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Measurement of liquid flow in open channels — Measurement of discharge by the ultrasonic (acoustic) method

Mesure de débit des liquides dans les canaux découverts — Mesure du débit à l'aide de la méthode ultrasonique (acoustique)

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Contents

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Annex

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.

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.

International Standard ISO 6416 was prepared by Technical Committee ISO/TC 113, *Measurement of liquid flow in open channels*, Sub-Committee SC 1, *Velocity area methods*.

This second edition cancels and replaces the first editions ISO 6416:1985 and ISO 6418:1985, of which it constitutes a major revision and a combination.

Annex A forms an integral part of this International Standard.

Measurement of liquid flow in open channels — Measurement of discharge by the ultrasonic (acoustic) method

Section 1: General

1.1 Scope

This International Standard describes the establishment and operation of an ultrasonic (acoustic) gauging station for the measurement of discharge in a river, an open channel, or a closed conduit with a free water surface. It also describes the basic principles on which the method is based, and the operation and performance of associated instrumentation. It is limited to the "time of travel of acoustic pulses" technique, and does not apply to systems that make use of the "Doppler shift" or "correlation" or "level-to-flow" techniques.

1.2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 748:1979, *Liquid flow measurement in open channels — Velocity-area methods.*

ISO 772:1988, *Liquid flow measurement in open channels — Vocabulary and symbols.*

ISO 1100-2:1982, *Liquid flow measurement in open channels — Part 2: Determination of the stage-discharge relation.*

ISO 4373:1979, *Measurement of liquid flow in open channels — Water-level measuring devices.*

ISO 5168:1978, *Measurement of fluid flow — Estimation of uncertainty of a flow-rate measurement.*

1.3 Definitions

For the purposes of this International Standard, the definitions given in ISO 772 apply.

1.4 Units of measurement

The International System of Units (SI) is used in this International Standard.

Section 2: Method of measurement

2.1 Principle

2.1.1 When a sound pulse is transmitted through water in motion, in a direction other than that which is normal to the mean direction of movement, the time taken to travel a known distance will differ from that taken in stationary water of the same temperature, salinity, sediment concentration and depth. If the sound pulse is transmitted in the same direction as that in which the water is flowing, the time taken to cover the known distance will be shorter than in stationary water; if the pulse travels in a direction that is opposite to that in which the water is flowing, the time of travel will be longer.

2.1.2 If the time taken for a sound pulse to travel a measured distance between two reference points in one direction is compared with the time taken to travel between the same two points in the opposite direction, the difference observed is directly related to the average velocity of the element of water in the "flight path" bounded by the two reference points. This is referred to as the "path velocity".

2.1.3 This basic principle, in combination with appropriate instrumentation, allows accurate measurement of the mean velocity of the element of a body of water that is located in the line that joins the two reference points. A method of sampling flow velocity, which provides more information about the average condition of the entire body of flowing water than does a point measurement, but which still falls short of being a fully representative measurement of the total flow, is thus available.

2.1.4 However, just as a number of point samples of flow velocity can be integrated to provide an estimate of mean cross-sectional velocity, path velocity measurements can be mathematically transformed for the same purpose. The relation between the path velocity and that along the line of flow in the channel (known as "line velocity") is

$$v_{\text{line}} = \frac{v_{\text{path}}}{\cos \phi}$$

where ϕ is the angle between the path and the direction of flow (see figure 1).

2.1.5 In open-channel flow measurement, practical considerations will normally dictate:

a) that the reference points at either end of an acoustic "flight path" are located on opposite banks of the watercourse;

b) that the line that joins them intersects a line that represents the mean direction of flow at a known angle which normally lies between 30° and 60°.

At intersection angles greater than 60°, the time differences between sound pulses in opposite directions may become excessively small and difficult to measure. This problem may not be significant where high velocities are to be measured, but if velocities are low (i.e. where time differences between forward and reverse sound pulses are themselves small), difficulties may arise.

At an angle of 90°, there will be no time difference between forward and reverse pulses.

With large angles, there is also an increase in the error in velocity computation that results from related errors in the measurement of the angle. This is due to the presence of the cosine function in the equation relating time difference to velocity (see 2.8.1). Table 1 demonstrates this effect.

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

Path angle, ϕ degrees	Velocity error for 1° difference between actual and assumed flow direction %
30	1
45	2
60	3

At intersection angles less than 30°, the length of resulting "flight paths" may be excessive, presenting problems of signal strength and/or signal reflection from the channel bed or water surface. There may also be practical problems with site selection, since the length of the river or channel reach occupied by the gauge may become excessive, or cease to be quasi-uniform.

2.1.6 To allow discharge to be calculated, not only should an estimate of mean velocity in the gauge cross-section be available but the cross-sectional area of the water should also be known. A system for flow determination using the ultrasonic principle 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.

2.2 Characteristics of sound propagation in water

2.2.1 General

The sound spectrum encompasses a wide range of frequencies. The audible range lies between approximately 50 Hz and 15 000 Hz, and is generally referred to as "sonic". Frequencies less than 50 Hz are usually termed "subsonic". At frequencies above 15 000 Hz, the term "ultrasonic" is normally applied.

2.2.2 Speed of sound in water

The speed of sound in fresh water varies from about 1 400 m/s to a little above 1 500 m/s, over the normal ambient temperature range. This represents a variation of approximately 7 % (see table 2). The speed of sound depends on the density and elasticity of the medium and is independent of frequency.

Table 2 — Speed of sound in water at different temperatures

Temperature °C	Speed of sound (approximate) m/s
0	1 400
10	1 450
20	1 485
30	1 510
40	1 530

NOTE — In water containing dissolved salts, the speeds are higher.

2.2.3 Transmission of sound in water

2.2.3.1 General

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

2.2.3.2 Spreading loss

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

2.2.3.3 Attenuation loss

Attenuation loss is the reduction in acoustic intensity due to the resistance of the medium to the transmission of acoustic energy. It is analogous to the loss of electric energy in a wire, where there is no spreading loss. Attenuation loss is directly proportional to the square of the frequency.

2.2.3.3.1 Scattering

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

2.2.3.3.2 Absorption

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

2.2.4 Reverberation

Reverberation is the energy returned by reflectors other than target reflectors. Reverberation of sound in water is analogous to the familiar optical effect which impairs the utility of automobile headlights on a foggy night.

2.2.5 Refraction

The path taken by an acoustic pulse will be bent if the water through which it is propagating varies significantly in either temperature or density. In slow moving rivers, with poor vertical mixing, the effect of the sun upon the surface may produce a vertically distributed temperature gradient. This will cause the acoustic path to bend towards the bed. With a temperature gradient of 0,5 °C per metre of depth, over a path length of 50 m the vertical deflection will be about 2 m. In contrast, the effect of vertical density gradients (such as may be associated with salt water intrusion into the gauged reach) is to bend the path towards the surface. Similar effects may be produced by horizontally distributed temperature or density gradients such as may be associated with partial shading of the water surface from insolation, or with the confluence of tributary waters of contrasting characteristics.

2.2.6 Reflection

Sound is reflected from the water surface and, to a lesser extent, from the channel bed (see 2.5.2.3). The bed may even be a net absorber of sound. As an acoustic wave propagates across a river (generally as a cone of around 5° width) it will intersect with the water surface and be reflected, suffering a 180° phase change in the process. The secondary wave will proceed across the river and arrive at the opposite bank. Its arrival will be sensed by the target transducer later than the direct wave, and the difference in arrival time will be a function of the difference in the respective lengths of the direct and indirect paths.

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

$$D_{\min} = 27\sqrt{\frac{L}{f}}$$

where

$D_{\min}$ is the minimum depth, in metres;

L is the path length, in metres;

f is the transducer frequency, in hertz.

A similar restriction may apply to the channel bed, particularly if it is smooth and, hence, reflects rather than absorbs an acoustic signal.

2.3 Application

2.3.1 General

Like all variants of the basic velocity-area method, the ultrasonic method is suitable for use in some situations, and unsuitable in others. Constraints and limitations on its use are given in 2.5. In this clause, emphasis is placed on positive attributes.

2.3.2 Open channels

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

2.3.2.2 The method is capable of providing high accuracy of flow determination over a wide range of flows contained within a defined gauge cross-section. Relevant aspects of measurement uncertainty are given in 2.11. Flow determination of predictable accuracy can be available from the time of first commissioning.

2.3.2.3 Use of the method creates no obstruction to navigation or to the free passage of fish. It creates no significant hazard or loss of amenity for other river users or riparian interests. If carefully designed, the gauge can be physically unobtrusive.

2.3.3 Backwater effects

The method is generally tolerant of the backwater effects created by tides, tributary discharges, reservoir or head-pond water level manipulation, periodic channel obstruction and downstream weed growth.

2.3.4 Multiple channels

At locations where total flow is divided between two or more physically separate channels, the technique allows instrumentation to be used to determine individual channel flows separately and then to combine these basic data to create a single unified determination.

2.3.5 Flood plain flow measurement

2.3.5.1 Where flow may not readily be contained within a single well-defined cross-section, and in particular where there is significant flow that bypasses the main gauge cross-section by way of an extensive flood plain, it may be possible to subdivide the flood plain, by means of minor civil engineering works, into a series of "channels" in which the flow can be measured separately.

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

2.3.6 Flow measurement in closed conduits

The ultrasonic method is also applied to the measurement of flow in closed conduits, including both storm-water and foul sewers, under both free-flowing and surcharged conditions. Special attention should be paid to the design of transducer mountings, to eliminate the risk of fouling, but the absence of any absolute need to introduce an obstruction to free flow in the sewer can be a significant advantage.

2.4 Gauge configuration

2.4.1 General

The ultrasonic method is only one of a number of different ways in which the velocity of moving water can be sampled to provide basic measurement from which discharge can be computed. The velocity sampling technique can be combined with more than one sampling strategy to match the method

- with local site circumstances;
- with the needs of the gauge user for measurement accuracy or operational reliability; or
- with the resources available to the user to maintain the gauge in an operational state.

2.4.2 Single path systems

2.4.2.1 In its most basic form, the ultrasonic gauge can operate satisfactorily with a single pair of transducers, giving only a single "line" velocity determination. Provided that a relation can be established between this sample and the mean cross-sectional velocity, discharge can be computed as readily by this simple means as by a more complex method.

2.4.2.2 Transducer mountings may be constructed to be moveable in the vertical plane. Using this facility, a vertical velocity profile may be determined, employing the gauge instrumentation in a manner analogous to the use of the rotating element current meter. The transducers may then be set, for operational purposes, at an elevation that provides as close an estimate as possible of the mean cross-sectional velocity. Discharge may be computed and a relatively simple form of instrumentation design adopted.

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

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

2.4.2.5 The single path gauge also relies upon there being a relatively stable velocity profile, essentially unaffected by changes in the relation between water level and flow. It may be unsuited to locations that experience a significant backwater effect.

2.4.2.6 The single path gauge is inherently vulnerable to transducer damage or malfunction. There is no built-in component redundancy capability (see 2.9).

2.4.3 Multipath systems

2.4.3.1 At sites where

- there is wide and frequent variation in water level and/or flow; or
- velocity distribution in the vertical deviates significantly from the theoretical; or
- there is significant risk of backwater effects acting upon an otherwise stable stage/discharge relation; and
- the ultrasonic technique is nevertheless the most appropriate for use,

it will normally be necessary to install two or more paths to provide a more accurate estimation of mean velocity in the cross-section than is possible with a single path only.

2.4.3.2 The number of paths that may be installed is limited only by the design of the gauge instrumentation chosen to meet the required constraints of accuracy, reliability and cost. The aim is to achieve an acceptable representation of the vertical velocity profile in the gauge cross-section, at all levels or flows, from the highest to the lowest likely to be experienced.

2.4.3.3 Where a high level of performance security (i.e. freedom from operational interruption or degradation) is also a goal in the system, it may be desirable to provide an additional number of "redundant" paths, such that physical damage to, or malfunction of, one or more paths has a minimal effect upon the overall accuracy of measurement.

2.4.3.4 Multipath gauge configuration may also be appropriate as a means of accommodating complex cross-sectional geometry.

2.4.4 Crossed path systems

2.4.4.1 One of the fundamental principles of the ultrasonic technique is that the angle at which each individual "flight path" in a system intersects the line representing the mean direction of flow at that elevation shall be known accurately. Errors in this angle are magnified in the discharge computation process (see table 1).

2.4.4.2 In practice, it may 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. The gauge site itself may not be ideal, and there may be directional effects associated with sub-optimal channel geometry or approach conditions. At low flows in particular, the effects of complex bed geometry may override the normal control of mean direction from the bank.

2.4.4.3 Where it is suspected that the flow is not parallel to the channel banks, and where the likely resulting error in the flow computation is thought to be significant, it may be possible to introduce an element of self correction by configuring the gauge to have one or more sets of its "flight paths" installed as pairs, set at the same elevation but laid out in the form of a symmetrical cross (see figure 1).

2.4.4.4 In this configuration, each path oriented, for example, in an upstream direction from the left bank, should be matched by an equivalent path, set at the same elevation, but oriented in a downstream direction from the same bank, and "aimed" at a point on the right bank directly opposite the downstream, left-bank transducer. The twin paths should normally be disposed so as to intersect in midstream, and to form the equal sides of a pair of congruent, isosceles triangles. Gross mismatch between path lengths should be avoided, because of the likelihood of there being significant differences in cross-sectional geometry between the two paths.

2.4.4.5 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 identical (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. 2.11 deals with the basic measurement uncertainties inherent in this component of the system, and gives guidance on what may be realistically attainable and, hence, on what may be considered to be "significant" (see annex A).

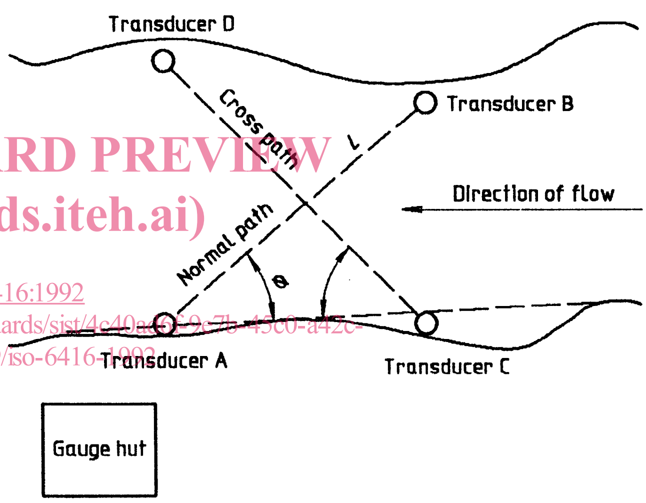

Figure 1 — Plan of crossed path gauge

2.4.4.6 Provided that the true mean direction of flow does not change significantly over the measured reach, then simple averaging of the two paired line velocities will produce a close approximation to the true mean water velocity at that elevation, the inherent errors in each being largely self-cancelling. The risk of error remaining, because of changing flow direction through the gauged reach, may be reduced by keeping the reach as short as possible.

2.4.4.7 At locations where high gauge reliability is required, the principle of measurement redundancy 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 river bank.

2.4.5 Reflected path systems

2.4.5.1 The basic ultrasonic system normally requires that there are sets of transducers on both banks of the channel. It is required that signal and power cables should cross the channel, either overhead, or on the bed, or trenched into the bed.

2.4.5.2 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.

2.4.5.3 In such situations, recourse may be made to a system configuration that has both transmitting and receiving transducers on the same bank, communicating via a passive reflector located on the opposite bank (see figure 2). Reflector design is considered in 3.2.1.2.

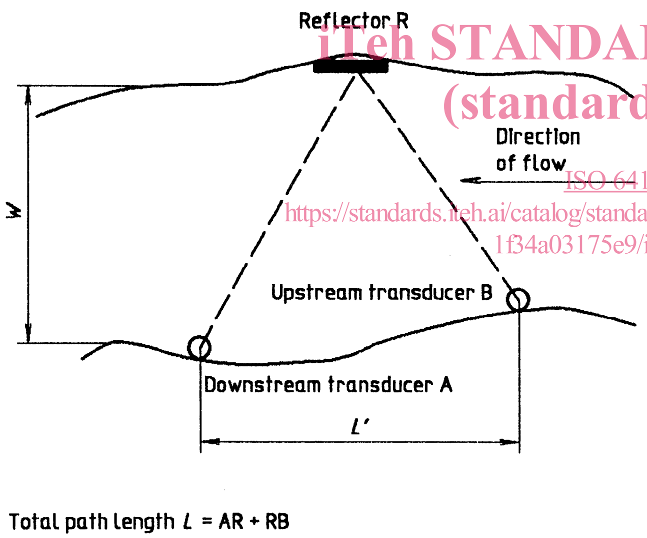

Figure 2 — Plan of reflected path gauge

2.4.5.4 This configuration may also be used to achieve longer "flight paths", where these are needed to improve measurement accuracy at low velocities without making the nominal path angle more acute.

2.4.5.5 A further advantage is that the path angle does not need to be taken into account in the equation for computing line velocity (see 2.8.1.2), thus eliminating a significant potential source of uncertainty.

2.4.6 Systems using divided cross-sections

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

2.4.6.2 Where site geometry is complex (for example a main channel with flood berms), where there is a need for measurement over a wide flood plain, or where there is an exceedingly wide main channel to gauge, it may be possible to achieve operational viability by dividing the cross-section into a number of separate channels, each channel being treated as a relatively simple gaugeable entity, and adding together the individual results (see 2.3.5.1).

2.5 Site selection

2.5.1 Practical constraints

2.5.1.1 Access

There should be good access to any site at which the ultrasonic technique is to be used. During its installation, significant civil engineering works may be required, and heavy construction equipment may be needed on site. The technique relies upon the application of electronic technology, and both commissioning and subsequent servicing require the use of specialized electronic equipment. The need to manhandle such equipment over long distances should be avoided.

2.5.1.2 Power supply

Short period (48 h) battery operation of sophisticated systems and long term (3-6 months) operation for simple systems having a low sampling rate is feasible. Long periods (many years) of operation from batteries for data loggers and telemetry devices are also feasible. However for reliable, sustained operation of a multipath flow-meter, the technique requires provision of a continuous source of electrical energy. Thus, connection to a source of mains power at acceptable cost should be possible, or on-site generation capacity should be provided.

2.5.1.3 Calibration and corroboration measurement

The technique provides an absolute determination of velocity. However, in systems designed to have only a small number of separate flight-paths, it may be necessary to carry out periodic calibration exercises to establish the relation between indicated velocity (and, hence, computed flow) and some alternative determination of velocity in the cross-section. Even in multipath systems, where the velocity of the cross-section is inherently well sampled, there will often be a demand from data users for "corroboration" measurement by means of an alternative method. It is prudent, wherever possible, to bear in mind the needs of acceptable alternative measuring methods when choosing a site for an ultrasonic gauge.

2.5.2 Physical constraints of the measurement site

2.5.2.1 Geometry of the cross-section

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

2.5.2.2 Stability of the cross-section

Instrumentation systems which compute flow require that the relation between water depth and cross-sectional area be known. This relation should be stable with respect to time. Locations that are subject to significant bed level or profile instability should be avoided.

2.5.2.3 Channel aspect ratio

Sound pulses generated by ultrasonic system instrumentation transmit through water as cones of projection. If the channel to be gauged is wide relative to its depth, the cone of projection of one or more transmitting transducers may intersect with the bed or the water surface before reaching the related receiving transducer, resulting in signal reflection (see 2.2.6). Unless the system is designed carefully, this may present the instrumentation with insuperable difficulties in signal interpretation, and spurious measurement may result.

The ultrasonic system is unsuitable for use in wide, shallow channels (for details concerning flood plain flow measurement, see 2.3.5). Limiting conditions at a particular site will depend upon the number of paths to be installed and the number of paths remaining operational during low water. Limiting width/depth ratios can be computed readily, and alternative design strategies are available.

Low-frequency sound attenuates less with distance than does sound of high frequency (see 2.2 for details). Where the path length is short, the use of low-frequency sound may result in the time-of-flight measurement error attaining an unacceptable level (see table 3).

Table 3 — Sound frequency versus path length and clearance

Path length m	Typical minimum clearance between transducer and water surface or channel bed m	Operating frequency kHz	Uncertainty in velocity determination due to time-of-flight measurement error m/s
300	3,0 to 1,5	30 to 100	0,005 to 0,001 5
150	1,0 to 0,6	100 to 300	0,003 to 0,001 3
80	0,5 to 0,35	200 to 500	0,003 to 0,002
30	0,3 to 0,15	300 to 1 000	0,006 to 0,003
10	0,12 to 0,07	500 to 1 500	0,013 to 0,007

Minimum clearance D_{min} is calculated using the equation given in 2.2.6.

Uncertainty is based upon the assumption that the average timing of an acoustic signal can be determined to ± 1/50 (2 %) of the wave period ± 20 ns. In systems designed for small channels (under 5 m wide) a timing uncertainty of ± 3 ns can be achieved (see 3.2.3.6).

2.5.2.4 Weed growth

The gauge cross-section should be free of weed growth, which seriously attenuates the acoustic signal. Different types of weed may have different effects, because it is the air included within the plant structure which produces the unwanted result.

2.5.2.5 Water temperature gradients

Refraction of the acoustic signal can be caused by temperature gradients in the water, and signal loss may result (see 2.2.5). Channel reaches that maintain deep water during low-flow periods (with consequent low mean velocities) may suffer from this problem during periods of high insolation.

2.5.2.6 Sediment load

The presence of solids suspended in the water may have a significant effect upon signal attenuation, causing both reflection and scatter. At locations where concentrations greater than 1 500 mg/l may be experienced for significant periods, or where reliable measurement is particularly important under such conditions, the ultrasonic technique may not be suitable (see 3.2.3.2).