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Hydrometry — Measurement of discharge by the ultrasonic transit time (time of flight) method

Hydrométrie — Mesure du débit par la méthode du temps de transit ultrasonique (temps de vol)

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

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

This fourth edition cancels and replaces the third edition (ISO 6416:2004), which has been technically revised. The main changes from the previous edition are:

— the title has been changed;

— a new subclause (7.7) on wireless systems has been added;

— former subclauses 9.2 and 11.6 have been removed;

— Clause 10 on site selection has been revised;

— Annex A (*Principle of measurement uncertainty*) and Annex B (*Performance guide for hydrometric equipment for use in technical standards*) have been added.

Hydrometry — Measurement of discharge by the ultrasonic transit time (time of flight) method

1 Scope

This document 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 document is not applicable to measurement in rivers with ice.

NOTE This document focuses on open channel flow measurement. IEC 60041 covers the use of the technique for full pipe flow measurement.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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, *Hydrometry — Vocabulary and symbols*

ISO 4373, *Hydrometry — Water level measuring devices*

ISO/TS 25377, *Hydrometric uncertainty guidance (HUG)*

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Applications

4.1 Types of applications

a) Open channels

b) Multiple channels

c) Closed conduits

This method does not need a man-made or natural control, as it does not rely upon the establishment of a unique relationship between water level and discharge.

4.2 Attributes and limitations

The following attributes and limitations shall be considered when deploying this measuring system.

Attributes	
1.	Potential for high accuracy
2.	Tolerant of back water effects
3.	Able to measure multiple channels and combine results to give total flow
4.	Capable of determining individual velocities at distinct heights within the water column
5.	Visually unobtrusive
6.	Fish friendly
7.	Mains power supply not essential
8.	Intrinsically safe systems available for use in explosive atmospheres
9.	No obstruction or head loss
10.	Suitable for large range of channel widths and depths
11.	Potential for built in redundancy
12.	Potential for relatively low operating costs

Limitations	
1.	A site with an unstable cross section needs to be avoided if possible
2.	Requires minimum depth of water to operate
3.	May require cables to both sides of channel
4.	Ragging of sensors by trash
5.	Potential attenuation of acoustic signal by
	suspended solids
	weeds
	entrained gasses
	temperature gradients
	salinity gradients

Detailed explanations of these attributes and limitations can be found in clauses throughout this document.

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 ($m^3 \cdot s^{-1}$). The definition of discharge is the product of the wetted cross-sectional area and the mean velocity vector perpendicular to it.

Thus:

$$Q = \bar{v} \times A \quad (1)$$

where

Q is the discharge, expressed in cubic metres per second ($m^3 \cdot s^{-1}$);

$\bar{v}$ is the mean velocity, expressed in metres per second ($m \cdot s^{-1}$);

A is the cross-sectional area, expressed in square metres (m^2).

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

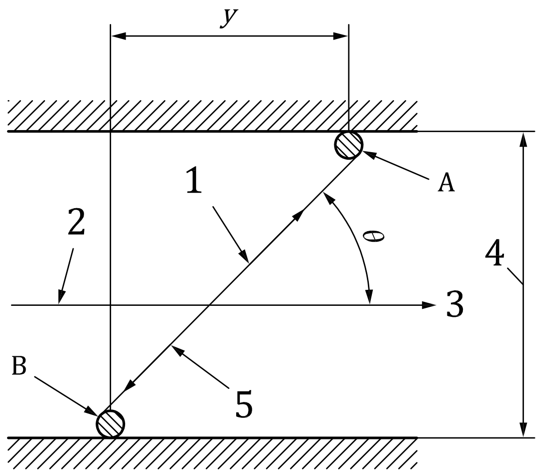
5.2.1 Discharge can be computed using the velocity-area method (see 5.1), provided that a relation can be established between the velocities determined by the transit time ultrasonic system and the mean cross-sectional velocity. If there are sufficient operational paths distributed sufficiently throughout the vertical to define the velocity profile, the resulting samples of flow velocity can be vertically integrated to provide an estimate of the mean cross-sectional velocity. Alternatively, if there are insufficient operational paths, a relationship between measured velocity (index velocity) and mean velocity can be established using a spot flow gauging technique, e.g. rotating element current meter or acoustic Doppler current profiler (ADCP).

5.2.2 The 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 length (L)

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-times for the ultrasonic pulses are:

$$t_{AB} = L/(c - v\cos\theta) \quad \text{and} \quad t_{BA} = L/(c + v\cos\theta) \tag{2}$$

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 (m);

c is the speed of sound in water, in metres per second ($m \cdot s^{-1}$);

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

Resolving for line velocity:

$$v_{line} = L \times (t_{AB} - t_{BA}) / (t_{AB} \times t_{BA} \times 2\cos\theta) \tag{3}$$

where v_{line} is the line velocity or the average velocity of the water across the channel in the direction of flow, in $m \cdot s^{-1}$.

6.1.3 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

6.1.4 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 should be at an angle between 30° and 65° to the mean direction of flow to minimize uncertainties.

6.1.5 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. 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.

6.2 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 20 Hz to 20 000 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 1,5 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 1 400 m·s^{-1} to a little over 1 500 m·s^{-1} (see Table 2). This will vary dependent on the characteristics of the water. However, these figures are offered as a guide based on a review of the available literature.

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

Temperature °C	**Speed of sound** (approximate) m·s^{-1}
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^{-1} higher.	

The speed of sound c in water is given by:

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

where

c is the speed of sound in water, in metres per second (m·s^{-1});

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 (m).

6.2.3 Propagation losses

6.2.3.1 Transmission of sound in water

6.2.3.1.1 Only a portion of the acoustic energy transmitted reaches the target. The remainder is lost for a variety of reasons. The loss in signal strength is called "propagation loss", which consists of *spreading loss* (6.2.3.1.2) and *attenuation loss* (6.2.3.1.3).

6.2.3.1.2 *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 effect depend on the following factors:

— path length;

— diameter of ultrasonic transducer;

— frequency characteristics.

6.2.3.1.3 *Attenuation loss* is the reduction in the acoustic intensity caused by the resistance of the medium to the transmission of acoustic energy. It is analogous to the loss of electrical energy in a wire where there is no spreading loss.

Attenuation loss is attributable to *scattering* and *absorption*.

— *Scattering* is the redirection in all directions of the incident acoustic wave energy by suspended matter in the water, e.g. air bubbles and suspended solids. The effect is greater at higher transducer frequencies.

— *Absorption* is the process by which acoustic energy is converted into thermal energy by the friction in the water, when it is subjected to repeated compressions and expansions by a passing sound wave. This effect is also frequency dependent.

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. 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.

6.2.3.2 Reverberation

Reverberation is the energy returned by reflectors other than the transducers. This is analogous to the effect which reduces the effectiveness of car headlights on a foggy night.

6.2.3.3 Refraction

This is the bending of the acoustic pulse path if the water varies significantly in temperature or density. For example in slow moving rivers, with poor vertical mixing, the effect of the sun on the surface may produce a vertically distributed temperature gradient.

6.2.3.4 Reflection

Sound can be reflected from the water surface and/or the bed of the river which can cause errors in the signal timing.

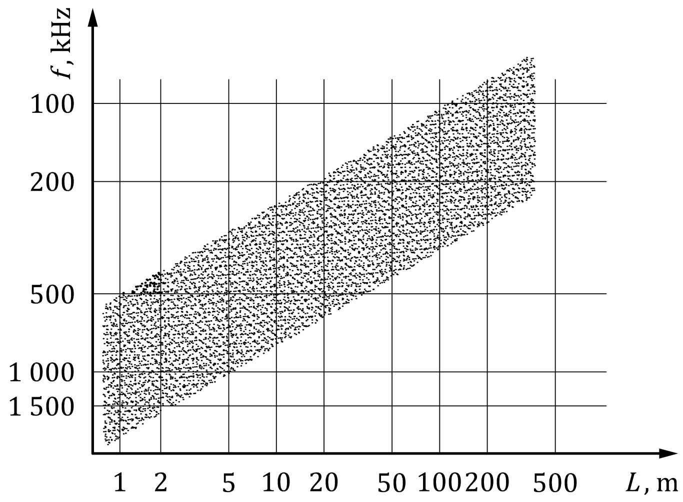


Figure 2 — Commonly used transducer frequencies for various path lengths

6.2.4 Signal path bending

6.2.4.1 The path taken by an acoustic pulse is bent (refraction), 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 an upward directed temperature gradient vector. This causes the speed of sound to be higher near the surface and, consequently, the acoustic path to bend towards the river bed.

The acoustic wave propagates across the channel as a cone. If a vertical temperature gradient, as described above, 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 horizontal 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 create a higher speed of sound near the bottom and thus 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.

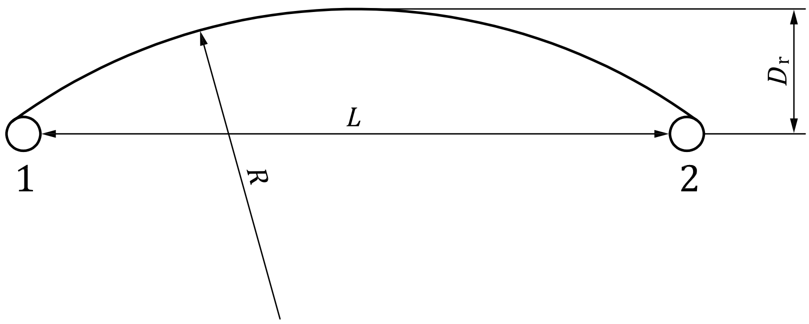
6.2.4.2 The approximate degree to which the signal path is bent is given by:

$$R = c_1 (d_2 - d_1) / (c_1 - c_2) \quad (5)$$

where

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

c_1, c_2 are the speeds of sound at depths d_1 and d_2 respectively, in metres per second (m·s^{-1}). [These speeds can be calculated using Formula (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 scattered from the water surface and, to a lesser extent, from the channel bed. This is due to the fact that the contrast in acoustic impedance is much higher between water and air than between water and the bottom (sand, rock, mud).

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 shall 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 Formula (7):

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

where

d_{min} is the minimum clearance of water required between velocity path and water surface, 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 Hz.

6.2.5.2 The minimum clearance of water required above and below the velocity path for the various transducer frequencies and path lengths is given in Table 3 (column 3).

The minimum total water depth is given in Table 3 (column 4). The value for d_{min} is twice the minimum clearance for the sensor below the free water surface.

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

Path length L m	Transducer frequency f kHz	Minimum clearance m	Minimum total water depth d_{min} m
1	1500	0,02	0,04
1	1000	0,03	0,06
1	500	0,04	0,08
3	1000	0,045	0,09
3	500	0,065	0,13
10	500	0,12	0,24
10	200	0,19	0,38
30	500	0,21	0,42
30	200	0,33	0,66
50	500	0,27	0,54
50	200	0,43	0,86
100	200	0,60	1,20
100	100	0,90	1,80

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 velocity paths, vertical spacing, angle to flow, the use of in-line, crossed or reflected configurations may all be specified.

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.

Calibration will be required due to the uncertainty in the mean velocity estimation. Prior to a satisfactory calibration being completed it may be possible to estimate the mean velocity using velocity profile theory.

7.2.2 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.

7.2.3 The single-path gauge is inherently vulnerable to transducer damage or malfunction. There is no built-in component redundancy capability (see 7.3.3).

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 aim may be 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 Multi-path gauge configurations may also be appropriate for sites 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.

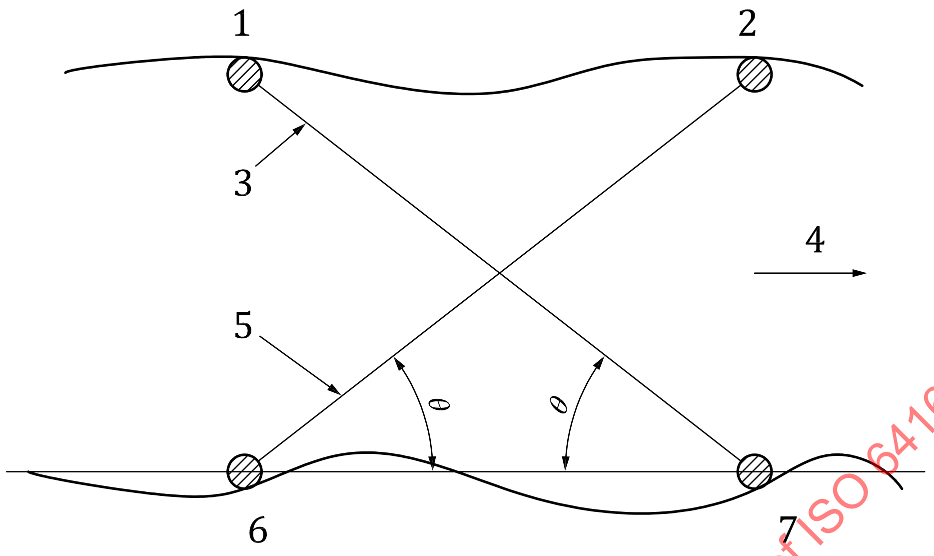
7.4 Crossed-path systems

7.4.1 One of the fundamental requirements of the ultrasonic transit time 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 Formula (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, say of less than 10 channel widths upstream or 3 widths downstream, there is the possibility that the flow will not be parallel to the channel banks. It may 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, 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 crossed path should be arranged so as to intersect in mid-stream.

The path angle, θ, for the uppermost paths should be between 30° and 65° to minimize uncertainties. 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 should not be less than 30°.

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 %. (Clause 14 deals with the basic measurement uncertainties inherent in this component of the system.)

7.4.7 The use of crossed paths will not 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.

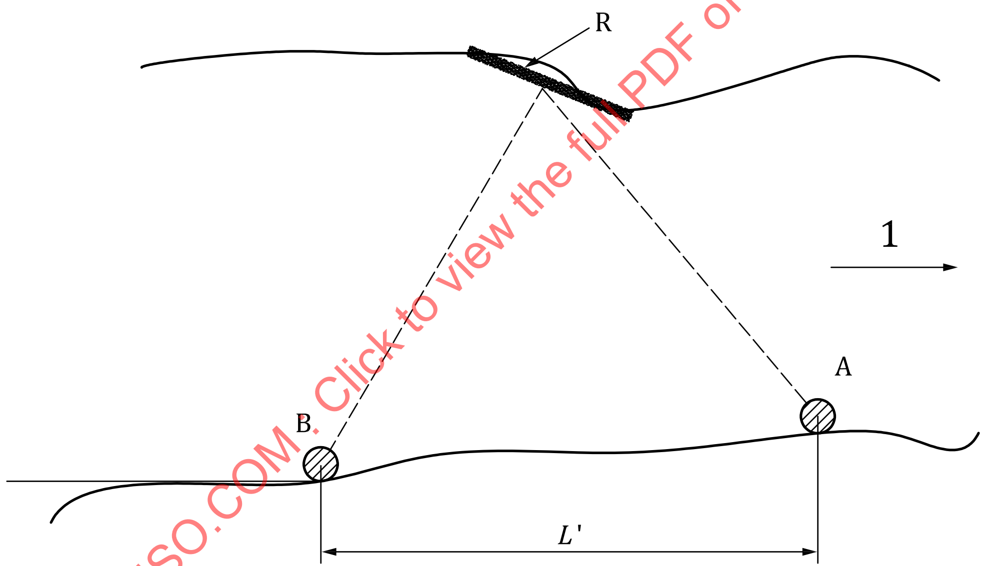
7.4.9 Interleaved crossed paths are paths which cross at different elevations. This arrangement is sometimes used to reduce the number of paths required. The number of paths is spread throughout the channel height to try to obtain good sampling of the vertical velocity profile while attempting to achieve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

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

7.5 Reflected-path systems

7.5.1 The basic ultrasonic transit time 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).



Key

1 direction of flow
A downstream transducer
B upstream transducer
R reflector
L' projected distance parallel to the direction of flow

NOTE Total path length L = AR + RB.

Figure 5 — Plan for reflected-path gauge

7.5.2 The formula for calculation of water velocity is:

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

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, possibly requiring larger transducers of a lower frequency and making the system more susceptible to propagation losses and beam bending.

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 need 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).

Taking into account the potential problems, careful examination of the location and flow conditions should be made when consideration is given to the installation of a reflected path system, and it should only be used when all possibilities for locating transducers on opposite banks have been exhausted.

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 Formula (9) below for water velocity is derived from Formula (8):

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

where

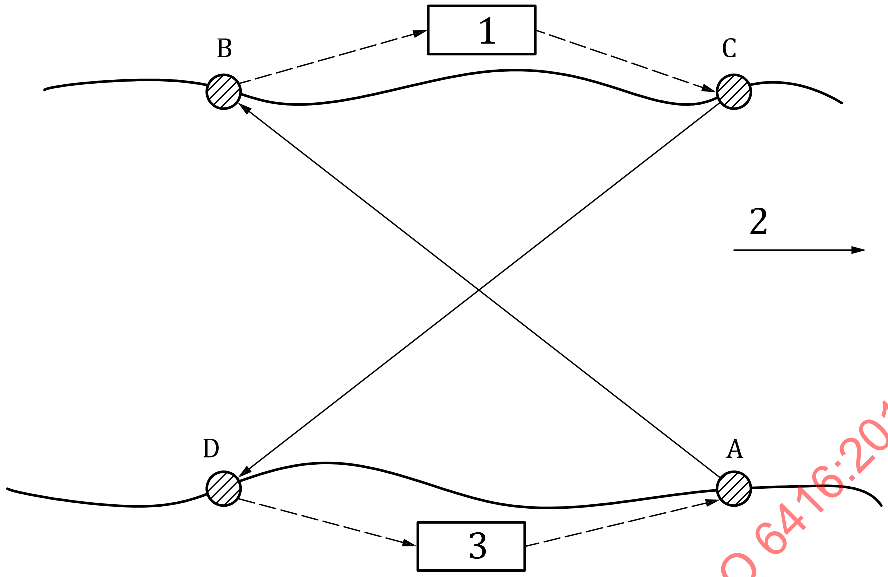
v is the average velocity of the water across the channel in the direction of flow;

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 transducer D via the transponder;

t_{DA} is the transit time from transducer D to transducer 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.



Key

1 transponder unit
2 direction of flow
3 electronic unit
Total path length *L* = AB + CD.

A downstream transducer
B upstream transducer
C downstream transducer
D upstream transducer

Figure 6 — Plan for a gauge employing a transponder

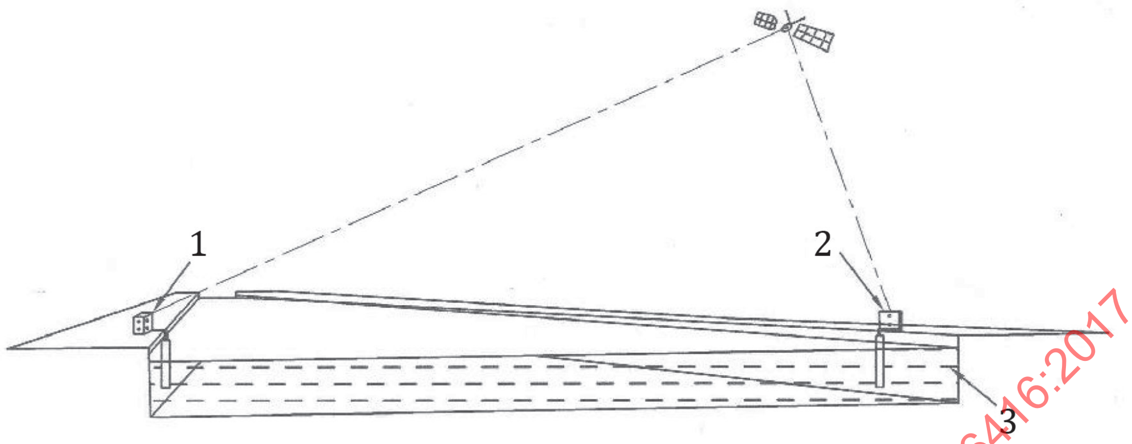
7.6.3 In this configuration, the paths are no longer than for a conventional system, and so the problems experienced by a reflector system (see 7.5.3) are avoided.

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.

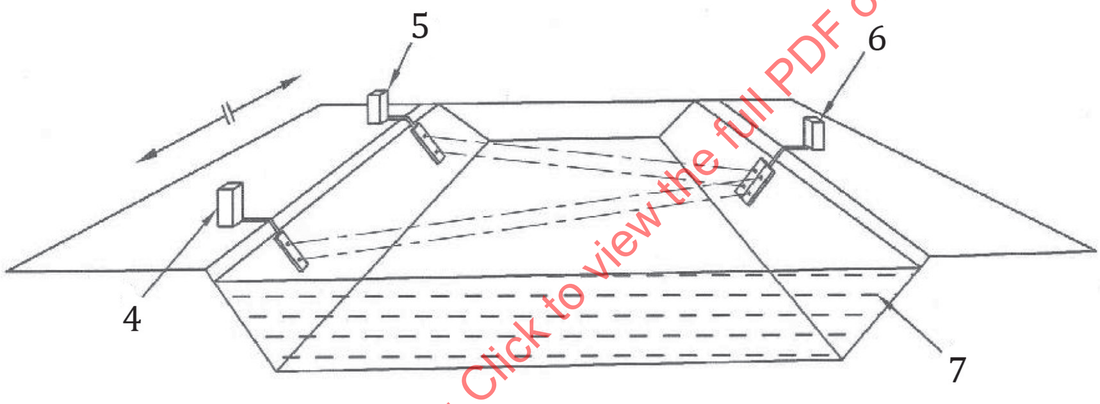
7.6.5 A disadvantage of the transponder configuration is in the complexity of the electronics of the transponder unit, especially if the system is multi-path or needs to be battery-powered.

7.7 Wireless systems (if a cable crossing is not possible)

The wireless system's mode of operation is based on the transit-time method. On either side of the channel, autonomous systems are installed such that their line of sight is diagonal to the flow of water. Both systems communicate with each other by means of directional radio and are also equipped with GPS receivers. The satellite data from these receivers provide high precision standard frequency and accurate timing pulse to ensure that both systems operate absolutely synchronous. One master system should be able to control multiple slaves. It should also be possible to set up multi-path systems, crossed path systems and responder systems (see Figure 7).



a) Wireless systems — Level single path system



b) Wireless systems — Level responder system

Key

1 system master
2 system slave
3 water in the channel
4 system master - GPS receiver
5 system slave - GPS receiver
6 responder
7 water in the channel

Figure 7 — Wireless systems

7.8 Systems using divided cross-sections

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

7.9 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 Determination of discharge

8.1 Single-path systems

8.1.1 The "time of flight"/"transit time" technique described in this document is a velocity area method. Discharge is therefore determined using the continuity equation,

$$Q=\bar{v}\times A \tag{10}$$

where

Q is the discharge, expressed in cubic metres per second ($m^3 \cdot s^{-1}$);

$\bar{v}$ is the mean velocity, expressed in metres per second ($m \cdot s^{-1}$);

A is the cross-sectional area, expressed in square metres (m^2).

8.1.2 In systems where only a single-path determination of velocity is made, or where there are a limited number of operational paths, it will be necessary to establish a relation between this and the mean velocity in the cross-section. If this relation is stable, calculation may be straightforward, with flow derived as

$$Q=C_v\bar{v}A \tag{11}$$

where C_v is a velocity factor, preferably derived by gauging (calibration) throughout the flow range or by a calibrated model, varying with the ratio of the path elevation to the water depth.

8.1.3 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).

NOTE The effective number of paths is not the same as the number of paths (see 14.3.2).

8.1.4 Formula 11 can also be used to calculate flow for single-path systems utilizing the reflected-path system (see 7.5).

8.1.5 Alternatively, the mean velocity can be determined using a velocity index rating (see ISO 15769) whereby:

— the mean velocity is a function of the measured (index) velocity, or

— the mean velocity is a function of the index velocity and stage.

8.1.6 For many installations with a limited number of paths, the velocity determined by the instrument will not be the same as the mean velocity in the measuring section since in most channels the instrument will not sample the entire flowing cross-section The mean velocity is determined using the instrument velocity(ies). This determination is undertaken by using a relationship between the mean velocity and the instrument velocity(ies), usually referred to as the index velocity. Velocity index relationships can take the following general forms:

$$\bar{v} = fn(v_{\rm i}) \tag{12}$$

$$\bar{v} = fn(v_{\rm i}, h) \tag{13}$$

where

$v_{\rm i}$ is the instrument/index velocity, expressed in metres per second ($m \cdot s^{-1}$);

h is the stage, expressed in metres (m).

The cross-sectional area is determined using the stage-area relationship.

8.1.7 The computation process is summarized as follows.

The following steps are required in the velocity index rating development process.

a) Develop a stage-area relationship at the instrument measuring section. This can be undertaken at any time, usually when flows are low.

b) Undertake a series of gauging exercises over as wide a flow and stage range as possible. The number of gauging exercises required will be dependent on the physical characteristics of the site, similar to the development of conventional stage-discharge relationships (refer to ISO 1100-2).

c) During each gauging, the instrument stage and velocity(ies) should be recorded at a suitable frequency, e.g. 1 min intervals.

d) For each gauging, the discharge should be computed and divided by the corresponding cross-sectional area at the instrument cross-section to obtain the mean velocity. The cross-sectional areas can be obtained from the stage-area relationship. The cross-sectional area at the instrument site and not the gauging site should be used for this calculation, if they are at different locations.

e) The average instrument stage and velocity should be computed for the period of the gauging. The estimated mean velocity, instrument velocity and where appropriate the stage can then be used to derive the velocity index rating.

NOTE Further details on the development of velocity relationships are contained in ISO 15769.

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 utilize 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. 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 the 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.

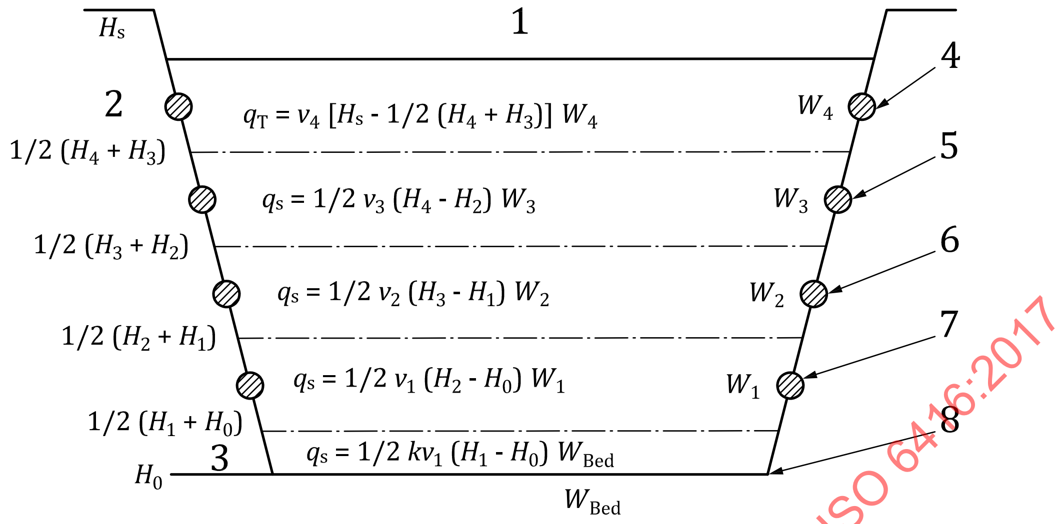
8.2.1.7 Multi-path configurations utilizing the reflected-path or transponder system should calculate flow as if they were multi-crossed-path flow gauges, using either the mid-section or mean-section methods.

8.2.2 Mid-section method

8.2.2.1 In the mid-section method (see Figure 8), 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 need 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	H	height, in metres, above a defined datum
2	top panel	H_s	surface height
3	bottom panel	H_0	bed height
4	path 4, height H_4	W	width of the cross section, in metres, at the corresponding height
5	path 3, height H_3	v	velocity, in metres per second, determined by the corresponding path
6	path 2, height H_2	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
7	path 1, height H_1	q_s	flow in the corresponding panel or slice
8	bed, height H_0	q_T	flow in the top panel which contains the highest working path

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

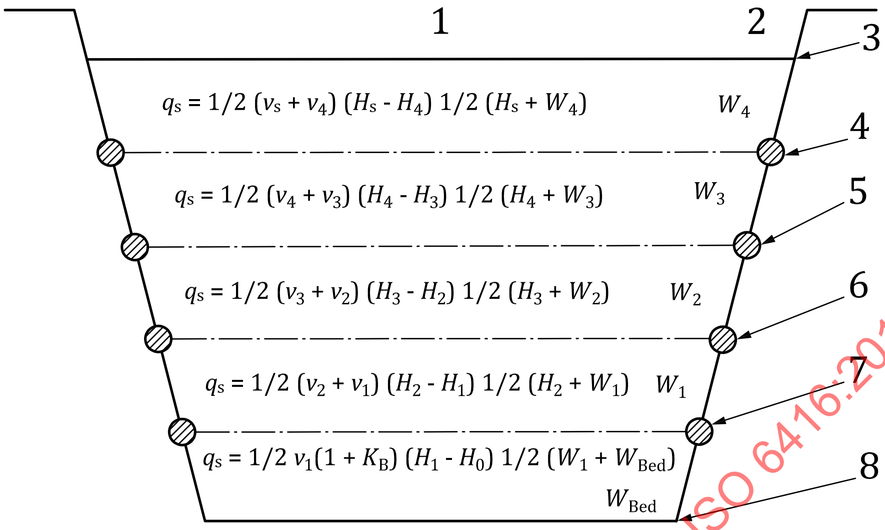
Figure 8 — Example of flow calculated by mid-section method using four operational paths

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, and preferably by current-metering or modelling (see ISO 748).

8.2.3 Mean-section method

8.2.3.1 In the mean-section method (see Figure 9), 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

2 width W_s

3 bottom panel

4 path 4, height H_4

5 path 3, height H_3

6 path 2, height H_2

7 path 1, height H_1

8 bed, height H_0

H height, in metres, above a defined datum

W_s 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 vs is 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 0,7 and 0,9

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 $q = q_0 + q_1 + q_2 \ldots q_T$

Figure 9 — Example of flow calculated by mean-section method using four operational paths

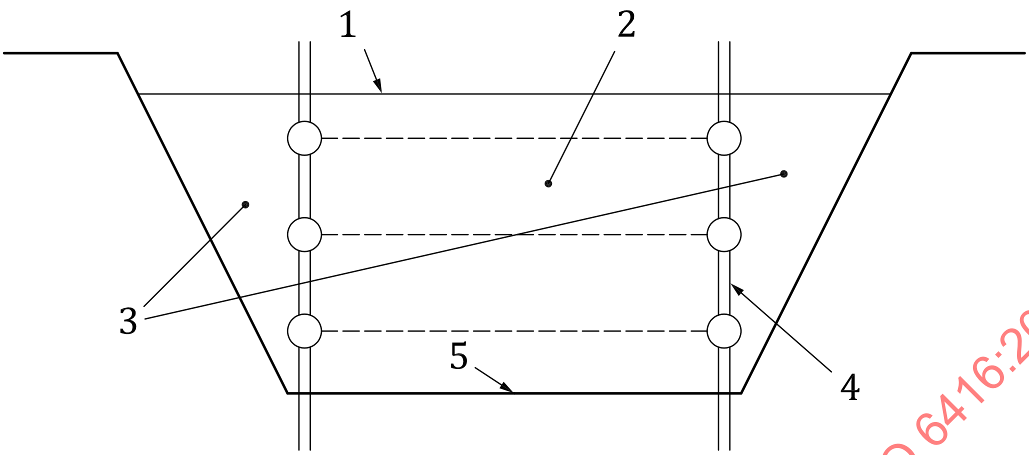
8.2.3.2 A mean panel “width” is computed from site-survey data stored in the flow computer; it is not necessarily defined by the transducer positions. Panel “thickness” is determined by the difference in elevation between paths; for the lowest panel this becomes the difference in elevation between the lowest path and the mean 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 10).

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 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 10 — Installation with transducers in the channel

9 System verification and calibration

9.1 The transit-time technique provides an absolute determination of velocity normal to the cross-section 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.

9.2 In principle, calibration, is required only for the computation of discharge from single-path systems, or for situations where there are only a limited number of effective paths (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 and limited 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. In the case of complex situations or changes to channel conditions, numerous gaugings may be required.

NOTE The effective number of paths is not the same as the number of paths (see 14.3.2).

9.3 Even with multi-path systems, where the velocity distribution is inherently well-sampled, there is often a need for “verification” by means of an alternative method.

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.

9.4 Single-path systems (or systems with a small number of separate operational paths) require calibration to establish the relation between line velocity (index velocity) and mean velocity for the range of stages likely to be experienced (see 8.1), and to conduct periodic checks to ensure that the relation remains stable. Calibration may be achieved using current meters including ADCPs.

10 Site selection

The following factors should be considered when selecting sites for transit time ultrasonic systems.

a) Minimal alteration should take place to the natural state of the bed and banks. If significant changes are made, it is likely that they will revert to their original state after a few years.

b) The channel should be straight as possible with banks parallel. The bed profile should be as even as possible.

c) The site and cross section should remain stable over time. Locations that are unstable should be avoided.

d) The measuring section should be free from weed growth because this can seriously attenuate the acoustic signal.

e) In river sections greater than 30 m wide and with a heavy sediment loads (>500 mg/l), a signal propagation survey should be undertaken to ensure the acoustic technique will be suitable.

f) The channel shall have a minimum water depth. (see Table 3).

g) If the site is subjected to an uneven velocity profile, then a multi path configuration should be deployed.

h) The impact of entrained air in channels that are downstream of dams, weirs, waterfalls, hydraulic jumps, mills, power plants, sewer outfalls or other potential sources of entrained air should be considered. A signal propagation survey should be undertaken if this is suspected.

i) If excessive electromagnetic interference is suspected, then suitable signal screening should be discussed with the supplier.

j) A mains power supply near to the site would be advantageous, while not essential, this is likely to improve resilience of the site.

k) Easy access to the site during construction, repairs, regular verification or quality control visits is essential.

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 and their possible effect upon overall system performance should be known before gauge design is undertaken.

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,

n) mains power and PSTN availability and

o) GSM signal for modem connection.

11.3 Survey of the cross-section

The cross-section of the proposed measurement section should be surveyed thoroughly. If circumstances allow, the survey should extend from as much as 10 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.

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. The survey may be done using an ADCP device with the capability to measure both the velocity distribution and the channel profile.

Some ADCP devices have the additional capability to carry out a 3-D bathymetric survey of the whole bed section within the proposed measurement location.

11.5 Survey of signal propagation

For measurement locations where a higher risk of signal attenuation is considered possible, a sound propagation survey should be undertaken.

12 Operational measurement requirements

12.1 General

To calculate discharge, an ultrasonic transit time flow gauge requires the input of a number of different items of information; it should contain a means of

— storing details of the relation between water depth and cross-sectional area,

— determining the water depth or stage and

— determining the water velocity for each path.

In addition, it should be capable of executing the mathematical functions necessary to calculate flow from the relevant stored and directly determined data.

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 specialized instrumentation and

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

All the 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 the 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

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).

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.

12.5 Determination of mean bed level

12.5.1 Mean bed level refers to the mean elevation of the channel bed within the area bounded by the banks of the channel and the upstream and downstream transducer arrays. This can be determined by surveying a number of cross-sections within this area.

The accurate determination of mean bed level of the river section in the measuring reach is essential for the accurate estimation of discharge. Therefore, it is important that bed surveys are undertaken prior to commissioning a site and then followed up by regular surveys. The following specification is generally recommended.

At each site, a minimum of 7 cross-sections (6 cross-sections for uni-directional sites) should be carried out. These will include:

a) one cross-section at right angles to the banks at the upstream transducer rack(s);

b) one cross-section at right angles to the banks at the downstream transducer racks;

c) three cross-sections equally spaced between the cross-sections referred to in a) and b) above;

d) two diagonal cross-sections along the line (flight path) of the bottom transducers (only one is required at uni-directional sites).

It is not essential, but is often advantageous, to also survey several cross-sections upstream of the measuring reach since this can provide useful information on approach conditions, e.g. shoals, which could create strange flow patterns.

12.5.2 The method of estimation of mean bed level varies between hydrometric practitioners. The mean bed level can be estimated in one of three ways.

a) Take all the survey points below the lowest flight path and calculate the arithmetic average of these, i.e. the arithmetic average level in the rectangle defined by the banks and the upstream and downstream transducer racks.

b) Estimate the mean bed level for each cross-section by dividing the area by the surface width and calculate the average of the mean bed levels determined in this manner.

c) Estimate the mean bed level solely using the cross-section(s) along each transducer [flight path line(s)] by determining the area and dividing by the water surface width to obtain the mean bed level. The argument in favour of this method is that you are measuring the cross-section along the line of velocity measurement/measuring cross-section, i.e. this is the actual velocity measurement section to be used when applying the continuity equation.

The latter method is the most hydraulically correct since the mean bed level estimate is based solely on levels along the line of the measuring cross-section(s).

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.

12.6 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 resorting 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

13.1.1 The equipment of a gauging station consists of

— pairs of transducers located at the ends of each velocity path in the gauge configuration,

— one or more water depth or stage measurement device,

— flow computer unit, connected to the transducers and depth device and

— recording or telemetry equipment, which may be integral with the flow computer system.

13.1.2 The 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; and

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

13.2 Design and construction of equipment

13.2.1 Transducers

13.2.1.1 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 6.2.5.2) 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 13.9.7). 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.

13.2.1.2 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 arc sin β.

$$\beta = \frac{370}{f \times d} \tag{14}$$

where

f is the transducer frequency, in hertz;

d is the diameter of the transducer, in metres.

13.2.1.3 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.

13.2.1.4 The mountings should be designed so that:

a) any build up of silt does not obscure the ultrasonic path;

b) silt and debris can be removed without undue difficulty;

c) 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;

d) the transducers are not easily misaligned or damaged by debris, the passage of boats, unauthorised interference, frost or ice;

e) they do not corrode in such a way as to collapse or be difficult to disassemble;

f) their shapes do 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.

13.2.2 Transducer cables

Where suitable impedance matching circuitry is used within the flow computer unit, it is possible to eliminate the problems normally associated with different cable lengths between the flow computer and transducers. However, if this is incorporated, it is important that asymmetrical delays are not introduced by poor matching of the electronic circuits. There could also be a cost implication.

Where impedance matching is not available but the cables between the flow computer and transducers are shorter than 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.

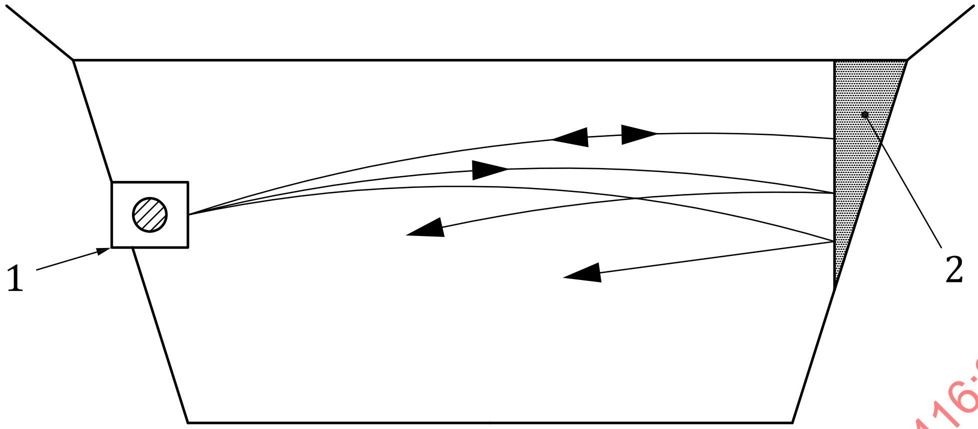
This problem can be avoided by ensuring that the lengths of the cables to the upstream and downstream transducers for a given path are of the same length (±2 m).

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). Note that Figure 12 only indicates the signal “B to A”. To obtain a complete determination, the signal “A to B” is also required.



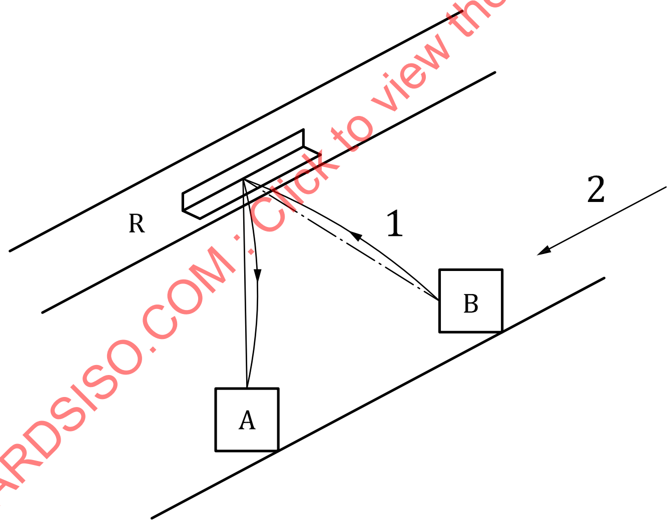
Key

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

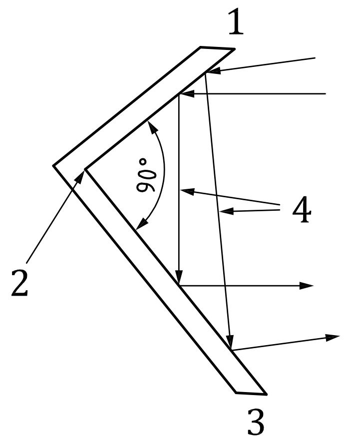
2 direction of flow

A receiver

B transmitter

R reflector

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) mm, 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 an indeterminate period.

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, 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 the 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 pass band 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 13.5.2.1, or else the use of such filters should be avoided.

13.5.3 Signal maintenance (gain control)

When signals are attenuated by sediment loading, seasonal weed growth, 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 an AGC, increasing the gain increases the interfering noise while attempting to maintain the signal. In order to cope fully with signal attenuation in the presence of noise, the transducer drive voltage needs 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 an AGC, because the gain would then need 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 optimize the signal-to-noise ratio, while 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 while 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 the

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 document, 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 need 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 to 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 Formula (15).

$$U_v = U_t \times 1\,450^2/(L \times 2 \cos\theta) \quad (15)$$

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 analogue or digital (RS232, RS485, 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. If the equipment on site is battery-powered, the telemetry system can be used to switch it on only at such times as 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;

NOTE 1 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;

NOTE 2 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 are 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 12 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 9). 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

Hydrometric uncertainty estimations shall be undertaken in accordance with ISO/TS 25377 (hereafter referred to as the HUG). Additional information is given in ISO/IEC Guide 98-3 (hereafter referred to as the GUM).

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 and therefore 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, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand" (see the GUM). 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.

The GUM states that uncertainties of any measurement shall be determined to one standard deviation. The uncertainty at one standard deviation is referred to as the “standard uncertainty”.

One standard deviation equates to a confidence level of about 68 %. The uncertainty at two standard deviations is twice the standard uncertainty. Therefore if the standard uncertainty is estimated, it can then be multiplied by two to obtain the uncertainty at two standard deviations or the 95 % confidence level. This multiplying factor is referred to as the “coverage factor”. If the uncertainty is expressed at three standard deviations (approximately 99 % confidence level), the coverage factor would be three.

When stating uncertainties the confidence level or the coverage factor i.e. the number of standard deviations should be stated.

EXAMPLE If the uncertainty was calculated to be 8 % for an estimated discharge of 55,1 $m^3 \cdot s^{-1}$ at the 95 % confidence level, the statement of uncertainty is stated as:

Discharge = 55,1 $m^3 \cdot s^{-1}$ with an uncertainty of 8 % at the 95 % confidence level based on a coverage factor of $k = 2$

An introduction to uncertainty is contained in Annex A. This includes a description of Type-A and Type-B uncertainties and probability distributions that are relevant to hydrometric uncertainty analysis.

14.3 Uncertainty in discharge

14.3.1 Uncertainty equation

The following equation may be used to estimate the uncertainty in discharge for a time of flight system where the mean section or mid-section (see 8.2.2 and 8.2.3) are used to determine the discharge:

$$U_Q = [U_p^2 + 1/p\,(U_{lv}^2 + U_w^2 + U_d^2)]^{1/2} \quad (16)$$

where

- U_p is the uncertainty in integration consisting of the limited number of effective (see below) paths (p) used (from ISO 748:2007, Table E.4) and the method of computation (see 13.12.2);
- 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 i.e. water level relative to mean bed level

If a velocity index rating is used to derive mean-velocity and thus determine discharge (see 8.1), then the methods for deriving uncertainties in discharge estimates using velocity index ratings should be applied.

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 mm 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 at least 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 ffective number of paths would be one.

14.3.3 Uncertainty in the line velocity, U_{lv}

Formula (3) may be written:

$$v_{lv} = L\Delta t/2t^2 \cos\theta \tag{17}$$

where

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

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

From this, the uncertainty U_{lv} is:

$$U_{lv} = (U_L{}^2 + U_{\Delta T}{}^2 + 4U_T{}^2 + U_{\cos\theta}{}^2)^{1/2} \tag{18}$$

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 cosθ, thus:

$$U_w = (U_L{}^2 + U_{\cos\theta}{}^2)^{1/2} \tag{19}$$

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 ISO 748:2007, Table E.4, 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 14.3.3. 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 Formula (18) gives:

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

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 Formula (16), 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 gauging (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 ISO 748:2007, Table E.4, 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.

$U_{\Delta T}$ – 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 14.3.3. 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, $U_{\Delta T}$, U_T, $U_{\cos\theta}$ in Formula (18) gives:

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

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 Formula (16), thus:

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

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

Thus

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

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 9.0 have been applied.

Therefore, the uncertainty in an individual determination of discharge for this example with assumed component uncertainties is ±8,0 %.

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 ISO 748:2007, Table E.4, 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 Formula (18) 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 Formula (16), 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 $U_{Q(95)}$ 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 %.