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Hydrometry — Measurement of discharge by the ultrasonic (acoustic) method

Hydrométrie — Mesure du débit à l'aide de la méthode ultrasonique (acoustique)

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 6416 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 1, *Velocity area methods*.

This third edition cancels and replaces the second edition (ISO 6416:1992), which has been technically revised.

INTERNATIONAL STANDARD **ISO 6416:2004(E)**

Hydrometry — Measurement of discharge by the ultrasonic (acoustic) method

1 Scope

This International Standard describes the establishment and operation of an ultrasonic (transit-time) gauging station for the continuous measurement of discharge in a river, an open channel or a closed conduit. It also describes the basic principles on which the method is based, the operation and performance of associated instrumentation and procedures for commissioning.

It is limited to the “transit time of ultrasonic pulses” technique, and is not applicable to systems that make use of the “Doppler shift” or “correlation” or “level-to-flow” techniques.

This International Standard is not applicable to measurement in rivers with ice.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772:1996, *Hydrometric determinations — Vocabulary and symbols*

ISO 4373:1995, *Measurement of liquid flow in open channels — Water-level measuring devices*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Applications

4.1 Open channels

4.1.1 The method is suitable for use in river flow measurement, a significant advantage being additional freedom from siting constraints in comparison with other available techniques. In particular, the method does not demand the presence of a natural control or the creation of a man-made control at the proposed gauge location, as it does not rely upon the establishment of a unique relation between water level and discharge.

4.1.2 Gauges using the method are capable of providing highly accurate flow determinations over a range of flows contained within a defined gauge cross-section. They are tolerant of the backwater effects created by tides, downstream tributary discharges, downstream weed growth, reservoir or head-pond water level manipulation, and periodic channel obstruction.

NOTE For locations subjected to significant bed level or profile instability, it may not be possible to use gauges.

4.1.3 Use of the method usually creates no obstruction to navigation. It creates no significant hazard or loss of amenity for other channel users or riparian interests. However, some species of fish may be sensitive to some types of ultrasonic signal. The gauge can be designed to be physically unobtrusive.

4.1.4 For use in remote locations, the electronic equipment can be designed to operate from battery power. To economise on power consumption, the system is usually set to sample the flow for short periods and to return to a quiescent condition between samples. (see 10.1.3 and 13.9.5).

4.1.5 The method is not really suitable for use when the channel is covered with ice, because of the difficulty of determining the cross-sectional area of the water. Although this is a limitation of use, the method may still have value in determining water velocity under the ice, if transducers can be positioned in unfrozen water.

4.2 Multiple channels

4.2.1 At locations where the total flow is divided between two or more physically separate channels, such as under a multiple-arched bridge, the instrumentation can be configured to determine individual channel flows separately and then to combine these to create a single unified determination of flow.

4.2.2 If flow may not readily be contained within a single well-defined cross-section, and in particular if there is significant flow that bypasses the main gauge cross-section by way of an extensive flood plain, it may be possible to subdivide the flood plain into a series of “channels” in which the flow can be measured.

4.2.3 A station designer may decide to provide a comprehensive flood-plain measurement capability by this means or may, alternatively, simply provide a flow or velocity sampling facility. In the latter situation, gauged cross-sections may be constructed in the flood plain. These do not normally provide total coverage, but merely provide locations at which flood-plain flow can be sampled for subsequent examination and analysis.

4.2.4 It should be noted that systems designed to determine flood-plain flow may suffer from the practical difficulties of

a) inability to commission the system due to there being no water in the measurement section,

b) maintenance of the section, including weed cutting, debris clearance and repair of vandalism.

4.3 Closed conduits

The ultrasonic method can also be applied to the measurement of flow in closed conduits, including both storm-water and foul sewers, under both free-flowing and surcharged conditions.

For systems used in foul sewers, special attention should be paid to the following:

a) the source of the water, especially whether it is from an aeration tank or from a section of channel containing aerators or from a hydro-electric plant. The air dissolved in the water from such sources may cause bubbles to form, and these may inhibit the operation of the flow gauge (see 10.3.1);

b) possible aeration of the water caused by a hydraulic jump or weir upstream of the measurement section, especially under storm conditions (see 10.3.1);

c) the design of transducer mountings, to eliminate the risk of fouling by grease, rags and paper;

d) the need for the system to meet local codes of practice for electrical equipment installed in potentially explosive atmospheres. This usually requires a certified intrinsically safe design for both the transducers (which can be piezo-electric sources of ignition) and for the electronic unit (see for example EN 50014);

e) the change in the flow computation algorithm when the conduit is surcharged.

For foul sewers which are less than about 4 m in width, a high loading of suspended solids is unlikely to present a serious problem of signal attenuation (see 6.2.3).

5 Method of measurement

5.1 Discharge

5.1.1 Discharge, as defined in ISO 772, is the volume of liquid flowing through a cross-section in a unit time. It is usually denoted by the symbol q and expressed in cubic metres per second (m^3/s). The definition of discharge is the product of the wetted cross-sectional area and the mean velocity vector perpendicular to it.

5.1.2 The measurement methods may either determine the bulk quantity discharge q directly, by measuring the time taken to fill a tank of known volume, or the methods may be indirect and require calculation of the discharge from measured flow velocities in all points of the wet cross-section. The latter are generally referred to as “velocity-area methods”. In practice it is not possible to measure velocities at all points, and so the velocity-area methods deal with only a limited number of measuring points.

The transit-time method is a velocity-area method using flow velocities which have been determined by the equipment, and which are averaged along one or more lines which are usually, but not necessarily, horizontal.

5.2 Calculation of discharge from the transit-time measurement

5.2.1 Flow measurement by the ultrasonic transit-time technique is analogous to flow measurement by current meters. However, while the most commonly used current-metering method is based on the estimation of mean velocity at a series of verticals dispersed across the gauged cross-section, in the transit-time method the velocity samples are horizontally orientated (and vertically distributed). In principle, flow can be computed by exactly the same methods applied to a current meter gauging (see ISO 748). However, in practice, the different graphical methods available do not lend themselves easily to automatic computation, and only the arithmetic methods are useable.

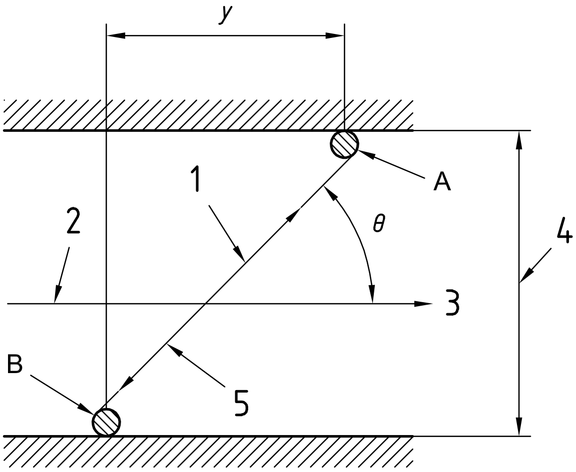
5.2.2 Discharge can be computed, provided that a relation can be established between the estimated (horizontally averaged) flow velocity and the mean cross-sectional velocity. If the measured velocity at a single elevation is not sufficient to establish this relation, measurements at more elevations can be carried out. The resulting samples of flow velocity can be vertically integrated to provide an estimate of mean cross-sectional velocity.

5.2.3 Discharge calculation also requires the cross-sectional area of the water to be known. An ultrasonic transit-time system will, therefore, normally be capable not only of making sample measurements of velocity, but also of determining (or accepting a signal from some other device determining) water depth, and of storing details of the relation between water depth and cross-sectional area. It will also normally be capable of executing the mathematical functions necessary to compute flow from the relevant stored and directly determined data.

6 Flow velocity determination by the ultrasonic (transit time) method

6.1 Principle

6.1.1 An ultrasonic pulse travels in a downstream direction faster than a similar pulse travels upstream. The speed of a pulse of sound travelling diagonally across the flow in a downstream direction will be increased by the velocity component of the water. Conversely, the speed of a sound pulse moving in the opposite direction will be decreased. The difference in the transit time in the two directions can be used to resolve both the velocity of sound in water as well as the component of the velocity along the path taken by the ultrasonic pulses.



Key

1 v_{path} component of water velocity along the path
2 v_{line} component of water velocity in the direction of the flow
3 direction of flow
4 channel width
5 ultrasonic path

A, B transducers
θ angle between the path and the direction of flow
y downstream distance between transducers

Figure 1 — Schematic illustrating the general principle

6.1.2 For the path between transducers A and B in Figure 1, the transit time for the ultrasonic pulses are:

$$t_{\text{AB}} = L/(c - v \cos\theta) \text{ and } t_{\text{BA}} = L/(c + v \cos\theta) \qquad (1)$$

where

t_{AB} is the transit time from transducer A to B, in seconds;

t_{BA} is the transit time from transducer B to A, in seconds;

L is the path length (distance between transducer A and transducer B), in metres;

c is the speed of sound in water, in metres per second;

v_{line} is the line velocity or the average velocity of the water across the channel in the direction of flow, in metres per second;

θ is the angle between the path and direction of flow.

Resolving for line velocity:

$$v_{\text{line}} = L \times (t_{\text{AB}} - t_{\text{BA}}) / (t_{\text{AB}} \times t_{\text{BA}} \times 2 \cos\theta) \qquad (2)$$

6.1.3 The transit times in Equation (2) are for the water path only, and do not include the fixed delays due to the travel times through the faces of the transducers and cables, delays in the transmitter and receiver circuits, and delays in signal detection (which may be affected by signal distortion). These fixed delays do not affect the transit-time difference ($t_{AB} - t_{BA}$), but will affect the term ($t_{AB} \times t_{BA}$). This factor is of particular importance for small channels or where long cable runs to the transducers are required.

Typical delay times for the transducers and electronic circuits are between 4 μs and 20 μs.

The delay time for the cables is typically 1 μs per 200 m of cable, i.e. for 100 m each way, transmit and receive.

Taking the signal delays into account, Equation (2) for the computed water velocity becomes:

$$v = L \times (t_R - t_F) / [(t_R - \delta) \times (t_F - \delta) \times 2 \cos\theta] \tag{3}$$

where

t_R is the transit time from the electronic unit via transducer A to B and back to the unit, in seconds;

t_F is the transit time from the electronic unit via transducer B to A and back to the unit, in seconds;

δ is the signal delay.

For a channel of width 1 m, with path angle of 45° and total signal delay of 10 μs, an error of 2 % in the computed water velocity would be introduced if the delay effect were to be ignored.

For wider channels, the effect of the signal delay is reduced in proportion to the path length, and may be insignificant.

6.1.4 It should be noted that the calculation of water velocity is

- independent of the speed of sound in water,
- proportional to the difference in transit times,
- inversely proportional to the product of the transit times,
- critically dependent on the angle between the path and the direction of flow (see Table 1).

Table 1 — Systematic errors incurred if the assumed direction of flow is not parallel to the channel axis

Path angle θ degrees	**Velocity error for 1° difference between actual and assumed flow direction** %
30	1,0
45	1,7
60	3,0

6.1.5 In open-channel flow measurement, practical considerations will normally dictate that

a) the transducers at either end of an “ultrasonic path” are located on opposite banks of the watercourse;

b) the line joining them is at an angle to the mean direction of flow, which should be between 30° and 65°.

6.1.6 The following limitations are encountered in open-channel flow measurement.

a) At intersection angles greater than 65°, the time difference between sound pulses in opposite directions may become small and therefore subject to a relatively large uncertainty, especially at low velocities.

b) At an angle of 90°, there will be no time difference between forward and reverse pulses, and thus velocity cannot be determined.

c) With large angles, there is also an increase in the error in velocity computation that results from assumptions made in the assessment of the angle. This is due to the presence of the cosine function in the equation relating time difference to velocity (see 6.1.3). Table 1 demonstrates this effect.

d) At intersection angles less than 30°, the following problems can arise.

   1) The length of the channel occupied by the gauge can become excessive, and cease to be quasi-uniform.

   2) The direction of flow relative to the path may not be constant.

   3) There can be practical problems with site selection, due to the length of the channel which is required to be set aside for the flow gauge, and maintained free of debris and weeds.

   4) The excessive length of the paths can cause problems of signal strength and/or signal reflection from the channel bed or water surface, especially if vertical temperature gradients are present.

6.1.7 To calculate discharge, the flow gauge should contain a means of storing details of the relation between water depth and cross-sectional area, determine water depth or stage, determine water velocity for each path, and be capable of executing the mathematical functions necessary to calculate flow from the relevant stored and directly determined data (see Clause 7).

6.2 Sound propagation in water

6.2.1 General

Sound is a mechanical disturbance of the medium in which it propagates. It encompasses a wide range of frequencies. The audible range is from approximately 50 Hz to 15 000 Hz, and is generally referred to as “sonic”. Frequencies less than 50 Hz are usually termed “subsonic”, and those above 15 000 Hz “ultrasonic”. Transit-time systems operate in the ultrasonic range at frequencies typically between 100 kHz and 1 MHz.

The performance of transit-time systems depends heavily on the characteristics of sound propagation in water. These characteristics are briefly described here.

6.2.2 Speed of sound in water

The speed of sound in water is independent of frequency, but depends on the temperature, salinity and pressure of the water. In open channels, the effect of pressure is negligible. Over the normal ambient temperature range, the speed of sound in fresh water varies from about 1400 m/s to a little over 1 500 m/s (see Table 2).

Table 2 — Speed of sound in non-saline water at different temperatures

Temperature °C	**Speed of sound** (approximate) m/s
0	1 402
10	1 447
20	1 482
30	1 509
40	1 529

NOTE 1 The above figures apply to the water in most natural fresh-water rivers and foul sewers.

NOTE 2 In seawater the corresponding speeds are approximately 50 m/s higher.

The speed of sound c in water is given by [6]:

$$c = 1\,402{,}4 + 5{,}01T - 0{,}055\,1\,T^2 + 0{,}000\,22\,T^3 + 1{,}33S + 0{,}000\,13S^2 - 0{,}013\,TS + 0{,}000\,1\,T^2S + 0{,}016d \qquad (4)$$

where

c is the speed of sound in water, in metres per second;

T is the water temperature, in degrees Celsius;

S is the salinity of the water, in grams salt per litre water;

d is the depth of water, in metres.

6.2.3 Propagation losses

Only a portion of the acoustic energy transmitted reaches the target. The loss in signal strength is called propagation loss, and consists of spreading loss and attenuation loss.

Spreading loss is the reduction in acoustic intensity due to the increase in area over which the given acoustic energy is distributed. Losses due to this cause depend upon the relation between the path length, the diameter of the ultrasonic transducer and its characteristic frequency. Spreading occurs in accordance with the inverse square law, which applies in general to all forms of radiant energy. However, if signals are measured as voltages, where energy is proportional to the square of the voltage, then the spreading loss follows an inverse law. This effect can only be observed over short path lengths, up to about 20 m, in clean water. Above this value, attenuation losses due to absorption and scattering start to take effect.

Absorption is the process by which acoustic energy is converted into heat by friction between the water molecules, as the sound wave is subjected to repeated compressions and expansions of the medium. In general, this loss is a function of frequency squared.

Scattering is the modification of the direction in which acoustic energy is propagated, caused by reflections from the innumerable inhomogeneities in the water, for example microscopic air bubbles and suspended particulate matter. These inhomogeneities result in changes in specific acoustic impedance, causing the signal to reflect and scatter. The effect is greater at higher transducer frequencies.

Losses due to absorption and scattering increase exponentially with increasing path length. This means that if the suspended solids loading in sewer water were such as to cause a loss of half the signal energy when the signal propagates through a metre of water, then that signal would be halved again after passing through another metre of water. For a path length of 20 m, the signal would be reduced to one millionth of the value expected for clean water.

For a 5 m path length in a foul sewer, a signal reduction of a factor of 30 (a factor of about 5,5 in voltage) would be tolerable, but for a 20 m path length it is unlikely that any signal would be observable.

For these reasons, transducers of lower frequency are used for the longer paths. The range of values of transducer frequency f for a given path length L is illustrated in Figure 2.

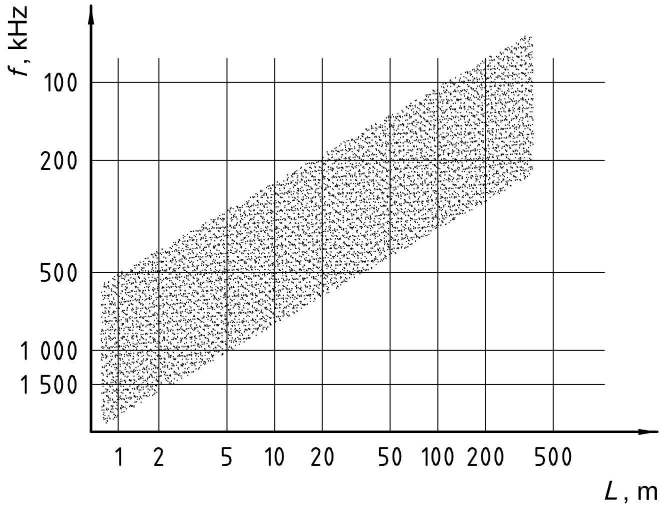


Figure 2 — Commonly used transducer frequencies for various path lengths

6.2.4 Signal path bending

6.2.4.1 The path taken by an acoustic pulse is bent if the water through which it is propagating varies significantly in either temperature or salinity. In slow-moving rivers, with poor vertical mixing, the effect of the sun upon the surface produces a vertically distributed temperature gradient. This causes the acoustic path to bend towards the river bed.

The acoustic wave propagates across the channel as a cone. If a vertical temperature gradient exists, only that ray which starts in a certain upward direction will arrive at the other end of the path. With a temperature gradient of 0,5 °C per metre of depth, over a path length of 50 m the vertical deflection D_r (as defined in Figure 3) will be about 0,5 m. In contrast, the effect of vertical density gradients (such as may be associated with salt water intrusion into the gauged reach) is to bend the path towards the surface.

Similar effects can be produced by horizontally distributed temperature or density gradients, as is the case with partial shading of the water surface from insolation such as found at the confluence where a tributary with waters of contrasting characteristics joins.

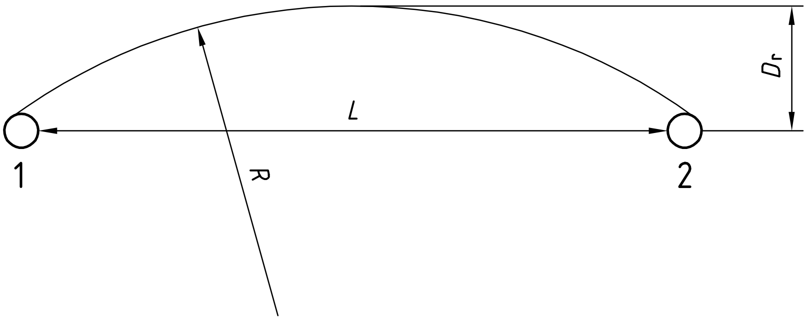
6.2.4.2 The approximate degree to which the signal path is bent is given by:

$$R = c_1 (d_2 - d_1) / (c_1 - c_2) \tag{5}$$

where

R is the radius of curvature of the ultrasonic path, in metres (see Figure 3);

c_1, c_2 is the speed of sound at depths d_1 and d_2 respectively, in metres per second [which can be calculated using Equation (4)].



Key

1 transducer
2 transducer

D_r deflection of the ultrasonic path
L path length
R radius of curvature of the ultrasonic path

Figure 3 — Signal bending as a result of a vertical temperature gradient

The deflection D_r of the ultrasonic path from a straight line is given by

$$D_r = R - \sqrt{\left(R^2 - 0{,}25L^2\right)} \qquad (6)$$

where L is the path length, in metres.

6.2.5 Reflection

6.2.5.1 Sound is reflected from the water surface and, to a lesser extent, from the channel bed. The bed is usually a net absorber of sound. As the acoustic wave propagates across a channel (generally as a cone of around 5° width), some part of it will intersect with the water surface and be reflected, suffering a 180° phase change in the process. The secondary wave will proceed across the channel and arrive at the opposite bank. Its arrival will be sensed by the target transducer later than the direct wave, and the difference in arrival time will be a function of the difference in the respective lengths of the direct and indirect paths.

Errors in signal timing will occur if the secondary signal interferes with the first cycle of the direct signal. To avoid this effect, the difference in the two paths should exceed one acoustic wavelength (speed of sound/frequency). This will be achieved if the depth of water above the acoustic path exceeds that given by Equation (7):

$$D_{\text{min}} = 27\sqrt{\frac{L}{f}} \qquad (7)$$

where

D_{min} is the minimum depth of water above the path and also the minimum clearance between the bed and the path, in metres;

L is the path length, in metres;

f is the transducer frequency, in hertz.

6.2.5.2 The minimum depth of water above the path for the various transducer frequencies and path lengths is given in Table 3.

Table 3 — Examples of minimum clearance for various transducer frequencies and path lengths

Path length L m	Transducer frequency f kHz	Minimum depth D_{min} m
1	1500	0,02
1	1000	0,03
1	500	0.04
3	1000	0.045
3	500	0.065
10	500	0,12
10	200	0,19
30	500	0,21
30	200	0,33
50	500	0,27
50	200	0,43
100	200	0,60
100	100	0,90

6.2.5.3 A similar restriction may apply to the channel bed, particularly if it is smooth and reflects rather than absorbing an acoustic signal. Signals reflected from the bed do not suffer a phase change.

7 Gauge configuration

7.1 General

7.1.1 Flow measurement stations using the ultrasonic method may be configured in many ways to take into account

a) local site circumstances,

b) the measurement uncertainty and operational reliability required,

c) the range of flows for which reliable data are required,

d) the resources available to the user to maintain the gauge in an operational state.

7.1.2 The number of depth sensors, number of paths, vertical spacing, angle to flow, the use of in-line, crossed or reflected configurations may all be specified.

The water depth shall be measured, using either one or more devices as specified in ISO 4373, or using upward-looking ultrasonic devices which are incorporated into the flow meter's electronic system. An error in the determination of depth by this method will occur if there is a difference between the mean temperature of the river and that where an ultrasonic depth transducer is positioned. A temperature difference of 5 °C will produce an error of about 1 %, depending on the offset between the transducer and the bed. The system designer should be aware of the possibility of such an effect occurring and include it in the estimate of uncertainty or, in extreme cases, select another method of depth determination. The designer should also be aware that if there are such temperature differences in the river it is likely that serious beam bending would occur and the ultrasonic method of flow determination may not be suitable anyway (see 6.2.4).

It should be stressed that a suitable site is of prime importance (see Clause 10). Although the effects of some undesirable site characteristics can be reduced by the installation of a more sophisticated system, a superior performance at a lower equipment cost will be achieved on a better site. It is recognized that the system designer often has to accept the site characteristics which are presented, but these can ultimately limit the achievable performance, both in terms of measurement uncertainty and reliability under adverse conditions.

7.2 Single-path systems

7.2.1 In its most basic form, the ultrasonic gauge can operate satisfactorily with a single pair of transducers, giving only a single “line” velocity determination. This single pair of transducers need not necessarily be mounted horizontally.

Provided that a relation can be established between this sample and the mean velocity in the cross-section, discharge can be computed. However the uncertainty of the flow determinations will inevitably be greater than that of the methods used to calibrate the velocity relationship. The cost of calibration, which will involve flow determinations by an alternative method at various flows and seasons, can be high.

If the relationship is estimated using the mean figures for velocity coefficient C_V from Table 4 (see 9.2), then an uncertainty of 15 % can usually be expected. Under limited circumstances, a single-path installation is capable of an uncertainty much better than this. These circumstances are

a) the depth range is limited to d/D between 0,4 and 0,7,

b) the velocity profile can be quantified,

c) the velocity profile does not vary significantly with level or flow variations.

7.2.2 Transducer mountings may be constructed to be movable in the vertical plane. Using this facility, a vertical velocity profile can be determined employing the gauge instrumentation in a manner analogous to the use of the rotating-element current meter. The transducers can then be set, for operational purposes, at an elevation that provides as close an estimate as possible of the mean velocity in the cross-section (see Figure 10).

7.2.3 In this variant, transducer settings may also be altered seasonally, to take differences in flow regime into account, but there can be practical limitations to the frequency with which such alterations can reasonably be made and therefore limitations to the general utility of this configuration.

7.2.4 For the single-path gauge with movable transducers, the range of water levels at the gauge site should normally be small or, at least, such changes as do occur should be slow. Quite wide variations in water level can sometimes be accommodated if the phenomenon is seasonal, for example in a groundwater-fed stream where discharges vary only slowly from day to day but where there may be distinctly different winter and summer regimes. The slowness of these variations can permit resetting of transducer levels on a seasonal basis.

7.2.5 The single-path gauge also relies upon there being a relatively stable velocity profile, essentially unaffected by changes in the relation between water level and flow. It is unsuited to locations that experience a significant change in velocity profile caused by upstream weed growth or silt deposition, and also to sites which experience significant backwater effects.

7.2.6 The single-path gauge is inherently vulnerable to transducer damage or malfunction. There is no built-in component redundancy capability (see 7.3.3). However, the system is simple and of low cost.

7.3 Multi-path systems

7.3.1 It will be necessary to install a multi-path flow meter system at sites where

a) there is wide and frequent variation in water level and/or flow,

b) the velocity distribution in the vertical deviates significantly from the theoretical, and may vary with seasonal weed growth,

c) there are significant backwater effects affecting the vertical velocity profile.

7.3.2 The number of paths that can be installed is limited by the cost of the installation and by the design of the gauge instrumentation. The aim is to achieve an acceptable representation of the vertical velocity profile in the gauge cross-section, at all levels and flows, from the highest to the lowest required to be measured.

The uncertainty in flow determination should be evaluated using the methods given in Clause 14. For a given configuration, the calculations should be performed for a range of water levels and flows.

7.3.3 If a high level of performance security (i.e. freedom from operational interruption or degradation) is also a goal in the system, it is desirable to provide additional “redundant” paths as well as water-depth sensors, such that physical damage, obstruction or malfunction of one or more of them has a minimal effect upon the overall uncertainty of measurement.

7.3.4 In some channels, especially where surcharge is possible, water-depth sensors using different technologies and ranges may be required to provide data over the whole range of operation. An automatic arbitration routine to select the most appropriate sensor will be needed.

7.3.5 Multi-path gauge configurations are also appropriate for sites where the flow is split between multiple channels, and where the cross-section of the channel varies in a complex way with depth. This is particularly so for channels which surcharge or where the flow meter section is located under a bridge.

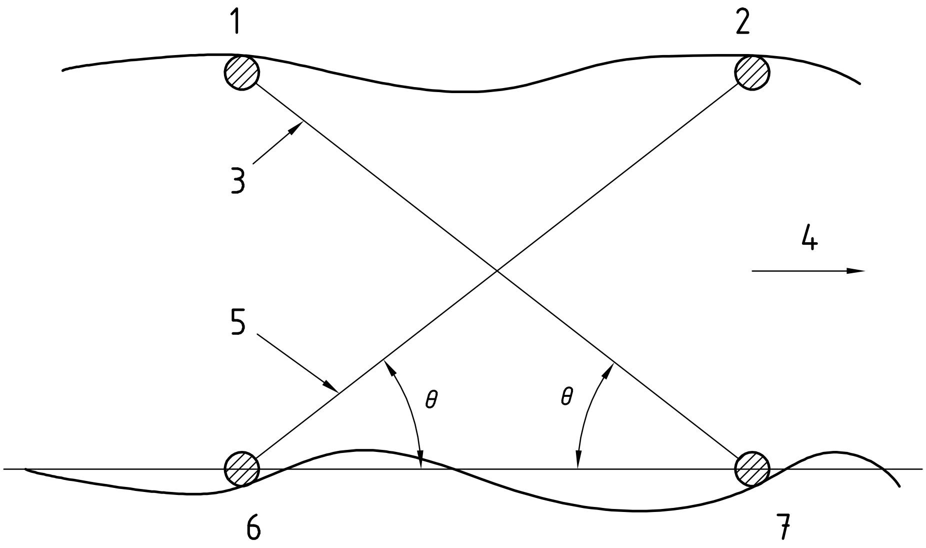
7.4 Crossed-path systems

7.4.1 One of the fundamental requirements of the ultrasonic technique is to know the angle at which each individual path in a system intersects the line representing the mean direction of flow at that elevation. Errors in this angle directly affect the computation (see Table 1).

7.4.2 In practice, it can be difficult to determine precisely the mean direction of flow at a given site. The assumption that it is parallel to the banks may not always hold. It may be true at some parts of the flow/level range, but not at others. At low flows in particular, the effects of complex bed geometry and upstream weed growth can affect the mean direction relative to the banks.

7.4.3 If the flow is not parallel to the banks (often referred to as “skew flow”), it follows that the direction cannot be constant across the channel. Indeed, the variation in flow direction across the channel can be so large that the approximation formula as given in Equation (3) is erroneous, and a more complex treatment would be desirable. However, since this requires some knowledge of the spatial variation of flow direction, it is not normally possible to do anything other than apply the approximation, so such a situation is best avoided.

7.4.4 If there is a bend or asymmetric change in the channel shape less than 10 channel widths upstream or 3 widths downstream, it may be assumed that the flow will not be parallel to the channel banks. It will therefore be necessary to introduce an element of self-correction by configuring the gauge to have one or more sets of paths installed as pairs, set at the same elevation but laid out in the form of a symmetrical cross (see Figure 4).



Key

1	transducer
2	transducer
3	cross path
4	direction of flow
5	normal path
6	transducer
7	transducer

Figure 4 — Plan for crossed-path gauge

7.4.5 The twin paths should normally be disposed so as to intersect in mid-stream, and to form the equal sides of a pair of congruent isosceles triangles. Gross mismatch between path lengths should be avoided, because of the likelihood of there being significant differences in cross-sectional geometry between the two paths.

The path angle, θ, for the uppermost paths should be between 40° and 65°. If the path angle is less, the flow-meter section will be long, and the flow direction may not be constant throughout the section. This would impair the compensating effect of the crossed-path configuration.

In trapezoidal channels, if it has been decided to mount the transducers on each bank in sloping arrays normal to the flow direction, the angles for the paths near to the bed may be much less than 40°.

7.4.6 Within the system instrumentation, each line velocity in a crossed pair should be computed separately. If the two velocities computed for a pair of crossed paths are similar (within computational and measurement error), then the path angle assumed by the system design may be taken to be correct. If the two velocities are significantly different, then the assumed path angle is incorrect. Neither of the computed line velocities will be correct; one will be high and the other low. In natural rivers, typical differences between the velocity determinations of crossed paths may be as high as 20 % (9.2.7 and 9.2.8 deal with the computation of resultant velocity, and Clause 15 deals with the basic measurement uncertainties inherent in this component of the system).

7.4.7 The use of crossed paths will compensate completely for skew flow.

A large difference between the pair of paths should be taken as a warning that flow direction is not well defined, and errors can result even after averaging.

7.4.8 At locations where high gauge reliability is required, the principle of measurement redundancy (see 7.3.3) may be combined with the use of crossed-path geometry to reduce the risk of system failure through physical damage, by having transducer arrays that are physically separated on the channel bank.

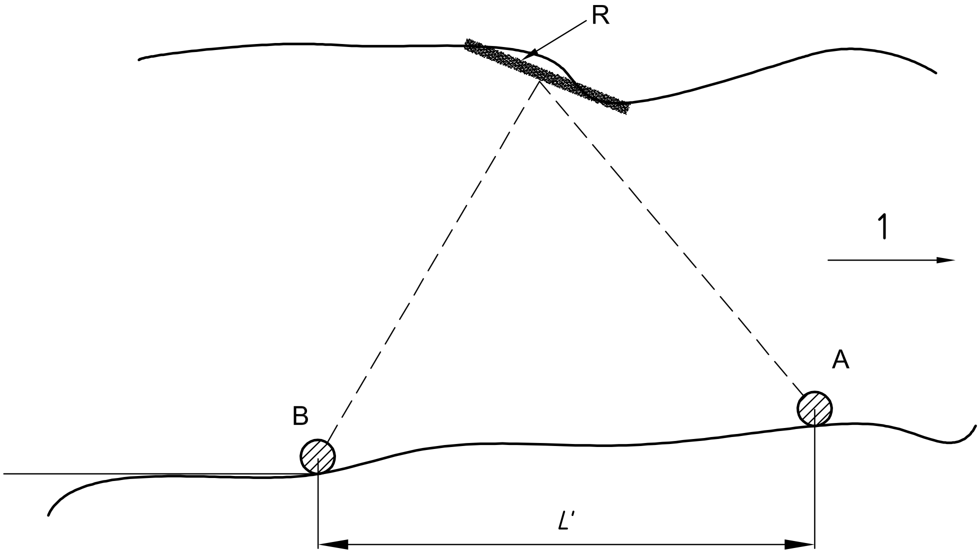
7.4.9 Interleaved crossed paths are paths which cross at different elevations. This arrangement is sometimes used to reduce the number of paths to save cost. The affordable number of paths is spread throughout the channel height to try to obtain good sampling of the vertical velocity profile whilst attempting to achieve some compensation for skew flow.

Whilst there is some justification for this approach where all the interleaved crossed paths are under water at all states of depth, significant errors could result if changes in water level cause one path to stop whilst its crossed partner continues to operate.

7.5 Reflected-path systems

7.5.1 The basic ultrasonic system normally requires that there be sets of transducers on both banks of the channel. It is required that signal cables should cross the channel, either overhead, or on the bed, or trenched into the bed. Alternatively, there may be situations in which it is inappropriate to provide live transducers on both banks. One bank may be inaccessible, making system servicing difficult.

In such situations, a system configuration may be used that has both transmitting and receiving transducers on the same bank, communicating via a passive reflector located on the opposite bank (see Figure 5).



NOTE Total path length L = AR + RB.

Key

1 direction of flow

A downstream transducer

B upstream transducer

R reflector

L' projected distance parallel to the direction of flow

Figure 5 — Plan for reflected-path gauge

7.5.2 The equation for calculation of water velocity is:

$$v = L^2 \times (t_{AB} - t_{BA}) / (2\, L' \times t_{AB} \times t_{BA}) \tag{8}$$

where

v is the average velocity of the water across the channel in the direction of flow;

L is the path length (distance from transducer A to the reflector R and to transducer B);

t_{AB} is the transit time from transducer A to transducer B via the reflector R;

t_{BA} is the transit time from transducer B to transducer A via the reflector R;

L' is the projected distance parallel to the direction of flow, between transducers A and B.

7.5.3 As a result of this configuration, the paths become approximately twice as long. However, longer paths can be a disadvantage, requiring possibly larger transducers of a lower frequency and presenting a greater chance of signal attenuation under conditions of high sediment load.

7.5.4 The configuration of a reflector system is not that of symmetrical crossed paths, and it is possible for the direction of flow to change within the gauging section. The reflector system therefore will not give reliable correction for skew flow.

7.5.5 A disadvantage of the reflector system is that of alignment. Not only do the transducers have to be aligned but so does the reflector. Indeed, most reflector designs are such that in at least one plane the angular deviation of the beam will be twice the misalignment of the reflector, making it particularly sensitive (see 13.3).

7.6 Systems using transponders

7.6.1 In rivers, where it is impractical to install cables across the river, transponders (which are analogous to reflectors) may be used.

A transponder is a system of transducers and electronic circuits, installed as indicated in Figure 6. When B receives a signal from A, it causes a new signal to be transmitted from C to D. When C receives a signal from D, it causes a new signal to be transmitted from B to A.

7.6.2 The Equation (9) below for water velocity is derived from Equation (8):

$$v = L^2 \times (t_{AD} - t_{DA}) / (2 \times L' \times t_{AD} \times t_{DA}) \tag{9}$$

where

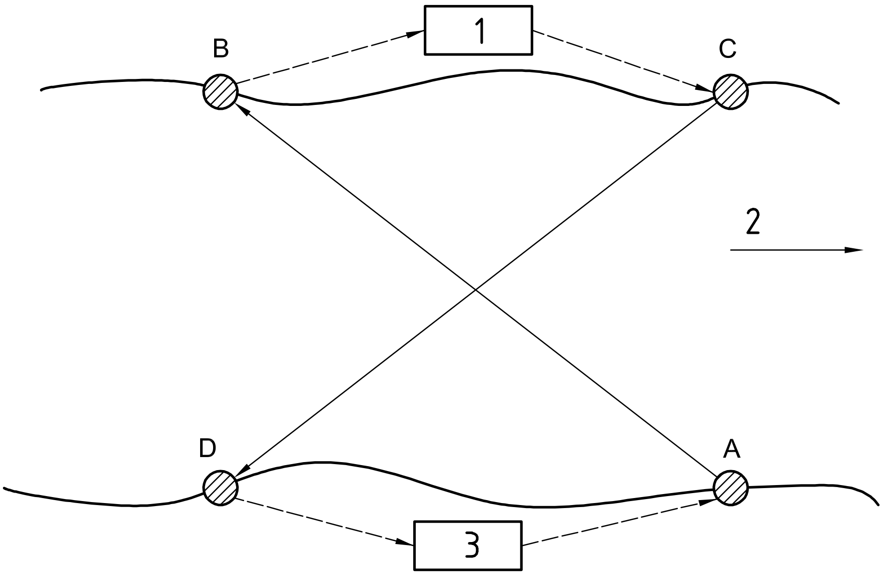
v is the average velocity of the water across the channel in the direction of flow;

L is the path length (distance from transducer A to B plus from transducer C to D);

t_{AD} is the transit time from transducer A to D via the transponder;

t_{DA} is the transit time from transducer D to A via the transponder;

L' is the projected distance parallel to the direction of flow, between transducers A and D plus that between transducers B and C.



NOTE Total path length $L = \text{AB} + \text{CD}$

Key

1 transponder unit
2 direction of flow
3 electronic unit

A downstream transducer
B transducer
C transducer
D upstream transducer

Figure 6 — Plan for a gauge employing a transponder

7.6.3 In this configuration the paths are no longer than for a conventional system, and so the problems experienced by a reflector system (see 7.5.3) are avoided.

7.6.4 The configuration of a transponder system can be made similar to that for symmetrical crossed paths; it can therefore provide automatic correction for skew flow.

7.6.5 A disadvantage of the transponder configuration is in the complexity of the electronics of the transponder unit, especially if the system is multi-path or has to be battery-powered.

7.7 Systems using divided cross-sections

7.7.1 Modern instrumentation technology allows the adoption of exceedingly complex path configurations, the resulting system control and computational implications being accommodated with relative ease.

7.7.2 If site geometry is complex (for example a main channel with flood berms), if there is a need for measurement over a wide flood plain, or if there is an exceedingly wide main channel to gauge, it may be possible to achieve operational viability by dividing the cross-section into a number of separate channels, each channel being treated as a relatively simple gaugeable entity, and adding together the individual results (see 4.2).

7.8 Sloping paths

It may be appropriate to install paths which are not horizontal, particularly with but not restricted to single path systems. For example, the lowest path of a multiple path system may be deployed in this manner.

The reasons for this are

a) if a single-path system is being used in deep water (e.g. for reasons of economy), a better estimate of velocity can be obtained if the path is sloping because it will obtain contributions from a "band" of water rather than a single line, and

b) if the channel cross-section is much deeper on one side than the other, a horizontal path would not sample the velocity in the deeper part. Thus, a potentially large part of the cross-sectional area would then be assigned to a velocity measured at a higher level. To avoid this, the bottom path can be constructed to be lower on the deeper side than on the other. The level assigned to that path will be equal to the average level of the two transducers.

8 Calculation of discharge

8.1 Single-path systems

In systems where only a single-path determination of velocity is made, it will be necessary to establish a relation between this and the mean velocity in the cross-section (see 9.2). If this relation is stable, calculation can be straightforward, with flow derived as

$$q = C_{\text{v}}\, v \cdot A \qquad (10)$$

where

q is the discharge rate, in cubic metres per second;

C_{v} is a velocity factor, derived empirically or by modelling, varying with the ratio of the path elevation to the water depth;

v is the velocity, in metres per second, determined in a single path perpendicular to the cross-sectional area A

A is the cross-sectional area, in square metres, which is a function of the water depth.

In systems where the single path is located at a depth that is representative of mean velocity in the cross-section, the value of C_{v} may be unity. It may take some other value and still be stable, or it may vary with depth of flow. It will be necessary to establish the value(s) of function C_{v} by calibration (see Clause 9).

In the absence of an established calibration, the relationship for mean C_{v} for different depths given in Table 4 may be used initially, although care shall be taken to ensure that the conditions are applicable as stated in 9.2.3. However see 7.2.1.

This formula can also be used to calculate flow for single-path systems utilizing the reflected-path system (see 7.5).

8.2 Multi-path systems

8.2.1 General

8.2.1.1 A multi-path system is one in which there are at least two ultrasonic paths at different elevations beneath the water surface It may be thought of as being built up by a series of panels on top of one another. The panel dimensions can be derived from the fixed geometry of the channel, in which a panel elevation is determined by the positions of the acoustic paths, and a panel thickness is defined by the differences in elevations of these paths. Flow computation may utilise either the mid-section or the mean-section method.

8.2.1.2 In practice, more line-velocity determinations are available from active paths, and the closer they are to bed and surface, the less the uncertainty associated with these aspects of velocity estimation. In station designs where the lowest path is close to the bed, predetermined assumptions can be made concerning the estimation of the near-bed velocity, without the need for current metering, and without increasing the uncertainty in total flow measurement.

8.2.1.3 There will be times when individual paths in a multi-path system are rendered inoperative, either because of obstruction or through physical damage to transducers or through failure of other parts of the instrumentation. In a well-designed system, flow determination should nevertheless continue to be possible, even if uncertainty is slightly increased. The increase in uncertainty depends upon the ratio of failed paths to operational paths. If there is more than one failed path, residual uncertainty will also depend upon the distribution of failed paths among the remaining operational ones. If they are adjacent, the resultant error will be greater than if they are not.

8.2.1.4 An alternative to the above integration methods is to use the measured path velocities to determine the general form of the velocity profile. This general form should account for proper bottom and surface boundary conditions. Such a form is likely to be site-specific, and requires confirmation by current-metering. With this information, and the cross-section geometry, the discharge can be calculated.

It should be remembered that the relationship can be affected by upstream weed growth, and may therefore be unstable and change with the seasons.

8.2.1.5 The arithmetic mean of the readings obtained from the crossed paths at the same elevation should be used to produce a single line-velocity at that elevation. If one path fails, its partner can be taken alone. However, if the angles to flow direction of the two crossed paths are substantially unequal, an error will be produced. Asymmetrical geometry is therefore not recommended (see 7.4.4 and 7.4.7). Unless an empirically developed weighting factor is automatically applied when a path fails, an error will remain. The weighting factor may vary with flow and season (as a result of asymmetric weed growth). If an attempt is made to establish the factor automatically, care should be taken to ensure that it is not developed at very low flow, when the differences between the readings of the two crossed paths can be very great; nor when a path is about to fail when its readings may be erroneous.

8.2.1.6 An alternative method for dealing with crossed paths is to calculate two discharge figures, one for each plane of paths, utilizing either the mid-section or mean-section method. The channel flow is calculated as a simple average of the two results. If all active paths are operating, there will be no difference in the result. This method is less sensitive to path failure than one involving the averaging of individual crossed-path velocities.

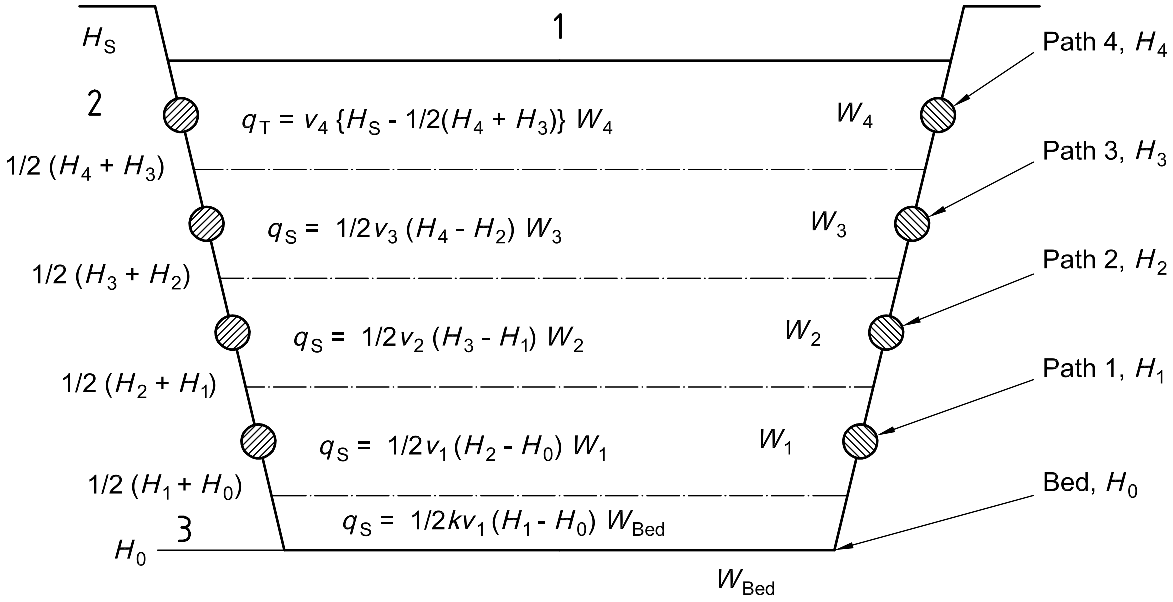
8.2.1.7 Multi-path configurations utilizing the reflected-path or transponder system should calculate flow as if they were multi-crossed-path flow gauges, using either the mid-section or mean-section methods.

8.2.2 Mid-section method

8.2.2.1 In the mid-section method (see Figure 7), each path velocity should be taken to be the mean for the panel defined by the two lines mid-way between the path in question and the next highest and the next lowest in the transducer array; the panel "width" should be the channel width at the elevation of the path.

8.2.2.2 The highest panel in the vertical stack is defined as being bounded below by the line that is halfway between the line of the highest "active" path and the one immediately below it. It is bounded above by the water surface. The mean velocity in this highest panel is taken to be the velocity measured in the highest active path.

8.2.2.3 The mean "width" of the top panel is the mean of the width of the channel in the plane halfway between the highest active path and the one immediately below it, and at the water surface. This latter value may have to be derived by interpolation between the known widths of the channel at the elevation of the highest submerged path, and that at the next highest submerged path.



Key

1 water surface
2 top panel
3 bottom panel

H	height, in metres, above a defined datum
W	width of the cross section, in metres, at the corresponding height
v	velocity, in metres per second, determined by the corresponding path
k	factor which relates the mean velocity of the lowest panel to that determined by the path 1. Normally this is between 0,4 and 0,8
q_S	flow in the corresponding panel or slice
q_T	flow in the top panel which contains the highest working path

Total flow $q = q_0 + q_1 + q_2 \dots q_T$

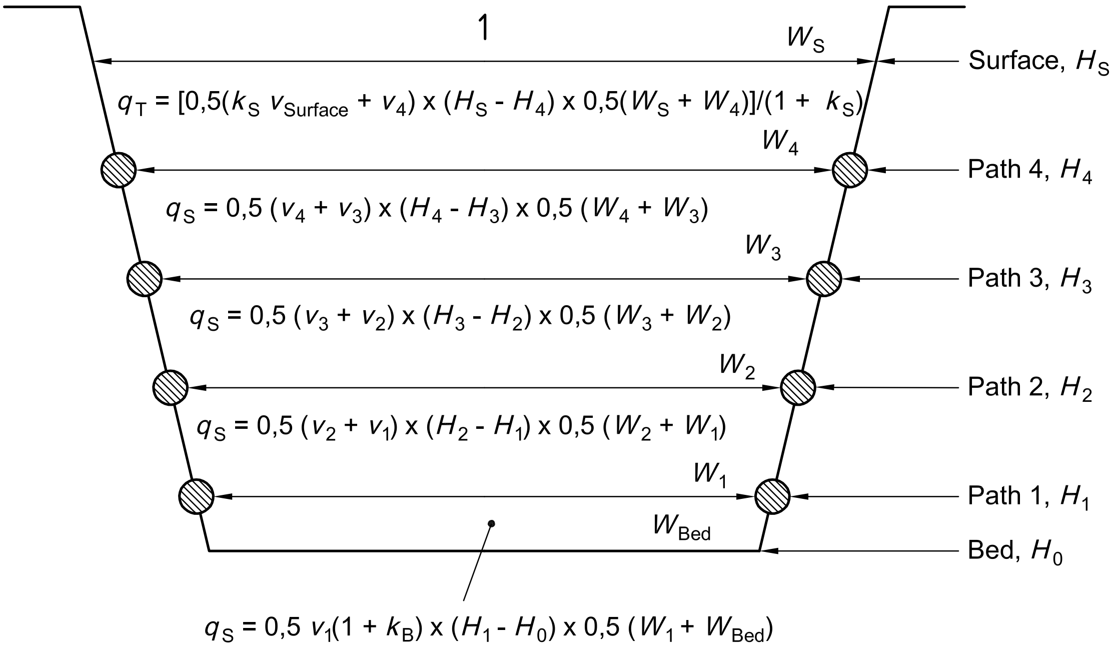
Figure 7 — Example of flow calculated by mid-section method using four operational paths

8.2.2.4 The “thickness” of the highest panel is the difference in elevation between the water surface and a point midway between the two highest paths.

8.2.2.5 The bottom or lowest panel in the vertical “stack” is defined as being bound by the line which is midway between the lowest “active” path and the bed. The mean width of the lowest panel is the width of the channel at a point midway between the lowest “active” path and the bed. Some interpolation of channel geometry may be required to identify this value accurately. The mean velocity in the lowest panel will be that measured by the lowest path, multiplied by a factor which will normally lie between 0,4 and 0,8. This factor, which is site-specific and may vary with stage, can be determined empirically by current-metering (see 9.1.2 and ISO 748).

8.2.3 Mean-section method

8.2.3.1 In the mean-section method (see Figure 8), the mean panel velocity is the mean of the two velocities measured by the paths which bound the panel. In the highest panel, the mean velocity is calculated from a limited extrapolation of the velocities determined in the top two active paths. In the lowest panel, the mean velocity is the mean of the velocity measured by the lowest path and the near-bed velocity. The near-bed velocity, which will be site-specific and may vary with stage, can be determined empirically by current-metering (see ISO 748).



Key

1	water surface
H	height, in metres, above a defined datum
W	width of the cross-section, in metres, at the corresponding height
v	velocity, in metres per second, determined by the corresponding path
v_s	surface velocity, given by $v_s = v_4 + (v_4 - v_3) \cdot k_s \cdot (H_s - H_4)/(H_4 - H_3)$ where k_s is a multiplying factor between 0 and 1 but limited to a value of $v_4 + (v_4 - v_3)$ in the event of $(H_s - H_4)$ being greater than $(H_4 - H_3)$.
k_B	factor which relates the velocity at the bed to that determined by path 1; normally between 0,4 and 0,8
q_s	flow in the corresponding panel or slice
q_T	flow in the top panel which contains the highest working path

Again, total flow $q = q_0 + q_1 + q_2 \dots q_T$

Figure 8 — Example of flow calculated by mean-section method using four operational paths

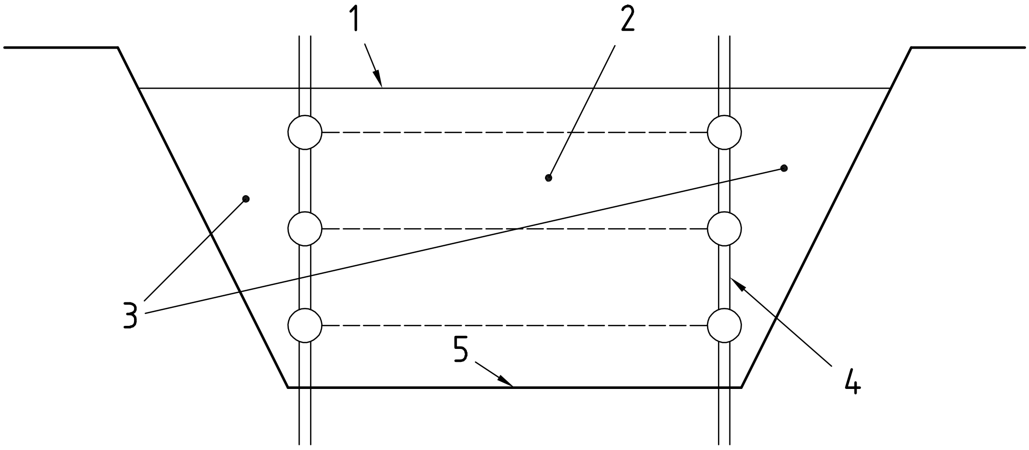
8.2.3.2 A mean panel “width” is computed from site-survey data stored in the flow computer; it is not necessarily defined by the transducer positions. Panel “thickness” is determined by the difference in elevation between paths; for the lowest panel this becomes the difference in elevation between the lowest path and the bed, and for the highest panel this becomes the difference in elevation between the highest “active” path and the water surface.

If the channel becomes surcharged, the algorithm for the flow in the highest panel should be changed to one similar to that for the lowest panel, to take into account the friction of the top of the conduit.

8.3 Systems with transducers in the channel

In channels where the banks are irregular in cross-section or covered in weed, it may be acceptable to install the transducers on piles placed at a distance from the banks (see Figure 9).

The proportion of the "unmeasured" to the "measured" flows will vary with depth and weed accumulation on the banks. It will usually be necessary to assess the "unmeasured" components at various flow conditions using current meters (see 9.1.2) and to add an allowance for the "unmeasured" flow to produce a total flow for the channel. However, if the proportion is small, the corrections to be applied may be small, and the uncertainty generated by these effects may be acceptable.



Key

1 water surface
2 measured flow
3 unmeasured flows
4 vertical transducer stack
5 bed

Figure 9 — Installation with transducers in the channel

9 System calibration

9.1 General

9.1.1 The travel-time technique provides an absolute determination of velocity from travel times, path angles and lengths, without requiring any calibration (see Clause 6). Provided that the acoustic pulses in the two opposite directions are transmitted practically simultaneously, the determination of the path flow velocity component does not depend on the velocity of sound [see Equation (3)].

9.1.2 Calibration, in principle, is required only for the computation of discharge from single-path systems, (see 8.1); and for systems where the transducers are located in the channel at a distance from the channel banks (see 8.3). For single-path systems, the calibration is mainly related to the vertical distribution of the flow velocity. This distribution is included in the measurements of multi-path systems, and if the paths provided in the system design are sufficiently numerous, there should be no need for calibration. However, if the bottom panel represents a large part of the total cross-sectional area, either current-meter calibration of this panel's flow, or a careful analysis of its likely profile will be necessary.

9.1.3 Even with multi-path systems, where the velocity distribution is inherently well-sampled, there will often be a user's demand for "verification" by means of an alternative method. Often, the verification will have a greater uncertainty than the determination made by the multi-path flow meter.

Verification differs from calibration. The ultrasonic flow meter is deemed to be verified if the uncertainty bands of the flow determinations from the two methods overlap. The results of the alternative method should not be used to change the parameters of the ultrasonic flow meter.

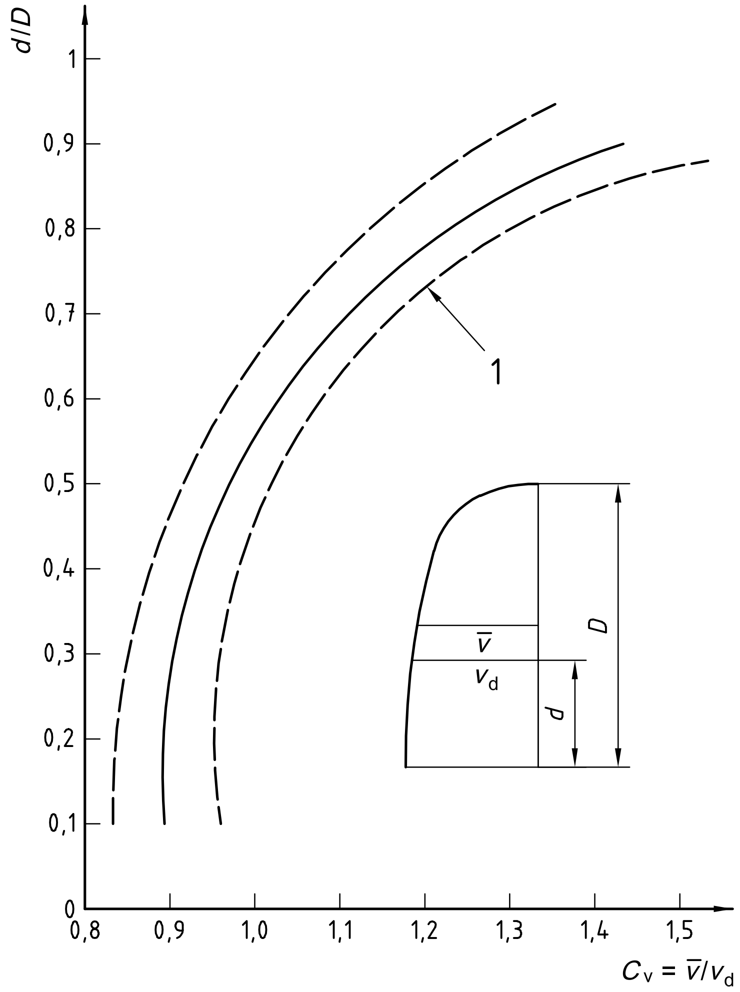
9.1.4 Single-path systems (or systems with a small number of separate paths) require calibration to establish the relation between line velocity and mean velocity for the range of stages likely to be experienced, and to conduct periodic checks to ensure that the relation remains stable. Calibration may be completely theoretical if the velocity distribution is well known. Calibration may be achieved using current meters or the ultrasonic system itself.

9.2 Single-path systems

9.2.1 When a single pair of transducers is fixed in position, it should be set at an elevation which gives the average velocity in the cross-section of that part of the flow range of particular interest to the user. If the vertical velocity distribution is logarithmic, then the average velocity will be sampled by positioning the transducers at approximately 0,6 D from the surface, where D is the depth of flow above the mean bed level (see Figure 10).

9.2.2 In situations where the vertical velocity distribution is not logarithmic, appropriate analysis of the observed distribution will yield positioning information for the transducers. Vertical velocity distributions can be defined by means of the velocity coefficient $C_\mathrm{v} = \bar{v}/v_d$ determined for various values of the relative position d/D from 0,1 to 0,9, where $\bar{v}$ is the vertically averaged velocity and v_d is the line velocity at distance d from the surface. Thus the optimum elevation of the transducers is at the value of d/D when $C_\mathrm{v} = 1$ (see Figure 10).

9.2.3 However, when the stage changes the transducers will no longer give the average velocity. They will underestimate it for an increase in stage and overestimate it for a decrease in stage. An independent calibration should establish the relevant relations. This can be done through the procedure explained in 9.2.2 for several stages of flow. The measured values of C_v are to be related to the d/D values (see Figure 10 and Table 4). The data points will have some scatter, depending upon the geometrical similarity of the vertical distributions. The standard deviation should be computed for each value of d/D at the 95 % confidence level. When the stage changes, the appropriate value of C_v can be found from Figure 10 at the corresponding value of d/D. It should be noted that Figure 10 is an example only, which depends heavily on local site conditions.



Key

1 95 % confidence level for C_v 2 × σ (Table 4)

Figure 10 — Plot of mean of C_v values against d/D values, based upon data from Table 4

Table 4 — Examples of observed coefficients of velocity C_v $(= \bar{v}/v_\text{d})$ for values of d/D between 0,1 and 0,9

Example number	C_v for values of d/D								
	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
1	0,839	0,854	0,874	0,898,	0,930	0,973	1,044	1,189	1,508
2	0,845	0,854	0,874	0,894	0,924	0,971	1,047	1,196	1,495
3	0,840	0,857	0,878	0,897	0,925	0,967	1,034	1,186	1,499
4	0,852	0,866	0,884	0,907	0,931	0,964	1,025	1,152	1,440
5	0,838	0,857	0,881	0,914	0,944	0,982	1,042	1,149	1,420
6	0,847	0,867	0,884	0,909	0,940	0,977	1,036	1,148	1,401
7	0,851	0,871	0,893	0,923	0,951	0,989	1,046	1,138	1,373
8	0,863	0,873	0,896	0,920	0,932	0,972	1,030	1,113	1,430
9	0,871	0,882	0,888	0,905	0,929	0,968	1,018	1,115	1,367
10	0,893	0,900	0,914	0,929	0,953	0,985	1,012	1,078	1,229
11	0,769	0,806	0,829	0,880	0,928	1,005	1,095	1,275	1,642
12	0,845	0,871	0,899	0,929	0,960	0,994	1,018	1,097	1,300
13	0,856	0,870	0,894	0,918	0,944	0,981	1,032	1,112	1,335
14	0,868	0,883	0,900	0,917	0,944	0,983	1,035	1,094	1,284
15	0,810	0,832	0,849	0,878	0,913	0,969	1,068	1,264	1,629
Mean C_v	0,846	0,863	0,882	0,908	0,937	0,979	1,039	1,154	1,424
Standard deviation, σ	3%	3%	2%	2%	1%	1%	2%	5%	8%
NOTE Based upon field observations, at mean water depths between 1,939 m and 2,201 m, of seven separate ultrasonic line velocities determined at depths between 0,149 m and 1,613 m.									

10 Site selection

10.1 Practical constraints

10.1.1 The site at which the ultrasonic flow meter is to be installed should be easily accessible. During its installation, civil engineering works may be required, and heavy construction equipment may be needed on site. The technique relies upon the application of electronic technology, and both commissioning and subsequent servicing require the use of specialized electronic equipment. The need to manhandle such equipment over long distances should be avoided.

10.1.2 If there is a demand for verification measurement by means of an alternative method, it is prudent to bear in mind the needs of acceptable alternative measuring methods.

10.1.3 Continuous operation of sophisticated multi-path systems from a battery-powered source for short periods (48 h) is feasible. Long-term operation (3 months to 6 months) employing systems having a low sampling rate (e.g. 20 s sample every 30 min) is also feasible. However for reliable sustained operation of a multi-path flow-meter, the technique requires provision of a continuous source of electrical energy.

10.2 Physical constraints of the measurement site

10.2.1 The channel to be gauged should be straight, with its opposite banks parallel. The bank-to-bank bed profile should be as nearly horizontal as possible. There should be a minimum change in cross-section geometry between the upstream and downstream extremities of the gauged section.

10.2.2 The flow calculation requires a cross-sectional shape to be stable with respect to time. Locations that are subject to significant bed level or profile instability should be avoided.

10.2.3 The gauge cross-section should be free of weed growth, as it seriously attenuates the acoustic signal. Different types of weed can have different effects, because it is the air included within the plant structure which causes scattering of the acoustic wave.

10.2.4 Refraction of the acoustic signal can be caused by temperature gradients in the water, and signal loss may result (see 6.2.4). Channel reaches that maintain deep water during low-flow periods (with consequent low mean velocities) may suffer from this problem during periods of high insolation.

10.2.5 Problems may be encountered at sites with variable water density, e.g. sites subject to the periodic intrusion of saline or brackish water. The effects are similar to those due to water-temperature gradients (see 6.2.4). The key factor is the periodic nature of the intrusion. The technique is not precluded from use in brackish or saline waters, but signal loss due to refraction or reflection can occur. In estuaries, brackish water intrusions can cause cross-gradients and time may need to be allowed for the flow to stabilize and densities to become uniform, before measurements can be achieved.

10.2.6 Suspended solids in the water may significantly affect signal attenuation, causing both reflection and scatter. In rivers having a width of the order of 30 m or more, and where concentrations greater than about 1 500 mg/l can be experienced for significant periods, or where reliable measurement is particularly important under such conditions, the ultrasonic technique may not be suitable.

If such conditions are considered likely, a signal propagation survey should be performed (see 11.5).

10.2.7 Sound propagates through water as cones of projection. Usually, the cone of a transmitting transducer will intersect with the bed and the water surface before reaching the related receiving transducer, resulting in signal reflection (see 6.2.5). This may present the instrumentation with difficulties in signal interpretation, and spurious measurement may result. The minimum clearance D_{min} between a path and the bed or water surface can be calculated using Equation (7). However, more severe practical limits may apply, governed by boulders on the bed which may obstruct a path, temperature or salinity gradients, and surface standing waves which may either obscure the path or entrain air at high velocities.

In general, the ultrasonic system is unsuitable for use in wide, shallow channels. Limiting conditions at a particular site depends upon the number of paths to be installed and the number of paths remaining operational during low water, the roughness of the bed and the amplitude of surface waves at high velocities.

10.2.8 For effective operational use of the gauge, velocity profiles in the gauged cross-section should show only minimal differences between the upstream and downstream extremities. Reaches that exhibit significantly changing velocity profile should be avoided. If no alternative sites are available, consideration should be given in the gauge design to

a) making the gauged reach as short as possible,

b) incorporating additional paths to achieve better velocity sampling in the vertical, or

c) making provision to correct for non-parallel flow by means of a crossed-path system.

10.3 Physical constraints which are distant from the measurement site

10.3.1 The presence of entrained air bubbles in the water may cause problems due to reflection and scattering of the propagated acoustic wave. Locations which are downstream of aeration tanks, dams, weirs, waterfalls, hydraulic jumps, mill or power-plant tail-races suffer from this problem, which can persist for many hundreds of metres downstream from the source. The ultrasonic gauge should be located at least 3 min flow travel time downstream of the source of aeration for narrow channels, 10 min for channels of 30 m width and up to 30 min for wider channels. For channels containing sewage, the effect of aeration is more pronounced and longer recovery times are necessary.

If aeration is possible, a signal propagation survey as described in 11.5 should be done.

10.3.2 The physical properties of the water in the channel reach to be gauged should be as homogeneous as possible. Signal attenuation can result if an upstream tributary is injecting water of a significantly different physical character (water temperature or salinity). Full mixing of the water may not be achieved for a considerable distance downstream of the confluence.

10.3.3 Velocity profiles departing significantly from the ideal can be generated by bed, bank or tributary confluence conditions at remote locations, but can persist to have an effect at the gauge. These remotely-generated hydraulic effects can be present during some channel-flow states, but not during others. Locations near severe bends in the channel, or close to tributary streams of hydrological regimes different from that of the main stream, should be avoided.

10.3.4 Some instrumentation can suffer significantly from ambient electrical noise, which can originate quite a distance from the gauge location. To reduce this risk, the electronic equipment of the flow meter should be in compliance with EN 50082-2. Signal cables may incorporate a screen to reduce the effects of noise. Another precaution which can be taken is to employ signal amplification at the transducers. Depending on the manufacturer's advice about the instrument's sensitivity to noise, a survey to check the presence of excessive electromagnetic interference may be advisable.

10.3.5 If the free migration of fish is important, tests may have to be performed to demonstrate that the particular types of ultrasonic signal generated by the proposed flow gauge do not inhibit the migration.

11 Site survey — Before design and construction

11.1 General

Detailed site survey work should be carried out to evaluate the risks to system performance that might arise from each of the constraining factors outlined in Clause 10. Their likely effect upon overall system performance should be known before gauge design is undertaken. All surveys should be carried out more than once, at times that are representative of both high- and low-channel stages and flow states, and of seasonal climatic and vegetation extremes.

11.2 Visual survey

A visual survey should be undertaken on both banks of the watercourse, for an appreciable distance upstream and a short distance downstream of the potential site, to check that no obvious hazards to system performance are evident.

The factors of interest include

a) water-level range,

b) weed growth,

c) possible sources of aeration,

d) sediment concentration,

e) location of bends and weirs,

f) location of confluence and discharges into the channel,

g) river traffic,

h) the effects of the operation of navigation locks or power-generation facilities,

i) security from unauthorized interference,

j) land ownership,

k) bed and bank condition (shape and stability),

l) velocity profiles,

m) access for construction, operation and servicing.

11.3 Survey of the cross-section

The cross-section of the proposed gauge should be surveyed thoroughly. If circumstances allow, the survey should extend from as much as ten channel widths upstream to two channel widths downstream. No fewer than three cross-sections should be surveyed, but more are preferable. The results of cross-section surveys should be compared for evidence of bed and bank stability.

Cross-sections should be selected that are representative of

a) extreme low-flow conditions,

b) conditions immediately after a significant flood or tidal event,

c) conditions representative of any seasonal variations in the channel regime.

Ideally, a history of the cross-section geometry should be obtained over a number of years. If at all possible, surveys should be undertaken just before and immediately after the high flow season.

11.4 Survey of velocity distribution

For many channels it is obvious whether there is likely to be skew flow or an unusual velocity distribution, and the optimum configuration of paths can be specified with a reasonable degree of confidence. However, often this is not the case, for example in natural rivers where the approach conditions are not constant for sufficient distance. If such doubt exists, a detailed velocity profile survey should be carried out at the potential site early in the design process, to ascertain whether a crossed-path configuration is required. This should demonstrate the existence (or otherwise) of effective hydraulic uniformity in the reach of channel to be gauged. Particular efforts should be made to obtain measurements that are representative of extreme low-flow conditions since, in general (but not always), this is where the effects of any non-uniformity are likely to be greatest.

The survey may be done using current meters (see ISO 748). Not less than three cross-sections in the gauge reach should be profiled, one each at the upstream and downstream extremities, and one at a central location. If resources allow, the velocity-profile survey should match the detail of the physical survey of the cross-section, and extend both upstream and downstream of the proposed gauge location.

Results of the velocity-profile survey should be plotted graphically to show velocity isopleths in each surveyed cross-section, and the results inspected for evidence of distortion or change in the direction of the velocity vector through the reach.

Alternately, the survey may be done using temporary ultrasonic gauging equipment. The survey installation should consist of at least four transducers, deployed to form a pair of crossed paths (see 7.4.5), and capable of being moved vertically to sample velocity at different depths.

Analysis of the computed water-velocity data for pairs of crossed paths at different elevations (see 7.4.6) will indicate whether or not skew flow is present.

11.5 Survey of signal propagation

In some cases there will be reasons to suspect that sound propagation could be a problem and the risk of proceeding with an installation is high. The presence of possible sources of interference, the proposed use of long transducer cables or the presence of an upstream source of aeration (aeration tanks, dams, weirs, waterfalls, hydraulic jumps, mill or power-plant tail-races) are examples of such reasons.

The site should be checked for excessive levels of electrical noise or radio interference. Potential sources include public broadcasting transmitters, emergency services communications, or power installations. The characteristic frequency and amplitude of any interference, as seen by the transducers, should be noted and incorporated in the system specification.

Sources of electrical noise do not always operate continuously. It is prudent to carry out a survey on more than one occasion and, in addition, to inspect potential sources in the locality of the proposed site, whether or not any noise has been observed.

In these circumstances, it is recommended that an acoustic survey be carried out to determine whether sound propagation and noise conditions are likely to be satisfactory. The equipment should consist of sets of transducers with support systems suitable for temporary mounting in the channel, and a dual time-base oscilloscope or other method capable of displaying the signal waveform. The waveform to be displayed may consist of a few cycles having a characteristic frequency between 100 kHz and 1 000 kHz, delayed from the transmit signal by about 0,7 ms per metre of path length.

Tests should be made to observe in particular the strength, shape, variability and signal-to-noise ratio of the signal. The presence of a distorted received waveform, which appears to be inverted or which exhibits a longer than usual rise time, indicates the presence of aeration.

This work may be carried out in conjunction with the survey of velocity distribution using the ultrasonic method (see 11.4).

11.6 Other survey activities

11.6.1 Water-temperature surveys should be carried out, at a time when there is a reasonable combination of low velocity and high insolation at the site, to ascertain whether or not temperature gradients are likely to be present in the water.

Surveys of salinity (or electrical conductivity) should also be carried out if it is suspected that the channel could contain brackish water.

From these, the vertical deflection of the ultrasonic path should be computed, using the method given in The minimum distance between the surface and the highest working path should be the greater of ($D_\mathrm{r} + D_\mathrm{min}$) and D_min from Equations (6) and (7). (In the case of salinity gradients, D_r will be in the negative direction.)

11.6.2 In watercourses that are known to carry a high suspended-sediment load, and at locations where there is a marked tidal effect, a suspended-sediment survey should be undertaken. Such a survey should be designed to be representative of a full range of water depths and flows. The ability of tidal flows to pick up and take into suspension sediment from the channel bed should be verified.

12 Operational measurement requirements

12.1 General

For successful operation, an ultrasonic flow gauge requires the input of a number of different items of information. The manner in which these are accommodated will depend to some extent upon the detailed design of the instrumentation itself, but all are essential to the process of determining flow.

12.2 Basic components of flow determination

The essential components in the computation of flow are

a) the variables of water velocity and depth; which are provided by the specialised instrumentation,

b) the constants of bed elevation and cross-section widths throughout the wetted cross-section, which are provided by survey during system commissioning.

All data in the system are subject to measurement uncertainty (see Clause 14). However, system constants (e.g. channel width and bed elevation) or data derived by reference to some fixed datum (water depth), require particular attention during the operational life of the gauge to minimize systematic errors.

There should be provision in the system design for relatively stable data (cross-section width and mean bed level) to be easily altered, in the event that the geometry of the cross-section undergoes some significant change.

Transducer locations should not normally be subject to movement, but it is prudent to resurvey them periodically.

12.3 Water velocity determination

The water velocity determination is normally the primary function performed by the ultrasonic instrumentation.

Each adequately submerged path should be sampled as frequently as possible, and over as long a period as possible, commensurate with the need to obtain a computed result before a significant change in flow can occur. A well-engineered system should be capable of executing at least 30 complete cycles of the entire transducer array per minute. Multiple sampling of individual paths is an essential system feature, since there is a relatively high likelihood of any single sample failing, for some reason. If reliable computation of individual path velocities is to be attained, then a large number of samples should be available for averaging.

All the submerged paths in a multi-path system should be sampled sequentially, at a rate sufficient to ensure that no significant changes in flow occur during the time taken to carry out one complete measurement cycle. It may be detrimental to transducers to “fire” them when they are out of the water, and system design should allow for those that are above water level to be inactive.

In multi-path systems with very long paths, the transit time could limit the cycle rate. Though paths should be sampled sequentially, it is possible to start one before the previous transit is finished without causing confusion.

12.4 Determination of water stage or depth

This function may be incorporated within the ultrasonic instrumentation, or may be derived from separate instruments. The variable is normally derived in surrogate form. The actual determinant is normally the water level, relative to a fixed datum. The relationship between this datum and the assumed mean bed level in the gauge cross-section is normally taken as a system constant. As indicated in 12.2, this datum relationship should be checked periodically, since its stability depends upon the stability of the channel bed. Any one of a wide variety of available water-level measurement methods conforming to ISO 4373 may be used.

Mean bed level refers to the mean elevation of the channel bed within the area bound by the banks of the channel and the upstream and downstream transducer arrays. This can be adequately determined by surveying detailed cross-sections of the channel at five equidistant points, the limits of which are the upstream and downstream transducer arrays. In addition, cross-sections can be taken along the line of the lowest path(s). It is appropriate to take the arithmetic average of all points surveyed which lie below the elevation of the lowest path. The number of points should not be less than 50.

In channels of width 100 m and greater, it may be appropriate to use alternative techniques such as echo sounding, and a graphical value of mean bed level may be determined.

These surveys should be repeated annually and/or after a major flood event which may have changed the bed geometry.

Until the stability of the channel bed is established, frequent resurveys should be made. If the channel bed moves significantly, the cross-section area for a given water level will change. The computed flow will then be in error by approximately the same proportion as the relative change of the cross-sectional area.

12.5 Channel width

Channel width is not continuously measured, but is ascertained by conventional land survey techniques, and thereafter exists as one or more system constants, entered into the computation system as part of a system set-up procedure at the time of commissioning.

The measurements of channel width may sometimes be mathematically derivable from measured path lengths and angles. If the sides of the gauge cross-section are, in fact, defined by the civil engineering works upon which the transducers are mounted, then the width of the flow cross-section can also be defined in this way.

If, on the other hand, the transducer locations do not define the lateral extremities of the cross-section, then separate measurements of channel width are necessary.

The channel width should be checked periodically (although not as frequently as bed geometry). A high degree of accuracy (better than 0,1 %) is readily attainable in the determination of distance, without resort to unusual methods or equipment. This degree of accuracy should be sought since acoustic path length is one of the fundamental system measurements. The basic ultrasonic flow-measurement technique can accommodate quite varied channel bank geometries. Individual paths in a multi-path system can be of different lengths and can intersect the mean direction of flow at different angles, if the physical design of the gauge demands it.

13 Gauging station equipment

13.1 General

The equipment of a gauging station consists of

- pairs of transducers located at the ends of each path in the gauge configuration,
- one or more depth or stage transducers,
- electronic unit, connected to the transducers and depth transducers,
- recording or telemetry equipment, which may be integral with the electronic unit.

The electronic unit or flow computer performs the following operations:

a) stores parameters describing the paths, depth devices and channel cross-section;

b) determines the depth of flow and decides which pairs of transducers (paths) to operate;

c) energizes the transducers in sequence;

d) receives the resulting signals which have traversed the paths;

e) performs tests on the signals to determine whether they are acceptable;

f) measures the times of travel between the energizing of a transducer at one end of a path and the receipt of a signal at the other end of this path;

g) using these measured times, and also the differences in times between forward and reverse signals in the same path, computes path velocities for all paths in use;

h) performs tests on the computed data to determine whether they are acceptable;

i) computes flow from water depth, path velocities and site geometry;

j) outputs the resulting data to a data recorder or a telemetry system.

13.2 Design and construction of equipment

13.2.1 Transducers

The transducers are usually operated in a pulsed mode. They are stressed electrically by a short high-voltage pulse and then allowed to emit. They are mechanically damped so that they emit for between 6 cycles and 20 cycles. The transducer characteristics are chosen such that

a) the signal attenuation (described in 6.2.3) is acceptable. Generally the lower the characteristic frequency, the lower the signal loss;

b) the minimum depth criterion (see 6.2.5) is met. The lower the characteristic frequency, the greater the required depth of water above and below the path;

c) the timing accuracy needed to resolve the minimum flow is achieved (see 13.9.6). The lower the characteristic frequency, the greater the uncertainty in defining the exact time of arrival of the signal. The degree to which the exact frequencies of the transducers at either end of each path are matched is also critically important, especially if the signal detection method involves detection after the first half-cycle of the signal waveform.

The diameter of the transducer is directly related to the width of the cone of projection of the sound pulse. The larger the diameter, the narrower the cone and hence the greater the energy density of the sound pulse. Cone width is also related to frequency. The higher the frequency, the narrower the cone.

In general, the cone angle, expressed in degrees, of the sound pulse is equal to arcsin β:

$$\beta \frac{3\,700}{f \times d} \tag{11}$$

where

f is the transducer frequency, in hertz;

d is the diameter of the transducer, in metres.

13.2.2 Transducer mountings and their installation

The design of the transducer mountings should allow for

a) adjustment of direction in the horizontal plane, independent of any adjustment in the vertical plane,

b) accurate indication, to the nearest ± 1°, of direction above the water surface when adjustment is being made (by use of a portable jig, if necessary),

c) accurate alignment, to the nearest ± 1°, in the vertical plane, preferably integrated in the design of the mounting itself,

d) easy removal for cleaning and transducer replacement where practical , without the need to use divers or special equipment. Realignment should not be required during re-assembly after adjustment or repair.

The mountings should be designed so that:

- any build up of silt does not obscure the ultrasonic path;
- silt and debris can be removed without undue difficulty;
- signal cables are not easily damaged by floating debris, stones or other objects falling on them, the passage of boats dragging anchors, ice, rodents or the removal of transducers for cleaning or repair;
- the transducers are not easily misaligned or damaged by debris, the passage of boats, unauthorised interference, frost or ice;
- they do not corrode in such a way as to collapse or be difficult to disassemble;
- their shape does not cause air to be trapped in the water in front of a transducer, at any stage in the measurement range over which it is required to operate.

13.2.3 Transducer cables

If the cables between the transducers and the electronic unit are shorter than about 100 m and of different lengths, there is a potential problem with reflection of electronic signals causing distortion, resulting in serious differential timing errors. These errors are most significant for small channels or low water velocity.

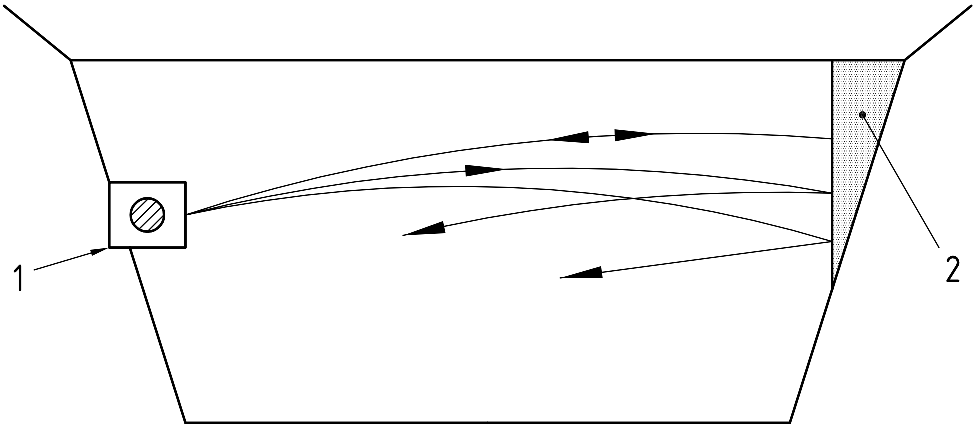
This problem can be avoided by ensuring that the lengths of the cables to the upstream and downstream transducers for a given path are of the same length, (± 2 m). Alternatively, suitable impedance-matching circuitry or the location of electronic circuits at the transducers can be used. If this is done, it is important that asymmetrical delays are not introduced by poor matching of the electronic circuits. There could also be a cost implication.

13.3 Reflectors

13.3.1 Two types of reflector may be used in situations where this variant of the method is appropriate. They may be flat (see Figure 11), or of angular construction (see Figures 12 and 13). Both devices reflect sound pulses according to the normal laws of optical reflection.

13.3.2 The flat reflector is most suited to channels with vertical banks, where a single sheet of material extends the full depth of water. However, if vertical temperature gradients exist, the acoustic beams will be bent, and the condition illustrated in Figure 11 will occur. Only rays normal to the reflector in the horizontal plane will be reflected towards the receiving transducer.

13.3.3 The angular reflector (see Figures 12 and 13) is suited to channels with sloping banks, and is capable of functioning at sites subject to a small temperature or salinity gradient. However, separate reflectors are required for each ultrasonic path, and they should be located so that reflections from the wrong reflectors (generally those at lower depths) do not arrive at a receiver at a time that can be mistaken for the correct signal (see also 13.5.3.1). Note that Figure 12 only indicates the signal “B to A”. To obtain a complete determination, the signal “A to B” is also required.

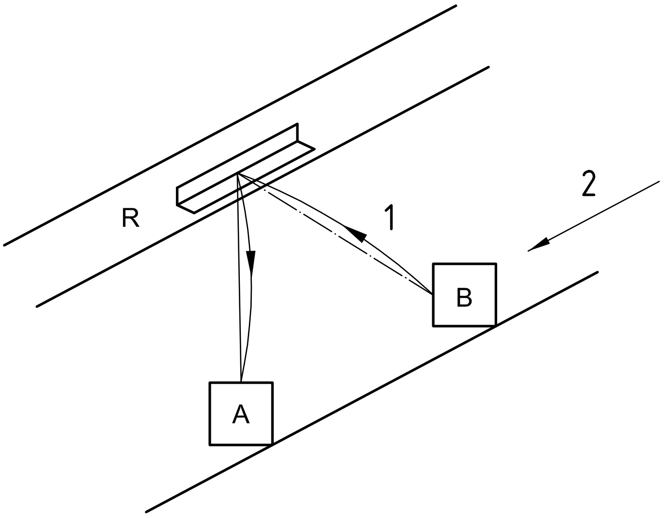


Key

1 transducers
2 flat plate reflector

NOTE Only the ray which is normal to the reflector will be reflected back to the receiver.

Figure 11 — Flat reflector showing effect of temperature gradients

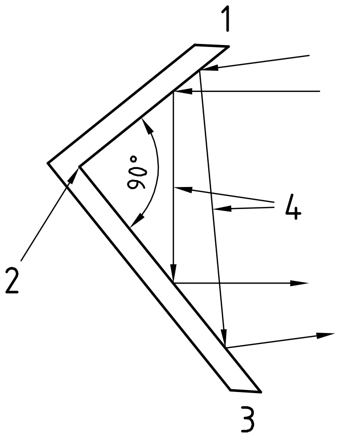


Key

1 beam curved by temperature gradient
2 direction of flow

R Reflector
A Receiver
B Transmitter

Figure 12 — Angular reflector showing effect of temperature gradients



Key

1 chamfer edge
2 minimum possible radius
3 chamfer edge
4 incident and reflected beams travelling in the same direction

Figure 13 — Detail of angular reflector

13.3.4 Both types of reflector should be aligned accurately. The flat reflector should be vertical, otherwise the depth at which the signal is reflected becomes uncertain. The uncertainty in this case is equal to:

$$0,5\, L \tan \alpha$$

where

α is the angle, in degrees, between the reflector and the vertical;

L is the path length, in metres.

An error of 0,3° in verticality, on a total path length of 100 m (across the channel and back), would result in reflection of the acoustic signal at a depth 0,26 m different from that required, and would preclude the operation of a path that was set at 0,3 m below the water surface.

The accuracy of vertical alignment is less critical in the case of the angular reflector. Errors up to 5° are unlikely to inhibit operation (see Figure 13).

13.3.5 The accuracy of alignment required in the horizontal plane is related to the horizontal length of the reflector; the longer the reflector, the less critical is its horizontal alignment.

13.3.6 The alignment of flat reflectors shall be adjustable in both vertical and horizontal planes. The angular reflector need only be adjustable in the horizontal plane. Both adjustments should be capable of being made independently, and under water.

13.3.7 The material of the reflector should be rigid. Stainless steel and galvanised steel are suitable. The surface roughness and waviness per 100 mm should be better than ± 0,05 wavelength of the acoustic signals over the active area. The thickness of the reflecting material should be at least (2 000/f) m, where f is the acoustic frequency (in hertz), otherwise the signals will pass through the reflector, and not be reflected (i.e. at least 4 mm thick for an acoustic frequency of 500 kHz).

13.4 Civil engineering works

During gauge construction installation, the channel banks and bed should not be altered from their natural state more than is absolutely necessary. If significant changes are made, there is a strong likelihood that they will revert to their original state after a certain time.

13.5 Signal timing and processing

13.5.1 General

The process of detecting the point in time at which an ultrasonic signal arrives at the receiving transducer shall be carried out with the greatest precision. Errors in the detection process lead to errors in the determination of velocity. In particular, it is the difference in transit times that is significant [see Equation (3)], especially when the path length is small and/or the velocity low.

Distortion of the signal, for example by ultrasonic or electronic reflections, or interference from an external electromagnetic source can create uncertainty in the detection time. Attenuation of the signal can also confuse the detection circuitry. The design of the flow gauge should minimize these effects, and ultimately cause the gauge to fail to a definite recognizable state when it can no longer detect correctly with certainty.

If the resolution of the electronic timer used to measure the transit times is too low, the uncertainty in water-velocity determination may be increased. However, the transit times vary randomly as a result of water turbulence, and the water velocity is computed from the mean of a large number of readings. Therefore, the required time resolution of e.g. 10 ns can be achieved with a timer having a resolution of perhaps many tens of nanoseconds.

13.5.2 Signal-to-noise ratio

13.5.2.1 Electromagnetic interference

To reduce the effect of interference and improve the signal-to-noise ratio, it may be necessary to design the system so that the signal amplifiers are located close to or integral with the transducers. Alternatively, balanced feeder connection to the transducers may be employed. Decisions on these techniques are governed by the results of the site survey, as well as by the overall design of the instrumentation itself. Care should be taken over the earthing (grounding) of screened and armoured cables, and especially over bank-side electronic units, otherwise damage from lightning may be unduly frequent. In general, earthing (grounding) should be effected at one point only (at the instrument housing), and all remote equipment and transducers should be isolated from earth (ground) with insulation capable of withstanding not less than 2 000 V.

Amplifiers in or near the transducers will introduce small delays or phase shifts. In applications where these are significant compared with the transit time differences, they shall be taken into account in the design otherwise the use of such amplifiers should be avoided. The amplifiers shall be designed or set up either with closely matched delays or measured delays; and both the delays and differential delays allowed for in the processing software.

13.5.2.2 Electronic filtering

The effect of noise which is of a frequency different to that of the transducer may be reduced by employing an electronic filter (which may be achieved using inductor-capacitor-resistor networks or by a digital signal processor). The passband of the filters should be designed such that the signals from the transducers are passed without excessive attenuation of the leading edge of the waveform. If the band is too limited, the first few cycles of the signal become difficult to detect, and this will greatly increase the uncertainty with which the exact time of arrival of the signals can be detected.

Electronic filters introduce small delays or phase shifts. In system designs where separate filters are used at either end of a path (i.e. where signal amplifiers are located close to or integral with the transducers), the differential delays may be significant compared with the transit time differences. These shall be taken into account as described in 13.5.1.1, or else the use of such filters should be avoided.

13.5.3 Signal maintenance (gain control)

When signals are attenuated by sediment loading, scattering, temperature gradients, debris or transducer deterioration, the first cycle may be so reduced that a simple detector may trigger off the second cycle. The resulting timing error may be equal to the period of the transducer frequency. If this occurs in only one direction, the error in the time difference could be serious (2 µs for 500 kHz transducers). For many gauges, designed for low flow determination, an error of many hundreds of percent could result.

The receiving amplifier shall be able to cope with the resulting large dynamic range of signal. In practice this may be difficult without it becoming saturated when conditions are such that the attenuation is small. The saturation could lead to timing errors which would be serious in many applications.

A system of automatic gain control (AGC) may be used to prevent the saturation of the amplifiers.

When using AGC, increasing the gain increases the interfering noise whilst attempting to maintain the signal. In order to cope fully with signal attenuation in the presence of noise, the transducer drive voltage has to be set to maximum.

The continuous use of maximum transducer drive voltage may be undesirable for the following reasons.

a) There may be a detrimental effect on the operating life of the transducers.

b) The “dead time” which occurs after the transducer is energized may be increased. This is particularly important when using transducers for depth measurement, since it determines the minimum depth of water that can be measured.

c) The power consumption may be increased. This may be significant for systems designed to operate on batteries.

A system of automatic adjustment of the transducer drive voltage to compensate for signal strength variations may be employed. It is unlikely that this would be acceptable if used alone without AGC, because the gain would then have to be set to maximum to cope with the worst case, thus making the system susceptible to interference. A combined system, using an algorithm to adjust both the gain and transducer drive voltage, may be desirable. This would optimise the signal-to-noise ratio, whilst maintaining a minimum drive voltage.

13.5.4 Signal detection

13.5.4.1 General

Having produced as good an electronic version of the ultrasonic signal as possible, the next process is to translate the point of arrival to an accurate time scale. The most important thing is the time difference, so the process applied to signals being received in both directions shall be identical. It is necessary to wait until a recognizable part of the waveform is received, usually after not more than a complete wavelength. To wait longer is to risk distortion from reflections from the water surface (see 6.2.5), and to suffer an increased uncertainty due to mismatch of the characteristic frequency of the transducers at either end of a path (see 13.2.1).

If there is any doubt about the validity of the signal, it is better to reject it than to produce a potentially grossly erroneous determination of velocity.

13.5.4.2 Time gating

Since the water velocity in practice has a minimal effect on the ultrasonic transit time, the time of arrival of sound pulses is predictable. Initially, the knowledge of the velocity of sound limits the precision to which the arrival would be expected, allowance having to be made for the whole range of velocities expected (see 6.2.2). Once operating, the velocity of sound will be known more accurately from measurements of transit times.

The amplifier outputs should be observed starting just a short time before the sound pulses are expected. By this means, spurious interference at other times is ignored.

When reflectors are used in a trapezoidal channel, signals from the wrong reflector may be received early. These can be rejected if accurate determinations of sound velocity can be obtained from other paths guaranteed not to suffer from stray reflections.

13.5.4.3 Shape analysis

The simplest detection process should have at least three thresholds, which shall be passed in a prescribed sequence for the signal to be considered detectable with confidence.

In critical applications, more complex methods of shape analysis should be employed. These would be expected to involve digitization of the whole or a substantial part of the received signals and real time mathematical analysis to determine the time of arrival of the first cycle, or alternatively the invalidity of the signal.

13.5.5 Post-detection filtering

Once the signals have been converted into transit time and time differences, water velocities can be computed. Many samples should be used in the velocity calculations to reduce random effects. Before inclusion in the calculations, the measurements from each ultrasonic path should be examined in order to reject any spurious results which may have passed the detection process.

The criteria depend on the particular site, but should include

a) excessive deviation of water velocity from an absolute limit expected for the path,

b) excessive rate of change of velocity compared with previous determinations,

c) excessive difference from other paths,

d) path timing corresponding to an anomalous velocity of sound.

The algorithm for accepting or rejecting results shall be very carefully designed to ensure that the system does not accept spurious results whilst rejecting good ones. In particular, the start-up conditions or those when a rejected path is being re-introduced are critical. Special care shall be taken in respect of the third criterion – comparison between paths – when a small number of paths (e.g. less than 4) are in use.

Apparently valid data should also be rejected if they are obtained during periods when the majority of data fail these tests.

13.6 System self-checking

The most likely elements of a system to fail are those associated with the “wet” end: transducers, drive circuits, amplifiers, multiplexes and signal detectors. Processing systems are generally reliable, and usually work either correctly or not at all.

System design should provide for regular, automatic testing of the following:

a) signal amplitude, as a check on transducer performance and amplifier gain;

b) transmit and receive circuit delays, as a check on drive circuits and multiplexes. A simple test is to measure the time delay between the initializing of the transmit command and the observation of this event in the receiver connected to the transmitter;

c) the accuracy of the pulse-timing circuits;

d) the ringing of the transducers when they are energized.

These tests should be conducted on all paths, including those which are not submerged [except for test a)]. Tests made using a dedicated dummy path will not highlight failures in multiplexes or individual transducer drivers.

13.7 Site-specific data (or site parameters)

Numbers characterizing a particular site should be stored in the processor system, in an alterable form which can be checked easily, but which is protected against accidental alteration, power failure and circuit card removal for maintenance. The amount of this data depends upon the range of configurations and channel dimensions which the system is designed to suit.

The list is likely to include

a) number and type of depth gauges,

b) elevation of depth gauges,

c) elevation of channel bed,

d) acceptable range of depths,

e) number of velocity paths,

f) units of flow to be computed,

g) averaging period for data,

h) individual path elevations,

i) individual path lengths,

j) individual path angles or factors related to these angles,

k) channel widths at various elevations,

l) acceptable range of velocities for individual paths, and rates of change,

m) factors used to derive the water velocity in the lowest panel (or at the bed) and at the surface,

n) depth of water above a path before it is brought into operation,

o) fixed delay times (in transducers, cables, transmitter- and signal-detector electronics),

p) delay test times.

13.8 Clock and calendar

A means should be provided to mark data collected by the gauge with time and date, using an on-site clock unit that is either part of the gauge instrumentation, or as part of a separate telemetry system.

13.9 System performance criteria

13.9.1 General

The principal system performance criteria should be defined by the prospective user, within the technical limits described in this International Standard, and those of current technology.

13.9.2 Operating environment

The operating conditions, including information on the extremes of temperature, humidity, atmospheric quality (for example, corrosive or explosive gases present) and also the likelihood of vandalism or of animals which could cause damage, should all be communicated to the system designer. For sophisticated systems, a temperature range of −15 °C to +60 °C can usually be accommodated without elaborate precautions or excessive cost. No condensation or corrosive gases should be allowed to contact the electronic circuit elements. Special cabinets may have to be provided, if gas or humidity problems exist.

13.9.3 Water environment

The range of water temperatures, depths, and suspended solids concentrations should be stipulated. Likely maxima are 35 °C, 50 m and 1 500 mg/l respectively. The presence of bubbles shall be avoided.

13.9.4 Mechanical environment

Indications of possible shocks during transportation to site should be provided to the system designer.

The system design shall incorporate packaging for transportation to suit the specified conditions.

Transducer mountings should be specified which withstand expected water velocities, impact by debris and boats, and the effect of ice.

13.9.5 Extreme environmental conditions

The extremes of environmental conditions likely to be encountered during storage or transport should be given. These should include temperature, humidity and barometric pressure.

13.9.6 Power source

Ultrasonic flow gauges are generally designed to be powered from an external source. This is partly a matter of the historical development of the technology and partly because the size of batteries needed to support unaided continuous operation for extended periods is excessive. However, in modern systems, battery back-up facilities to cover periods of short-lived mains failure are available, and small systems of a few paths are available with battery packs which can be run conveniently for reasonable periods from high capacity cells and solar panels.

13.9.7 Measurement uncertainty

The elements of total system uncertainty that are specific to electronic instrumentation relate to timing, interference effects, and the degree of sophistication in the algorithms used to compute flows from the basic data. The number of paths provided and their layout may be more important than the electronic aspects.

Most systems can determine time differences to ± 30 ns. With more sophisticated transducer firing, receiver design and signal detection methods ± 3 ns can be achieved, but such sophistication is normally only needed in small systems having path lengths less than 15 m, and short distances (a few hundreds of metres) between transducers and supporting electronics.

The uncertainty in the computed water velocity U_v, in metres per second, due to timing errors can be estimated by inserting the manufacturer's certified figure for timing uncertainty U_t (e.g. 5 ns) into Equation (12), which is derived from Equation (3) using 1 450 m/s as an example for the speed of sound.

$$U_v = U_t \times 1\,450^2/(L \times 2\cos\theta) \qquad (12)$$

where L is the path length, in metres.

Equipment designed for use in rivers which are several tens or even hundreds of metres wide may differ from that intended for channels of about 1 m wide. The differences include the choice of timing method, size and characteristic frequency of the transducers and the design of the transmitter and receiver circuits.

13.10 System output

13.10.1 Local display

The system instrumentation design should provide, as a bare minimum, data output capability and a display of important system information at the gauge site itself. This should include a digital display of water level and computed flow, and may incorporate the facility to call up for display other variables, such as individual path velocities, individual water levels and diagnostic data.

13.10.2 Local record

It may be appropriate to provide a continuous record of level, flow and diagnostic data on a local recorder or data logger. The logger may be either an integral part of the electronic unit or a separate device which is connected to it by an analog or digital (RS232, BCD parallel) interface. Wherever possible and appropriate, an indication should be provided that alerts gauge operators or users to the presence or past occurrence of data errors or gauge fault conditions (see 13.5 and 13.6).

Such an indication should include

a) signal travel times outside the expected range,

b) excessive time differences,

c) excessive number of signals failing the tests detailed in 13.5.4,

d) an indication of signal amplitudes.

13.10.3 Remote record

The same output facility that could support a local data recorder may be used to feed a more sophisticated device capable of relaying gauge data to a remote location, whether by land line, telephone line, terrestrial radio link or communications satellite link. If the equipment on site is battery-powered, the telemetry system can be used to switch it on only at such times when flow data are required, thus enabling the life of the batteries to be extended.

13.10.4 Diagnostic information

Well-designed ultrasonic instrumentation should enable appropriate diagnostic data to be easily obtained in real time by a user on-site or remotely, using a telephone, modem and PC, without the use of specialized electronic equipment. It should be possible to display such information, and it may be helpful to be able to record it, either locally or remotely.

This facility should also permit the user to inspect and edit the site-specific data (parameters). A security system to inhibit unauthorized changes may be required.

13.11 Installation

The equipment will often be installed on natural rivers or channels where precise dimensions are not known. The following information or settings should be obtained from surveys conducted during installation, with sufficient accuracy so that any errors will not add significantly to the uncertainty in the computation of flow:

a) path lengths: ± 0,1 %;

b) path elevations: ± 10 mm or better;

c) stage or water-depth sensor datum;

d) bed elevation, averaged over the gauged section. It should be noted that errors in the determination of bed elevation produce a proportional error in the computation of flow in the panel that contains the lowest path in a multi-path system. In a single-path system, the resulting error is proportional to depth;

e) angle between the mean direction of the channel banks and each path. An error of 1° will generally result in an error of 2 % to 3 % in velocity determination, depending upon the angle, (see Table 1);

f) transducer alignment, both vertical and horizontal (generally to ± 2°).

13.12 Commissioning

13.12.1 Following installation, the performance of the gauge should be checked for electronic consistency and, if required, verified by comparison with an independent determination of flow.

13.12.2 The following electronic elements and computations shall be verified as correct, using instruments such as oscilloscopes, pulse timers, thermometer and calculator:

a) individual transducers connected as expected and operated in their correct order;

b) acceptable amplitude of interference;

c) signal delay times;

d) signal amplitudes, with waveforms correctly phased;

e) determinations of travel time, as compared with those expected from path lengths and water temperature;

f) determinations of time differences, as compared with received-signal displacement on an oscilloscope;

g) for systems using reflectors, use of only the correct signals, and rejection of other signals;

h) computation of path velocity from path length, time and time difference;

i) computation of depth;

j) computation of flow from velocities and depth;

k) computation of flow, when various combinations of paths are faulty;

l) computation of averages in situations when various combinations of temporary faults occur, such as the presence of boats, power supply failure and interference;

m) electronic systems operate in accordance with the manufacturer's factory acceptance test levels.

13.13 Operating manual

A comprehensive operating and service manual, giving full instructions, and where necessary illustrations, shall be supplied with each system. The manual should include any maintenance and fault-finding information deemed desirable. A list of recommended spare parts should also be provided.

13.14 Maintenance

13.14.1 The objectives of maintenance are

a) to reassure the user that the flow data produced by the gauge lie within the expected uncertainty,

b) to repair any faults or deterioration in the equipment which impair, or might be expected to impair, the operation of the gauge,

c) to identify the cause of any spurious or apparently spurious data that may have been observed, or of real or apparent transitory equipment faults that may have been noted.

13.14.2 The mean time between failures (MTBF) in the instrumentation of a typical ultrasonic gauge (including transducers and electronics) may be expected to be greater than one year. In addition, failures may occur as a result of vandalism, loss of power supply, or the obstruction of transducers or paths by deposition of silt or debris. Self-checking routines in the system, described in 13.6, can indicate the presence of such faults often before they have reached a level likely to impair the performance of the gauge.

13.14.3 All data recorded by the gauge should be inspected as soon as possible after collection, to decide whether suspect or obviously spurious values are present, or if periods of malfunction have occurred. If the data from the gauge are not recovered by telemetry, it should be visited regularly, and any fault indications noted. The interval between site visits should be consistent with the period for which loss of data is acceptable to the user.

13.14.4 In the course of routine site visits, or inspections of telemetered data, the following should be observed and noted:

a) the malfunction of any path, as indicated by the built-in system self-check facilities;

b) the ultrasonic pulse travel times;

These should be compared with expected values for the current water temperature; this is of particular importance with reflected-path systems, where signals from different reflectors may, in adverse circumstances, be misinterpreted by the system electronics.

c) the proportion of successful to unsuccessful determinations of signal timings;

d) discrepancies between depth measurements if more than one depth sensor is used, and any discrepancies between the water depth recorded by the gauge compared with that indicated by an independent determination (e.g. a staff gauge);

e) the individual water velocities for each (fully submerged) path, noting their relative consistency;

f) the variability between successive velocity determinations, each averaged over a short period (e.g. 10 s);

NOTE Excessive variability (e.g. ± 20 %) almost certainly indicates an equipment fault.

g) the individual received-signal amplitudes.

13.14.5 In the absence of any indication of deterioration, detailed inspections of the equipment to identify deterioration should be made at intervals not exceeding twelve months. Such inspections ideally should be scheduled to coincide with times of extreme water stage, flow or weed growth. At high stage values, the operation of paths not normally submerged may be checked. At high flow, the effect of loading with suspended solids will be apparent (although the extreme normally occurs during the first flood after a low flow period). At times of high weed growth, skew flow as well as obstruction may be observed. At low values of stage, skew flow may be present. Any timing errors in the electronic equipment are most easily detected at low velocity (preferably zero).

The inspection should take the form of

a) a channel bed level survey, and if necessary, recalculation of mean bed level,

b) a check that all site-specific data (see 13.7) are correctly installed in the gauge,

c) a check on the electronic system, as indicated in 13.12.2, items a) to i) inclusive,

d) a visual check of the transducers, and of the amount of weed or debris which might obstruct the ultrasonic signals in the channel; a guide to the degree of prevalent signal obstruction will be available from the results of signal amplitude observations;

e) a check on the flow by an independent method should be made periodically, e.g. by current metering (see Clause 10). If conditions are liable to change, the interval between such checks should be less than 12 months. The cause of any discrepancy should be investigated.

The verifications indicated in 13.12.2, items j) to l), relate to the performance of the gauge software and, in a well-proven gauge design, this is unlikely to change.

13.14.6 If any of the checks carried out under 13.14.5 should fail, or if the gauge is known to be faulty from inspection of the data record or as a result of a site visit (see 13.14.4), the assistance of a qualified electronic technician should be obtained. The technician should be familiar with the site layout of the gauge, understand the hydraulic behaviour of the watercourse, and have received formal maintenance training provided by the manufacturer or supplier of the gauge. It should be the responsibility of the technician to repair the faults, to warn of any uncorrected equipment deterioration and to recommission the gauge [see 13.12.2, items a) to i) inclusive].

14 Measurement uncertainties

14.1 General

The uncertainty in a single measurement of discharge is dealt with in ISO/TR 5168, to which reference should be made. Additional information is given in the *Guide to the Expression of Uncertainty in Measurement* (GUM):1995, especially Clauses 2 and 3. In this clause, a general outline of the method for estimating the uncertainty in a single measurement of discharge is given. The individual components of the uncertainty are examined and examples of these are given. Although these are generally applicable, they should be verified by the user.

14.2 Definition of uncertainty

All measurements of a physical quantity are subject to uncertainties. These may be due to systematic errors (biases) in the equipment used for calibration and measurement, or to random scatter caused by, for example, a lack of sensitivity of the equipment used for the measurement. The result of a measurement thus is only an estimate of the true value of the measured quantity. Therefore, it is complete only when accompanied by a statement of its uncertainty.

The discrepancy between the true and measured values is the measurement error. The measurement error, which cannot be known, causes an uncertainty about the correctness of the measurement result. The uncertainty is expressed quantitatively as a “parameter ... that characterizes the dispersion of the values that could reasonably be attributed to the measurand” (GUM:1995, 2.2.3).

The GUM further states that the parameter may be, for example, a standard deviation or the half-length of an interval having a stated level of confidence, and that all sources of uncertainty, including those arising from systematic effects, contribute to the dispersion.

The measurement error is a combination of component errors that arise during the performance of various elementary operations during the measurement process. For measurements of composite quantities that depend on several component quantities, the total error of the measurement is a combination of the errors in all component quantities. Determination of measurement uncertainty involves identification and characterization of all components of error, quantification of the corresponding uncertainties, and combination of the component uncertainties. The uncertainties are combined using the statistical rules for combining standard deviations, giving proper consideration to correlations among all of the various sources of measurement error in order to account for both systematic and random errors. The resulting uncertainty values are termed standard uncertainties; they correspond to one standard deviation of the probability distribution of measurement errors.

In some applications, it is necessary to express the uncertainty of a measurement as a band or interval that may be expected to contain a specified fraction of the distribution of values that could reasonably be attributed to the measurand. Such an interval is obtained by multiplying the standard uncertainty by a factor *k*, usually in the range 2 to 3, called the coverage factor. The fraction of the distribution contained by the interval is called the level of confidence. The relation between the level of confidence and the coverage factor depends on the probability distribution of measurement errors.

In this clause, uncertainties are given as standard uncertainties (one standard deviation) unless otherwise stated, and are expressed as percentages of the measured values (relative or percentage uncertainties). It should be noted that the use of standard uncertainties is a change from previous editions of this standard, which used expanded uncertainties with a coverage factor of 2. If expanded uncertainties are required, the standard normal (Gaussian) distribution is used to determine the coverage factor corresponding to a specified degree of confidence. In particular, expanded uncertainties with a coverage factor of 2 have an approximate level of confidence of 95 %. The expanded uncertainty with a coverage factor of 1 has an approximate level of confidence of 68 %.

14.3 Uncertainty in discharge

14.3.1 Uncertainty equation

The following equation may be used to estimate the uncertainty in discharge:

$$U_q = [U_{\text{p}}^2 + 1/P\,(U_{\text{lv}}^2 + U_{\text{w}}^2 + U_{\text{d}}^2)]^{1/2} \tag{13}$$

where

U_{p} is the uncertainty in integration consisting of the limited number of effective (see below) paths (p) used (from Table E.4 of ISO 748:1997) and the method of computation [see 14.3 h) above];

P is the number of paths;

U_{lv} is the uncertainty in the line velocity (see below);

U_{w} is the average uncertainty in the channel width determination (see below); the channel width is the average width of the measuring section at the level of each pair of transducers; the width measurement is assumed to be taken at right angles to the direction of flow/banks;

U_{d} is the uncertainty in depth measurement.

If the mid-section or mean-section methods (see 8.2.2. and 8.2.3) are used to compute the discharge, the uncertainty for the depth of each slice should ideally be treated separately. However, in reality it is usually sufficient to consider the uncertainty in the overall depth measurement relative to mean bed level in the measuring cross-section. As modern water-level measuring equipment should be capable of measuring and recording the water level to within ± 3 to ± 5 mm (at two standard deviations), the largest component of the overall depth uncertainty is usually the uncertainty in the determination of mean bed level.

The above equation should be applied to two or three different flow conditions, e.g. low, medium and high, since the uncertainty varies with stage and velocity, and is also dependent on the number of operational flight paths.

14.3.2 Effective number of paths

Some “transit-time” ultrasonic installations, particularly if paths are crossed, may have several paths at effectively the same level or relatively close together. In such instances it may not be appropriate to use the total number of paths to determine the uncertainty in integration, due to the limited number of paths. Therefore, some professional judgement may be required in order to determine an effective number of paths. For example, if there are two operational paths in a cross-path system at the same elevation, the effective number of paths would be one.

14.3.3 Uncertainty in the line velocity, U_{lv}

Equation (2) may be written:

$$v_{\text{lv}} = \text{L} \cong t/2t^2 \cos\theta \tag{14}$$

where

$t = (t_{AB} + t_{BA})/2;$

$\cong t = t_{AB} - t_{BA}$

From this, the uncertainty U_{lv} is:

$$U_{lv} = (U_L^2 + U_{\Delta T}^2 + 4U_T^2 + U_{\cos\theta}^2)^{1/2} \tag{15}$$

where

U_L is the uncertainty in the path length;

$U_{\Delta T}$ is the uncertainty in the transit time difference (due to averaging this is sometimes assumed to be negligible);

U_T is the uncertainty in the transit time (often negligible);

$U_{\cos\theta}$ is the uncertainty in the path angle allowing for skew or oblique flow (see Table 1; for example for an angle of 60° the uncertainty is ± 3 % for ± 1° of skew flow).

14.3.4 Uncertainty in the channel width estimation, U_w

If the channel width at each transducer path level is determined by direct measurement, the uncertainty will be the average uncertainty in the individual width measurements. This will be dependent on the survey technique used and the physical characteristics of the channel.

If the width is obtained by resolving the path length using the angle of flow relative to the “flight path”, the uncertainty in the width will also be a function of the uncertainty in $\cos\theta$, thus:

$$U_w = (U_L^2 + U_{\cos\theta}^2)^{1/2} \tag{16}$$

14.3.5 Examples of uncertainty estimation

14.3.5.1 Example 1

A four-path “transit time” ultrasonic system is installed in a rectangular, concrete channel of width 3 m. The levels in the channel are controlled and never drop below a depth of 1 m. All four paths are evenly distributed in the vertical and are positioned so that the top and bottom paths always have sufficient depth of cover. The path angle is 60°. The uncertainty in the path-angle determination due to skew flow can be assumed to be ± 1° at the 68 % confidence level. The average velocity in the measuring section is always in excess of 0,25 m/s.

It is required to estimate the uncertainty in individual flow determinations.

U_p – As the four paths should always be operational and they are evenly distributed in the vertical, the effective number of paths (p) is four. From Table E.4 in ISO 748:1997, the uncertainty in integration due to the limited number of paths is ± 3 % (one standard deviation).

U_L – if it is assumed that the path length can be measured to ± 0,01 m at the 68 % confidence level (one standard deviation), then the path length uncertainty is ± 0,3 % i.e. absolute uncertainty divided by path length and expressed as a percentage.

$U_{\Delta T}$ – The uncertainty in the transit time difference is a function of path length, velocity, the clock sampling rate and period over which flow determination is averaged. The uncertainty of each individual measurement is reduced by the square root of the number of samples that are used for the time, averaged determination. The equipment supplier should provide the uncertainty in time difference and the number of samples that would be used for the particular configuration. For most applications, the uncertainty is insignificant and in the absence of information from the supplier a nominal ± 0,1 % is assumed.

U_T – For most modern systems the uncertainty is insignificant, and in the absence of information from the supplier a nominal ± 0,1 % is assumed. In some cases, however, mismatches in cable delays can affect this factor, as referred to in 6.1.3. The supplier should be consulted for an estimate of the uncertainty due to cable mismatches.

$U_{\cos\theta}$ – The path angle is 60°. If the uncertainty in the angle is ± 1° the percentage uncertainties for each path would be approximately ± 3 %. Therefore, an uncertainty of ± 3 % has been assumed.

Substituting for U_L, $U_{\Delta T}$, U_T, $U_{\cos\theta}$ in Equation (14) gives:

$$U_{lv} = [0{,}3^2 + 0{,}1^2 + (4 \times 0{,}1^2) + 3{,}0^2]^{1/2} = \pm 3\ \%\ \text{(at one standard deviation)}$$

U_w – If it is assumed that the channel width can be measured to ± 0,01 m at the 68 % confidence level (one standard deviation), then uncertainty for width is ± 0,3 %, i.e. absolute uncertainty divided by average channel width and expressed as a percentage.

U_d – If it is assumed that it is possible to measure the mean bed level to ± 5 mm and the water level to ± 2 mm at one standard deviation, for a depth of 1,000 m this gives percentage uncertainties of ± 0,5 % and ± 0,2 % respectively, giving a combined uncertainty of ± 0,54 %.

The overall uncertainty U_q in an individual low-flow estimate can be obtained by substituting for U_p, U_{lv}, U_w and U_d in Equation (12), thus:

$$U_q = [3{,}0^2 + 1/4(3{,}0^2 + 0{,}3^2 + 0{,}54^2)]^{1/2} = \pm 3{,}4\ \%$$

The expanded uncertainty in discharge at the 95 % level of confidence $U(95)$ is obtained by applying a coverage factor of $k = 2$.

Therefore

$$U_q(95) = 2 \times 3{,}4 = \pm 6{,}8\ \%$$

Therefore, the uncertainty in an individual determination of discharge for this example with the assumed component uncertainties is ± 6,8 %.

14.3.5.2 Example 2

A two-level cross-path system is installed on a natural channel with sloping banks that can be assumed to be trapezoidal. The following details are available for the site:

Width of cross-section at low path level:	11,50 m
Width of cross-section at high path level:	18,35 m
Path length – low-level transducers:	16,26 m
Path length – high-level transducers:	21,66 m
Height of lower transducers above mean bed level:	0,205 m
Height of higher transducers above mean bed level:	0,850 m
Design minimum depth relative to mean bed level:	0,425 m

Design maximum depth relative to mean bed level: 1,615 m

Minimum design velocity: 0,03 m/s

Maximum design velocity: 0,55 m/s

Low path angle: 45,0°

High path angle: 57,9°

It is required to estimate the uncertainty in individual low-flow and high-flow uncertainty estimates, assuming that no calibration or performance-checking gaugings (flow measurements) or velocity profiling has been undertaken.

14.3.6 Uncertainty estimate at low flow

U_p – At the minimum design depth of 0,425 m, two paths should be operating. However, as they are at approximately the same level, the effective number of paths is one (p). From Table E.4 in ISO 748:1997, the uncertainty in integration due to the limited number of paths is ± 7,5 % (one standard deviation).

U_L – If it is assumed that the path length can be measured to ± 0,1 m at the 68 % confidence level (one standard deviation), then uncertainty for low path length is ± 0,6 %, i.e. absolute uncertainty divided by path length and expressed as a percentage.

$U_{\Delta\mathrm{T}}$ – The uncertainty in the transit-time difference is a function of path length, velocity, the clock sampling rate, and period over which flow determination is averaged. The uncertainty of each individual measurement is reduced by the square root of the number of samples that are used for the time-averaged determination. The equipment supplier should provide the uncertainty in time difference and the number of samples that would be used for the particular configuration. For most applications the uncertainty is insignificant, and in the absence of information from the supplier a nominal ± 0,1 % is assumed.

U_T – For most modern systems the uncertainty is insignificant, and in the absence of information from the supplier a nominal ± 0,1 % is also assumed. In some cases, however, mismatches in cable delays can affect this factor, as referred to in 6.1.3. The supplier should be consulted for an estimate of the uncertainty due to cable mismatches.

$U_{\cos\theta}$ – The low path angle is 45°. As a cross-path system is installed, the uncertainties due to an error in the determination of the angle will be effectively, though not totally, averaged out. If the uncertainty in the angle is ± 3°, the percentage uncertainties for each path would be + 5,4 % and − 5,1 %. Therefore, an uncertainty of ± 0,3 % has been assumed for the cross-path system.

Substituting for U_L, $U_{\Delta\mathrm{T}}$, U_T, $U_{\cos\theta}$ in Equation (14) gives:

$$U_\mathrm{lv} = (0{,}6^2 + 0{,}1^2 + 4 \times 0{,}1^2 + 0{,}3^2)^{1/2} = \pm\ 0{,}7\ \%\ \text{(at one standard deviation)}$$

U_w – If it is assumed that the channel width can be measured to ± 0,2 m at the 68 % confidence level (one standard deviation), then uncertainty for low path width is ± 1,7 %, i.e. absolute uncertainty divided by average channel width and expressed as a percentage.

U_d – Assuming that it is possible to measure the mean bed level to ± 20 mm and the water level to ± 2 mm at one standard deviation, for a depth of 0,425 m, this gives percentage uncertainties of ± 4,7 % and ± 0,5 % respectively, giving a combined uncertainty of ± 4,7 %.

The overall uncertainty U_q in an individual low-flow estimate can be obtained by substituting for U_p, U_lv, U_w and U_d in Equation (12), thus:

$$U_\mathrm{q} = [7{,}5^2 + 1/1(0{,}7^2 + 1{,}7^2 + 4{,}7^2)]^{1/2} = 9{,}0\ \%$$

The expanded uncertainty in discharge at the 95 % level of confidence $U(95)$ is obtained by applying a coverage factor of $k = 2$.

Thus

$$U_q(95) = 2 \times 9{,}1 = \pm\, 18{,}0\ \%$$

NOTE This uncertainty estimate assumes that there has been no calibration/performance checking gauging. The uncertainty should be significantly reduced once this has been undertaken, and where appropriate adjustment/calibration methods similar to those described in 9.2 have been applied.

Therefore, the uncertainty in an individual determination of discharge for this example with assumed component uncertainties is ± 18,0 %.

14.3.7 Uncertainty estimate at high flow

U_p – At the maximum design depth of 1,615 m, four paths should be operating. However, as the paths are crossed and each pair is at approximately the same level, the effective number of paths is two (p). From Table E.4 in ISO 748:1997, the uncertainty in integration due to the limited number of paths is ± 3,5 % (one standard deviation).

U_L – If it is assumed that the path length can be measured to ± 0,1 m at the 68 % confidence level (one standard deviation), then the uncertainty for the high path length is ± 0,5 %. The average uncertainties in the high and low path length determinations are therefore approximately ± 0,55 %.

$U_{\Delta T}$ – A nominal ± 0,1 % has been assumed as for the low flow uncertainty estimate, even though at higher velocities the uncertainty in the time difference should be less.

U_T – A nominal ± 0,1 % has been assumed as for the low flow uncertainty estimate.

$U_{\cos\theta}$ – The high path angle is 57,9°. If the uncertainty in the angle is ± 3° the percentage uncertainties for each path would be + 8,3 % and − 8,4 %. Therefore, an uncertainty of 0,2 % has been assumed for the combined effect of uncertainties in the angle for the two effective paths.

Substituting for U_L, $U_{\Delta T}$, U_T, $U_{\cos\theta}$ in Equation (14) gives:

$$U_{lv} = (0{,}55^2 + 0{,}1^2 + 4 \times 0{,}1^2 + 1{,}0^2)^{1/2} = \pm\, 0{,}63\ \%\ \text{(at one standard deviation)}$$

U_w – If it is assumed that the channel width can be measured to ± 0,2 m at the 68 % confidence level (one standard deviation), then the uncertainty for the high path width is ± 1,1 %. The average uncertainty in the width measurement (high and low paths) is therefore estimated to be ± 1,4 %

U_d – If it is assumed that it is possible to measure the mean bed level to ± 20 mm and the water level to ± 2 mm at one standard deviation, for a depth of 1,615 m, this gives percentage uncertainties of ± 1,2 % and ± 0,1 % respectively, giving a combined uncertainty of ± 1,2 %.

The overall uncertainty U_q in an individual low flow estimate can be obtained by substituting for U_p, U_{lv}, U_w and U_d in Equation (12), thus:

$$U_q = [3{,}5^2 + 1/2(0{,}63^2 + 1{,}4^2 + 1{,}2^2)]^{1/2} = \pm\, 3{,}8\ \%$$

The expanded uncertainty in discharge at the 95 % level of confidence $U(95)$ is obtained by applying a coverage factor of $k = 2$.

Therefore

$$U_q(95) = 2 \times 3{,}8 = \pm\, 7{,}6\ \%$$

Therefore, the uncertainty in an individual determination of discharge for this example with assumed component uncertainties is ± 7, %.

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