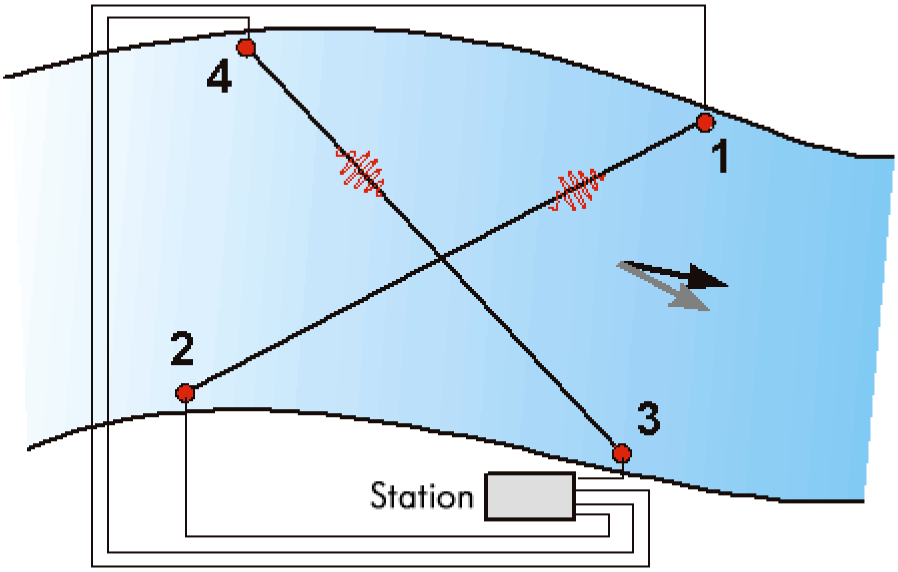

Ultrasonic Flowmeter Systems

Background information

TABLE OF CONTENTS

1. Introduction

Quantum Hydrometrie GmbH is an innovative and dynamic company located in Berlin, Germany, which develops and markets state-of-the-art ultrasonic flowmeter systems. As a specialist in integrated hydrometric system solutions, Quantum is a reliable partner in water management projects.

Quantum Hydrometrie was founded in 1994 by a group of people associated with the University of Technology, Berlin. Since then, Quantum Hydrometrie has grown quickly and established itself within Europe as a successful company; with over 200 projects completed, the Quantum product family has become the de-facto standard instrumentation used today by hydrologists to improve their understanding of water flow in rivers and channels. Quantum has also developed a discharge measurement system for pipes that has been extremely well received based on its reliability and efficiency.

This hand book is concerned with explaining the fundamental, theoretical foundations of ultrasonic discharge measurement, as well as possible applications and installation models of our flowmeter system. Ultrasonic discharge installations are rapidly replacing less efficient and less accurate traditional measurement methods and are increasingly being used in the measure of discharge in rivers, channels, and pipes. Because ultrasonic measurement is the most dynamic and cost effective measurement to date, it is important to introduce the new possibilities afforded by this method. We hope that you find this handbook both helpful and informative and are able to benefit from our excitement about ultrasonic measurement. If there are any questions, please contact us at:

Quantum Hydrometrie GmbH
Geneststr. 5
10829, Berlin
Germany

Tel: (0 30) 69 81 10-0
Fax: (0 30) 69 81 10-99

2. Applications

Discharge measurement is an important hydrographic and hydrometric concern. Here are some of the many possible applications:

- appropriate management of water supplies
- protection from high waters
- management of water projects (dams, pump works, reservoirs or storage basins, siphon constructions, etc.)
- calibration and validation of hydraulic and hydrometric calculations
- generation of statistics and records for consulting and other purposes
- bestowing of water rights

There exist different methods to determine the water velocity within a determined cross- section and thereby deriving the discharge measurement. Because of the various difficulties previously encountered with mechanical propeller type systems, the trend has been towards the development of modern electronic systems; for example, measurement with the help of ultrasonic technologies has led to the development of state-of-the-art flowmeters.

Traditional propeller systems measured the water velocity by the mechanical movement of propellers. The disadvantages to this method are as follows: propeller systems are both expensive and time consuming because they require more manual labor both to install and to operate; the measurement possibilities afforded by traditional propeller systems are also limited because a continuous discharge measurement is only possible in watercourses in which a stable discharge curve exists, i.e. the direct relationship between the water level and discharge is explicit and continuous.

Picture 1: An ultrasonic flowmeter in a water course with moving current

In opposition to mechanical methods, it is possible with ultrasonic discharge measurement to carry out continuos, fully automatic discharge measurements over extended periods of time and without any manual assistance. Not only does a continuous measurement provide more reliable data, but due to the dramatic reduction of required labor time, the ultrasonic flowmeter systems are more cost effective. Also, in water storage areas and bi-directional water flow areas where a direct relationship between the water level and the discharge does not exist, a continuous discharge measurement is not only possible with the help of ultrasound, but also more accurate and cost effective than mechanical methods of measurement. Another advantage to ultrasonic measurement is that the current of the river is in no way influenced by the measuring equipment, allowing for a more accurate measure.

3. Theoretical foundations

3.1 Overview of the measurement methods

Ultrasonic discharge measurement is an indirect measurement method, meaning that the discharge is calculated by means of an equation in a continuos measure of the water velocity and the water level.

For the velocity measurement with ultrasound, there are three possible methods:

- the sing-around method
- the ultrasonic-reproduction method
- the ultrasonic travel-time method

3.2 Sing-around method

On a defined path, a short ultrasonic signal is sent from one transducer to another so that the receiving transducer, with the help of a returning signal device, is triggered to send a new signal.

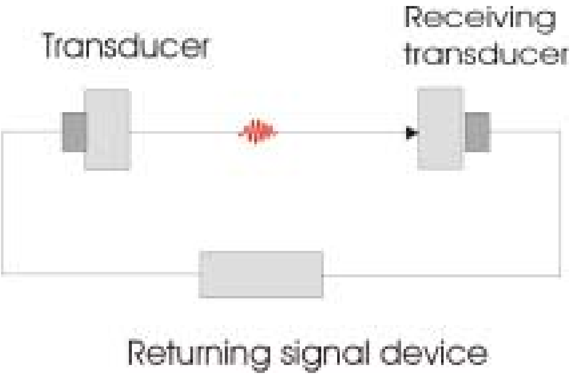

Diagram 2: Principle of the acoustic sing-around-method

With this model, it is possible to “capture” and “observe” an ultrasonic signal within short, measured distances over as long a period as needed. When the number of cycles that the ultrasonic signal has completed within a determined time period are counted, the frequency is obtained and with this particular frequency, the signal´s velocity is determined and thereby the velocity of the current.

3.3 Ultrasonic-reproduction method

With the Ultrasonic-reproduction principle, the ultrasonic transducer receives the reflected signal with a different frequency than was measured when the signal was first sent. Once the difference in the frequencies is determined, it is postulated how fast the current moves.

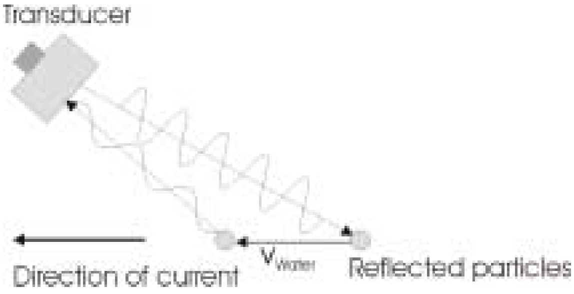

Diagram 3: Principle of the reproduction measurement

The frequency difference is marked by the shift in the reproduction frequency, which is proportional to the velocity of the reflected particles. In addition to the frequency shift, the travel time of the returning “reproduced” signals are measured. From this measure, the reduction of the particles found in the “reproduced” signals are determined, thereby enabling the determination of the velocity distribution along the measured path.

The reproduction principle is useful in the following areas:

- ADCP-measurement systems for discharge measurement in rivers and channels;
- ADCP-measurement systems for current measurement in oceanography ultrasonic-reproduction-detectors for the discharge measurement in waste water canals and small coagulates.

3.4 Travel-time method

The measuring principle of the travel-time method is based upon the direct measurement of the running time of the acoustic signals travelling between two ultrasonic transducers.

This method is described as follows: at least two ultrasonic transducers are installed so that the acoustic signals transmitted between them are diagonal to the water current. The acoustic signal running against the current has a longer travel time than the acoustic signal running with the current. The difference in travel times is directly proportional to the flow velocity and, when the cross section is known, directly proportional to the discharge.

The travel-time measurement is realized with two methods: the frequency method and the impulse method. With the frequency method, a sequence of defined frequency signals are sent through the watercourse between a sending and a receiving transducer, the travel-time of these signals being the object of measurement. With the impulse method, the travel-time of a short acoustic impulse is measured with a determined frequency.

The travel-time principle, configured with the impulse method, has the advantage that a continuous measurement is possible. It is because of this advantage that this particular travel-time principle has been applied with great success to the ultrasonic measurement of discharge in rivers, channels, and pipes. This is the method used by Quantum and accepted by today´s hydrologists as the method most worthy of the investment of capital.

3.5 Travel-time Measurement

For the determination of the travel time, an ultrasonic transducer receives an acoustic signal in the form of a square wave signal (sine wave signal). The transducer then transforms these signals, which were sent through the watercourse, in an acoustic wave packet. The travel-time of this wave packet is then measured.

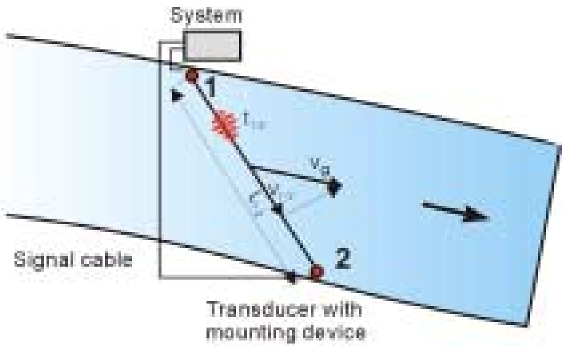

Diagram 4: A travel-time schematic diagram

The travel times t_{1-2} and t_{2-1} are determined with the direct travel-time method, whereby the zero crossing that was previously determined by the manufacturer with the help of an analogue or a digital signal recognizer is calculated.

The travel-time of the path traveling with the current is calculated with:

$$t_{1-2} = \frac{L_{1-2}}{c + v_{1-2}}$$

and the travel-time of the path t_{2-1}

$$t_{2-1} = \frac{L_{1-2}}{c - v_{1-2}}$$

whereby:

L_{1-2}	The length of the acoustic paths between transducers 1 and 2
V_{1-2}	The mean value between transducer 1 and 2 of the local current velocities along the acoustic path.

The travel-time difference Δt is then approximated with the acceptance c **>>** v.

$$\Delta t = \frac{2L_{1-2}v_{1-2}}{c^2}$$

Example:
The velocity of the acoustic signal in water depends on the salt content and the water temperature ca. 1400 until 1500 m/s.

For example, with a signal velocity of *c* = 1450 m/s, a path length of *L* = 10 m, and a current velocity of $v_{1-2} = 1$ mm/s (0,001 m/s), the measured time difference only amounts to $\Delta t \cong 9{,}5 \times 10^{-9}$ S.

With the travel-time method, the time measurement must be taken in nano seconds in order for the smaller current stream velocities to be resolved with the required exactness.

4. Quantum´s flowmeter system

Our ultrasonic flowmeter systems, which utilize the travel-time method, are known for their high quality and wide range of functions. Along with hydrometric consultations, Quantum offers complete and ready to use system installations which are known for their stability and wide range of capabilities.

4.1 System description

Our systems are known for their user-friendliness and accessibility. The software is easy to install and direct access to data is possible by modem through a PC or laptop. While remote data transmissions enable efficient access to the system from a remote computer, including the capability to store collected data, remote diagnosis functions enable easy and reliable maintenance. Because these diagnosis functions allow full access to the measuring system, expensive on-site repairs can be largely avoided, just another advantage to our ultrasonic flowmeter systems.

A variety of display and output options are available as well, ensuring that our ultrasonic flowmeters are efficient, compact, and require little maintenance.

4.2 Latest methods in digital processing

Because of our strong emphasis on the development of the latest methods in digital signal processing, our systems are able to deal with the most challenging hydrometric measurements facing hydrologists today; in particular, the dampening of the acoustic signal sent by the ultrasonic transducers by suspended solids or its disturbance by significant amounts of air bubbles can be almost eliminated by our ultrasonic flowmeter system. These topics are discussed in more detail later in the handbook.

4.3 Installation

Even within the most challenging rivers, a more accurate measurement can be achieved with the help of Quantum´s cost effective software. One advantage of our system is that the use of costly equipment to align the transducer heads during installation can be avoided: due to the latest signal recognition technology, the geometry of the signal paths is determined by functions within the software and not by the physical positioning of the transducers, meaning that not only is the installation less costly, but the resulting measurement more accurate.

4.4 Configuration possibilities

The arrangement of the transducers depend on the flow conditions found in the river at the place of measurement.

4.4.1 Single Path System

If the current runs parallel to the banks, a single path system can be used. This configuration consists of two transducers, which both send and receive the acoustic signal, being installed on one level and diagonally to the direction of flow.

The single path system is best suited to channels, canals and other constructed waterways with easily definable cross-sections.

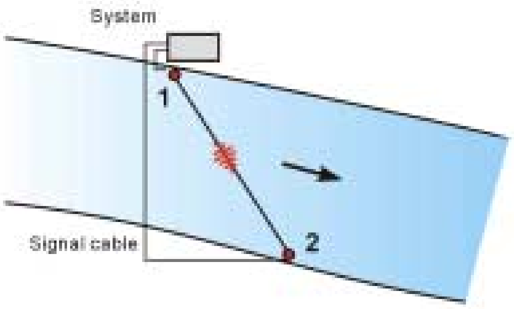

Diagram 5: Single path system

The acoustic signal travels alternatively between **1-2** (with the current) and **2-1** (against the current).

4.4.2 Crossed Path System

Rarely does the main current run parallel to the bank. Bends in the river, the profile geometry, and differing depths influence the water flow. In these cases, a crossed path system is recommended because a second “crossed” path, installed on the same level and crossed to the first path, enables the calculation of the angle between the main current and the river bank, providing a more accurate measure.

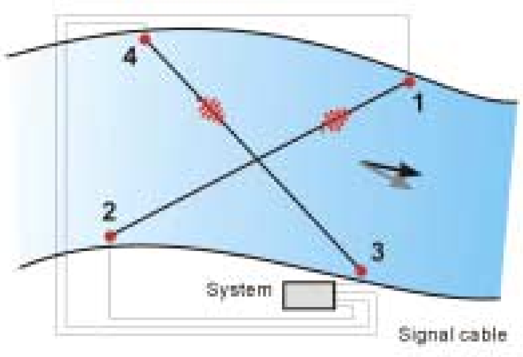

Diagram 6: Crossed path system

The running time of the acoustic signals between transducers **1-2** and **3-4** are simultaneously measured. The reversed measure is then taken between transducers **2-1** and **4-3**.

4.4.3 Responder system

Both the single and crossed path systems require that signal cables cross the river. In situations where this is inappropriate, a responder system is recommended. This configuration consists of the installation of a responder on one side of the river, opposite to the transducer(s) located on the same side of the river as the measuring system.

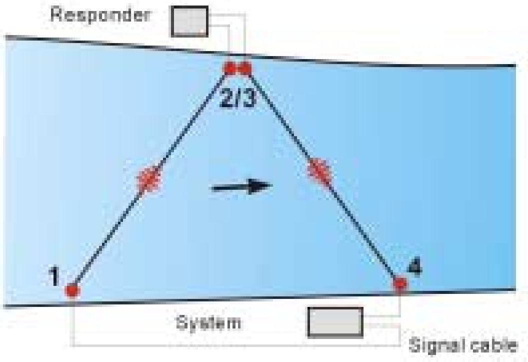

Diagram 7: Responder system

In a Responder configuration, the acoustic signal is first sent against the current, along the path defined by transducers **4** and **3**. With minimal delay, the signal is guided by the responder and once again sent against the current, along the path defined by transducers **2** and **1**. Next, the measure of the running time when the acoustic signal travels with the current is taken when the signal travels in the opposite direction, along the paths defined by **1-2** and **3-4**.

4.4.4 Multiple level measurement

All three of the above systems are also available as multiple level measurements. This configuration is recommended at sites with an irregular profile or a large variation in water level; the installation of two or more levels enables a better measure of irregular profiles and changing water levels.

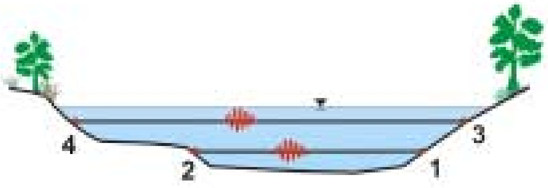

Diagram 8: Multiple level measurement

Each individual level can be configured with a single or crossed path system.

Even though all of the configurations have application possibilities, they do differ in reliability. For example, the discharge measurement is most accurate with a multilevel, crossed path system; while the measure of the main current direction is most accurate with the crossed path system, the profile of the measured area is best measured with a multiple level measurement.

5. Calibration

A continued understanding of our measuring principle is possible with a discussion of calibration. What we mean by calibration is as follows: the deviation of the measured values are determined from a determined reference value.

The hydrometric calibration of an ultrasonic flowmeter installation is based on the established relationship between the unknown velocities found in the determined profile and the mean velocity of the current.

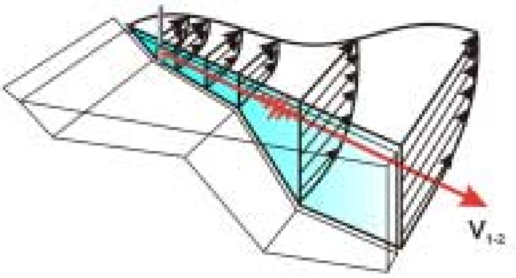

Diagram 9: Typical example of a velocity profile in a determined cross-section

This relationship can be determined through a theoretical deduction, mathematical calculation, or a mechanical measurement in the natural environment.

To differentiate between the theoretically grounded velocity coefficient and a specific calibration factor from a measurement installation, it makes sense to split the k-Factor equation into two parts.

$$k = k_1 \cdot k_2$$

With:

k_1	Theoretically derived velocity coefficient
k_2	Calibration factor for a specific measurement installation

It is then possible to calculate the discharge with the following equation:

$$Q = k_1 \cdot k_2 \cdot A \cdot v_g$$

With the two measurements v and A, is it possible to calculate the discharge Q and to determine the calibration factors k_1 and k_2 in accordance to a determined signification.

5.1 Velocity coefficient k_1

5.1.1 Empirical

For wide natural watercourses, the velocity distribution is mostly a function of the water depth. According to ISO 6416 (1992), the theoretical velocity coefficient k_1 is valid for natural watercourses, and is dependant on the height of the installed measurement paths. The following table has the resulting numerical values.

Table 1 Allocation of k_1-factors according to ISO 6416

Z/h	0,1	0,2	0,3	0,4	0,5
K_1	0,846	0,863	0,882	0,908	0,937

Z/h	0,6	0,7	0,8	0,9	
K_1	0,979	1,039	1,154	1,424	

With:

z/h Transducer installation level/water depth

These values were ascertained from 15 measurements in 7 different measurement sites (1,94 m< h_m<2,20m).

5.1.2 Logarithmic velocity distribution

It is also possible to calculate the mean current velocity in natural watercourses by an approximation based on the velocity distribution. Best suited to water courses in which the banks exceed a 90 degree angle(b>10h), this method requires that a single path measurement be installed 40% of the water depth above the watercourse floor. From this measurement, the mean current velocity corresponds to the total measured current velocity in the cross-section. With the calculation of the calibration factor, the relationship between the current velocity V_g and the mean current velocity V_m finds an acceptance of 1.

Based on an ultrasonic flowmeter installation, the mean current velocity is directly measured by an acoustic signal which is installed 40% of the water depth above the watercourse.

Any time the water depth in a watercourse changes, or the watercourse floor becomes rougher so that secondary currents are created, there is an impact on the measurement of the velocity distribution. The secondary currents interact with each other and cause the slower water particles located closer to the banks to be transported into the main current area. The result is the reduction of the water velocity and the increased loss of friction, which renders the velocity distribution logarithm invalid.

5.1.3 Hydro-numeric modeling

For concrete canals with rectangular or trapazoidal cross-sections, the influence of offset margins on the velocity profile cannot be neglected.

In these instances, it is possible with the help of hydrometric numeric models (for example SIMK-modeling, Koelling, 1994) to calculate the velocity distribution in cross-sections with a constant current, making it possible to ascertain the size of the velocity coefficient k_1 for every arbitrary altitude along the measurement path (See diagram 10).

Through the repetition of the simulation calculation, with the help of the Finite-element network, and the analysis of the different water levels, the complete calibration for the measurement installation as function $k_1(h)$ is obtained in relation to the water level.

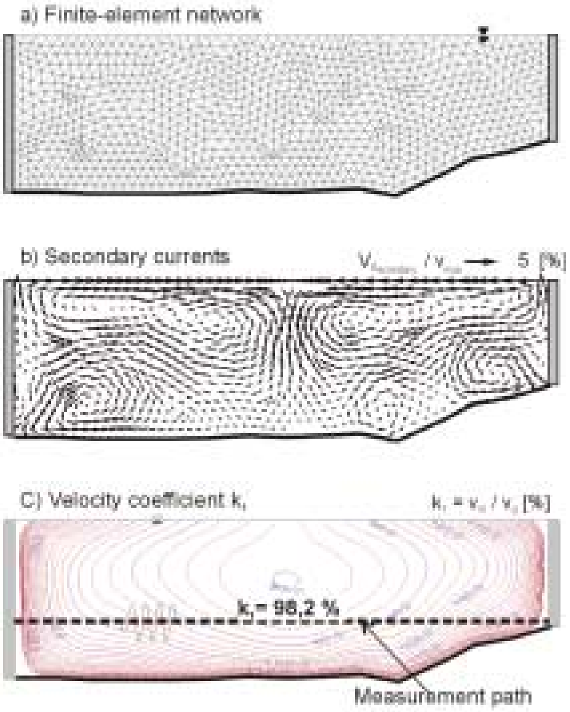

Diagram 10: Determination of the k_1 value in the measurement path with the help of the SIMK-methods (Koelling, 1994)

5.2 Calibration factor k_2

In natural watercourses where a selected cross-section is influenced by tidal waters or changing floor levels (i.e. variation in the watercourse geometry), the deviation of the theoretical velocity profile can also be calculated.

Further impacts on the velocity profile results from bends in the water course, wind on the water surface, ground or water surface currents located before drainage pipes or spill way gates. Diagram 11 shows the different velocity profiles in relation to the profile shape of the water course floor.

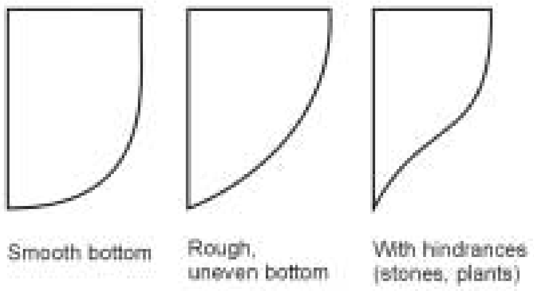

Diagram 11: Different forms of the velocity profile

The specific deviations found in the theoretical velocity coefficients k_1 in specific measurement installations are corrected with the discharge measure of a second velocity coefficient factor k_2.

In these cases, it is essential that a manager carry out the hydrometric calibration as a result of the unforeseeable nature of the current behavior in the measurement installation area.

Respective to the water level and discharge, different calibration factors could be given so that for the calibration factor k_2, the following general correlation must find acceptance.

k_2 = f(water level w, current angle ϕ)
with A = f(w) and Q = f(ϕ)
k_2 = f(cross-section A, discharge Q)

From the reference measurements derived from the hydrometric calibration referred to earlier, it is possible to calculate functional correlation for the calibration k_2 that take the form of a calibration matrix.

For a multiple-point measurement, a hydrometric propeller type system is employed to carry out a point measurement of the current velocity throughout the entire cross-section. The total discharge is determined through the vertical and horizontal integration of the individual point measurements.

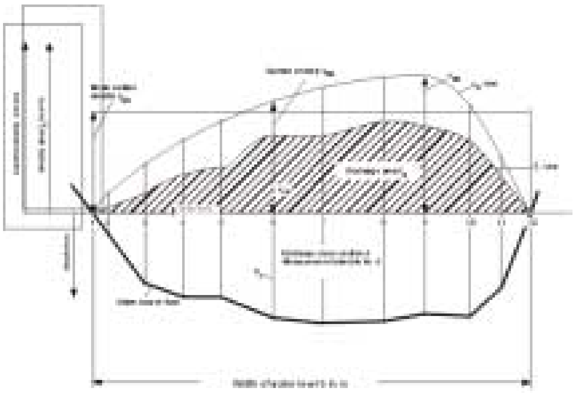

Diagram 12: Discharge cross-section according to the velocity area method (Pegelvorschrift, 1992)

In large watercourses where a multiple-point measurement is possible only with a substantial cost, there exists another possibility to measure the velocity profile; the ADCP (Acoustic transducer current profiler) is a measurement method that operates on the transducer-effect model to ascertain the velocity of the current. That measurement system is mounted on a special boat or float. It is uncommon, however, that such a measurement is required.

6. Measurement uncertainties due to physical factors

6.1 Suspended particles

When an acoustic signal is sent through water, the signal loses some energy. As a result, the amplitude of the acoustic signal continually decreases and the signal is dampened. This dampening means that the intensity of the received signal is less than the intensity of the original sent signal. While the amplitude decreases as the acoustic signal travels through water, other parameters remain unchanged, for example the frequency, etc.

The damping of the acoustic signal is the result of two factors:

Friction
Some of the energy of the acoustic signal is converted into frictional heat as the result of the water viscosity.

Dispersion
When the acoustic signal collides with suspended particles in water, part of the energy contained in the signal is dispersed.

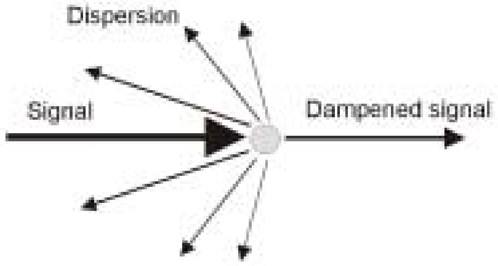

Diagram 13: An example of the dispersion that happens when the acoustic signal encounters suspended particles in water

Small particles have the tendency to vacillate with the same frequency of the acoustic signal, causing a relatively large amount of acoustic energy to be lost through the friction factor. Larger particles with a diameter from 0,1 to 1 mm have the tendency to cause the dispersion of the acoustic energy (see diagram 14).

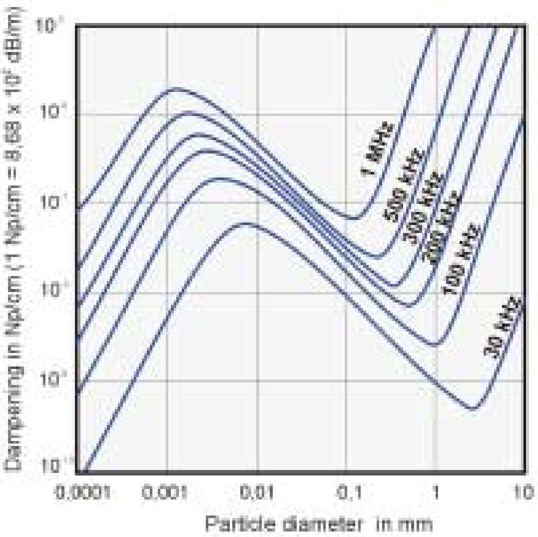

Diagram 14: Dampening of an acoustic signal in relation to the particle diameter and signal frequency (Laenen, Smith, 1982)

It is clear from diagram 13 that the amount of dampening that takes place at similar concentrations and sizes of suspended particles is primarily dependent on the frequency of the acoustic signal.
So a signal with a frequency of 30 kHz at factor 10 (diameter of suspended particles in mm) will be dampened less than a signal with a frequency of 200 kHz.

Because there are limits to how much the piezoelectronic crystal can be enhanced, the maximum path lengths under the same conditions are primarily determined through the acoustic frequency.

Note: in general, the reliability of the flowmeter system increases with the use of lower frequencies. Because low frequency transducers cost more, however, it is important to avoid extra cost in particular measurement installations where higher frequency transducers are both cost effective and reliable.

6.2 Air bubbles

Air bubbles that develop for example when water descends into a watercourse from a gate of a dam or when air bubbles rise from oxygen producing plants on the floor of a water course cause the dampening of the acoustic signal. The physical effect of air bubbles is similar to that of suspended particles, including the problem of friction (the conversion of the signal´s energy into heat) and dispersion. In opposition to suspended particles in water, however, air bubbles are easily compressible and thereby have a further effect on the acoustic velocity.

In measurement sites with a large presence of oxygen either created by biological processes or trapped in the water, it is typical that during the day the measurement is disturbed or completely stopped. After sunset, the acoustic conditions improve because the biological processes decrease and the flowmeter is able to function again.

Similarly, the air bubbles created by ships also cause the dispersion of the acoustic signal. This interference, however, usually doesn´t cause any loss of data, but rather a reduced quantity of measurement values in the average measurement time.

6.3 Temperature and salt content

The ultrasonic signal´s velocity in water is also influenced by different distinctions in temperature and salt content. When a strong temperature difference exists between the air and water, an energy transfer takes place between these two elements. This leads to the development of a temperature gradient in the water that diverts the acoustic signal from its normal horizontal path. The diversion can be so severe, that the signal fails to meet the receiving transducer. In this case, when there exists no acoustic connection between the sender and the receiver, a measurement is of course impossible. Salt content gradients have a similar influence.

These physical conditions have to be accounted for by the proper selection of the measurement site location and suitable components.

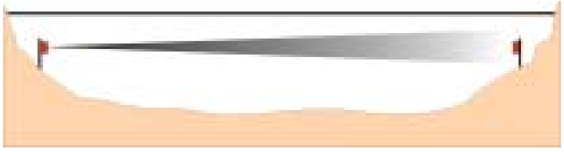

Diagram 15: No vertical density differentiation

Temperature changes of 1°C per meter appear predominately in slow flowing water courses and are usually 0,5 m deep. In the underlying water layers, the temperature changes are less.

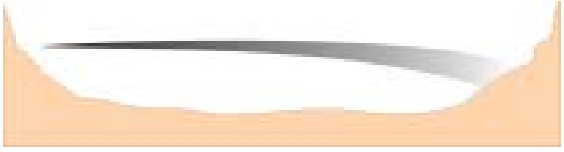

Diagram 16: Significant vertical density differentiation as the result of temperature gradients caused by sunlight

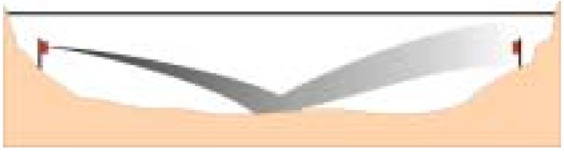

Diagram17: Extreme vertical density differentiation as the result of salt content

Temperature changes are also prevalent in the following instances: in a cool water intake in which a substantial amount of warm water enters into the watercourse; near power plants where cool water reenters the river and rejoins the natural current; where water from a dead channel flows together with the main current of the cross-section; where deepwater mixes with the natural discharge; or in the case where a sea opening and a river with differing temperatures meet each other.

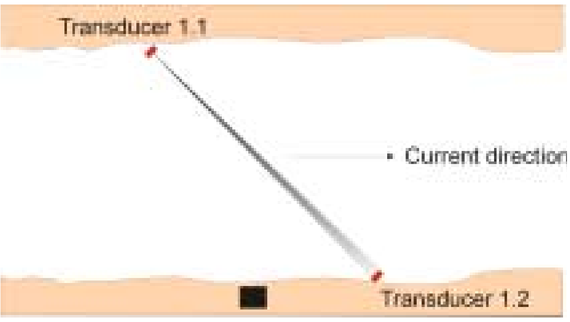

Diagram 18: No horizontal density differentiation

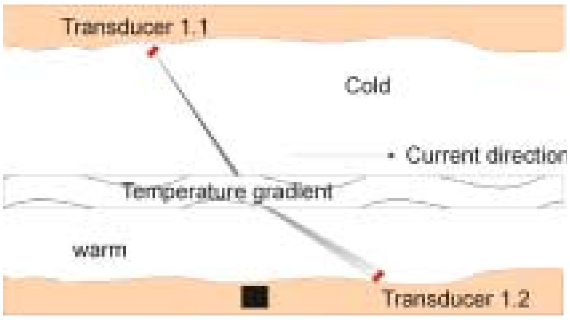

Diagram 19: Horizontal density differentiation as the result of the introduction of warm water

In diagram 20, the diversion of the signal as the result of temperature differences is illustrated. The temperature gradient averages 0,1°C per meter with a distance of 200m between the transducers. The result is as follows: the most concentrated part of the signal, because of a shift that takes place when it passes through the temperature gradients, ends up 4m from the ideal course, meaning the signal reaches the bank 4m from the receiving transducer. The sent signal is spread out during propagation by the beam angle established in the sending transducer; for example, when a beam angle of 5° is configured with a path length of 500 m, the diversion of the signal amounts to 24 m under the same temperature gradient. A beam angle of 5° is in this case not enough for the signal to be detected on the opposite bank.

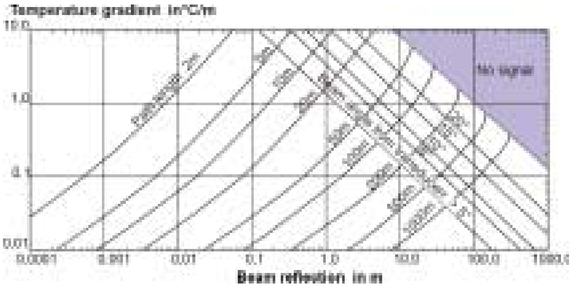

Diagram 20: An estimation of the signal´s diversion in a linear temperature gradient with different path lengths

Since this problematic effect occurs only in instances of intensive solarization, in extremely slow current velocity in water courses or bi-directional tidal areas, in a large introduction of salt water into watercourses, installations on normal inland water courses are usually not effected by this disturbance.

The calculation of the beam angle takes place with the formula from VIGOREUX (1979). A formula to calculate the signal´s velocity is provided by DEL GROSSO (1974). For the velocity of the signal c:

$$c = 1402{,}39 + 0{,}156 \cdot P + 5{,}011 \cdot T -$$
$$0{,}05509 \cdot T^2 + 0{,}2215 \cdot 10^{-3} \cdot T^3 +$$
$$1{,}330 \cdot S + 0{,}13 \cdot 10^{-3} \cdot S^2 -$$
$$0{,}0128 \cdot T \cdot S + 0{,}097 \cdot 10^{-3} \cdot T^2 \cdot S$$

With:

c	Signal velocity in m/s
T	Water temperature in °C
S	Salt content in %◦
P	Depth of the measurement layer from the water surface in m

The application of this formula is restricted to 0°C < T < 40° and 0%◦ < S < 40 %◦. Within these limits, the exactness of the formula exceeds 0,5%◦ and its use is not recommended.

For the radius of the curvature of the acoustic signal in water:

$$\frac{1}{R} = -\frac{1}{c}\frac{\partial c}{\partial n}$$

with:

c	Signal velocity in m/s
R	Bending radius in m
n	Normal arrangement of the signal propagation

For the approximation of the radius of the curvature of a horizontal signal in water of 10°C:

$$R = -1450\left(3{,}63\frac{\partial T}{\partial P} + 1{,}13\frac{\partial S}{\partial n}\right)^{-1}$$

In summer, strong solarization has a greater effect on the water temperature in the upper layers than the lower layers so that a negative temperature water gradient appears. In winter, with temperature beneath 4°C, this effect is reversed.

In instances of different salt content gradients, the larger amount of salt content is always located in the lower layers, thereby creating always a positive gradient.

In general, a negative temperature gradient in summer causes the signal to diverge into the lower, deeper layers of the water course. A positive salt content gradient causes the signal to diverge into the upper layers.

7. Problem solving or Error detection

There is a distinction between random and systematic errors.

7.1 Random errors

According to LÄNDERARBEITSGEMAINSCHAFT WASSER (1992), the insecurity of ultrasonic discharge measurement systems is mainly attributed to the following four points:

1. **Selection of the measurement site**
   Shifting current directions, air bubbles, suspended particles, temperature stratification, the presence of too much oxygen in the water, and a water velocity that is too slow are all problematic for discharge measurement with ultrasound.

2. **Installation and calibration of the measurement system**
   System positioning, inexact or incorrect geometric indications, inexact or incorrect reference measurements (dependant on the chosen method)

3. **Location of the measurement system**
   Faulty or defected measurement system (electronic error), choice of integration time that is too large (>10 min) or too small (<1 min)

4. **Analysis of the measurement data**
   Inaccurate evaluation of the troublesome points, insufficient attention to reference guides pertaining to the various surrounding conditions.

According to RACK (1982), the accuracy of a discharge measurement with a single path system is quoted at $f_{ges.}$=5%; the random errors in the determination of the calculated sizes (longitudinal, angle, and time measurement) are accounted for in so far as the uncertainty of the correlation between the measured value v_g and the discharge Q is also accounted for.

For an estimation of how big the anticipated random measurement errors are, the individual errors are calculated by the measurement of the current velocity in measurement path (f_v), the cross-section area (f_A), and the calibration factor(f_k). With the help of a quadratic law of error propagation, the total error of the discharge measurement(f_Q) is the following:

Equation:

$$f_Q = \sqrt{f_v^2 + f_A^2 + f_k^2}$$

7.2 Systematic errors

Accessing systematic failures is more difficult; i.e. disturbance within the measured cross-section, data mistakes, system defects, etc. These failures can range from an insignificant but constant influence to a complete system breakdown.

An evaluation of whether or not an irregularity exists can be known only when the troublesome influence is found and its effect on the measurement values eliminated.

In a single path system, when the actual current direction deviates from the assumed current direction, a velocity perpendicular to the measurement path can be calculated with the following equations that doesn´t correspond to the actual velocity:

$$v_g = \frac{v_{1-2}}{\cos\phi_{1-2}}$$

with:

ϕ_{1-2} The angle between the measurement path and the current direction.

$$v_g = \frac{L_{1-2}}{2\cos\phi_{1-2}}\left(\frac{1}{t_{1-2}} - \frac{1}{t_{2-1}}\right)$$

The relationship between the calculated discharge and the actual discharge is dependant on the path angle ϕ and the size of the angle deviation α between the assumed and actual current direction.

As shown in picture 27, the larger the angle, the larger the deviations appear in the assumed mean current direction.

When the current direction is constant, these systematic mistakes are corrected by the calibration measurement, a correction of the ultrasonic discharge measurement system which indicates too big or too small of a velocity measurement respective to the discharge measurement.

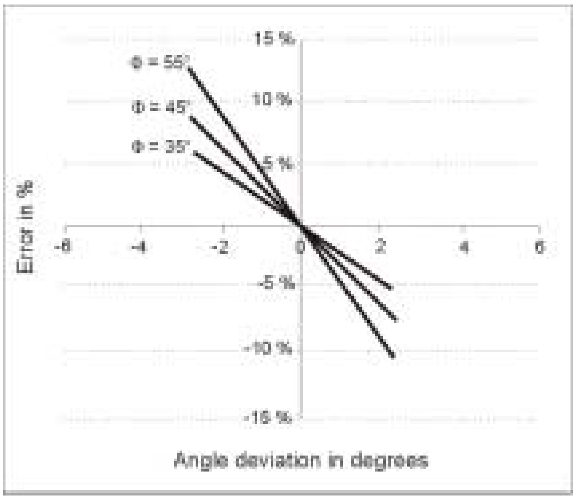

Diagram 21: Relative error in a discharge calculation is dependant on the angle calibration between assumed and actual current directions (single path system)

8. Environmental compatibility

On principle, our ultrasonic measuring systems are installed to minimize any negative impact on local ecological function. The installations are constructed in existing river banks, meaning that both the transducers and the accompanying cables are mostly unobservable. Usually the cabinet that contains the measuring system is the only observable part of the installation. In areas where even a small cabinet is obtrusive, such as wildlife preserves or city installations, special building elements can be used to conceal the equipment as much as possible.

According to a conclusive study by the Federal office for the Environment and Nature, ultrasonic signals have no negative affects on animal life found near our measuring sites. Between 1999 and 2001, biologists from the Rostock University studied the effects of a crossed path ultrasonic system on a natural river environment. The influence of the acoustic signals on the movement of fish was the focus of the study. By employing a measuring system that could be switched on and off, and installing video cameras that could observe the movements of fish at various depths, it was found that that acoustic signals had no effect on the movement of the fish. (Rothbarth & Winkler, 2001)

9. Installation location evaluation

9.1 Hydraulic conditions

To determine whether or not a cross-section is suitable for an ultrasonic discharge measurement system, it is important to evaluate the hydraulic conditions present at the desired installation site. Table 2 contains the most important criteria:

Table 2 Hydraulic conditions

Criteria	Conditions	Test possibilities
Incoming flow	Optimal: The water course must be 5 to 10 times the water course width above the measurement installation and 1 to 2 times the watercourse width below the installation. Alternative: Crossed path system	On site inspection Access to site plan
Dammed areas	Without problem	On site inspection
Water level	Manufacturer warranty is dependant on a sufficient water level. Consultation of the manufacturer.	Consider-ation of the hydraulic statistics
Velocity distribution	No cross-sections with predominate back streaming zones allowed	On site inspection Hydraulic probe measure-ment in possible cross-sections
Wind influence	Negligible	

9.2 Morphological conditions

The morphological conditions are concerned with the physical condition of the installation site itself. Table 3 contains the most important criteria:

Table 3 Morphological conditions

Criteria	Conditions	Test possibilities
Water course floor	Stable construction, no sediment and no erosion	Comparison of the translated cross-section measurements Geographical surveys
Bank	Definite form, stable construction, banks with shallow slopes must have a run-off formation	On site inspection
Measure-ment path	No stones or other hindrances in measurement path, no vegetation blocking measurement path	On site inspection A profile view along the measurement path with a reference point.
Location above a barrage	Measurement cross-section should be located from the barrage 3 to 4 times its depth.	On site inspection

In the incidence of an instable river floor, the changes caused by the instability must be quickly ascertainable because the area of the cross-section plays an important role in the calculation of discharge.

Similarly, installations with large foregrounds must be avoided. In the instance of large foregrounds, even if the river floods a little, the accuracy of the measurement is largely impacted and the mean velocity measure becomes volatile. Therefore, in installations where there is slight flooding or even partial flooding, it is impossible to carry out a trustworthy measurement with any of the methods described.

9.3 Physical conditions

For the proper function of the ultrasonic measurement system, compliance to the following physical conditions listed in the table below is necessary.

Table 4: Physical conditions

Criteria	Conditions	Test possibilities
Temperature gradient	Measurement sites should not be installed below cool water intakes or stagnate water (dead channel) With a temperature difference of >3 until 5 °C in water Consultation of the manufacturer	Temperature profile of the area
Salt gradient	Normally problematic only in coastal watercourses Consultation of the manufacturer	Measurement of the salinity
Air bubbles	Measurement points are to be installed 5 to 10 times the width of the water way below the dam. With possible entry of small microscopic air bubbles as the result of pumps installed against the water current. Consultation of the manufacturer	On site inspection Site plan
Suspended particles	Until 10 g/l Consult manufacturer about the recommended transducer frequency	Suspended particle measurement

9.4 Practical and logistical conditions

In general, the measurement system has to be accessible on every bank because installation requires the use of heavy and bulky machinery. For example, the installation and mounting of the transducers in the banks is only possible with heavy machinery suited for that purpose.

Despite the small amount of power input required for a trustworthy and stable operation of the flowmeter, a bus bar is still recommended. In fact, our system can also be run with solar power, even though a connection to a local electrical system is often more economical due to the low operating expenses and maintenance costs of electric power. To prevent unwanted interruption of the measurement due to temporary power failures, the installation of a battery is also recommended.

Because it is important from time to time to check the accuracy of a measurement system, the installation site should not be exclusively suitable for ultrasonic measurement. Rather, there should be the possibility either at the site itself or nearby to install another type of discharge measurement system to carry out controlled comparisons when they are required.

Table 5 contains the most important practical conditions For ultrasonic measurement.

Table 5: Logistical practical conditions

Criteria	Conditions	Test possibil-ities
Access to measurement installation	Accessibility also for heavy machinery	On site
Energy supply	Optimal: energy supply with 220 V Alternative: solar energy	On site
Data transmission	Optimal: conventional telephone network Alternative: wireless modem	On site
Cable arrangement	Contained in a protective pipe dug into the bank. Watercourse cable crossing: availability of a bridge or the laying of the cable along the watercourse floor; alternative also exists to tunnel through the watercourse bottom. When it is not possible for cables to cross the watercourse: Responder installation-placement possibility for the responder on the opposite bank which eliminates the need for a cable crossing	On site
Entrance for propeller type systems	Possibility of comparable measurements with hydrometric propeller type systems or transducers: Bridge nearby? With ADCP-measurements: Is it possible to leave a measurement boot in the water?	On site

9.5 Installation configurations

If the current runs parallel to the banks and the profile is regular so that the current is not strongly influenced, a single path system can be used. This configuration consists of two transducers, which both send and receive the acoustic signal, being installed on one level and diagonal to the direction of flow. This is the most basic configuration with ultrasonic measurement.

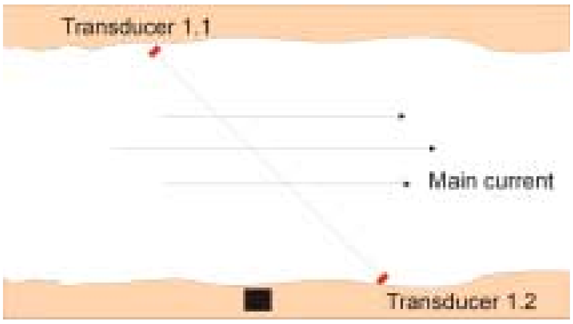

Diagram 21: Single path system, parallel current

One disadvantage to the single path system is that if a problem arises with the system, for example damage due to high water or ship traffic, there is no second path to continue the discharge measurement.

For hydrometric measurement with ultrasonic transducers, it is important to know the exact angle between the main current and the acoustic signal which crosses it.

If the direction of the current is influenced by physical factors, such as meandering currents, changes in direction because of differing water depths or curves in the watercourse, or the presence of a converging stream, a crossed path system is recommended; with the installation of a second “crossed” path on the same level as the first path, a more exact calculation of the angle between the main current and the river bank is possible and thereby a more accurate measure.
In natural watercourses, the crossed path system is the best option to obtain a discharge measurement with the highest possible accuracy.

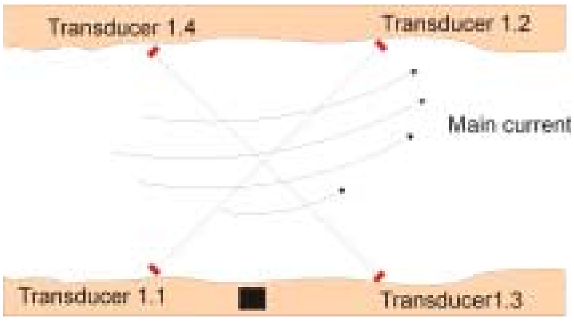

Diagram 22: Crossed path system

Although only a few years ago it was thought important to install multiple level systems, people in the field of discharge measurement are now more reserved in their evaluations. Of course, the initial calibration costs are avoided with a multiple level system, because the calibration required until the varying water levels and current velocities and resulting k-worth values for the entire measured area are already known. New methods are now available which are based on calibration; because the K-worth value is dependant on the discharge and water depth of the river, and therefore can be numerically derived, these new methods offer an alternative to the higher costs of a multiple level measurement. With a multiple level measurement, there still exists the advantage that if the discharge measurement fails on one of the measurement levels, it remains possible to continue to collect data with the remaining measurements. **Multiple level systems are still preferred in cross-sections with large fluctuations in the water level.**

The maximal range of the acoustic signal in a watercourse is determined by its acoustic frequency and transmitter power, the transmitting power being limited by the most constructive setting for the piezoelectronic crystal. Finally, it is important to know that in watercourses that contain a lot of suspended matter, lower frequency signals are more effective than high frequency signals which tend to be dampened to a larger extent by suspended matter. Therefore, in the case of high waters or flooding, the installation of low frequency transducers substantially increases the reliability of the measurement.

For large measurements or watercourses that contain a lot of suspended matter, low frequency transducers are employed, the maximal watercourse width being 1500 m. For your knowledge, these low frequency transducers are bigger than the high frequency transducers. High frequency transducers are employed for smaller measurements, the minimal water width being 0,5m, and in instances of comparatively clear water.

10. Design and construction

10.1 Project plan

The realization of an installation requires several steps. First, there is a preliminary inquiry into the best location for the installation of the ultrasonic flowmeter system. Next follows a preliminary draft of the installation which is the foundation for both the specifications required by state regulations and the award of contract. The subsequent project outline is issued if the permission of the property owner is given and the realization of the project is foreseeable.

The project outline contains the following:

- Technical drawings of the installation and mounting of the transducers
- Plans for the electrical and lightening protection set up
- Specifications to meet state regulations for hydrometric projects
- Cost estimate

Required documentation

- Local site plan (measurement scale at least 1:5.000)
- Cross-section pictures of the designated measurement site
- Map of the site´s infrastructure (electric and telephone lines; gas and water pipes)
- Abstract from the register´s plan

Permits for the following procedures involves the responsible institution in the following areas:

- Environmental protection agency

- Water or ground water public authorities
- Water and land organizations
- Office for water and ship transportation
- City and community administrations
- Energy public utilities
- Gas public utilities
- Phone companies

According to the regulations, an application has to include a description of the plans, including the project drawings, installation layouts, cable layouts, etc.

10.2 Building specifications

The building specifications can be outlined by Quantum or by a contractor hired by the customer. Suitable to services potentially performed by contracted labor include:

The digging of a trench for the underground cables

- The laying of the pipe to protect the cable and the insertion of the signal cable
- Energy feeding
- Telephone feeding
- The mounting of a water level measure
- The purchase of fixture devices for the mounting of the transducers
- Construction of an outdoor housing or cabinet

The manufacturer accepts responsibility for the following services:

- The installation and alignment of the transducers
- The installation and alignment of the measurement system, including the external sensors (for example, the readable water level, the output W and Q on the external data collector)
- The starting of the measurement system

10.3 System inspection and warranty

The system inspection follows standard hydrometric regulations. The components are tested in the following combinations:

- All of the input and output interfaces
- The measured value outputs for the site and the remote data transfer
- The accuracy of the measurement values for the water level (with the help of a known reference value)
- The accuracy of the discharge measurement values (with help from comparative measurement procedure)
- The ordering of the building specifications
- The ordering of the transducer alignment procedure and the labeling of the components.
- Documentation (Handbook, documentation of the measurement site, etc.)

The warranty for all of the performed building services lasts 24 months; for the flowmeter system, the warranty lasts 12 months.

11. The management and maintenance of the ultrasonic measurement system

The technical management and maintenance of the ultrasonic measurement system can be carried out better as a complete working system rather than as a group of individual components.

11.1 Transducer

- It is possible for the transducers to meet different measurement conditions due to different frequency possibilities
- The simplest and most secure transducer installation
- The simplest alignment and locking device
- Visible marking of the transducer position in the river bank or channel

11.2 Signal cable

- Protection against underground and above ground shifts
- Explicit and systematic labeling of the lines
- Documentation in a cable log

11.3 Measurement electronic

- Simple modular construction

- Easy access and exchangeability of parts in case of repair; for example the ability to change circuit boards
- Ability to receive information from easy to understand visual elements; for example through LED, etc
- Availability of an interface for data migration
- Simple on-site and remote communication with ultrasonic flowmeter system
- Warranty of the data collection and data storage over a predetermined time period in the case of power failure (for example with the installation of an back-up battery unit).
- Automatic start in case of power failure
- Possibility of using a system simulator to test the system

11.4 Housing

- Documentation of labeling system
- Documentation of all of the components
- Easy exchangeability of housed components, for example modem, heating system, air ventilator, security equipment, etc.

11.5 Software

- Easy graphic user interface for the regulation and servicing of the flowmeter
- Password security
- Data control of the measurement values with a concise time-variation curve
- On-line graphic quality test for the acoustic signal
- On-line graphics of the flow velocity, discharge, water level, and ultrasonic signal velocity
- Protocol of the flowmeter system
- Data output in ASCII-format
- Documentation of the software and the employed algorithm

11.6 Water and site maintenance

The effort needed to care for the measured cross-section depends on the conditions of the banks and the watercourse floor. The important points are:

- to keep the measurement paths free from vegetation and other blockages
- to record changes in the cross-section geometry after high waters
- to test the condition of the watercourse floor when a cross-section exists in a slow moving river, the danger being that the geometry of the cross-section could change due to sedimentation.

The exact overall requirements are difficult to specify; the amount and frequency of the maintenance must be individually determined. Quantum can help the customer develop a specific and effective maintenance plan.

12. Work safety regulations

In the installation of the ultrasonic flowmeter systems, it is important to take into account work safety and transport safety.

It is especially important to pay attention to the regulations pertaining to work with electrical installations involving high voltages in close proximity to water.

Underwater work is only permitted by trained, professional divers.

13. Literature in English

Cole. J:A: (1979): The deflection of an acoustic beam by temperature and salinity gradients. WDU/WRC Ultrasonic river gauging seminar reading.

Del Crosso (1974): Journal of the Acoustical Society of America, No. 56, 1084

Laenen, A.; Smith, W. (1983): Acoustic Systems for the Measurement of Streamflow. U.S. Geological Survey Water-Supply Paper 2213

A complete list of literature can be found at the end of the Germany copy of this handbook.