



FlowTracker Used in Palenque Hydro-Archaeology Project

Contributed by: Pennsylvania State University professor Dr. Christopher Duffy and PhD Candidate, Kirk French.

Synopsis: Ancient ruins serve as the backdrop for this study on how a “modern” Mayan culture may have altered the regions natural water cycle.

Set in the foothills of the Tumbalá mountains of Chiapas Mexico, the ancient Maya site of Palenque is situated on a ledge overlooking the swampy plains that stretches northward all the way to the Gulf coast.

The Palenque Hydro-Archaeology Project (PHAP) is moving forward in its search for a better understanding of the site’s hydrology. PhD Candidate, Kirk French, and his professor from Pennsylvania State University, Dr. Christopher Duffy, arrived at Palenque in early May, with goals to explore Palenque’s watershed and scout locations for the installation of more stream sensors. Additionally, the team wished to test the viability of using SonTek/YSI FlowTracker Handheld ADV on Palenque’s many waterways.

As a hydrologist in the Civil Engineering Department at Penn State, Duffy has ongoing projects in the southwestern U.S. and on the Susquehanna River in Pennsylvania. He is interested in testing his model for human impacts on hydrological processes at Palenque and believes the Maya of Palenque modified their landscape to such a degree that it possibly altered the areas hydrological cycle.

Although the site of Palenque originated at about 100 BC, it did not become a major population with importance in the Maya culture until 600 AD. Rulers during this period lead the construction of what is considered by historians the first sophisticated urban-water delivery system. Underneath the palace and through a long, corbel-vaulted tunnel, a stream ran through carrying a constant supply of running water. Flowing water through a monumental structure like that has been deemed a feat of engineering genius.



French and Duffy accomplished their goals and have since returned to Pennsylvania where they have analyzed the data gathered from the streams and weather station.



According to Duffy, the FlowTracker proved to be ideal for this study due to its portability, accuracy and efficiency in taking many measurements along stream profiles for assessing losing and gaining channel reaches.

He says with this information the team is now able to construct a water and energy budget for the site and a weather station has been installed and now they are able to locate the stream gauge.

For more information on this application note, or the FlowTracker, email SonTek® at inquiry@sontek.com.

WWW.SONTEK.COM

Discharge Uncertainty Calculations Using a SonTek FlowTracker

Craig Huhta, Senior R&D Engineer
John Sloat, Principal Hydrologist
SonTek/YSI Inc.
6837 Nancy Ridge Drive, Suite A,
San Diego, CA 92121 USA

Abstract- The SonTek® FlowTracker is an acoustic Doppler velocimeter (ADV) designed for wading discharge measurements using established methodology (ISO, U.S. Geological Survey, and others). There is increasing interest and emphasis on the uncertainty of hydrographic measurements, including wading discharge measurements. Several sources (including ISO standards) have developed algorithms for calculating this uncertainty. To date, these procedures have been used primarily as research and post-processing tools, and have had limited direct impact on field measurement techniques. Two different uncertainty calculations have recently been implemented in the FlowTracker: the ISO calculation and one developed by researchers at the U.S. Geological Survey. The algorithms calculate the overall uncertainty of the discharge measurement and the contribution of different factors (depth, velocity, etc.). The calculations are performed in real time, providing the operator with immediate feedback on measurement uncertainty and the components that contribute to the uncertainty. The details of both uncertainty calculations are described, and results of each calculation are compared for a number of field measurements.

I. BACKGROUND

The SonTek® FlowTracker is acoustic Doppler velocimeter (ADV)^[1] designed for wading discharge measurements^{[2][3][4]}. It includes algorithms for the measurement and calculation of discharge following established methodology (including ISO and U.S. Geological Survey standards). The FlowTracker was introduced in 2001 and has been adopted for use world wide (over 1000 systems sold to date). A common FlowTracker mounting, showing the probe and handheld controller on a top setting wading rod, is shown in Figure 1.



Figure 1 – SonTek FlowTracker on Top Setting Wading Rod

II. OVERVIEW

Beginning with firmware version 3.0 and software version 2.00, the FlowTracker estimates the uncertainty of every discharge measurement. This calculation is done

two different ways: the ISO calculation and a method referred to as the Statistical calculation.

The ISO uncertainty calculation is based upon the international standard and provides users with the results of a published, accepted technique. However, in some cases this calculation does not provide a reliable indicator of data quality.

The Statistical uncertainty calculation uses a method developed by researchers at the U.S. Geological Survey. This is the default calculation used by the FlowTracker as it appears to provide a more reliable indicator of measurement quality.

In the FlowTracker real time display, the user can select which discharge uncertainty calculation to display. The FlowTracker software displays the results of both uncertainty calculations.

III. ISO CALCULATION

The FlowTracker implementation of the ISO uncertainty calculation is based upon a working version of ISO standard number 748^[5] from 2003. While it is normally not appropriate to use a working version, an exception was made since the working version provides a more thorough calculation than the released ISO standard (dated 1997).

Equation 1 shows the ISO method to calculate uncertainty applied to a FlowTracker discharge measurement. All values are given as relative (percentage) uncertainty.

Equation 1 – ISO Uncertainty Calculation

$$u_Q^2 = u_m^2 + u_s^2 + \frac{\sum_{i=1}^m \left((b_i d_i v_i)^2 \left(u_{b_i}^2 + u_{d_i}^2 + u_{p_i}^2 + \left(\frac{u_{c_i}^2 + u_{e_i}^2}{n_i} \right) \right) \right)}{\left(\sum_{i=1}^m (b_i d_i v_i) \right)^2}$$

- u_Q = uncertainty in discharge
- u_m = uncertainty due to number of verticals (see below)
- u_s = uncertainty due to calibration errors in measurements of width, depth and velocity. This is assumed to be dominated by accuracy of the FlowTracker calibration (1%).
- m = number of verticals across the width of the stream
- b_i = width at vertical i
- d_i = depth at vertical i

- v_i = mean velocity at vertical i
- u_{bi} = uncertainty in the width measurement at vertical i . This is assumed to be 0.5%.
- u_{di} = uncertainty in the depth measurement at vertical i . This is assumed to be 0.5% for depth > 0.30 m (1 ft), and 1.5% for depth < 0.30 m (1 ft).
- u_{pi} = uncertainty due to the limited number of velocity measurements at vertical i (see below)
- $u_{ci} + u_{ei}$ = uncertainty in velocity measurements at vertical i , with contributions from instrument uncertainty (u_{ci}) and real fluctuations in the river velocity (u_{ei}). The combination of these two terms is directly measured by the FlowTracker as the standard error of velocity (v_{Lerr}), and is calculated as $(u_{ci}^2 + u_{ei}^2 = (v_{Lerr} / v_i)^2)$
- n_i = the number of velocity measurements at vertical i

Velocity and depth are measured at a limited number of verticals across the stream, and are assumed to vary linearly between them. To estimate the uncertainty of this assumption, the ISO provides a guideline based upon the number of verticals shown in Table 1.

Table 1 – ISO Uncertainty for Number of Verticals

Number of Verticals	Uncertainty % (u_m)
5	7.5
10	4.5
15	3.0
20	2.5
25	2.0
30	1.5
35	1.0
40	1.0
45	1.0

Sauer and Meyer^[6] provide essentially the same data, and convert this to Equation 2 to calculate this uncertainty for any number of verticals (u_m is in percent; m is the number of verticals). This is the equation used by the FlowTracker when calculating the ISO uncertainty estimate.

Equation 2 – ISO Uncertainty for Number of Verticals

$$u_m = 32 * m^{-0.88}$$

This estimate is based on a statistical analysis of many rivers. It does not take into account the data available at an individual site which could strongly influence the overall uncertainty. For example, it might be possible with 5 verticals to accurately measure the flow in a broad concrete channel of constant depth, as the velocity distribution will likely be very consistent. In comparison, a natural stream can show large velocity and depth changes and the accuracy of a discharge measurement with 5 verticals would be much lower. The ISO calculation does not account for this difference. This is perhaps the most significant shortcoming of the ISO calculation.

A limited number of velocity measurements are made at each vertical; the mean velocity is calculated using as-

sumptions about the velocity distribution. The ISO standard provides the data in Table 2 to estimate the uncertainty associated with these assumptions.

Table 2 – ISO Uncertainty for Number of Velocity Measurements

Measurement Method	Uncertainty (u_{pi})
1 point (0.6 * depth)	7.5%
2 points (0.2 and 0.8 * depth)	3.5%
5 points (surface, 0.2 / 0.6 / 0.8 * depth, bottom)	2.5%
Distribution method (change between points < 20%)	0.5%

For the FlowTracker, we have simplified Table 2 to estimate the uncertainty based only on the number of measurements in the vertical as shown in Table 3.

Table 3 – SonTek Formulation of ISO Uncertainty For Number of Velocity Measurements

Number of Measurements	Uncertainty (u_{pi})
1	7.5%
2	3.5%
3	3.0%
4	2.7%
5 or more	2.5%

In Equation 1, the ISO calculation breaks the sources of uncertainty into two groups. The first group are uncertainty sources that are applied for each vertical: width (u_{wi}), depth (u_{di}), method (u_{pi} , for the number of velocity measurements at each vertical), and velocity ($u_{ci} + u_{ei}$). These uncertainty sources are weighted based on the discharge of each vertical. The second group contains values applied to the measurement as a whole: the accuracy of instrument calibration (u_j), and the number of verticals (u_m). All uncertainty sources are assumed to be independent.

Although Equation 1 appears complicated at first glance, it is straight forward to implement in the FlowTracker. Each term is either measured directly by the FlowTracker or can be determined from the ISO standard. The summation to determine uncertainty is done by the FlowTracker at the same time as the discharge calculation (which uses a similar summation).

In addition to overall uncertainty, the FlowTracker looks at the contribution of each parameter. To calculate the contribution of each parameter, the calculation is repeated while setting all other parameters to zero. At the end of each discharge measurement, the FlowTracker real time display shows the overall uncertainty and the largest individual source of uncertainty. The FlowTracker software shows the contribution of each parameter.

- Accuracy (u_j): uncertainty due to the accuracy of the FlowTracker calibration
- Depth (u_{di}): uncertainty due to depth measurements

- Method (u_{pl}): uncertainty due to the number and location of velocity measurements at each vertical
- Number of verticals (u_m): uncertainty due to a limited number of verticals
- Velocity ($u_{ci} + u_{ei}$): uncertainty due to velocity measurements (instrument uncertainty and real fluctuations in the flow)
- Width (u_w): uncertainty due to width measurements

IV. STATISTICAL CALCULATION

The method we refer to as the Statistical calculation was developed by researchers at the U.S. Geological Survey (USGS): Tim Cohn, Julie Kiang, and Robert Mason^[7]. It has also been called the interpolated difference technique, although a final name has not been selected. As of August 2006, they have not published this technique but have plans to do so in the future. The calculation described here should be considered preliminary, and may be subject to change.

The Statistical technique takes a very different approach from the ISO method. The ISO looks at the physical characteristics of the measurement and discharge calculation to estimate uncertainty. The Statistical technique is a strictly statistical approach, using adjacent values of each measured variable to estimate the uncertainty in these measurements. This paper presents only an overview of this technique, deferring a full description to future publications of Cohn, Kiang and Mason.

The basic form of the Statistical calculation (Equation 3) is similar to the ISO calculation. As with the ISO calculation, all values in Equation 3 are given as relative (percentage) uncertainty.

Equation 3 – Statistical Uncertainty Calculation

$$u_Q^2 = u_s^2 + \frac{\sum_{i=1}^m \left((b_i d_i v_i)^2 (u_{bi}^2 + u_{di}^2 + u_{vi}^2) \right)}{\left(\sum_{i=1}^m (b_i d_i v_i) \right)^2}$$

- u_Q = uncertainty in discharge
- u_s = uncertainty due to calibration errors in measurements of width, depth and velocity. This is assumed to be dominated by accuracy of the FlowTracker calibration (1%).
- m = number of verticals across the width of the stream
- b_i = width at vertical i
- d_i = depth at vertical i
- v_i = mean velocity at vertical i
- u_{bi} = uncertainty in width at vertical i . The Statistical technique does not include a method for calculating this value, so we use the ISO value of 0.5%.
- u_{di} = uncertainty in depth at vertical i (see below).
- u_{vi} = uncertainty in velocity at vertical i (see below).

To estimate the uncertainty in depth and velocity, the Statistical technique uses adjacent measurements. The

calculation is the same for depth or velocity (the depth calculation is shown here).

A basic assumption of a discharge measurement is that velocity and depth change linearly between verticals. Following this assumption, we can estimate the depth at vertical i (d_i) by using depth values from the adjacent verticals (d_{i-1} and d_{i+1}). For simplicity the calculation below assumes equal spacing of verticals; the FlowTracker uses a linear interpolation based on the location of each vertical for the estimated value.

$$d_{i_est} = (d_{i-1} + d_{i+1}) / 2$$

An estimate of the uncertainty in depth for vertical i can be calculated as the difference between the estimated and measured depth.

$$\Delta_i = d_{i_est} - d_i$$

Individual uncertainty estimates (Δ_i) are subject to considerable variability; combining all estimates from a given measurement gives a better overall estimate of uncertainty. Equation 4 calculates an overall estimated of the uncertainty in depth measurements (σ_d), a statistical average of the individual uncertainty estimates (Δ_i). This value (σ_d) is in depth units (m or ft). (The derivation of Equation 4 is deferred to future publications of Cohn, Kiang and Mason.)

Equation 4 – Statistical Depth Uncertainty (Depth Units)

$$\sigma_d^2 = \left(\frac{2}{3} \right) \left(\frac{1}{(m-2)} \right) \sum_2^{m-1} (\Delta_i^2)$$

The relative uncertainty is then calculated in Equation 5. This relative depth uncertainty (u_{di}) is used directly in Equation 3. A similar term is calculated for velocity (u_{vi}).

Equation 5 – Statistical Depth Uncertainty (Relative)

$$u_{di} = \left(\frac{\sigma_d}{d_i} \right)$$

Perhaps the biggest advantage of the Statistical technique is that the estimated uncertainty takes into account variability in depth and velocity across the stream, and hence includes measurement uncertainty, stream conditions (i.e. different bottom types), and the assumption that depth and velocity change linearly between stations.

As with the ISO calculation, Equation 3 breaks the sources of uncertainty into two groups. The first are uncertainty sources that are applied for each vertical: width (u_{wi}), depth (u_{di}), and velocity (u_{vi}). These uncertainty sources are weighted based on the discharge of each vertical. The other uncertainty source is applied to the measurement as a whole: the accuracy of instrument calibration (u_s). All uncertainty sources are assumed to be independent.

In addition to overall uncertainty, the FlowTracker looks at the contribution of each parameter. To calculate the contribution of each parameter, the calculation is

repeated while setting all other parameters to 0. At the end of each discharge measurement, the FlowTracker real time display shows overall uncertainty and the largest individual source of uncertainty. The FlowTracker software shows the contribution of each parameter.

- Accuracy (u_a): uncertainty due to the accuracy of FlowTracker calibration.
- Depth (u_d): this term includes both uncertainty in the depth measurement and the effect of changes in depth between verticals.
- Velocity (u_v): this term includes instrument uncertainty, real variations in velocity (turbulence), and the effect of changes in velocity between verticals.
- Width (u_w): uncertainty due to width measurements

V. COMPARISON

Why offer two different uncertainty calculations - shouldn't one be sufficient? To answer this, we look at the results of each method.

The ISO calculation seems a natural choice: it is well documented and from an internationally recognized agency. However, analysis shows the ISO does not always provide a meaningful indication of the measurement quality. In contrast, the Statistical technique appears to provide a good indicator of measurement quality, particularly at sites with variable flow conditions. However, it is currently an unpublished technique and may be subject to change in the future. Since there are drawbacks to each technique, we decided to present results from both calculations.

To compare the two uncertainty calculations, we used a set of 24 FlowTracker discharge measurements. These represent a range of conditions: discharge values from 0.004 to 8.6 m³/s (0.13 to 300 ft³/s) and mean velocity from 0.01 to 0.50 m/s (0.03 to 1.6 ft/s). The measurements were all made in natural streams at a variety of locations in North America. Figure 2 compares the Statistical and ISO calculations from all 24 files.

- The Statistical calculation shows uncertainty values from 2.1 to 19%; the ISO calculation shows values from 2.4 to 8.4%.
- If you remove one outlier (a file with very low velocity), the Statistical calculation varies from 2.1 to 15.1% while the ISO varies only from 2.4 to 4.3%.
- Uncertainty under 5% is considered a "Good" measurement by many agencies; hence the ISO equation would rate all but one of these measurements as "Good". This is clearly not the case upon closer analysis of some files.

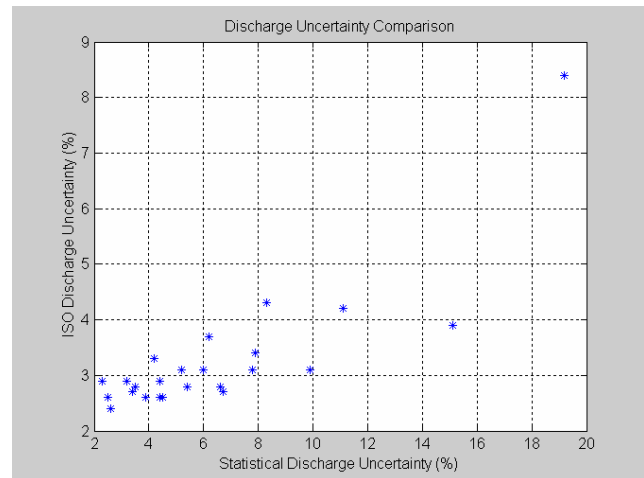


Figure 2 – Uncertainty Calculation Comparison

To understand the differences, we look at some individual files. Figure 3 shows depth and velocity profiles from a site where Statistical uncertainty is 2.5% while ISO uncertainty is 2.6%. As both calculations indicate, this is a good measurement with smooth, linear variations in depth and velocity with few large inconsistencies. Both calculations correctly represent this.

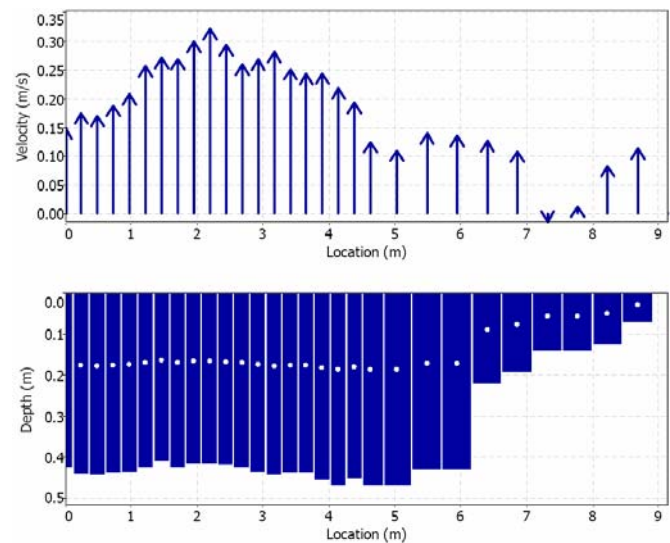


Figure 3 – Uncertainty Comparison, "Good" File

Figure 4 shows depth and velocity profiles from a file where the Statistical uncertainty is 15.1% while the ISO uncertainty is 3.9%. Looking closely at the measurement, there are a number of large and dramatic changes in both depth and velocity (particularly velocity, for example measurements at locations 5.5 and 8.1 m). This indicates either unusual flow conditions (which would require more verticals to resolve) or measurement problems. The ISO calculation still reports an uncertainty (3.9%) that would be considered good by most users. The Statistical calculation reports a much higher uncertainty (15.2%), correctly indicating that there are areas for concern in the measurement quality.

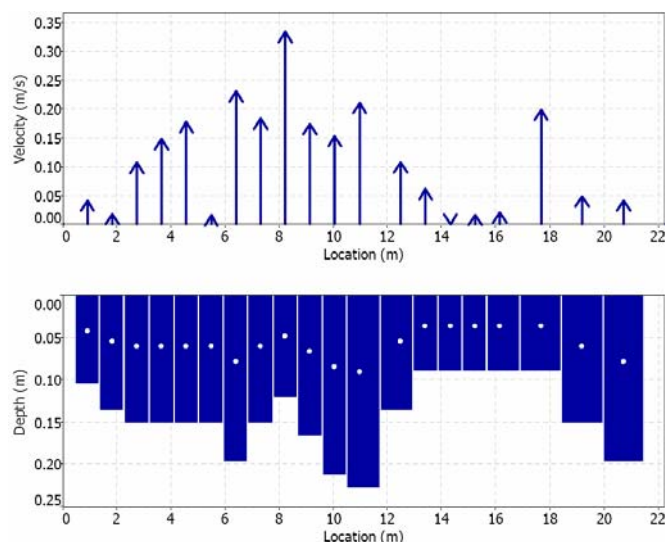


Figure 4 – Uncertainty Comparison, “Bad” File

It is also interesting to look at the contribution of each parameter to the estimated uncertainty. For the ISO calculation, 6 different parameters contribute to the overall uncertainty: width, depth, velocity, method, number of stations, and accuracy (FlowTracker calibration). For the Statistical calculation, there are 4 parameters: width, depth, velocity and accuracy (FlowTracker calibration again).

For the ISO calculation, the number of stations is the largest single component of uncertainty for 22 out of 24 files; method and velocity are each the largest source in one file. Since the number of stations parameter is essentially based on a statistical analysis of many rivers, rather than data from the specific measurement site, this raises significant concerns if it is the largest source of uncertainty. The contribution of velocity is generally small, except in cases where the mean velocity is very low (velocity is the largest component of uncertainty in a file where the mean velocity is 0.01 m/s (0.04 ft/s)). The measurement method is generally a modest contributor to overall uncertainty, but can be significant in files with low overall uncertainty (<3%). The contribution of width, depth and accuracy to the overall ISO uncertainty is small to negligible.

For the Statistical calculation, the velocity term is the largest individual source of uncertainty in all 24 files. Keep in mind that this term includes not only uncertainty in the velocity measurement, but also variation in velocity between stations (which is typically the dominating factor). Depth adds a small but notable amount to the Statistical uncertainty calculation; again, this is dominated by the variation in depth between stations. The contributions of width and accuracy are small to negligible. Analysis of this data tends to indicate that variation between stations, both of depth and velocity, are the most important factor in overall measurement uncertainty.

VI. CONCLUSIONS

The ISO and Statistical calculations provide practical methods to estimate discharge uncertainty, and have been implemented for automatic analysis in the FlowTracker. Shortcomings in the ISO calculation reduce its ability to reflect the quality of a discharge measurement; however we felt that it was still necessary to show the results of this method since it is a standard technique. Because of the ability of the Statistical calculation to better distinguish data quality, we recommend using this calculation.

With the automatic calculation of discharge uncertainty, we hope to accomplish two things: to provide operators with feedback that improves the quality of their measurements, and to contribute to data analysis that improves uncertainty calculations in the future.

Regardless of the instrument used, the quality of any field measurement relies heavily on the technique employed by the operator. One of the best ways to improve measurement quality is to provide information and feedback that helps the operator improve their technique. The FlowTracker uncertainty calculation is one part of SonTek/YSI's efforts to provide this feedback.

VII. ACKNOWLEDGMENTS

The authors would like to thank Julie Kiang, Tim Cohn, and Mike Rehmel of the U.S. Geological Survey for their help explaining and describing the Statistical technique, and their willingness to share their work.

VIII. REFERENCES

- [1] SonTek and ADV are registered trademarks of SonTek/YSI, Inc., San Diego, CA, USA.
- [2] Craig Huhta, *Handheld acoustic Doppler velocimeter (ADV) for water velocity surveys*. Hydraulic Measurements and Experimental Methods, EWRI and IAHR, 2002.
- [3] Scott Morlock and Gary Fisher, *Hydroacoustic current meters for the measurements of discharge in shallow rivers and streams*. Hydraulic Measurements and Experimental Methods, EWRI and IAHR, 2002.
- [4] Gary Fisher and Scott Morlock, *Discharge measurements in shallow urban streams using a hydroacoustic current meter*. Hydraulic Measurements and Experimental Methods, EWRI and IAHR, 2002.
- [5] ISO 748, *Hydrometry - Measurement of liquid flow in open channels using current meters or floats*. Working version 2003.
- [6] V.B. Sauer, and R.W. Meyer, *Determination of Error in Individual Discharge Measurements*. U.S. Geological Survey, Open File Report 92-144. 1992.
- [7] Tim Cohn, Julie Kiang, and Robert Mason, U.S. Geological Survey. Personal communication, June-August 2006.

SonTek/YSI, founded in 1992 and advancing environmental science in over 100 countries, manufactures affordable, reliable acoustic Doppler instruments for water velocity measurement in oceans, rivers, lakes, harbors, estuaries, and laboratories. Headquarters are located in San Diego, California. Additional information can be found at www.sontek.com

TODAY, TOMORROW AND TWO GENERATIONS AHEAD

Lower Colorado River Authority data delivers on-the-spot forecasts and 80-year projections

Keith Ging, senior hydrologist in the Hydromet Operations group of the Lower Colorado River Authority (LCRA), has a Texas-sized challenge. "Our main purpose is to determine how much water is flowing into streams and canals, how much water is flowing into our lakes and out of our lakes, and to make sure that data gets to the people who can use it in their decision-making," says Ging in LCRA's headquarters in Austin, Tex.

The stakes are high. When thunderclouds build over the state's central Hill Country, discharge data from his team's 60 stream gauges forms a key line of defense in the fight to keep residents of more than 30 counties safe from flash floods, which can swell a 60 cfs stream to 300,000 cfs in a matter of hours. On a day-to-day basis, it's a vital tool for optimizing lake levels and ensuring proper water delivery to the organization's three irrigation systems. And it's part of LCRA's crystal ball as the organization considers whether it can modify its storage and conveyance systems to link with the city of San Antonio while still meeting the needs of its own growing population, its farmers, and the Matagorda Bay ecosystem fed by the lower Colorado.

Capturing the data is no small task. LCRA's 60 stream gauges and eight SonTek/YSI Argonaut®-SL canal-monitoring gauges are the backbone of the organization's 237-station hydrological/meteorological data acquisition

network. Called the Hydromet for short, the network is scattered across LCRA's territory of 600 river miles, 18,000 square miles of drainage area, 1,100 miles of canals, and six impoundments called the

Highland Lakes. Stage and flow through streams and canals, water levels at LCRA's six dams, and weather data feed into LCRA's headquarters via its own 900 MHz radio system.

The system is slated for expansion – LCRA is expanding to 270 Hydromet stations over the next two years to improve river and lake forecasting models.

Counting Every Drop

Hard data and solid models are increasingly important to LCRA. "We're trying to count every drop now, more so than we ever have in the past," says Ging. Situated between a \$115-million-per-year recreation industry on the lakes, a \$234-million annual rice crop and a

\$63-million-per-year commercial fishing industry on Matagorda Bay, LCRA's water touches a lot of lives and a sizable chunk of the regional economy.

In November 2005, Ging's team conducted a study of groundwater inflows into the LCRA system, part of a feasibility study exploring a proposed connection between LCRA and the city of San Antonio. For fast, accurate flow data at various points along the river channel, the hydrologists used FlowTracker® acoustic Doppler



David Murdoch of the Lower Colorado River Authority deploys a trimaran-mounted RiverSurveyor to measure flow throughout the vertical water column. In obstructed reaches, the instrument's stationary software delivers excellent data to a simple, intuitive interface, says Murdoch's colleague, Keith Ging.

SonTek/YSI, 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.

velocimeters mounted on wading rods. Quantifying the water that flows into the river from underground is helping LCRA's Operations team fine-tune its releases to most efficiently maintain in-stream flow requirements and send enough fresh water into Matagorda Bay. Fine-tuning releases for irrigation is also a big improvement. Ging's team used acoustic Doppler flow meters (which measure both water velocity and stage) to make index velocity ratings to ascertain how much water is really



John Roberts of the Lower Colorado River Authority's Hydromet Operations Group used FlowTracker acoustic Doppler velocimeters to conduct a study of water discharged from one of its dams, checking hydroturbine ratings. The group also used the FlowTrackers to study fresh water inflows from groundwater – vital information for exploring a proposed interbasin water sharing plan, and for managing the LCRA's extensive system.

flowing through the system. “By measuring both level and velocity, then indexing that velocity to the mean channel velocity, our discharge data improved dramatically,” Ging says. “We are in a variable backwater environment. Flow from pump ratings is just a snapshot in time, but conditions are constantly changing, which requires more advanced technology, measuring velocity directly.

An accurate tab on water in the canals is vital to meet state reporting requirements on diversions. Knowing the difference between the run of the river and stored water also helps LCRA bill appropriately for the water – each is billed at a different rate. Water diversion data can also be linked with weather data to help determine just how much water to send on its three-to-five-day journey from the lakes to the irrigation systems. Send-

ing a full allocation down the river – then encountering rain events – means the volume of the lake releases is lost, flowing to the bay instead of feeding municipal and industrial demands along the river.

Life or Death

Counting every drop takes on special urgency when flash floods blast through LCRA's area.

When clouds gather in the hills, LCRA's staff meteorologist and hydrologists begin assessing weather data, including feeds from the Hydromet system. LCRA models predict lake levels and downstream flows, which guide decisions on emergency releases from the lakes.

Getting that data isn't easy. Measuring flow during floods is dangerous work, and traditional methods



David Murdoch of the Lower Colorado River Authority deploys a trimaran-mounted RiverSurveyor to measure flow throughout the vertical water column. In obstructed reaches, the instrument's stationary software delivers excellent data to a simple, intuitive interface, says Murdoch's colleague, Keith Ging.

are often inaccurate. Ging describes flow meters with 100-pound weights being pulled nearly horizontal by rushing currents. And when depth can change by four to eight feet per hour, sampling protocols that take an hour or more can yield vastly different readings between start and finish.

LCRA has added three SonTek/YSI RiverSurveyors®, trimaran-mounted, 3-D river discharge systems that use Doppler sonar to take quick, accurate discharge readings as the units transect the channel. “We're able to take measurements in conditions that we really couldn't

get into with mechanical flow meters,” Ging says. “The RiverSurveyor has allowed us to get some measurements we couldn’t have taken in the past because of safety concerns, and others because submerged debris would have interfered with mechanical flow meters. We’re looking at the whole vertical column, not just surface velocity. And we can get our measurements in 20 or 30 minutes

system can raise DO by 2 mg/L, significantly improving water quality downstream, notes Wedig. He points out that operating the aeration system reduces the efficiency of the hydropower generators by about 10 percent, so knowing when the aeration is really needed can make a difference on the bottom line.

The Environmental team’s data also looks into the future. When Wedig picked up signals indicating nutrient enrichment in the Highland Lakes, LCRA began developing a water quality model. “It’s the first modeling effort we’ve ever done for water quality,” he says. “We’ve completed the second year of data collection, and we’ve collected some highly relevant stormwater runoff data.”

Big Study, Big Plans

LCRA’s most ambitious studies to date will be key to deciding whether to proceed with an ambitious interbasin water sharing plan that would help meet future water needs in the lower Colorado basin and the San Antonio area. The plan was developed during a regional water planning process that occurs statewide in Texas every five years. Regional planning groups for the lower Colorado River basin and the city of San Antonio – now the seventh-largest city in the U.S. – both identified future water needs in their regions.

The project would capture and store excess and unused river flows in one to three new holding basins near the Gulf Coast. Intake structures would transport water from the river to the basins. A 160-mile-long water line would deliver the water to San Antonio Water System (SAWS), the city’s water utility.

LCRA would deliver up to 150,000 acre-feet of water annually to SAWS for up to 70 years. The amount of water sent to SAWS gradually would decline during the last 10 years of the agreement, after which water supplies would stay in the lower Colorado basin to meet future water needs.

The project, called the LCRA-SAWS Water Project, is under tremendous scrutiny during the six-year study period. Consultants, scientists and technical experts are studying the project’s environmental, engineering, conservation, groundwater and socioeconomic impacts. LCRA and SAWS have agreed the project won’t proceed if the six-year study period shows that costs are too high, not enough water is available, or the project doesn’t meet



Lower Colorado River Authority senior hydrologist Keith Ging uses a FlowTracker acoustic Doppler velocimeter to gather fast, accurate data for flow studies.

and we’re done. Safety-wise, that’s a huge improvement.”

Environmental Watch

The flow data collected by Ging and his team of 16 complements the work of LCRA’s Environmental team, headed by senior aquatic scientist John Wedig. With four YSI 600XLM sondes and grab sample kits, the team gathers 30 to 32 pieces of information at each of more than 70 sampling sites around the lower Colorado system. Data is available to the public online at <http://waterquality.lcra.org>, and drives operational decisions at headquarters and the Hydro Operations Control Center at Buchanan Dam.

Close tracking of temperature and dissolved oxygen (DO) levels deep in the lake behind Mansfield Dam track the thermocline and signal potential problems with hypoxia. If DO falls below safe levels, Wedig can alert Operations, which can engage an aeration system on one of their hydropower turbines. The aeration

specific legislative requirements.

San Antonio, which anticipates a 40-percent shortfall in drinking water by the time its population doubles in 2050, wants the water. Farmers in LCRA's service area want a reliable source of water to help even out weather-related swings in irrigation availability, but they'll have to fine-tune farming tactics and irrigation systems to conserve 118,000 acre feet per year to make the deal work. And environmental groups and fishermen are worried about making sure enough fresh water makes it downstream to Matagorda Bay.

LCRA is halfway through the six-year study period, and early feedback from scientists and regulators indicates that the organization is proceeding with due care and attention to detail.

"What's nice to see is that they've been very proactive on two fronts," says Barney Austin, Director of the Surface Waters Resources Division of the Texas Water Development Board. "One, involving stakeholders – anyone with an interest in the river and bay ecosystems has been invited to participate throughout the process. There are different kinds of stakeholders out there, from the non-technical to the extremely technical, and each one brings something to the table. LCRA has done a great job of keeping all those stakeholders involved while collecting data in a scientifically rigorous manner. Second, they are also being extremely vigilant in bringing in the scientific peer review process, and on a step-by-step basis ensuring the science is properly vetted."

Years of data have been augmented by laser-sharp focus on key elements of the system. For instance, in an intensive 72-hour component of the study, Wedig's team took salinity, temperature, DO and pH readings at eight sites in a 350-square-mile area of Matagorda Bay. Meanwhile, Ging's team was aboard boats in the river, measuring discharge into its delta, running among six

locations to keep the data flowing.

Together, the teams built a comprehensive view of flow in and out of the bay – from both the river and the Gulf of Mexico – and building a knowledge base on the effect of those flows on salinity and other quality parameters. LCRA's Matt Ables even animated the data

using a Flash-driven program, bringing the numbers to life for stakeholders.

Vital Information

LCRA's comprehensive studies of the LCRA-SAWS project won't be completed until 2010 at the earliest. Before then, the lower Colorado and its Highland Lakes will surely face floods and drought. Water skiers will play on the lakes, oystermen will ply

the bay, and farmers will flood their rice fields – and all will benefit from the behind-the-scenes work of Ging, Wedig and their teams at LCRA. So will their children and grandchildren.

"The need to understand and quantify the amount of water we have available – and to understand the environmental impacts of using the water – is particularly important, and will become even more so in the future," says Austin. "It's very important to get as much data as we can on our water resources."

For additional information on the Lower Colorado River Authority, visit www.lcra.org.



A Lower Colorado River Authority hydrologist remotely directs a catamaran mounted RiverSurveyor along a transect across a canal. Along a transect or using stationary software, the RiverSurveyor uses Doppler sonar to quickly, accurately measure flow in the vertical water column.

*SonTek/YSI
9940 Summers Ridge Road
San Diego, CA 92121
Tel: +1 858 546 8327
Fax: +1 858 546 8150
Email: inquiry@sontek.com
Web: www.ysi.com*



Streamflow Measurements with FlowTracker Handheld ADV on a Wading Rod

January, 2001 - SonTek's FlowTracker Handheld ADV (Acoustic Doppler Velocimeter) was used by the U.S. Geological Survey (USGS) Indiana District personnel to measure discharge in eight local streams. Tag lines were set up, and the FlowTracker was mounted on a top-setting wading rod (Figure 1). The FlowTracker's hand-held keypad/LCD display was mounted on a bracket near the top of the wading rod (Figure 2). The FlowTracker's ADV probe was mounted to the wading rod using the probe's built-in attachment (Figure 3).

Eight discharge measurements were made in different streams with stream flows ranging from 1.3 cfs to 400 cfs, and velocities from less than 0.1 ft/s to nearly 3 ft/s. Measurements were compared to conventional AA and Pygmy-style instruments with good overall agreement.

Figure 1. FlowTracker mounted on a top-setting wading rod.

Figure 2. The probe is shown mounted to the wading rod. The unique 2D/3D design allows for 2D velocity measurements in water as shallow as one inch, or 3D measurements in deeper water.

Figure 3. The integrated display and processor lets you easily compute streamflow on the fly.

Note: Use of this instrument by USGS personnel does not imply endorsement by the USGS.

The following link is to a Technical Memorandum issued by the U.S. Geological Survey's Office of Surface Water. This memorandum describes the USGS policy on the use of the FlowTracker for discharge measurements. The information presented in this memorandum is a courtesy from the USGS, and should not be construed as an endorsement. Additionally, this memorandum is provided "as-is"; that is, the USGS does not provide support for this memorandum outside its own agency.
<http://hydroacoustics.usgs.gov/memos/OSW2004-04.pdf>



SonTek/YSI
9940 Summers Ridge Road
San Diego, CA 92121
Tel: +1 858 546 8327
Fax: +1 858 546 8150
Email: inquiry@sontek.com
Web: www.ysi.com

Tow Tank Testing with FlowTracker Handheld ADV

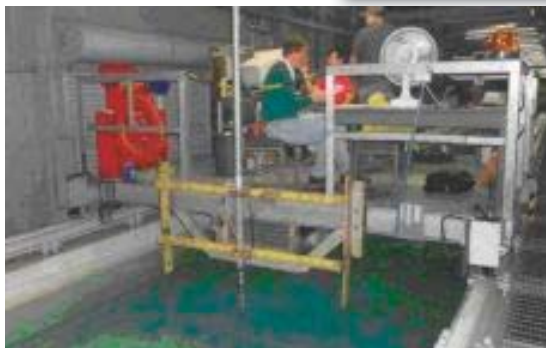
Mississippi, USA

January, 2001 - SonTek's FlowTracker Handheld ADV (Acoustic Doppler Velocimeter) was tested at the U.S. Geological Survey (USGS) tow tank at Stennis Space Center, Mississippi. SonTek ADVs have been well established for many years as the preferred sensor for high-resolution 3D velocity measurements. The FlowTracker (Figure 1) provides ADV performance from a simple keypad/LCD interface that allows rapid data collection in any environment (no PC required). The purpose of these tests was to evaluate the accuracy of velocity measured by the FlowTracker ADV against the speed of the tow cart.



Figure 1. FlowTracker

Figure 2. USGS Tow Tank



The USGS tow tank (Figure 2) is 450 feet long, 12 feet wide, and 12 feet deep. For this test, cart speeds from 0.1 to 5.0 ft/s were used. The FlowTracker ADV was mounted from a pole in the center of the cart at a depth of 12 inches, and data were collected with the probe rotated at several different angles (to $\pm 40^\circ$) into and away from the flow.

Figure 3 shows FlowTracker ADV current speed vs. cart speed for runs perpendicular and 10° off perpendicular to the flow. A regression of all runs in Figure 3 gives a slope of 0.99 and an offset of 0.009 ft/s. This is well within the accuracy speci-

fications of the ADV ($<1\%$) as well as expected uncertainties due to residual currents in the tank (± 0.01 ft/s).

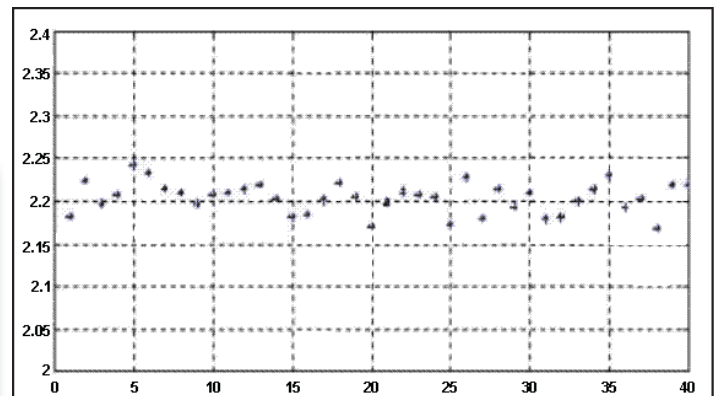


Figure 3. ADV Measured Velocity vs. Cart Speed

The FlowTracker ADV's time response was also tested. Since the ADV records velocity data once per second (and each 1-second sample is completely independent), it is interesting to look at this data to determine the time required for the ADV to make an accurate measurement of velocity. Figure 4 shows the ADV velocity data for one run, with results typical for data at all cart speeds. In this run, the ADV mean velocity was 2.203 ft/s (difference of 0.7% from cart speed); the standard deviation of 1-second velocity data was 0.018 ft/s (0.8% of cart speed).

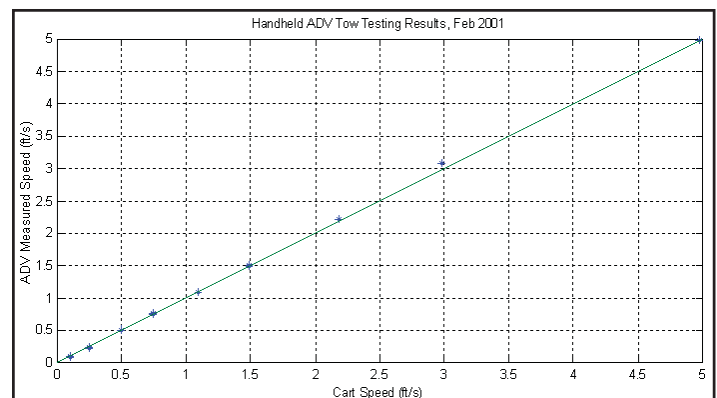


Figure 4. ADV 1-s Velocity Data at 2.2 ft/s

SonTek/YSI, 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.

This demonstrates that the FlowTracker ADV can offer excellent performance for observing real variations in water flow on a 1-second time scale (accuracy is 1% of measured velocity for each 1-second sample). For the mean water velocity at a given location, the averaging time required will be strictly a function of the real variations in the flow. Uncertainty in the ADV velocity will have no significant impact.

The results of this test show that the FlowTracker ADV can offer excellent performance in measuring water velocity at various speeds and also on small time scales. For a full copy of the report, please contact SonTek.

Note: The results shown here, while made using USGS facilities and with support from the USGS, are presented by SonTek and do not imply any endorsement of this product by the USGS.

The following link is to a Technical Memorandum issued by the U.S. Geological Survey's Office of Surface Water. This memorandum describes the USGS policy on the use of the FlowTracker for discharge measurements. The information presented in this memorandum is a courtesy from the USGS, and should not be construed as an endorsement. Additionally, this memorandum is provided "as-is"; that is, the USGS does not provide support for this memorandum outside its own agency.

<http://hydroacoustics.usgs.gov/memos/OSW2004-04.pdf>

SonTek/YSI
9940 Summers Ridge Road
San Diego, CA 92121
Tel: +1 858 546 8327
Fax: +1 858 546 8150
Email: inquiry@sontek.com
Web: www.ysi.com



Model Verification with FlowTracker Handheld ADV

Fort Collins, Colorado, USA

The Hydraulics Laboratory at Colorado State University, in Fort Collins, Colorado, includes extensive facilities capable of operating numerous physical models. The laboratory undertakes modeling projects looking at issues including erosion, sediment transport, and structure design.

In a recent project, a physical model was constructed to study a portion of the South Platte River in Denver, Colorado. The goal of the study is to examine the feasibility of a diversion structure that would minimize the upstream floodplain boundary while maintaining the required amount of diversion flow. Of importance in determining these objectives is the hydraulics of the flow upstream and through the diversion structure. To obtain the hydraulics, a variety of equipment was used including a SonTek FlowTracker Handheld Acoustic Doppler Velocimeter. The FlowTracker (below) was used to collect two-dimensional flow velocities within the areas of interest.



SonTek/YSI
9940 Summers Ridge Road
San Diego, CA 92121
Tel: +1 858 546 8327
Fax: +1 858 546 8150
Email: inquiry@sontek.com
Web: www.ysi.com

Arkansas Stream Gauging Program using SonTek FlowTracker

Arkansas, USA

June, 2005 - The diverse range of environments found in Arkansas -- from mountainous streams (Figure 1) to delta rivers and both flood and drought conditions -- provides significant measurement and procedural challenges for field hydrologists. In an effort to improve their level of service to the public, the U.S. Geological Survey's (USGS) Arkansas Water Science Center began using the SonTek FlowTracker as part of their stream-gauging program in 2001. The Science Center has nine Hydrographers who routinely make field trips as part of the data collection operation.



Figure 1. Common stream-gauging conditions in Arkansas.

In the past, all measurements had been made using mechanical propeller meters, such as the Price AA and Pygmy meters. By 2005, all mechanical meters were replaced with SonTek FlowTrackers. All the Hydrographers now use the FlowTracker exclusively for measuring discharge in wadeable streams (Figure 2). Use of the FlowTracker has not only increased the operational efficiency of the Water Science Center, it has also enhanced their ability to make measurements in environments previously thought immeasurable.

The key reasons behind the switch to the FlowTracker were:

- **Improved operational efficiency** - Due to the elimination of note-taking, calibration, and manual calculations, field personnel can now make more stream measurements in the same amount of time.
- **Elimination of maintenance** - As the FlowTracker has no moving parts, there is no need for any ongoing maintenance by the user.
- **Reduce training times** - New field personnel can be trained in how to use the FlowTracker in less than half the time it used to take for mechanical equipment.
- **Higher measurement accuracy** - The high precision of the FlowTracker results in better rating definition.
- **Increased range of measurement conditions (extreme events)** - The FlowTracker is able to accurately measure stream flows in the shallow and slow-moving drought environment.



Figure 2. The integrated display and processor lets you easily compute streamflow on the fly.

Note: Use of this instrument by USGS personnel does not imply endorsement by the USGS.

SonTek/YSI
9940 Summers Ridge Road
San Diego, CA 92121
Tel: +1 858 546 8327
Fax: +1 858 546 8150
Email: inquiry@sontek.com
Web: www.ysi.com

Shallow-water flow measurements around hot springs in Yellowstone National Park with FlowTracker

August, 2001 - Within Yellowstone National Park, there are several hot springs and small streams where water depths are on the order of a couple of inches or less. Traditional methods of measuring water velocity are neither practical nor effective under these conditions. With this in mind, the Yellowstone Center for Natural Resources (YCNR) required a current measurement instrument that is portable enough to fit in a backpack (many of the sites are only accessible by foot), readable in bright daylight, has sufficient internal recording capability, and is able to withstand the high water temperatures sometimes present in the hot springs.

In August, 2001, a demonstration of the SonTek FlowTracker was set up to evaluate the feasibility of the Handheld-ADV for this application. Observing the demonstration were representatives from the U.S. Geological Survey, the University of Montana, and the National Park Service. SonTek's Chris Ward made the trip to Yellowstone for the field demonstration.



Figure 1. FlowTracker being used in hot spring.

One of the sites chosen for the evaluation was Beryl Spring, which is 15 miles south of Mammoth Hot Springs in Yellowstone. Normally accessible by the public, Beryl Springs was off-limits because park officials considered it to be an explosion hazard. As such, personnel from the YCNR make frequent observations of environmental parameters around the hot spring to better understand this phenomena. One of the important parameters is discharge from the hot spring itself.



A wading rod was not necessary to make the measurements because the water is so shallow. Great care had to be taken in where one stood and where the ADV probe was placed so that hot steam from the ground did not burn the observers' skin (Figure 1).

The ADV probe was positioned in several different sections. Usually, only one velocity measurement was possible in a cross-section as the water was so shallow. The observers were intrigued by the FlowTracker's ability to output two-dimensional velocity, water temperature, and reflected echo intensity to the LCD screen (Figure 2).

By all accounts, the demonstration was a success, and the YCNR was satisfied with the FlowTracker performance. An order was soon placed by the YCNR.

Figure 2. The integrated display and processor lets you easily compute streamflow on the fly.

SonTek/YSI
9940 Summers Ridge Road
San Diego, CA 92121
Tel: +1 858 546 8327
Fax: +1 858 546 8150
Email: inquiry@sontek.com
Web: www.ysi.com

Automated Quality Control in the SonTek® FlowTracker®

Abstract- The SonTek® FlowTracker® was introduced in 2001 with the intention of providing laboratory quality ADV® (acoustic Doppler velocimeter) velocity measurements in a format suitable for wading discharge measurements. Since that time, the FlowTracker has gained widespread support both in the U.S. and overseas as a modern alternative to conventional mechanical current meters. The original firmware algorithms inside the FlowTracker mimicked conventional practices and offered limited QA/QC criteria back to the user. In order to extend full advantage of the ADV technology and the FlowTracker's micro processing capabilities, extended features were added to the device in the form of a firmware and software release in the fall of 2006. These new features focus on automated quality assurance and quality control and take advantage of the extensive set of parameters available with FlowTracker data collection. An Automatic QC Test is conducted at the start of each measurement to verify all aspects of instrument operation; results are analyzed in real time and stored with each data file. User supplied data (measurement location, water depth) are monitored to look for possible data entry errors. Quality control parameters (including signal to noise ratio, standard error of velocity, flow angle, and section discharge) are analyzed with each velocity measurement. These parameters are compared to adaptive criteria that adjust with changing stream conditions; the operator is notified immediately of any suspect measurements. At the end of each measurement, the overall measurement uncertainty is calculated along with the contribution of different parameters (this indicates the primary sources of uncertainty). We will discuss the approach we have taken to implementing these features, how they should be interpreted by the user, and how it can result in a more robust and reliable discharge measurement.

I. BACKGROUND

The SonTek FlowTracker is an acoustic Doppler velocimeter (ADV)^[1] designed for wading discharge measurements^[2] ^{[3][4]} following established methodology (including ISO^[5] and U.S. Geological Survey standards). Since its 2001 introduction the FlowTracker has been adopted by a large number of agencies in the U.S. and abroad. A typical FlowTracker mounting, showing the probe and handheld controller on a top setting wading rod, is illustrated in Figure 1.

As with any instrument, using the proper technique is critical for data quality. If the FlowTracker can offer feedback to the user and detect potential problems before or as they occur, this can only improve the overall measurement process

and resulting data quality. Potential problems may be related to measurement procedures, or to the velocity or discharge data collected with the FlowTracker. QA/QC procedures can be used to establish a long term basis to monitor data quality from site to site.

In addition to velocity the FlowTracker generates a number of other parameters that can be used to ensure the validity of the velocity measurement. These parameters reflect on the operation of the instrument and the measurement technique being used. The intelligent review and reporting of these QA/QC parameters has been named Smart QC. These new features should significantly improve the quality and reliability of data collected with the FlowTracker.

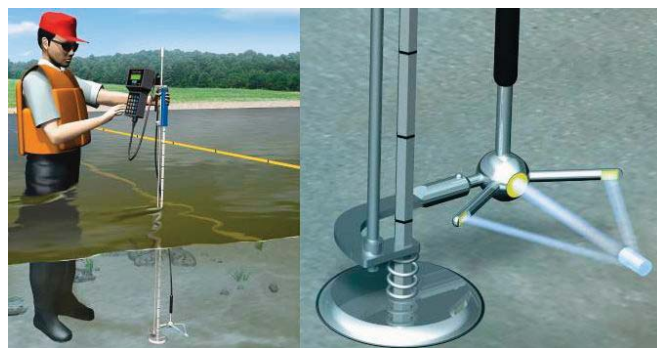


Figure 1 – SonTek FlowTracker on Top Setting Wading Rod

II. OVERVIEW

In a wading discharge measurement, velocity and depth measurements are made at a number of locations across the width of a river or other open channel. Following established methodology, these measurements are combined to compute the total discharge in the river. The Smart QC algorithms in the FlowTracker are designed specifically to work with discharge measurement procedures, although the routines are also applied to general purpose (non-discharge) velocity measurements as well.

The goal of Smart QC is to provide is the best overall discharge measurement possible, in the least amount of time. To do this the FlowTracker evaluates all data used to calculate discharge, verifying the integrity of each part as the measurement is made. These tests can be divided into the following areas.

SonTek/YSI, 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.

- Verify the FlowTracker is working properly
- Check for errors in user supplied data
- Review QA/QC data for each velocity measurement
- Warn user of any suspect data, repeat or add measurements as appropriate
- Calculate overall discharge uncertainty

Some SmartQC features operate as data is being collected, others are performed after several data points, and some are done when a discharge measurement is completed.

III. VERIFYING INSTRUMENT OPERATION

To make a valid measurement, naturally the FlowTracker must be working properly. To check basic system operation at each measurement site, we have implemented the Auto QC Test. This is an automated version of the PC software BeamCheck (also called ADVCheck), which should be run once per week in the office as part of regular system testing.

The user is prompted to run the Auto QC Test at the start of each discharge measurement. The test is run directly from the FlowTracker handheld controller (without being connected to a PC). When prompted, the user places the FlowTracker probe in open, moving water (well away from any underwater obstacles), and presses a key to start the test. The system collects ~30 seconds of data and analyzes that data to verify all major aspects of system operation.

Data collected with the Auto QC Test is identical to data collected with the BeamCheck software; the test results are recorded in the FlowTracker data file and displayed by the PC software. A sample output of the Auto QC Test is shown in Figure 2 (as it appears in the PC software output).

As with the BeamCheck software, the Auto QC Test

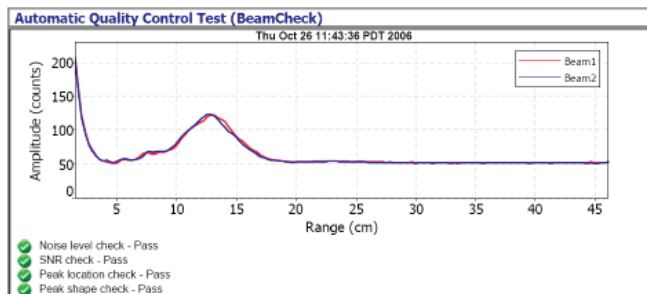


Figure 2 – Sample Auto QC Test Results

shows a plot of signal strength from all beams versus time (distance) from the transducers. The Auto QC Test results are analyzed for four separate features, the same four items rec-

ommended for primary BeamCheck analysis (and described in detail in the FlowTracker manual).

Noise level

- Is the system noise level within expected bounds?

SNR (signal to noise ratio)

- Is SNR sufficient for reliable operation?
- Are all beams seeing the same SNR?

Peak location

- Is the sampling volume peak in the expected location?
- Do all beams see the peak in the same location?

Peak shape

- Does the sampling volume peak show the expected smooth, bell shaped curve?

A warning is given if any test results fail the expected criteria. If this occurs, reposition the probe (in case there was interference from an underwater obstacle) and repeat the test. If the warning persists, connect the FlowTracker to a PC and run the BeamCheck software for more detailed analysis; if necessary contact SonTek/YSI for more guidance on evaluating system operation.

IV. USER SUPPLIED DATA

During a discharge measurement, the operator inputs location and water depth for each station across the river. Location and depth are used to calculate area for each station; area is multiplied by velocity to give discharge. A typical discharge measurement might have 25 stations, so the operator enters many data points. Naturally errors in data entry occur, and if not detected they can significantly affect the final discharge calculation and the amount of time for the entire measurement process (if a measurement must be repeated).

Measurement stations are typically spaced evenly across the width of the river. During operation, the FlowTracker predicts the next station location based upon previous location values (assuming equal station spacing); if station spacing changes, the operator has to manually modify the predicted station location. The FlowTracker reviews input location data based upon the following criteria.

Station spacing

- Has the station spacing changed significantly?
- If so, this may indicate a data entry error.

Station order

- Is the new location out of order – such as between two existing stations or prior to the starting edge?
- Out of order stations are allowed (they will be sorted into the correct position for discharge calculations), but they must be confirmed by the operator.

In general, water depth should not change drastically between adjacent stations (a large change in depth might indicate that another station should be added between the two locations). To check for data entry errors, the FlowTracker compares all water depth values to water depth for adjacent station(s). The user is instantly warned of any large change in depth and prompted to verify the depth data.

The percentage of total discharge covered by any one station is also important. Most agencies have a policy that no individual station should include more than a certain percentage of the total discharge (this value varies from agency to agency, but 10% is typical). If a single station exceeds this value, an additional station should be added.

- If the user has provided a rated discharge value for the river, the percent of rated discharge is reviewed at the completion of each station.
- At the end of each measurement, all stations are reviewed to see if any station exceeds a certain percentage of the total measured discharge.
- When this occurs, the user is prompted to add additional stations to reduce the percentage of discharge.

V. MEASUREMENT QA/QC DATA

With each velocity measurement, the FlowTracker provides a variety of data in addition to mean velocity (which is used for the discharge calculation). These values can be used to verify the integrity of the velocity data and include the following.

- SNR (signal to noise ratio)
- Standard error of velocity (displayed as V)
- Number of spikes
- Flow angle
- Boundary QC

Each of these values, and the associated QA/QC criteria, is described in detail below. Including these automated tests with every data file ensures that FlowTracker data are archived with a strong indication that the instrument was functioning properly at the time of measurement, and that the environment is well suited for a FlowTracker measurement.

SNR

SNR is the single most important QA/QC value reported by the FlowTracker. The FlowTracker measures velocity by looking at the reflections of a pulse of sound from particles in the water; SNR is a measure of the strength of this reflection and the ability of the FlowTracker to distinguish the reflection

from ambient electronic noise.

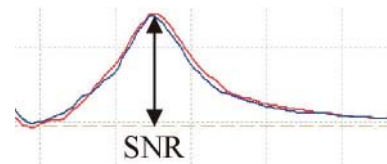


Figure 3 – SNR Peak on Auto QC Test Plot

When looking at Auto QC Test results (or a BeamCheck plot), SNR is the height of the bell curve that represents the sampling volume (Figure 3). SNR data for each FlowTracker velocity measurement is reviewed against a number of criteria to ensure reliable operation.

Minimum SNR

- Is SNR for all beams greater than 4 dB? This is the minimum level required for accurate velocity data.

Compare beam SNR

- Do all beams see that same SNR values?
- A large change between beams may indicate interference from an underwater obstacle or a problem with the FlowTracker probe.

SNR variation during the measurement

- SNR values are recorded once per second for each beam during the velocity measurement.
- Large variations in SNR during the measurement may indicate highly aerated water or interference from an underwater obstacle. Either of these can affect the reliability of velocity data.

Compare SNR from adjacent stations

- Is SNR at this station similar other stations in this file?
- Large changes in SNR between stations may indicate interference from an underwater obstacle.
- Changes in SNR may also be caused by local variations in the river and may not affect measurement quality.

Standard error of velocity

Standard error of velocity is a measure of the variation of velocity over the course of each measurement. Raw velocity data is recorded once per second; standard error is the standard deviation of the one second velocity data divided by the square root of the number of samples. By itself it estimates the uncertainty of an individual velocity measurement.

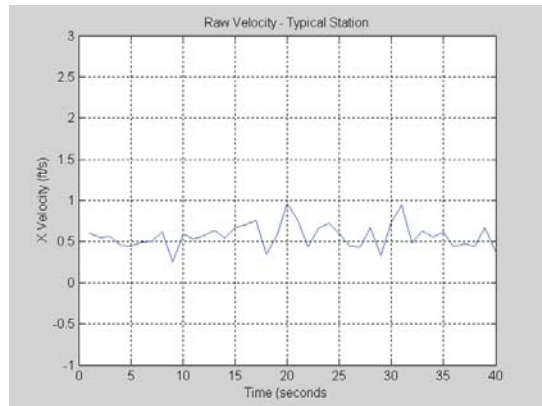


Figure 4 – Typical One Second FlowTracker Velocity Data

Standard error includes both instrument noise and turbulence in the measurement environment; turbulence is normally the largest component. A typical plot of raw velocity data is shown in Figure 4. In this example, the mean velocity is roughly (0.55 ft/s / 0.17 m/s) with modest variations around this mean. In highly aerated flow or if there is acoustic interference from an underwater obstacle, the variation of raw velocity data can increase dramatically. In this case, the standard error of velocity will also increase.

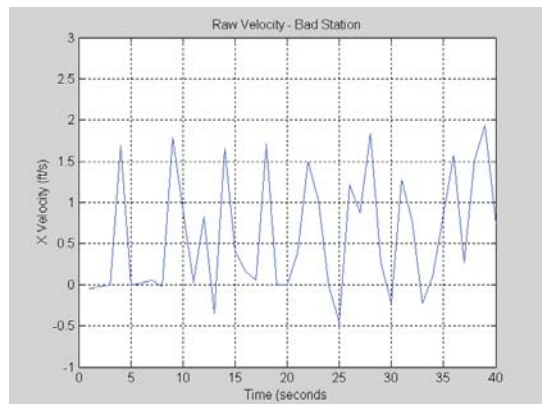


Figure 5 – One Second Velocity Data from Bad Station

Figure 5 shows raw FlowTracker velocity data from a station with interference from an underwater obstacle. While the mean velocity is (0.7 ft/s / 0.2 m/s), the one second velocity data varies from (0 – 1.5 ft/s / 0 – 0.5 m/s) with almost every sample. This results in a very high standard error of velocity that would trigger a warning to the operator.

The expected standard error of velocity will vary with the environment. A number of factors are taken into account when setting the standard error of velocity threshold value.

General minimum standard error

- Standard error values in good conditions are typically below (0.03 ft/s / 0.01 m/s).

High velocity

- Standard error of velocity will increase with velocity in the stream, so a minimum threshold of 5% of the

stream velocity is used.

High turbulence

- Some streams are more turbulent than others and will therefore show higher standard error values.
- An adaptive threshold is used taking into account standard error values seen from all previous measurements in a given file.

Spikes

All acoustic systems see occasional spikes in velocity data; it is a normal part of operation and does not necessarily indicate a problem with the measurement. A FlowTracker might normally see one or two spikes over the course of a typical averaging time (although many measurements will not see any spikes).

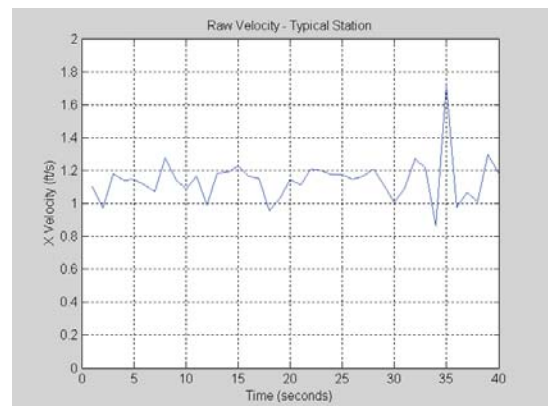


Figure 6 – Typical Raw Velocity Data with One Spike

Figure 6 shows the one second velocity data from a typical FlowTracker measurement. A single spike in velocity is seen at sample number 35. This spike is automatically filtered out of the mean velocity calculation, giving the true mean velocity (in this case about 1.1 ft/s / 0.35 m/s).

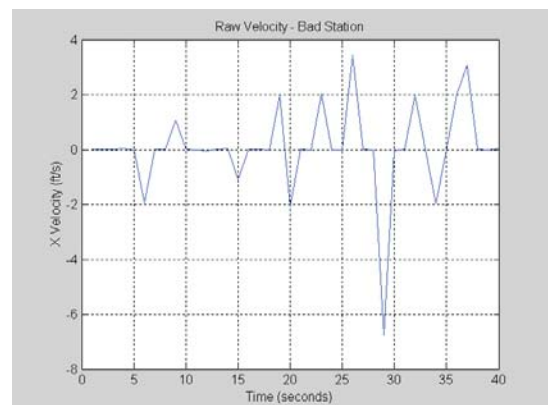


Figure 7 – Raw Velocity Data with Many Spikes

Figure 7 shows raw velocity data from a site with interference from an underwater obstacle; at this site the mean velocity is near 0 but there are a large number (8-10) of spikes over the course of the velocity measurement. This

high number of spikes indicates a problem with the measurement; most likely the probe needs to be re-positioned and the measurement can be repeated. Any time the number of spikes is greater than 10% of the total number of samples, this very likely indicates a problem with the velocity measurement. In this case the probe position and environment should be evaluated carefully and the measurement should be repeated.

Flow Angle

The FlowTracker measures the true two or three dimensional velocity of the water. For discharge measurements, the X axis of the probe is kept perpendicular to the tag line used for probe position. By using only the X velocity for discharge, the FlowTracker correctly accounts for any variation in flow direction when making the discharge calculation. Using the two dimensional velocity data, the FlowTracker also calculates the true flow direction and reports this value as part of the QA/QC information.

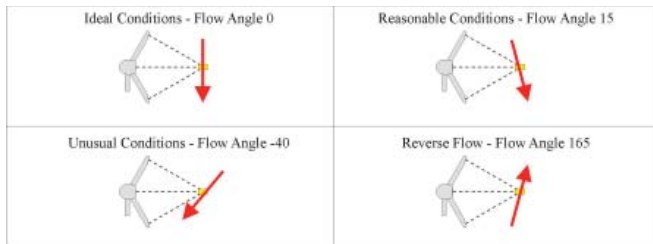


Figure 8 – FlowTracker Measured Flow Angle

At a good measurement site, the flow should be nearly perpendicular to the tag line at all stations, resulting in small measured flow angles from the FlowTracker (Figure 8). A large flow angle (typically considered greater than 20°) should be carefully reviewed. At some measurement sites, large flow angles are unavoidable and do not indicate a problem. In other cases, a large flow angle indicates either a problem with the measurement location or some type of interference with FlowTracker operation. If a large flow angle is reported but does not appear realistic, carefully evaluate the measurement location and repeat the measurement.

Boundary QC

The final QA/QC value used by the FlowTracker is also one of the most difficult to explain: the Boundary QC value. This is used to indicate possible acoustic interference from underwater obstacles. To understand this requires a brief explanation of pulse coherent processing, the technique the FlowTracker uses to measure the Doppler shift^[2].

- For each velocity measurement, the FlowTracker sends two short pulses of sound.
- Comparing the phase of the return signal from the two pulses, and knowing the time between the pulses, we mea-

sure the Doppler shift (which represents the movement of particles in the sampling volume) very precisely.

- The maximum velocity that can be measured is a function of the time between the two pulses, called the pulse lag.
- The FlowTracker sends pulse pairs with a number of different lags for each measurement; this is done for the most accurate data possible over a wide range of velocities.

The FlowTracker measures velocity at a point nominally (10 cm / 4 in) from the tip of the probe; this location is called the sampling volume. If an underwater object is in this sampling volume, naturally it will cause interference with the measurement. With pulse coherent processing there is more than one acoustic pulse in the water at the same time; there is also potential from interference from the other acoustic pulse (i.e. reflections from the first pulse may be arriving when we are trying to measure the second pulse).

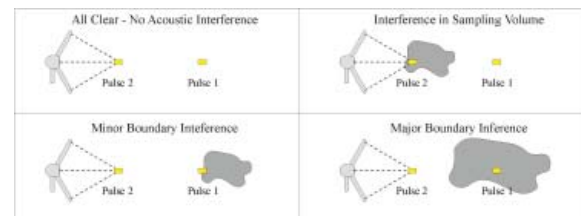


Figure 9 – Possible Boundary Interference Situations

Figure 9 illustrates a number of possible boundary interference scenarios. The relative locations of the two acoustic pulses in this figure are for illustration only; in real operation, a range of pulse spacing is used.

- Ideally, the sampling volume is free of any underwater obstacles and the first pulse is not hitting any obstacles when the second pulse is in the sampling volume case. In this situation, the FlowTracker can make velocity measurements without any adjustment (top left illustration in Figure 9).
- If an underwater obstacle is present in the sampling volume, the FlowTracker will always see interference and is unable to make accurate velocity measurements (top right illustration in Figure 9).
- If the first pulse is hitting an underwater obstacle at the same time the second pulse is in the sampling volume, then FlowTracker may see acoustic interference (bottom two illustrations in Figure 9).
 - It attempts to adapt its operation (by changing the distance between pulses) to avoid this interference.
 - If only minor adjustments are needed, the system can still collect high quality velocity data.
 - If major adjustments are needed, this may impact the ability to make a reliable velocity measurement (in particular to measure higher velocities). Ideally the probe should be re-positioned prior to the velocity measurement.

- It is still possible to make accurate measurements even when a boundary QC warning has been issued (i.e. if the probe cannot be re-positioned or if the warning persists), but data should be reviewed carefully.

VI. REVIEWING QA/QC DATA

The FlowTracker QA/QC procedures occur automatically over the course of the measurement. The exact timing of the test depends on the values being reviewed.

Data entry

- Location and depth data are reviewed when entered, and at the completion of the discharge measurement.

Boundary QC

- Boundary conditions are checked at the start of each velocity measurement; the user is warned of questionable conditions prior to making the measurement.

Measurement QA/QC values (SNR, standard error of velocity, number of spikes, and flow angle)

- These values are reviewed at the completion of each velocity measurement.
- All values are reviewed again at the end of the discharge measurement.

Station discharge

- If a rated discharge value has been input, station discharge is reviewed at the completion of each station (in comparison to the rated discharge value).
- In all cases, station discharge values are reviewed at the completion of the discharge measurement (in comparison to the measured total discharge value).

Whenever the operator sees a warning, the first step is to review the warning to see if it may reflect real conditions in the water. For example, if a high flow angle warning is issued, the operator should check if the water at that measurement location appears to be flowing with a large flow angle. If there is any question about the validity of the data, we recommend repeating the measurement after first carefully checking the probe location to be sure the sampling volume is well clear of any underwater obstacles. If the warning persists after repeated measurements, it may reflect real conditions in the water. In this case, the measurement can be accepted and the user can continue with the rest of the discharge stations; however, data should be carefully reviewed in post processing.

All criteria used for the automated QA/QC tests can be adjusted or disabled by the user (following instructions in the FlowTracker manual). In general, the default criteria should provide good performance with few false warnings.

VII. DISCHARGE UNCERTAINTY

The final piece of the automatic QA/QC procedures is to estimate the overall uncertainty of the discharge measurement. This estimates the very important question of how accurate is the measured discharge. The FlowTracker uses two different uncertainty calculations: the ISO method and one developed by researchers at the U.S. Geological Survey called the statistical method (both calculations are described in detail in a separate paper^[6]).

Uncertainty results are shown both in firmware (on the FlowTracker LCD) and in the PC software. The uncertainty provides a quantitative addition to the subjective measurement quality estimate that many agencies report with each measurement. In addition to overall uncertainty, the FlowTracker displays the contribution of different factors to this uncertainty to help improve measurement quality in the future.

VIII. CONCLUSIONS

Regardless of the instrument, the quality of any field measurement relies heavily on the operator's technique. One of the best ways to improve measurement quality is to provide information and feedback that helps the operator improve their technique. The primary goal of the FlowTracker Smart QC algorithms is to provide a part of this feedback and improve the overall quality and reliability of discharge measurements in the field.

A secondary benefit is that it can save time in the field because it can catch potential problems early in the measurement process, and eliminate the need to repeat an entire discharge measurement or revisit a site. Because all of the QC data are recorded, there are also long term benefits to an agency's overall ability to look at improvements in data quality over time.

The tests and warnings used by the FlowTracker are intended to be largely self explanatory, and should with time improve the operator's knowledge of the instrument and hence quality of measurement.

IX. ACKNOWLEDGMENTS

The authors would like to thank Mike Rehmel and a number of others from the U.S. Geological Survey for their help in developing and evaluating the automatic QA/QC procedures for the FlowTracker.

X. REFERENCES

- [1] SonTek and ADV are registered trademarks of SonTek/YSI, Inc., San Diego, CA, USA.
- [2] Craig Huhta, *Handheld acoustic Doppler velocimeter (ADV) for water velocity surveys*. Hydraulic Measurements and Experimental Methods, EWRI and IAHR, 2002.
- [3] Scott Morlock and Gary Fisher, *Hydroacoustic current meters for the measurements of discharge in shallow rivers and streams*. Hydraulic Measurements and Experimental

Methods, EWRI and IAHR, 2002.

- [4] Gary Fisher and Scott Morlock, *Discharge measurements in shallow urban streams using a hydroacoustic current meter*. Hydraulic Measurements and Experimental Methods, EWRI and IAHR, 2002.
- [5] ISO 748, *Hydrometry - Measurement of liquid flow in open channels using current meters or floats*.
- [6] Craig Huhta and John Sloat, *Discharge Uncertainty Calculations Using a SonTek FlowTracker*, Australian Hydrographer's Association, 2006.

SonTek/YSI
9940 Summers Ridge Road
San Diego, CA 92121
Tel: +1 858 546 8327
Fax: +1 858 546 8150
Email: inquiry@sontek.com
Web: www.ysi.com

