Technical Paper
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# Comparison of Doppler Flow Meter Types: Low-Cost Continuous Wave vs Multi-Cell, Pulsed Doppler Systems


## Introduction

Acoustic Doppler based current measurement systems are primary tools in the water and wastewater industries. In addition to measuring water velocity they can also include water level measurement and the ability to calculate discharge (flow), and their data output formats allow for easy connection to commercial data loggers, SCADA systems, PLCs, and remote telemetry equipment.

The following are some of the names often used for this type of instrument:

ADFM – Acoustic Doppler Flow Meter
ADVM – Acoustic Doppler Velocity Meter
AVM – Area Velocity Meter
"Ultrasonic" Flow Meter

The above terms are sometimes used interchangeably, as is the term "Doppler". However, not all Doppler systems use the same operating principles. Doppler systems used for flow measurement can be roughly divided into two categories: continuous wave (CW) and pulsed. SonTek's acoustic Doppler systems, such as the SonTek-IQ, are pulsed Doppler. Whether a continuous wave or pulsed Doppler will be suitable for any given site will depend on environmental factors and accuracy requirements.

**SonTek:**
Founded in 1992 and advancing environmental science in over 100 countries, manufactures affordable, reliable acoustic Doppler instrumentation for water velocity measurement in oceans, rivers, lakes, harbors, estuaries, and laboratories.

Headquarters are located in San Diego, California. SonTek is part of Xylem, Inc., a company that provides monitoring and data collection instrumentation to global water quality, water quantity, and aquaculture markets.

**Additional information:**
For more information about SonTek visit SonTek.com, or email SonTek directly at inquiry@SonTek.com.

Price is generally known as the main difference between CW and pulsed Doppler flow meters, and sometimes this weighs most heavily in choice of instrument. However, for most operators and managers, understanding the technical differences and their implications in the field would be helpful in making an informed choice to start, as well in operating the equipment and defending water data and decisions into the future. This tech note aims to explain some of the important technical differences in practical terms. A summary table of the differences is presented at the end of the paper.

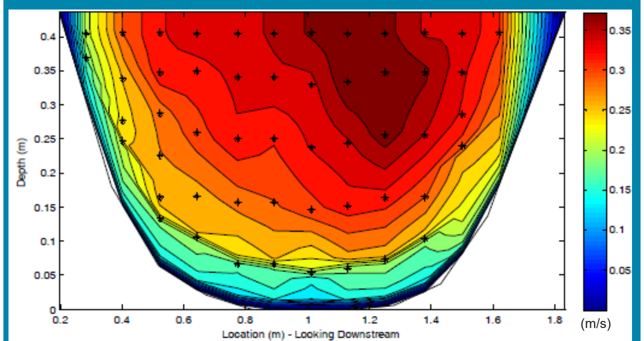
## Acoustic Doppler and Flow Measurement Basics

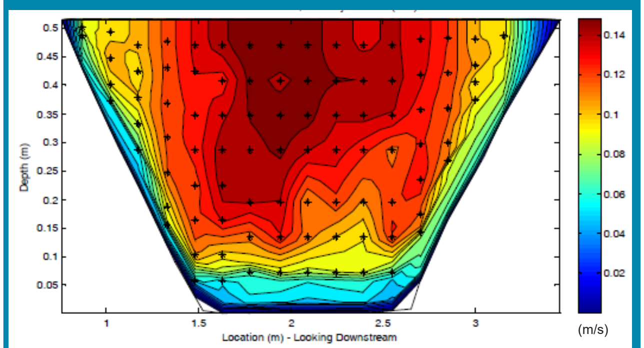
Acoustic Doppler current measurement systems measure the velocity of water using a physical principle called the Doppler shift. This principle states that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency. Note that a Doppler system does not actually measure the water velocity directly but instead measures the velocity of scattering particles suspended in the water column, with the assumption that the particles are traveling at the same speed as the water. If there are no scattering particles to reflect the signal, then a Doppler system will not be able to measure velocity.

The magnitude of the reflected signal will vary with the density of scattering particles in the water, the particle material and the acoustic reflectivity of that material at the transmit frequency, and the distance from the transducer. The transmitted acoustic signal spreads out geometrically from the transducer, and the sound also gets absorbed by the water. These transmission losses are proportional to the square of the range from the system, and the distance at which the reflected signal strength is reduced down to the noise level of the system determines the maximum measurement range.

It is important to note that such Doppler systems do not measure flow (discharge) directly. Flow is a calculated parameter, based on the measured velocity, measured water level and channel area. As the systems are only measuring the velocity in the part of the channel where the acoustic beams are located, a textbook theoretical model or site-specific calibration (index velocity calibration) is used to relate the instrument measured velocity to the mean channel velocity. The mean channel velocity (V) is then multiplied by the channel area (A) to provide discharge (Q=VA), where the channel area is determined by user-provided information on the channel geometry and location of the instrument in the channel, along with the measured water level. Thus, the accuracy of the computed flow is in-part dependent on how much information is available regarding the velocity distribution in the channel at the time the flow is being estimated.

Below are some examples of irregular velocity distribution in straight, well-cleaned concrete-lined canals (typical site photo shown), measured in densely-spaced, discrete single points with the FlowTracker Handheld ADV system undertaken during the development of the SonTek-IQ:




As shown in the examples, the velocity distribution in a channel is typically not uniform, and velocities near a boundary layer, such as the bottom or sides of a channel, usually are significantly lower.

Some important points to take away from this:

- *An instrument's velocity measurement accuracy is important, as any error in the velocity data will result in an error in the calculated discharge.*
- *Errors in the user-supplied channel geometry and instrument placement will result in errors in the calculated discharge.*
- *The method used to relate the instrument-measured velocity to the mean channel velocity will impact the accuracy of the calculated discharge.*

## Principle of Operation

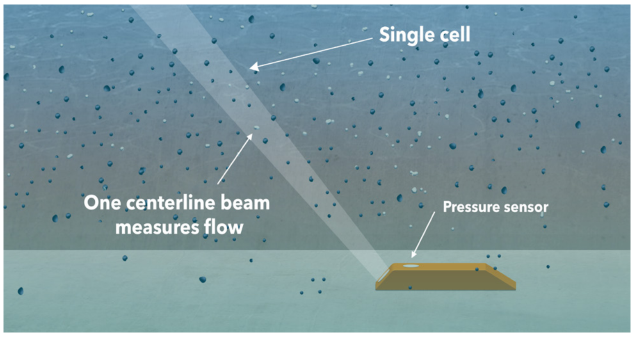
In some comparisons of Dopplers with other methods, the word "Doppler" automatically implies "continuous wave." This error leads to confusion and misrepresentation. Because pulsed Doppler and CW are quite different, it is always important to know which Doppler method is being referenced, as this section will explain.

Continuous wave systems are usually one-beam solutions, meaning one beam is employed to receive the acoustic signal. If the Doppler system is not identified as a "pulsed," "profiling" or "range-gated," instrument, it is usually implied that it is a CW system. CW systems most often utilize a separate transmit and receive transducer, transmitting a long acoustic pulse relative to the water depth. Essentially, they transmit a continuous signal into the water and simultaneously listen for the signal reflections. The received signal is therefore a combination of all reflected signal amplitudes and phases from all of the scattering material along the length of the acoustic beam, and any spatial information is unknown because it is impossible to associate a particular echo with a particular location along the beam.

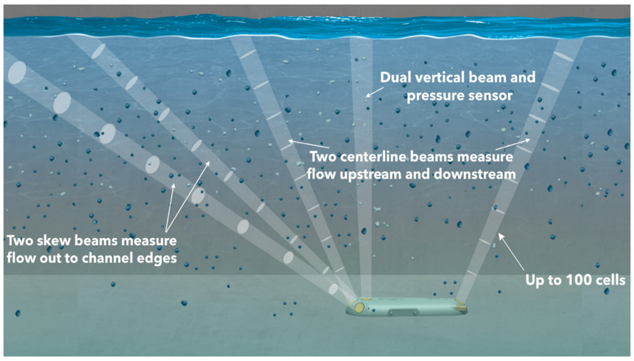
Particularly in shallow water, some CW systems are additionally prone to measuring signals which have reflected off the water surface or channel bed, again because the CW system does not track where in space the reflection came from. These erroneous boundary reflections can further introduce significant noise and bias to the true measurement.

Pulsed Doppler systems such as the SonTek-IQ transmit a short acoustic pulse into the water and then listen for the reflected signal in stages, where the time since the pulse was transmitted determines how far the pulse has propagated through the water and thus the location of the particles that are the source of the signal. By measuring the reflected acoustic signal at specific times following the transmit pulse, the system is able to measure a profile of the water velocity with range from the system, where the water column is divided into depth cells (also referred to as range cells or bins). Within each cell a water velocity is computed from the measured acoustic data. This has the effect of providing many discrete, closely-spaced measurements from the bottom to the water surface. Some pulsed-Doppler systems will report the velocity from a single measurement cell rather than outputting the measured velocity profile. That is, they calculate an averaged velocity after obtaining the velocity profile.

As each pulsed Doppler transducer is both a transmitter and receiver (referred to as "monostatic"), the system has to wait for a short period of time after the emitting the signal to allow time for the




A continuous wave (CW) Doppler system typically uses one acoustic beam to receive signals that have reflected off particles suspended in the water. Usually the system is placed in the middle of the channel, pipe, or stream which means the water velocity being measured is at the center of the channel, in front of the instrument. Some models integrate a pressure sensor for depth measurement.

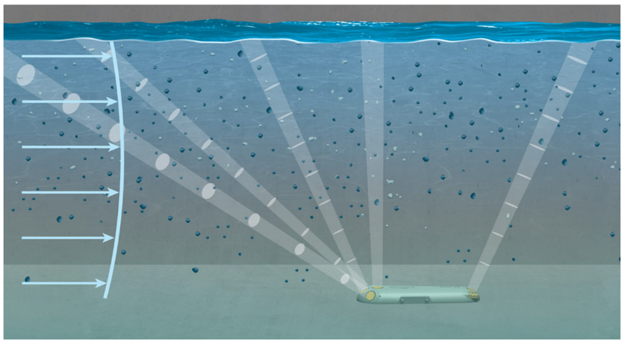



A pulsed Doppler system uses two or more acoustic beams to receive signals that have reflected off particles suspended in the water. The acoustic beam is further "divided" into discrete cells that measure the water velocity in layers throughout the water column. In the case of the SonTek-IQ, there are four acoustic beams--one looking upstream and one looking downstream in the center of the channel, one skew beam looking forward to the right side of the channel, and one skew beam looking forward to the left side of the channel. The SonTek-IQ also has a fifth acoustic beam to measure water depth, as well as a pressure sensor.


The SonTek-IQ Plus version offers a flow monitoring solution for larger canals and natural environments with depths up to 5 m. With the ability to collect velocity profiling data in cells as small as 2 cm across a channel horizontally and vertically.

transmit pulse to clear from the system. This pause creates an area immediately next to the system where it will not be able to collect data which is referred to as the 'blanking distance'.

The SonTek-IQ systems have four transducers for the measurement of water velocity: two aligned with the axis of the system measuring upstream and downstream, and two skew beams that allow the system to measure to the side of the system and therefore allow the SonTek-IQ to account for some of the horizontal velocity variability across the width of a channel. There is also an acoustic beam for accurately measuring water depth, in addition to a pressure sensor.

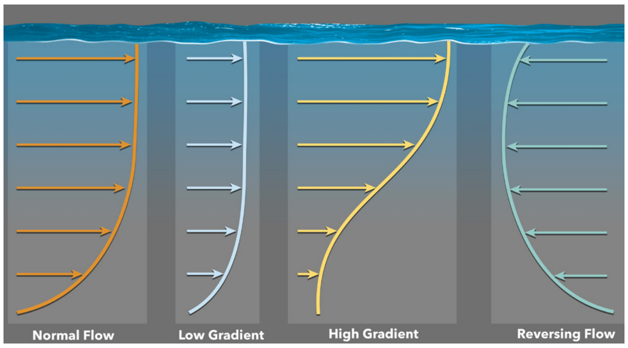


A Doppler flow meter (SonTek-IQ pictured) measures the water velocity from signals reflected off particles in the water. Usually, the water velocity (represented by arrows) changes with depth and distance to a boundary, forming a velocity (flow) profile (represented by the curved line). For a pulsed Doppler system like the SonTek-IQ, the particles' shapes, sizes, and distribution in the water do not bias the velocity measurement because each measurement consists of several measurements are made at multiple, known places in the water column.

## Bias Potential

One effect of a CW system's continuous, simultaneous transmit-receive style of operation is known as range bias. Because the transmitted signal gets weaker with distance from the system, the acoustic reflections from particles closer to the transducer will have a larger influence on the received signal than those farther away. If there were a uniform velocity distribution in the channel, the larger influence from the scattering particles located closer to the transducer would not matter. However, as noted earlier, the velocities in a channel are typically not uniform. The stronger signal contribution from scattering particles located near the transmitter result in a range bias toward acoustic reflections generated closer to the system.

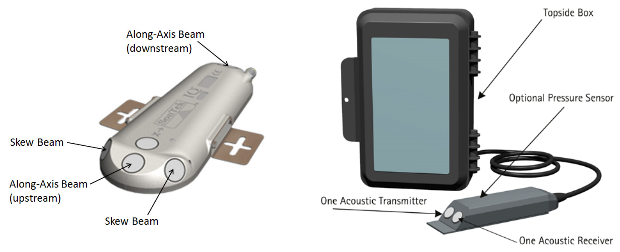
The range bias issue increases as the channel depth increases due to acoustic transmission losses (attenuation, absorption). As a result, there are limitations on the maximum channel depth for continuous wave systems since the maximum velocity typically occurs just below the surface. For example, there may be situations with high velocities near the surface that have a significant contribution toward the actual total flow, but the signal input from those near-surface velocities may be weaker than the input from slower velocities near the bottom. It is often the case that higher sediment concentrations or large particles exist along the bottom that have stronger reflective properties. To further complicate matters, this kind of bias can vary with time and conditions. Scattering particles are typically not uniformly distributed throughout the water column, and particles of different materials will have different reflective properties. For example, mineral sediments will have different scattering and reflective properties than flocculants, and the presence or absence of sediment clouds in the water column combined with their positioning, have the ability to induce biases of constantly changing magnitudes. Even the practice of calibrating CW systems at different flow rates may not be able to account for the myriad variables that may exist if the environment is very dynamic.




The pulsed Doppler system will capture the velocity profile information even as conditions change. This results in a more accurate measurement when flow varies or particulate concentrations vary with daily, seasonal, or operational factors. Lacking the ability to detect a flow profile, continuous wave systems usually rely upon flow calibrations, with each new flow or particulate condition possibly requiring a new calibration.

An example deployment of the SonTek-IQ in Vasca Tavoliere, in the Puglia region of Italy. This custom mounting frame was designed by Consorzio di Bonifica della Capitanata and is intended for safe and efficient instrument maintenance.

Pulsed Doppler systems are not affected by range bias. Because they are designed to measure precisely-timed, spatially-referenced velocity data, pulsed Doppler systems such as the SonTek-IQ will usually offer a higher velocity accuracy, higher maximum velocity, and greater depth range over which accurate discharge (flow) data can be computed. Pulsed Doppler systems therefore are considered more robust under a wider range of conditions, and under changing conditions due to hydraulics, water quality, and particulate size and composition.

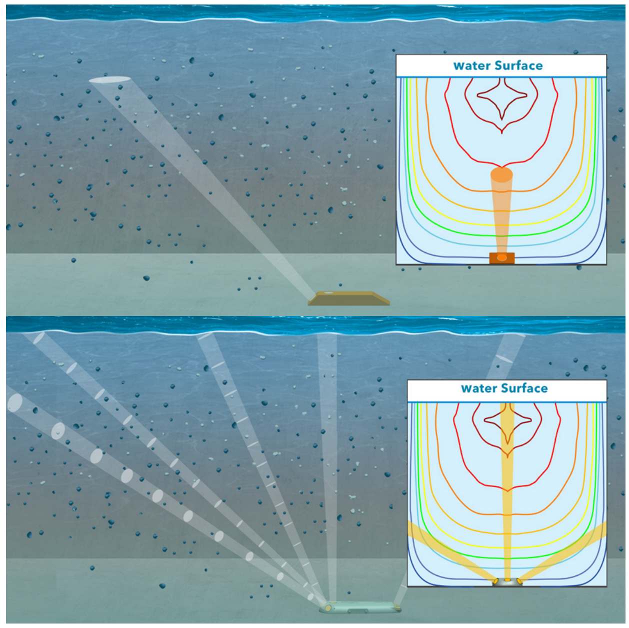



Typical hardware components for acoustic Doppler flow meters. Both continuous wave (CW) and pulsed Doppler systems can be found in one or two-piece configurations. The pulsed Doppler SonTek-IQ (left) consists of a single unit containing the sensors, processing, and communication electronics. Most continuous wave systems consist of two components, the sensor which is cabled to the topside box that houses processing and communication electronics.

## Beam Angle and Effective Range

A Doppler instrument's beam angle—the angle at which the acoustic beam is "looking up" into the water—depends on manufacturer and model. The angle of the beam is important because it can influence the effective measurement range of the instrument. The SonTek-IQ uses a beam angle of 35°off the vertical, which means the beam is more vertically orientated. In contrast, many CW systems use beam angles in a more horizontal orientation, for example, at 20° off the horizontal. An acoustic pulse, when sent at a more horizontal angle has a longer distance to travel before it reaches the water surface. The longer distance to travel makes a CW system's signals more susceptible to attenuation.

At some point, deeper water conditions can result in insufficient signal strength to measure the middle or upper layers of the water column. That some CW models operate at low power settings (producing weaker signals to begin with), further increases the possibility of signal losses at longer distances. Therefore, at higher water levels, a more horizontal beam angle can bias measurements toward water velocities nearer the bed. While again it is common practice to calibrate a CW sensor for such bias or unmeasured area, if the environmental conditions are not sufficiently stable, any changes to the water depth, flow regime or particulate conditions that influence signal attenuation for better or worse, will require a change in calibration in order to maintain data accuracy.

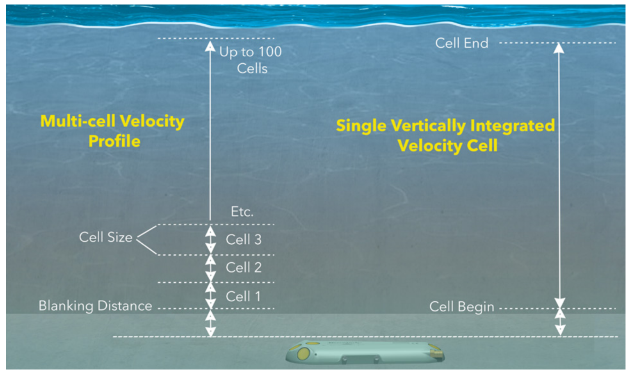



The SonTek-IQ uses a 35° off vertical beam angle, while many continuous-wave systems use more horizontally-oriented beam angles which often are not specified in documentation. Due to beam angle, many CW systems may suffer from greater signal attenuation at higher water levels, resulting in under-sampling of, or entirely unmeasured areas in, the upper layers of the flow field.

## Depth Requirement and Blanking Distance

Due to their continuous transmitting and receiving of the signal, CW systems usually have the benefit of a very small minimum blanking distance requirement. This allows for a continuous wave system to measure in somewhat shallower depths than a pulsed Doppler system, depending on the transducer design and size. Also, continuous wave systems are typically of a two-piece design, with a small underwater sensor cabled to a large box placed somewhere outside of the water. As the processing electronics, recorder, and communication module can be located in the large top-side box, the underwater sensor housing can be made smaller and allow for measurement in shallower depths.

Pulsed Doppler systems can be seen in either one or two-piece designs. The SonTek-IQ is a single unit, needs only to connect to an external power source in order to operate. However, as it includes the processing electronics and internal recorder, and uses more acoustic transducers, it can be larger in size than the small underwater sensor that is possible with most continuous wave designs. Additionally as noted earlier, pulsed Dopplers such as the SonTek-IQ impose a minimum blanking distance in the vicinity of the transducer face. This sometimes results in a greater depth requirement for operation of pulsed Dopplers than for CW Dopplers.

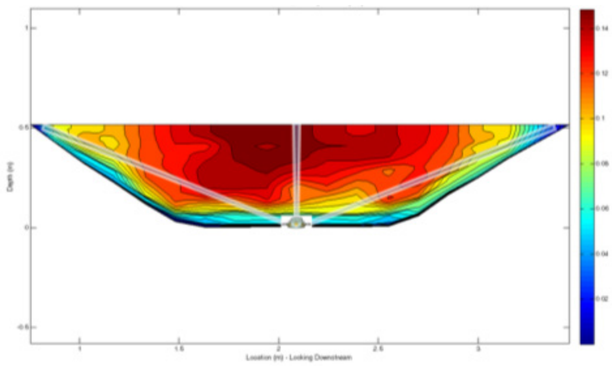



Pulsed Doppler systems are programmed to measure the water column in layers. The pulsed Doppler SonTek-IQ may be configured manually or may use SmartPulseHD--an intelligent, adaptive mode that automatically adjusts and optimizes the acoustic pulsing scheme to changing water depths and conditions. If desired, the user may instead define custom profiling parameters such as blanking distance and cell size. Note that the SonTek-IQ Standard model offers a pulsed solution that has a simplified output consisting only of the integrated measurement.

## Minimum Velocity Requirement

If low flows and low velocities are expected conditions, it is of importance to note that a CW system's operating principle may impose limitations. As continuous wave systems transmit and receive signals simultaneously, the transmit signal interferes with the CW system's ability to detect a zero Doppler shift; therefore zero or low velocities cannot be detected. As a result, continuous wave systems will exhibit a minimum velocity below which reliable operation cannot occur.

There typically is not a minimum velocity specification for a pulsed Doppler system. Because the transmit and receive pulses are timed, the pulsed Doppler electronics are capable of detecting a zero Doppler shift signal that is separate from the transmit signal. The minimum velocity then is essentially the system's velocity resolution. This increases a pulsed Doppler's efficacy in areas with backwater conditions, bi-directional flow, and stratified flow where low and near-zero velocities are more likely.

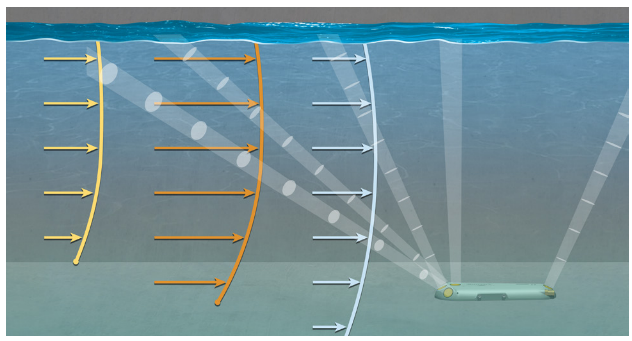


Among Doppler systems, the SonTek-IQ is further distinguished by its use of both centerline beams and skew beams. The skew beams allow velocity measurements to be made toward both sides of the channel.

## Flow Calculation

The raw data gathered from any Doppler instrument is velocity data. Though often overlooked, it is important to note how a Doppler instrument translates the measured velocity to a flow number.

As discussed earlier, a continuous wave system does not provide information about the velocity distribution in the water column. Its single measurement is a combination of all acoustic reflections from whatever is detectable in the beam path. The resultant signal can be affected by both attenuation and variations in sediment concentration in the water column and resultant range bias. Therefore, a continuous wave system usually requires a calibration in order to relate the measured velocity to the actual mean channel velocity with any degree of accuracy. When this calibration is made, it is only reliable for the specific conditions of the calibration. For a site with uniform and unvarying conditions, a continuous wave system is expected to perform similarly to a pulsed Doppler system. However, any change in the flow field conditions will require a new calibration in order for a continuous wave system to provide accurate



This additional information helps develop a more complete understanding of the flow throughout the measurement cross-section. Open channel flow conditions can be particularly difficult to quantify accurately without actual velocity profiles measured at some point, even if only occasionally as a check measurement. Without this additional information, the method used to calculate flow from measured velocity data often necessitates reliance upon assumptions and estimations.

velocity data. Applications where there can be varying conditions due to rainfall, backwater, high sediment loads near the bottom, etc., would require a new calibration to cover each specific situation. It is prudent to consider initial and potentially ongoing calibration costs in equipment, labor, or services if a certain accuracy requirement is needed.

Some continuous wave systems publish a flow accuracy specification, even though flow is a calculated parameter based on environmental factors as mentioned above, and on customer provided details that are not measured directly, such as channel area. These flow accuracy specifications usually rely on the assumption of ideal, simplified, and unchanging conditions, and as such they should be viewed with caution.

The SonTek-IQ Standard model measures the velocity profile and then processes the data to output a single measurement cell, and for the flow calculation it utilizes a theoretical model. The SonTek-IQ Plus and SonTek-IQ Pipe models provide a velocity profile, and for the flow calculation they allow the user to select between using a theoretical model or an index velocity calibration. As with CW systems, a site-specific calibration can more accurately relate the measured velocity to the actual mean channel velocity over a wider range of conditions than can a theoretical model. The SonTek-IQ's use of multiple beams further allows several more choices for finding a beam and region within the flow field that provides the most stable relationship as conditions change. In the case of the SonTek-IQ, flow algorithms were specifically designed for use in small channels, irrigation ditches, culverts, pipes, etc., with unique beam geometry that takes into account horizontal velocity variations across the width of a channel and improved performance for theoretical flow calculations based on detailed studies of velocity conditions in such applications (reference graphs on page 2).

Because of the flow calculation's many variables, which are dependent on the operator and environmental characteristics (channel area measurement, instrument installation and setup, hydraulic characteristics, etc.), SonTek publishes a velocity accuracy but not a flow accuracy specification for the SonTek-IQ systems. It is advised that flow accuracy in the field be estimated and checked regularly using proper field techniques and instrumentation such as portable mechanical current meters, Acoustic Doppler Velocimeters, or Acoustic Doppler Current Profilers, per accepted ISO or other government-prescribed standards. SonTek can provide additional references on these standards and methods upon request.

The SonTek-IQ Pipe is intended as either a bottom or top mounted flow meter that can be used in most industrial or agricultural applications. It can provide accurate flow values in pipes from 0.5m all the way to 5.0m, independent of whether these pipes are full or not.

While Doppler flow meters can be highly accurate, user setup and attention to detail can make the difference between good and bad flow data. Of particular importance is verification of the cross section dimensions at the location where the sensor will be installed.

# Summary table of technical differences between continuous wave (CW) and pulsed Doppler systems

| Consideration | CW Doppler | Pulsed Doppler |
|---|---|---|
| Principle of operation | Transmits and receives signals at the same time; averages data over one measurement region, or "cell" | Transmits and receives signals in discrete pulses; averages data in several discrete layers, or "cells" to form a velocity profile. |
| Number of beams | Relies on one beam for Doppler calculations. | Uses multiple beams for Doppler calculations. |
| Bias potential | Range bias may exist and affect flow measurements if flow and particulate conditions are variable. Surface and bed reflections may bias data. | Range bias potential is negligible. Flow and particulate variability is accounted for in spatially-referenced profile data. Pulses are timed to avoid surface and bed reflections. |
| Depth requirement (shallow) | Can operate in shallower depths than pulsed Dopplers (5 cm or less); can operate in smaller pipes. | Requires slightly deeper depths of operation (8 cm, 3"). |
| Depth requirement (deep) | May have difficulty at higher water levels or if water levels are variable, due to signal losses from beam angle and insufficient power. | Less likely to have difficulty at higher water levels, helped by beam angles oriented more vertically. |
| Minimum velocity requirement | May not measure very low flows. Reaches a point where zero or small Doppler shifts (low flow) cannot be measured. | Does not have limit on detectable Doppler shift. Better suited for low flows. |
| Flow calculation | Operates best in stable, uniform flow conditions; usually requires a flow calibration; measures along one axis (usually in the center of the channel) | May operate with or without a flow calibration; the SonTek-IQ measures along 4 axes; vertical and horizontal spatial distribution of flow is measured. |
| Accuracy need | May be adequate if variables in the flow calculation are constant and well-controlled; hydraulic conditions normal | May be needed if conditions are variable, and hydraulics are non-ideal or abnormal (backwater, gates, pumps, large reversing flow etc.) |

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