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Hydrometric uncertainty guidance (HUG)

Lignes directrices relatives à l'incertitude en hydrométrie

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Foreword

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Introduction

The management of a natural environment requires knowledge, by measurement, of what is happening. Only then can effective action be taken and the effectiveness of the action assessed. Much depends on the quality of the knowledge itself.

The quality of measurable knowledge is stated in terms of measurement uncertainty. The internationally agreed method for assessing measurement quality is the *Guide to the estimation of uncertainty in measurement* (GUM). Without this uniformity of measurement standards, equitable sharing of the environment is not possible and international obligations to care for the environment would be weakened.

The essential purpose of the GUM is that a statement of the quality of a measurement result will be presented with all measurements described in technical standards. Without this, no two measurements can be compared or standards set. Whereas the GUM is a reference document serving the universal requirements of metrology, the *Hydrometric uncertainty guidance (HUG)* document is specific to hydrometry, i.e. to the measurement of the components of the hydrological cycle. It borrows from the GUM the methods that are the most applicable to hydrometry and applies them to techniques and equipment used in hydrometry.

In the past, error analysis has provided an indication of measurement quality, but such statements cannot properly convey the quality of the result because it presupposes a knowledge of a true, error-free, value against which the measured result can be compared. The true value can never be known. Uncertainty therefore remains. For this reason, the GUM uses the concept of uncertainty and uses it for all stages and components of the measurement process. This ensures consistency.

The GUM defines standard uncertainty of a result as being equivalent to a standard deviation. This can be the standard deviation of a set of measured values or of probable values. This is broadly similar to the approach used in error analysis that preceded the uncertainty technique. However, the GUM provides additional methods of estimating uncertainty based on probability models. The two approaches are equivalent but uncertainty requires only a knowledge or estimate of the dispersion of measurement about its mean value, and not the existence of a true value. It is assumed that a careful evaluation of the components of measurement uncertainty brings the mean value close to a probable true value, at least well within its margin of uncertainty.

In more general terms, uncertainty is a parameter that characterizes the dispersion of measurable values that can be attributed to their mean value.

By treating standard deviations and probability models as if they approximated to Gaussian (or normal) distributions, the GUM provides a formal methodology for combining components of uncertainty in measurement systems where several input variables combine to determine the result.

Within this formal framework, the GUM can be consistently applied to a range of applications and, thereby, be used to make meaningful comparisons of results.

The HUG seeks to promote an understanding of the nature of measurement uncertainty and its significance in estimating the ‘quality’ of a measurement or a determination in hydrometry.

Hydrometry is principally concerned with the determination of flow in rivers and man-made channels. This includes

- environmental hydrometry, i.e. the determination of the flow of natural waters (largely concerned with hydrometric networks, water supply and flood protection),
- industrial hydrometry, i.e. the determination of flows within industrial plants and discharges into the natural environment (largely concerned with environment protection and also irrigation).

Both are the subject of international treaties and undertakings. For this reason, measured data needs to conform to the GUM to assure that results can be compared.

Hydrometry is also concerned with the determination of rainfall, the movement/diffusion of groundwater and the transport by water flow of sediments and solids. This version of the HUG is concerned with flow determination only.

The results from hydrometry are used by other disciplines to regulate and manage the environment. If knowledge is required of biomass, sedimentary material, toxins, etc., the concentration of these components is determined and their uncertainty estimated. The uncertainty of mass-load can then be determined from the uncertainty of flow determination. The components of this calculation are made compatible through compliance with the GUM.

For practitioners of hydrometry and for engineers, the GUM is not a simple document to refer to. The document has been drafted to provide a legal framework for professional metrologists with a working knowledge of statistical methods and their mathematical representation. A helpful document, NIST Technical Note 1297 [12], is an abbreviated version of the GUM written to be more accessible to engineers and to specialists in fields other than metrology.

The HUG, although simplifying the concepts, in no way conflicts with the principles and methods of the GUM. Accordingly, the HUG interprets the GUM to apply its requirements to hydrometry in a practical way, and, hopefully, in a way accessible to engineers and those responsible for managing the environment.

In addition, the HUG introduces and develops Monte Carlo Simulation, a complementary technique, which has benefits for hydrometry, insomuch as complex measurement systems can be represented realistically.

The HUG summarizes basic hydrometric methods defined in various technical standards. The HUG develops uncertainty estimation formulae from the GUM for these basic methods. The basic hydrometric methods described in the HUG may not be identical to those recited in the published technical standards. In such cases, the methods described in these standards are to be taken as authoritative. However, clauses in technical standards that concern uncertainty should be adapted to be in accordance with the HUG.

NOTE There is no unified definition of space coordinates within the hydrometric standards. The textbook conventional axes are adopted in this document when describing open channel flow: the x axis being horizontal and positive in the mean flow direction, the y axis being orthogonal to the x axis in the horizontal plane and the z axis being vertical positive.

Hydrometric uncertainty guidance (HUG)

1 Scope

This Technical Specification provides an understanding of the nature of measurement uncertainty and its significance in estimating the ‘quality’ of a measurement or a determination in hydrometry.

It is applicable to flow measurements in natural and man-made channels. Rainfall measurements are not covered.

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*

3 Terms and definitions

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

NOTE For a complete appreciation of the scope of definitions used in measurement uncertainty, the reader is referred to the GUM [10] or to NIST Technical Note 1297 [12].

3.1
standard uncertainty
uncertainty of the result of a measurement expressed as a standard deviation

3.2
type A evaluation of uncertainty
method of evaluation uncertainty by the statistical analysis of a series of observations

3.3
type B evaluation of uncertainty
method of evaluation uncertainty by means other than the statistical analysis of a series of observations

3.4
combined standard uncertainty
standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities

3.5
expanded uncertainty
quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the values that could be attributed to the measurand

3.6

coverage factor

numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty

4 Symbols and abbreviations

α	coefficient representing the effects of non-uniform energy (velocity) in a channel
$\gamma_{xx}, \gamma_{xy}, \gamma_{xz}$	angles between boat axes and the x axis.
σ	standard deviation
$\Delta' x, \Delta' y$	dispersion of measurement from the mean value of the set of x,y measurements for a symmetric distribution: $\Delta' x = 0{,}5\left(x_{\text{max}} - x_{\text{min}}\right)$, etc.
$\Delta' x^{+}, \Delta' x^{-}$	± dispersion about the mean value, $\bar{x}$, for an asymmetric distribution of measurements where $\Delta' x^{+} = \left(x_{\text{max}} - \bar{x}\right)$ and $\Delta' x^{-} = \left(\bar{x} - x_{\text{min}}\right)$.
Δ	small difference in a measured quantity $\Delta Q, \Delta h, \Delta T$, etc.
$\Delta y, \Delta z$	notional small distances in the y and z directions at a cross-section in the channel
Dc_2	in the dilution method, the downstream mixed change ($c_{\text{m}} - c_{\text{b}}$) of concentration of the tracer
A, $A(z)$, $A(h)$	cross-section area (in the y,z plane) of the flow
B	channel width
b	contracted channel width or flume throat width
c_{b}	dilution method, the background concentration of tracer
c_{T}	dilution method, the feed concentration of tracer
c_{m}	dilution method, the downstream mixed concentration of the tracer
C	discharge coefficient
C_v	velocity coefficient
d_i	deviation of an measurement (the ith measurement of a series) from the mean value of that series
E	datum elevation of a range measuring device
$f(h)$	relationship between head, h, and cross-section area, A
F_x, F_y	multiplying factors to be applied to the summation of velocity-area elements to account for the approximation of a summation process to a true integration of continuously varying parameters.
g	gravitation acceleration
h	head of water relative to a defined datum level in the channel
H	total head relative to a defined datum level in the channel
i,j	indices of a count $i = 1$ to n, or $j = 1$ to m of a series
J	false measurement detection factor
K	constant of a flow determination equation for a weir or flume
k_1, k_2	constants for the determination of flow by the dilution method
M	dilution method, the mass of tracer introduced into the stream

n	exponent of a flow determination equation for a weir or flume
n, m	number of measurement in a series
$p(x)$	probability function
Q	flow
Q_p	estimated flow passing close to boundaries or any region where measurement cannot be determined by the primary means
Q_T	dilution method, the flow of tracer into the stream
S	standard deviation of a set of measurements
t_e	factor to be applied to small numbers of samples to enable the standard deviation to be representative of large numbers of samples (see Annex A)
t_1, t_2	in the dilution method, the interval during which a change in concentration is detectable
T	absolute temperature, in Kelvin
T_n	Grubbs' test parameter
$U(x), u(y)$	uncertainty of measured variables x, y, etc.
$u_\mathrm{c}(p), u_\mathrm{c}(q)$	the combined uncertainty of determined results p, q, etc.
$u^*(x)$	the percentage uncertainty of a measurement of any quantity x
U_{95}	measurement uncertainty expanded to the 95 % level of confidence
$V_{\bar{x}}$	mean velocity through a yx plane intersecting a channel cross-section of the channel
$V_x(y,z)$	velocity in the x direction at point y, z in the channel
$\vec{V}$	water velocity vector relative to channel
$\vec{V}_{\mathrm{b}}$	boat velocity vector relative to the channel
$\vec{V}$	water velocity vector relative to boat
$V_{x'}{}', V_y{}', V_z{}'$	water velocity components relative to boat along boat coordinate axes
$V_{\mathrm{b}x'}{}', V_{\mathrm{b}y}{}', V_{\mathrm{b}z}{}'$	components of boat velocity relative the boat axes
$\gamma_{xx}, \gamma_{xy}, \gamma_{xz}$	angles between boat axes and the channel x axis.
x,y,z	channel coordinates
x',y',z'	boat coordinates
x,y	measurable variables

In this document, the term "uncertainty" refers to measurement uncertainty and the following forms of equation are used to signify

— a sum of n values of x $$x_1 + x_2 + x_3 + \ldots\ldots x_i + \ldots\ldots x_n = \sum_{i=1}^{n} x_i,$$

— a difference, $\Delta f(x)$, in the function, $f(x)$, due to a small change, Δx, in the value x $$\Delta f(x) = \frac{\mathrm{d}f}{\mathrm{d}x}\Delta x,$$

— a value of an integral, F, of a function, $f(x)$, between, $x = x_1$, and $x = x_n$ $$F = \int_{x_1}^{x_n} f(x)\,\mathrm{d}x.$$

5 ISO/IEC Guide 98 (GUM) — Basic definitions and rules

5.1 General

This section summarizes the methods described in the GUM for the expression of uncertainty in measurement. For a general introduction to measurement uncertainty, refer to Annex A.

5.2 The uncertainty of sets of measurements

The GUM describes measurement uncertainty as a value that characterizes the dispersion of measurements that could reasonably be attributed to the result. The GUM goes on to define standard uncertainty as uncertainty expressed as a standard deviation, s.

So, for a set of n measurements, uncertainty is related to the difference between each measured value, x_i, from the average value, $\bar{x}$, of the set. The standard deviation, and hence the uncertainty, $u(x)$, is:

$$u(x) = s = \sqrt{\frac{1}{n-1}\left[(\bar{x}-x_1)^2 + (\bar{x}-x_2)^2 + (\bar{x}-x_3)^2 + \ldots\ldots(\bar{x}-x_n)^2\right]}$$

where components $(\bar{x}-x_i)^2$ are the deviation of the ith measurement, x_i, from the mean value, $\bar{x}$.

Or, more concisely:

$$u(x) = s = \sqrt{\frac{1}{n-1}\sum_1^n d_i^2} \tag{1}$$

where $d_i = \bar{x} - x_i$ is the deviation of the ith measurement from the mean value, $\bar{x}$,

and

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

The larger the number, n, of measurements used to calculate the mean value, $\bar{x}$, the greater is the expectation that the mean value approaches the ‘true’ value. Therefore, the uncertainty of the mean value, $u(\bar{x})$, decreases as the number of measurements, n, increases. The GUM relationship for this is

$$u(\bar{x}) = \frac{1}{\sqrt{n}}u(x) \tag{3}$$

5.3 Random and systematic effects

Equation (3) applies only to the random variations of the measured quantity. This random effect is determined from the measured data and, as such, is evaluated after a set of measurements have been taken. Random effects can be determined from analysis of the historic data or by the instrumentation itself if it is designed to analyse the data in real time. Random effects diminish the average value of a set of n measurements by the factor $\frac{1}{\sqrt{n}}$. Random conditions often exist as natural turbulence. However, random variation can sometimes occur through human interpretation of a reading of an indicator, such as a staff gauge.

Uncertainties that are inherent to the measurement equipment or to the method are systematic. Systematic effects cannot be diminished by the use of Equation (3). During each measurement session, systematic effects can usually be taken as constant for the measurement device. Systematic components are

a) assessed as part of an installation or commissioning procedure, and/or

b) specified beforehand for the equipment by the manufacturer. Refer to Clause 9.

Refer to A.6 in Annex A for more information on random and systematic effects.

For the evaluation of the uncertainty of a continuous process, include unsteady effects as a random component. The quantity being measured may be varying slowly during the measurement process. This will widen the dispersion of measured values and hence add to the assessment of the random component. Such variation shall be part of the randomness of the measurement. If during the measurement process the rate of change is such that it significantly exceeds the natural dispersion of measurements, then the result shall be discarded.

5.4 Uncertainty models — Probability distributions

In hydrometry, measurements are often made using automated instruments. They have a margin of measurement within which measured values can vary randomly in steady conditions. If this uncertainty is inherent to the measurement process, it is a systematic component. It is commonly expressed as a probability distribution. Probability distributions have standard deviations about the mean value which are equivalent to the standard deviation of discrete measurements as defined above. The probability distributions equivalent to Equations (1) and (2) are

$$u(x) = \sqrt{\int_{-\Delta x}^{\Delta x} d(x)^2 \cdot p(x)\,\mathrm{d}x} \tag{4}$$

and

$$\bar{x}' = \int_{-\Delta x}^{\Delta x} x \cdot p(x)\,\mathrm{d}x \tag{5}$$

where $p(x)$ is a probability function and d is the dispersion. Refer to Annex A for details.

5.5 Combining uncertainties — The law of propagation

The GUM also defines a rule for combining uncertainties from several sources. It is called ‘the law of the propagation of uncertainties’. For a relationship, f, between a result, y, and variables, $x_1, x_2 ..... x_n$, defined as $y = f(x_1, x_2 ..... x_n)$, the combined uncertainty, $u_\mathrm{c}(y)$, of y is

$$u_\mathrm{c}(y)^2 = \sum_{i=1}^{i=n} \left(\frac{\partial f}{\partial xi} u(x_i) \right)^2$$

or

$$u_\mathrm{c}(y)^2 = \left(\frac{\partial f}{\partial x_1} u(x_1) \right)^2 + \left(\frac{\partial f}{\partial x_2} u(x_2) \right)^2 + ... + \left(\frac{\partial f}{\partial x_n} u(x_n) \right)^2 \tag{6.A}$$

where $x_1, x_2 ..... x_n$ are independent variables.

Equation (6.A) applies only where the variables $x_1, x_2 ..... x_n$ are uncorrelated, i.e. if variable x_i changes value, no other x variable is affected by that change. If two or more variables x do influence each other (i.e. they are correlated), then an additional component of uncertainty exists. Equation (6.A) then becomes

$$u_\mathrm{c}(y)^2 = \sum_{i=1}^{i=n} \left(\frac{\partial f}{\partial xi} u(x_i) \right)^2 + 2 \sum_{i=1}^{i=n-1} \sum_{j=i+1}^{j=n} \frac{\partial f}{\partial xi} \frac{\partial f}{\partial xj} u(x_i x_j) \tag{6.B}$$

Almost all hydrometric uncertainty estimations require the use of the simpler form, i.e. Equation (6.A).

The components can be random or systematic. The partial derivatives $\frac{\partial f}{\partial x_n}$ are referred to as 'sensitivity coefficients'.

5.6 Expressing results

Equation (6.A) expresses the final result in terms of standard uncertainty. For the Gaussian probability, used as a model distribution for general analysis, one standard deviation covers only 68 % of the range of possible results. This means that for a result expressed as

Flow rate = 10,8 l/s ± 0,6 l/s

or

$$Q = \bar{Q} \pm u(Q)$$

Only 68 % of the measurement will lie between 10,2 l/s and 11,4 l/s. Almost one third of the measurement can be expected to lie outside this band. Such a statement is of little value in hydrometry. A more meaningful statement is required that will cover a larger portion of possible results.

Subclause A.9 defines expanded uncertainty. By expanding the margin of uncertainty, a greater portion of the expected range of measurements is covered. For the Gaussian probability distribution, it can be shown that by doubling the uncertainty margin, 95 % of expected measurements are covered.

The same result expressed in the form

Flow rate = 10,8 l/s ± 1,2 l/s at the 95 % confidence level

or

$$Q = \bar{Q} \pm U_{95}(Q)$$

means that 95 % of the measurements are expected to lie between 9,6 l/s and 12,0 l/s. This is a more practical expression of the result.

In hydrometry, all measurements shall be expressed at the 95 % confidence level with a statement of the form:

Quantity = Value ± uncertainty at the 95 % confidence level

or

Quantity = Value ± percentage uncertainty at the 95 % confidence level

Refer to A.9 for more detail.

6 Open channel flow — Velocity area methods

6.1 General

Figure 1 shows the coordinate system used in this document with orthogonal axes x, y, z. The mean velocity is calculated in the x direction. The xy-plane is horizontal. The z axis is vertical. Note that a velocity $\vec{V}$ vector representing the mean velocity does not have to align with the x axis. The flow in the channel can be determined from velocities passing obliquely through an intersecting yz plane.

The origin of the coordinate system may be located at any point relative to the channel but is typically located at the hydraulic datum for weirs and flumes or, for velocity-area methods, on a gauge datum alongside the stream.

For example, vertical measurement can be $h(z)$, expressed from a hydraulic datum relative to the z_0 coordinate system origin.

The determination of flow in open channels requires the following:

a) the determination of the mean velocity $\overline{V}_x$ across the channel section; and

b) the measurement of the cross-section area $A(h)$, in the yz plane, through which the flow passes; h is the water depth.

The product of these two quantities is the discharge, Q.

$$Q = \overline{V}_x A(h)$$

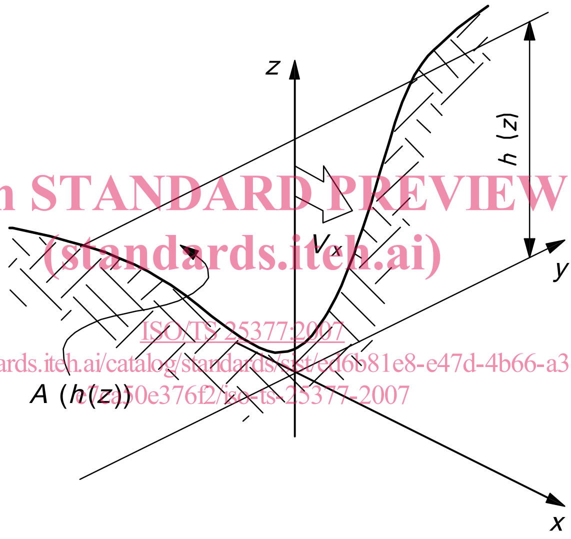

Figure 1 — Co-ordinate relationship at a channel cross-section

6.2 Mean velocity, $\overline{V}_x$

The evaluation of mean velocity shall deal with the V_x variability with respect to position, y,z, across the $V_x(y, z, t)$ channel and with respect to time, t. At the walls, friction slows the mainstream velocity to zero which causes steep velocity gradients to occur, illustrated in Figure 2. Velocity gradients and shear stress within the body of the flow induce vortices which causes turbulent conditions. Turbulence exists in a moving body of water even when the water surface appears tranquil.

The evaluation shall therefore scan the cross-section while integrating and averaging the velocity component in the x direction. The flow can be steady and hence $\overline{V}_x$ can be constant, but turbulence causes the local value of $V_x(y, z, t)$ to be unsteady.

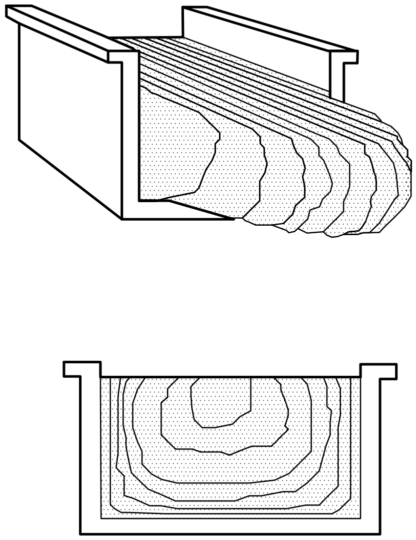

Figure 2 — Typical current profiles and contours

6.3 Velocity-area determination

The quantity, $\bar{V}_x$, is determined across the channel from instantaneous point velocities, $V_x(y, z, t)$. In this subclause, it is assumed that steady flow conditions prevail. If the flow does not vary with time, t, during the integration process, then

$$Q = \int_A \bar{V}_x\left(y,z\right)\mathrm{d}A \tag{7}$$

The 'arithmetic' method of integration is summation of velocity through notional stream tubes of defined area.

This is typically done by dividing the cross-section into a number of horizontal segments or vertical segments, then measuring velocity at frequent intervals along the centreline of each segment to determine the segment mean velocity. Flow through the segment is the mean velocity through the segment multiplied by the segment area. The flows through each segment are summated to give the total flow in the channel. Therefore, Equation (7) becomes

$$Q = F_y F_z \sum\nolimits_1^m \sum\nolimits_1^n V_x\left(y_i z_j\right) \Delta z_j \Delta y_i + Q_\mathrm{p} \tag{8}$$

where

F_y is a factor, often assumed to be unity, relating the discrete summation in the y direction to an ideal integration of a true continuous velocity profile;

F_z is a factor, often assumed to be unity, relating the discrete summation in the z direction to an ideal integration of true continuous velocity profile; and

Q_p represents perimeter flow passing between the region of segments and the channel boundary.

The summation method divides the area into $m \times n$ rectangular stream tubes of height, Δz_j, and width, Δy_i. A set of Δy_i stream tubes makes up each horizontal segment, and a set of Δz_j stream tubes makes up each vertical segment. For small values of m or n, special consideration shall be given to the F_y and F_z functions. The uncertainty of these factors is systematic to the summation process.

The term Q_p is the flow passing through a perimeter region that exists close to the channel floor and walls and the water surface where the velocity, $V_x(y_i, z_j)$, cannot be reliably determined. This can be due to the coarse y-z resolution of the measuring device, the presence of steep velocity gradients through a boundary region or interference from the walls on the measurement process (sonar reflections for example). In the perimeter region, the flow is estimated by extrapolating velocity profiles determined in the body of the flow.

6.4 Stationary determination of velocity

6.4.1 General

There are two methods of scanning the velocity profiles:

- stationary scans where the scanning device is static relative to the x,y,z coordinates when measurement are made; and
- moving scans in which the scanning device moves across the channel at a known velocity.

6.4.2 Vertical segments

A range of meter types may be used to determine point velocities within vertical segments. Various techniques are used to assess the mean velocity within each segment: single point, three points, five points, continuous lower/raise traverse.

The Doppler sonar provides a method of 'snapshot' integration along vertical segments by rapidly recording and processing velocities at a sufficient number of points to minimize the integration uncertainties.

Equation (8) then becomes

$$Q = F_y F_z \sum_1^n h_i \bar{V}_x\left(y_i\right) \Delta y_i + Q_\mathrm{p} \tag{9}$$

where $\bar{V}_x\left(y_i\right)$ is the processed mean value by automated summation (integration) of the velocities in the jth vertical segment. The Doppler sonar is also used in small channels where only a single vertical profile is integrated. In such cases, special attention shall be given to the evaluation of F_y and the area term, $h_1 \Delta y_1$.

6.4.3 Horizontal segments

An alternative method of 'snapshot' integration is to divide the cross-section into horizontal segments. The mean velocity is determined in each horizontal segment and hence the flow through each segment. This method is often used with transit-time sonar (see ISO 6416).

Equation (8) then becomes

$$Q = F_y F_z \sum_1^m b_j \bar{V}_x\left(z_j\right) \Delta z_j + Q_\mathrm{p} \tag{10}$$

where

$\bar{V}_x\left(z_j\right)$ is the processed mean value derived from scanning the velocities in the jth horizontal segment;

b_j is the length of the jth segment across the channel.

Compared with vertical segment methods, relatively few horizontal segments are used: F_z is not unity. Its value and its uncertainty shall be determined from ‘typical’ velocity profiles at the site.