquad \text{Tup} = \frac{L}{C + (V \times \cos\theta)}$$

$$V = \frac{(\text{Tdown} - \text{Tup})}{(\text{Tdown} \times \text{Tup})} \times \frac{L}{(2 \times \cos\theta)}$$

Where:

Tdown = Travel-time of the acoustic pulse from upstream transducer to downstream transducer
Tup = Travel-time of the acoustic pulse from downstream transducer to upstream transducer
C = Sonic velocity of the liquid
V = Velocity of liquid along pipe or channel axis
$\theta$ = Acoustic path angle with respect axial flow

***Figure 2. Transit-Time Velocity Equation***

The transit-time principle measures an average velocity across the pipe at a given chordal elevation. Figure 2 shows the velocity calculation based on the travel time of the sound pulse, the liquid sonic velocity, the acoustic path length, and the acoustic path angle. As shown in Figure 2, when the upstream and downstream travel times are combined to solve for the average velocity at a particular elevation; the sonic velocity variable cancels. This is important to note because a multiple chordal-path transit-time flowmeter is not dependant on the liquid sonic velocity and can be applied to applications with drastic changes in the temperature.

As previously mentioned, there are a number of variables that determine a flowmeter's overall system uncertainty (or accuracy). In a multiple chordal-path transit-time flowmeter system, these uncertainties are defined by four major components: the individual velocity measurements, cross-section area measurement, velocity integration (average velocity calculation), and random error. Typically the uncertainty of the velocity measurement and random error components are second order effects. The area measurement uncertainty is typically a fixed value and is based on the pipe diameter measurements taken during the installation. The largest contributor and most variable component to the overall uncertainty of a multiple path-chordal transit time flowmeter is the flow profile integration uncertainty.

In a four chordal-path elevation transit-time flowmeter, the acoustic chords are placed at ± 18 and 54 degrees with respect to the horizontal centerline of a pipe in full pipe applications. The integration technique used is called the Jacobi-Gauss Integration Method (or Chebyshev Method). Computational fluid dynamics (CFD) analysis has been used to estimate the integration uncertainty of this method over a wide range of velocity profiles (from fully developed symmetrical profiles to highly disturbed velocity profiles). These analyses and previous field experiences have shown that the uncertainty of the

Jacobi-Gauss integration is in a range of ± 0.2% to 1.2%. As such, when a multiple chordal-path transit-time flowmeter is installed in a worst-case hydraulic location, its maximum overall uncertainty will be better than ± 1.5% for a four elevation chordal transit-time flowmeter. Therefore, even in the presence of highly disturbed velocity profiles, a multiple chordal-path transit-time flowmeter can perform accurately.

## Site Certification Method and Uncertainty Analysis

A multiple chordal-path transit-time flowmeter is "Site Certified" during the installation. This "Site Certification Method" consists of physically measuring all of the parameters noted in the velocity equation in Figure 2. The travel times are measured in the flowmeter electronics using a high precision oscillator. The acoustic path length and acoustic angles are measured for each acoustic chordal path after the transducers have been installed. These measurements are defined as "as-built measurements" and are critical to the installed accuracy of a multiple chordal-path transit-time flowmeter. The area of the pipe or channel and verification of the acoustic chordal path placement are also checked during the installation of the transducers. Since these as-built measurements are verified during the installation, there is no need for future calibration if the system is fully functional. These measurement uncertainties are fixed and the measurement of a multiple chordal-path transit-time flowmeter will not drift over time. If there is a bias in the flow reading, it will be linear over the entire range of flow rates. This makes a multiple chordal-path transit-time flowmeter very repeatable as well as accurate and remains so over time.

In order to evaluate the uncertainty of a multiple chordal-path transit-time flowmeter, all uncertainties associated with the flow equation (Q = V x A) must be evaluated. The velocity component has a number of independent measurements that have their own uncertainties. The velocity component is comprised of the following parameters: Path Length; Path Angle; Travel Time Measurement; Protrusion Uncertainty; and Integration Uncertainty (which is used to determine the volumetric average velocity). The final flowrate uncertainty must include the wetted area uncertainty and random error. Random Error and Integration Uncertainty are determined after the multiple chordal-path transit-time flowmeter has been installed. Typical uncertainties for the individual measurements in a large UV installation are listed below:

- Path Length = ±0.1%
- Path Angle = ±0.2%
- Travel Time = ±0.05%
- Protrusion Effect = ±0.1%
- Area = ±0.4%
- Integration Uncertainty = ±0.2% to 1.2%
- Random Error = ±0.1%

Using the root sum squares method (or quadratic sum) to combine independent uncertainties, a typical four elevation multiple chordal-path transit-time flowmeter uncertainty (flowing full) can fall in the range of ±0.5% (with an Integration Uncertainty of 0.2%) to ±1.3% (with an Integration Uncertainty of 1.2%).

Multiple chordal-path transit-time flowmeter performance has been verified numerous times over the last 30 years by NIST traceable independent laboratories. In 2006, two 48” multiple chordal-path transit-time flowmeters were tested at the Utah State Water Research Laboratory. Both 48” multiple chordal-path transit-time flowmeters were tested in both the forward and reverse direction (a multiple chordal-path transit-time flowmeter can measure bi-directional flowrate). The testing configuration at the lab had optimal flow conditions and both 48” multiple chordal-path transit-time flowmeters tested within ±0.4% (the best test results during this period showed the multiple chordal-path transit-time flowmeter to be within ±0.12%). A number of tests have also been performed under difficult hydraulic conditions and have proven a multiple chordal-path transit-time flowmeter performance to be better than ±1.0% in these cases. This is important because large UV disinfection systems are rarely designed so that ideal flowmeter conditions can be achieved due to cost and spacing constraints.

## Experience at Clark County Water Reclamation District

At the Clark County Water Reclamation District (CCWRD) located in the Las Vegas area, the flow rate will typically be as low as 45 million gallons per day (MGD) and as high as 130 MGD within the same week. The arrival of tourists on the weekend can magnify the peaks of the diurnal flow pattern by 30 to 40 percent. In order to have a UV system that can efficiently disinfect the low flows and adequately disinfect the high flows, the system for CCWRD was designed with five 78 inch wide channels, each with 2 – 3 UV reactors and each with a flow capacity of 35 MGD. The system can be run with one channel in service with one reactor on at minimum power level for the lowest flow rate. As flow increases, reactor power output is increased until another reactor is required. Once the capacity of the first channel is reached, a second channel is opened and so on as the UV system reacts to increasing flows.

This process is fully automated, but can be adjusted by the operator based upon the results of laboratory analysis of the water quality. Having installed an accurate multiple chordal-path transit-time flowmeter in each of the five channels leading into the UV reactors enables the system operator to reduce electrical and maintenance costs by operating the system at optimum levels for the current flow rate while still achieving adequate disinfection to meet the NPDES permit requirements.

**Photo 3. UV Installation at Clark County Water Reclamation District**

Testing of the electrical power consumption of the UV system has indicated potentially significant cost savings based on effective control and operation of the of the lamp power output. For every 10% reduction in lamp power output, an approximate annual cost savings of $20,730 per channel can be recognized. Much of the potential savings comes from reducing the amount of time additional channels operate during high flow periods. The majority of the power consumption is used simply to bring the lamps up to minimum power output. By operating the lamps closer to the actual required output, the need to bring on additional channels is either reduced or eliminated. For example, by delaying the utilization of an additional channel for an hour and shutting down the same channel an hour earlier, an 8.3% power consumption reduction can be recognized for that channel. Thus, the more effective the control of the UV system, the greater the reduction in electrical power required to meet the defined disinfection requirement. This approach also extends the life of the equipment. The longer the lamps and ballasts operate, the sooner they will require replacement. Operating at higher power output levels shortens lamp and ballast life as well. If the lamps, ballasts and other supporting equipment operate less often and at lower power levels, their functional life will be extended. As such, additional, yet to be defined, cost savings can also be realized due to reduced wear and maintenance of the UV system. Installation of the multiple chordal path transit-time flowmeters in the CCWRD UV disinfection system has significantly assisted in achieving the goal of effective disinfection while maximizing the system’s efficiency.

## Conclusion

As the application of large UV disinfection systems continues to grow, the need for a viable flow measurement technology to address the challenges presented by these systems becomes more critical. The unique characteristics of the multiple chordal-path transit-time flow measurement technology enable a UV system to achieve the goal of assured continuous disinfection while maximizing the system's throughput and efficiency.