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INTERNATIONAL STANDARD

ISO 6416

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

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 6416 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.

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

1 Scope

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

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

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

2 Normative references

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

ISO 772 *Hydrometric determinations — Vocabulary and symbols*

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

ISO 15769 *Guidelines for the application of acoustic velocity meters using the Doppler and echo correlation methods*

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.

4 Applications

This method is suitable to determine flow in:

1. Open Channels
2. Multiple Channels
3. 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

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.	Site with unstable cross section need 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 10, 11, 12 & 13

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

Thus:

$$Q = \overline{V} \times A \tag{1}$$

Where Q = discharge (m^3s^{-1})

$\overline{V}$ = mean velocity (ms^{-1})

A = cross-sectional area (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

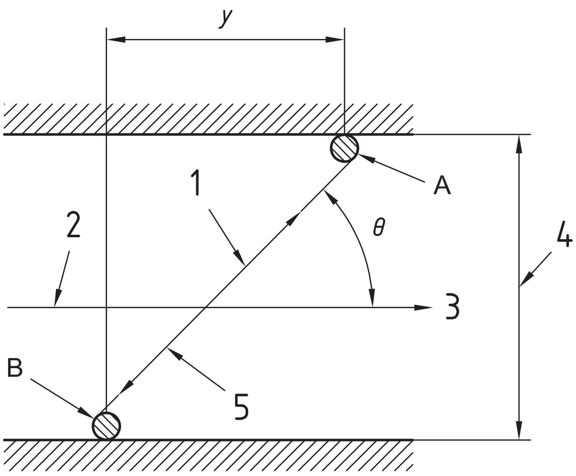
5.2.1 Discharge can be computed using the velocity-area method (see 5.1 above), provided that a relation can be established between the velocities determined by the transit time ultrasonic system and the mean cross-sectional velocity. If there are sufficient operational distributed sufficiently throughout the vertical to define the velocity profile, the resulting samples of flow velocity can be vertically integrated to provide an estimate of 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

A, B transducers

θ angle between the path and the direction of flow

y downstream distance between transducers

Figure 1 — Schematic illustrating the general principle

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

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

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;

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

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

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

Resolving for line velocity:

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

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

— independent of the speed of sound in water,

— proportional to the difference in transit times,

— inversely proportional to the product of the transit times,

— critically dependent on the angle between the path and the direction of flow (see Table 1).

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

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

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

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

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

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

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

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

c) With large angles, there is also an increase in the error in velocity computation that results from assumptions made in the assessment of the angle. 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 50 Hz to 15 000 Hz, and is generally referred to as “sonic”. Frequencies less than 50 Hz are usually termed “subsonic”, and those above 15 000 Hz “ultrasonic”. Transit-time systems operate in the ultrasonic range at frequencies typically between 100 kHz and 1.5 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 1400 m/s to a little over 1500 m/s (see Table 2).

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

Temperature °C	**Speed of sound** (approximate) m/s
0	1 402
10	1 447
20	1 482
30	1 509
40	1 529
NOTE 1 The above figures apply to the water in most natural fresh-water rivers and foul sewers.	
NOTE 2 In seawater the corresponding speeds are approximately 50 m/s higher.	

6.2.3 Propagation losses

a) *Transmission of sound in water*

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:

1. spreading loss; and
2. attenuation loss.

Spreading loss:

This is the reduction in acoustic intensity due to the increase in area over which the given acoustic energy is distributed. Losses due to this affect depend on the following factors:

- Path length;
- Diameter of ultrasonic transducer;
- Frequency characteristics.

Attenuation loss:

This 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 the following factors:

- Scattering: Reflection of the signal by suspended matter in the water e.g. air bubbles and suspended solids. The effect is greater at higher transducer frequencies.
- Absorption: Process by which acoustic energy is converted into heat energy by the friction between the water molecules as a sound wave is subjected to repeated compressions and expansions of the medium.

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

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

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

b) *Reverberation:*

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.

c) *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

d) *Reflection:*

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

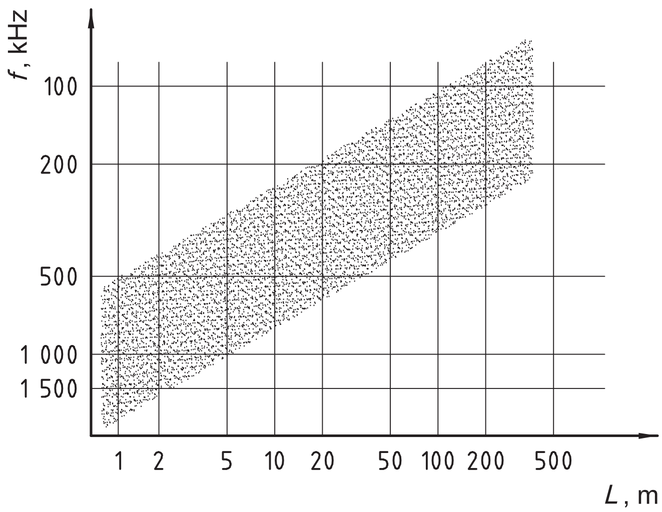


Figure 2 — Commonly used transducer frequencies for various path lengths

6.2.4 Signal path bending

6.2.4.1 The path taken by an acoustic pulse is bent if the water through which it is propagating varies significantly in either temperature or salinity. In slow-moving rivers, with poor vertical mixing, the effect of the sun upon the surface produces a vertically distributed temperature gradient. This causes the acoustic path to bend towards the river bed. The acoustic wave propagates across the channel as a cone. If a vertical temperature gradient exists, only that part of the cone which starts in a certain upward direction will arrive at the other end of the path.

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.

6.2.5 Reflection

6.2.5.1 Sound is reflected from the water surface and, to a lesser extent, from the channel bed.

Errors in signal timing will occur if the secondary signal interferes with the first cycle of the direct signal. To avoid this effect, the difference in the two paths should exceed one acoustic wavelength (speed of sound/frequency). This will be achieved if the depth of water above the acoustic path exceeds that given by Equation (4):

$$d_{\min} = 27\sqrt{\frac{L}{f}} \quad (4)$$

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 hertz.

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)

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

Path length L m	Transducer frequency f kHz	Minimum clearance $d_{\min}$ m	Minimum total water depth
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.

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

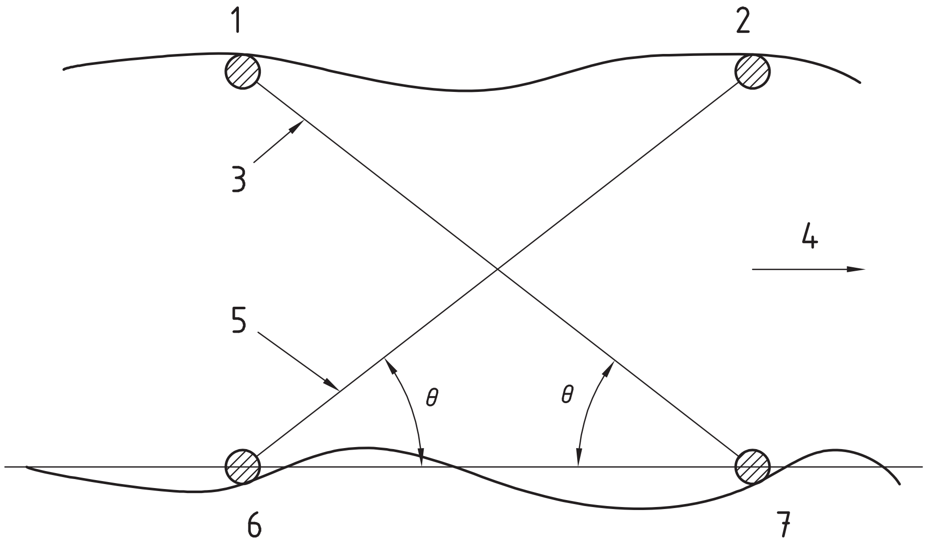
7.4 Crossed-path systems

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

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

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

7.4.4 If there is a bend or asymmetric change in the channel shape, 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 3).



Key

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

Figure 3 — Plan for crossed-path gauge

7.4.5 The crossed path should normally 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.

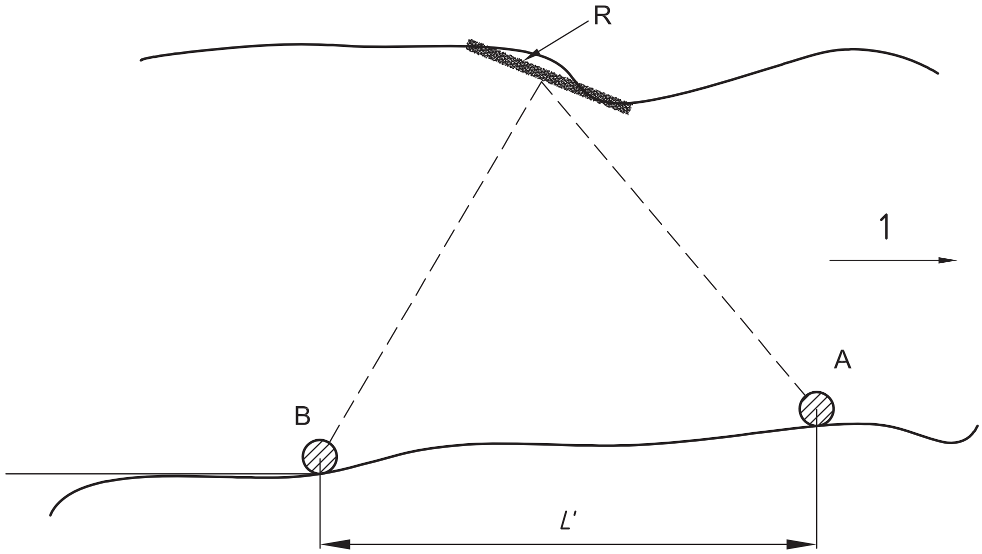
7.4.9 Interleaved crossed paths are paths which cross at different elevations. This arrangement is sometimes used to reduce the number of paths required . The number of paths is spread throughout the channel height to try to obtain good sampling of the vertical velocity profile whilst attempting to achieve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

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

7.5 Reflected-path systems

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

In such situations, a system configuration may be used that has both transmitting and receiving transducers on the same bank, communicating via a passive reflector located on the opposite bank (see Figure 4).



NOTE Total path length $L = \text{AR} + \text{RB}$.

Key

1 direction of flow

A downstream transducer

B upstream transducer

R reflector

L' projected distance parallel to the direction of flow

Figure 4 — Plan for reflected-path gauge

7.5.2 The equation for calculation of water velocity is:

$$v = L^2 \times (t_{AB} - t_{BA}) / (2\,L' \times t_{AB} \times t_{BA}) \qquad (5)$$

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 have to be aligned but so does the reflector. Indeed, most reflector designs are such that in at least one plane the angular deviation of the beam will be twice the misalignment of the reflector, making it particularly sensitive (see 13.3).

Taking onto 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 used when all possibilities for locating transducers on opposite banks have been exhausted.

7.6 Systems using divided cross-sections

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

7.7 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

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

$$Q = \overline{V} \times A \tag{6}$$

Where

Q = discharge (m^3s^{-1})
$\overline{V}$ = mean velocity at instrument measuring section (ms^{-1})
A = cross-sectional area at instrument measuring section (m^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

$$Q = C_v \overline{V} A \tag{7}$$

where

C_V is a velocity factor, derived by gauging (calibration) or by modelling, varying with the ratio of the path

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 Clause 14.3.2).

This formula (Equation 7) can also be used to calculate flow for single-path systems utilizing the reflected-path system (see 7.5).

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

1. Mean velocity is a function of measured (index) velocity; or

2. Mean velocity is a function of index velocity and stage.

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 whole of the 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:

$$\overline{V} = fn(V_i) \tag{8}$$

$$\overline{V} = fn(V_i, h) \tag{9}$$

Where

V_i = instrument/index velocity (ms^{-1})
h = stage (m)

The cross-sectional area is determined using the stage-area relationship (see clause 7.3).

The computation process is summarised 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 gaugings over as wide a flow and stage range as possible. The number of gaugings required will be dependent on the physical characteristics of the site, similar to the development of conventional stage-discharge relationships (see ISO 1100-2).

c) During each gauging the instrument stage and velocity(ies) should be recorded at a suitable frequency e.g. 1 minute 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. This can be obtained from the stage-area relationship. It should be noted that 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 ISO15769.

8.2 Multi-path systems

8.2.1 General

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

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

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

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

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

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

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

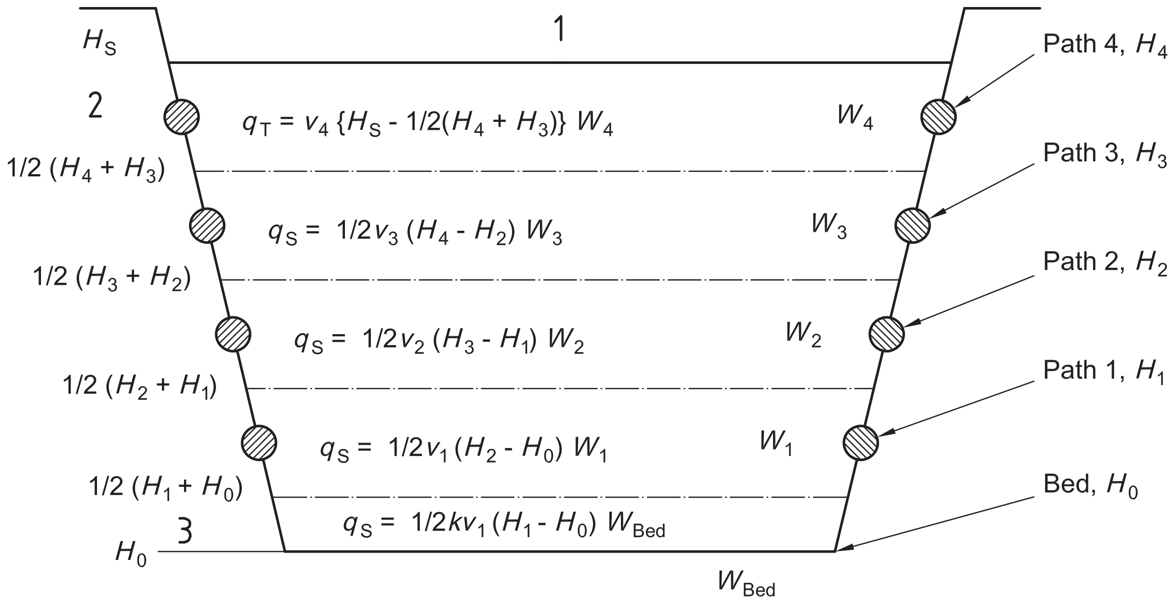
8.2.1.7 Multi-path configurations utilizing the reflected-path or transponder system should calculate flow as if they were multi-crossed-path flow gauges, using either the mid-section or mean-section methods.

8.2.2 Mid-section method

8.2.2.1 In the mid-section method (see Figure 5), each path velocity should be taken to be the mean for the panel defined by the two lines mid-way between the path in question and the next highest and the next lowest in the transducer array; the panel “width” should be the channel width at the elevation of the path.

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

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



Key

1 water surface

2 top panel

3 bottom panel

H height, in metres, above a defined datum

W width of the cross section, in metres, at the corresponding height

v velocity, in metres per second, determined by the corresponding path

k factor which relates the mean velocity of the lowest panel to that determined by the path 1. Normally this is between 0,4 and 0,8

q_S flow in the corresponding panel or slice

q_T flow in the top panel which contains the highest working path

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

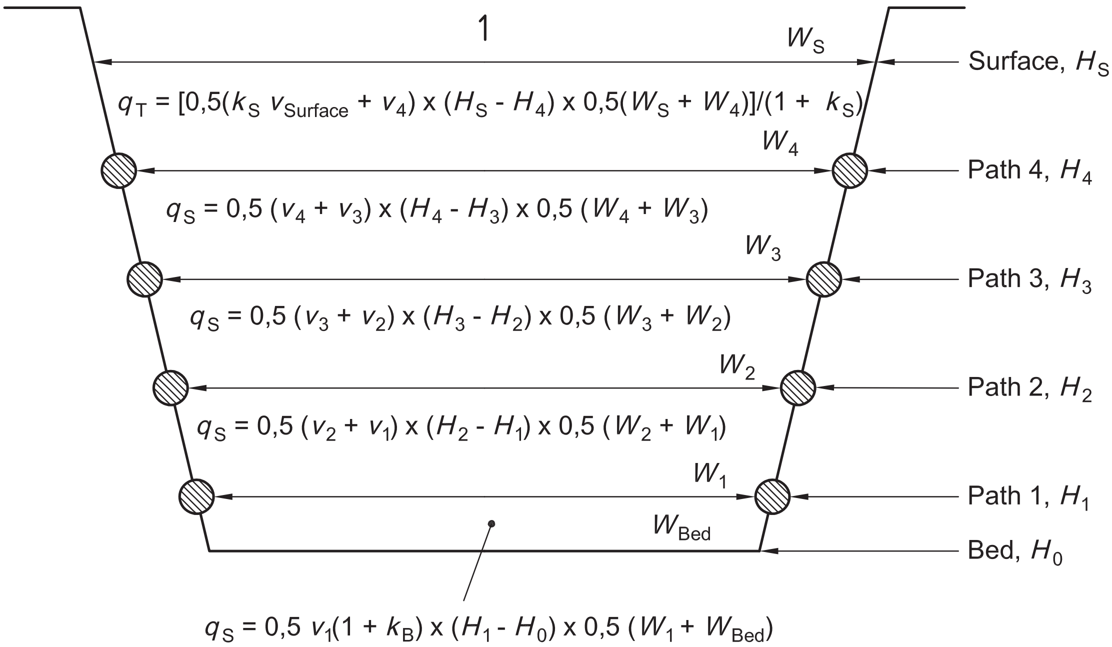
Figure 5 — Example of flow calculated by mid-section method using four operational paths

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

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

8.2.3 Mean-section method

8.2.3.1 In the mean-section method (see Figure 6), the mean panel velocity is the mean of the two velocities measured by the paths which bound the panel. In the highest panel, the mean velocity is calculated from a limited extrapolation of the velocities determined in the top two active paths. In the lowest panel, the mean velocity is the mean of the velocity measured by the lowest path and the near-bed velocity. The near-bed velocity, which will be site-specific and may vary with stage, can be determined empirically by current-metering (see ISO 748).



Key

1 water surface

H height, in metres, above a defined datum

W width of the cross-section, in metres, at the corresponding height

v velocity, in metres per second, determined by the corresponding path

v_s surface velocity, given by

$$v_s = v_4 + (v_4 - v_3) \cdot k_s \cdot (H_s - H_4)/(H_4 - H_3)$$

where k_s is a multiplying factor between 0 and 1 but v_s 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 0,4 and 0,8

q_s flow in the corresponding panel or slice

q_T flow in the top panel which contains the highest working path

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

Figure 6 — Example of flow calculated by mean-section method using four operational paths

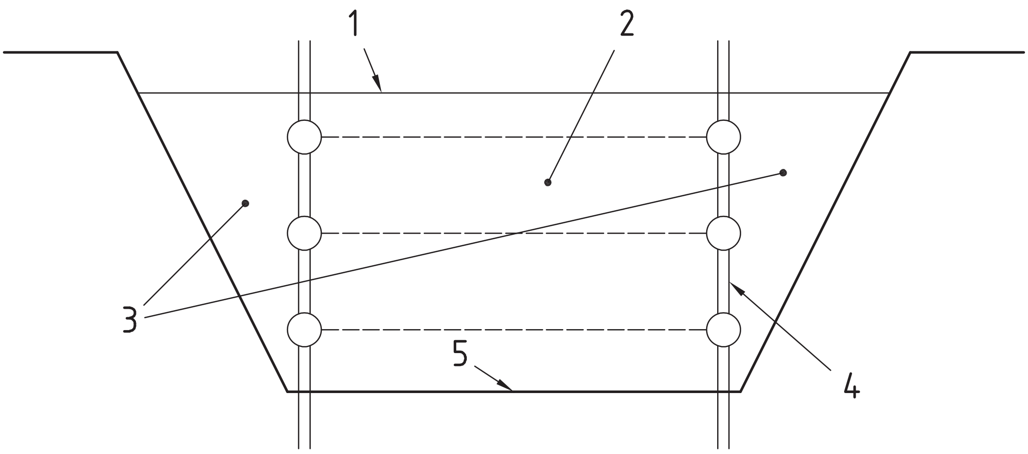
8.2.3.2 A mean panel "width" is computed from site-survey data stored in the flow computer; it is not necessarily defined by the transducer positions. Panel "thickness" is determined by the difference in elevation between paths; for the lowest panel this becomes the difference in elevation between the 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 7).

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



Key

1 water surface

2 measured flow

3 unmeasured flows

4 vertical transducer stack

5 bed

Figure 7 — Installation with transducers in the channel

9 System verification and calibration

9.1 General

9.1.1 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.

9.1.2 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. Note: The effective number of paths is not the same as the number of paths (see Clause 14.3.2).

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

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

9.1.4 Single-path systems (or systems with a small number of separate 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 Clause 8.1), and to conduct periodic checks to ensure that the relation remains stable. Calibration may be completely theoretical if the velocity distribution is well known. Calibration may be achieved using current meters including ADCPs .

10 Site selection

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

1. 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.

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

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

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

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

6. The channel shall have a minimum water depth. (see Table 3 6.2.5.2)

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

8. 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 .

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

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

11. 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

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 ten channel widths upstream to two channel widths downstream. No fewer than three cross-sections should be surveyed, but more are preferable. The results of cross-section surveys should be compared for evidence of bed and bank stability.

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 bathometric 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 the flow gauge requires the input of a number of different items of information and should contain a means of storing details of the relation between water depth and cross-sectional area, determine water depth or stage, determine water velocity for each path, and be capable of executing the mathematical functions necessary to calculate flow from the relevant stored and directly determined data.

The manner in which these are accommodated will depend to some extent upon the detailed design of the instrumentation itself, but all are essential to the process of determining flow.

12.2 Basic components of flow determination

The essential components in the computation of flow are

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

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

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

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