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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:

$$Q = \bar{v} \times A \tag{1}$$

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

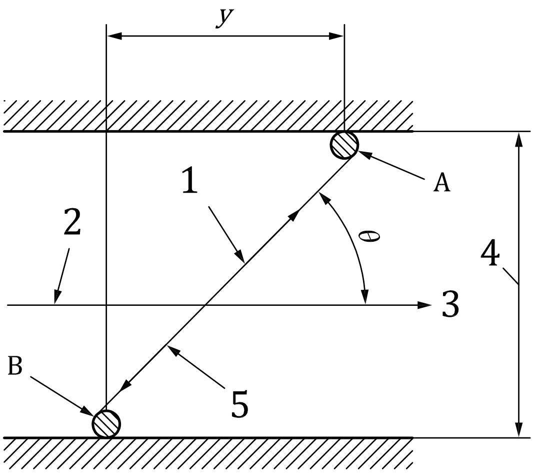
5.2.1 Discharge can be computed using the velocity-area method (see 5.1), provided that a relation can be established between the velocities determined by the transit time ultrasonic system and the mean cross-sectional velocity. If there are sufficient operational paths distributed sufficiently throughout 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:

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

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.

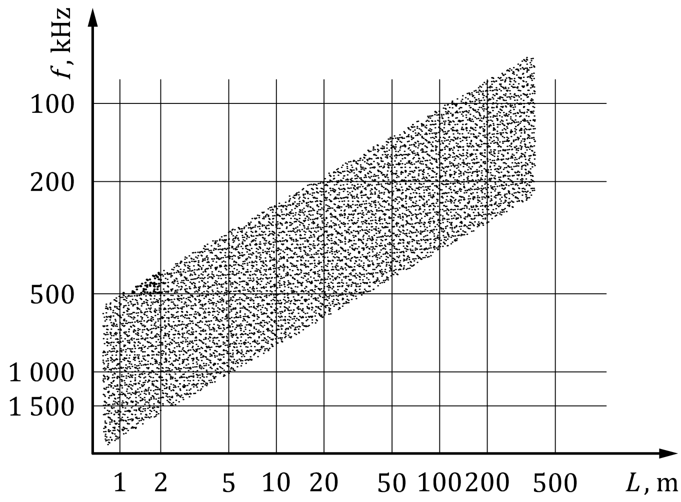


Figure 2 — Commonly used transducer frequencies for various path lengths

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.

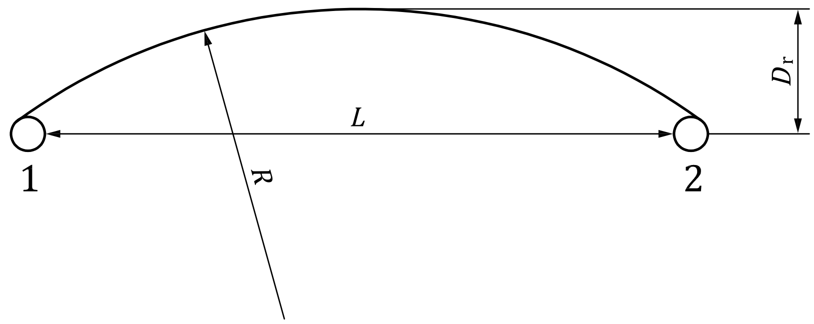
6.2.4.2 The approximate degree to which the signal path is bent is given by:

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

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.