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Hydrometry — Measuring river velocity and discharge with acoustic Doppler profilers

Hydrométrie — Mesure de la vitesse et du débit des rivières au moyen de profileurs à effet Doppler

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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Foreword

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Hydrometry — Measuring river velocity and discharge with acoustic Doppler profilers

1 Scope

Acoustic Doppler profilers are instruments and software packages used to measure water velocity, channel bathymetry, and river discharge. This Technical Specification gives the principles of operation, construction, maintenance and application of acoustic Doppler profilers to the measurement of velocity and discharge, and discusses calibration and verification issues. It is applicable to open-channel flow measurements with an instrument mounted on a moving vessel.

It is not applicable to measurement of liquid flow in small channels or partly-filled pipes using a single Doppler-based flowmeter at a fixed point in the cross section.

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.

3.1
Doppler shift
〈general〉 change in frequency of a sound source as it approaches and recedes from an observer

3.2
Doppler shift
〈acoustic Doppler instruments〉 difference or shift in frequency of emitted sound waves as they are reflected back from moving particles in the water

3.3
Doppler-based flowmeter
class of instruments that uses the principle of Doppler shift to compute water velocity and discharge

NOTE These instruments can be deployed at a fixed point in a cross section or on a moving vessel.

3.4
acoustic Doppler profiler
ADP
instrument that uses the principle of Doppler shift to compute water velocity and discharge

NOTE The instrument is usually mounted on a vessel that transits across a river channel perpendicular to flow.

3.5
ping
series of acoustic pulses of a given frequency transmitted by an acoustic Doppler instrument

3.6
ensemble
collection of pings

NOTE Because the measurement results from a single ping have a relatively high error, the results of more than one ping are usually averaged to obtain a single measurement.

3.7
transect
collection of ensembles from a single pass across a river, lake, or estuary

NOTE When measuring streamflow with an acoustic Doppler profiler, one transect may constitute a single measurement of discharge.

4 Background

Acoustic Doppler instruments for measuring water velocity have been in use for about 25 years, primarily in the study of ocean currents and estuaries. In the late 1980s, acoustic Doppler instruments began to be used to make velocity measurements from a moving vessel [3], [13]. The early instruments were narrow-band acoustic Doppler instruments that required deep water (> 3,4 m), which limited their use to deep rivers and estuaries. In 1992, a more advanced acoustic Doppler instrument, known as a Broadband Acoustic Doppler Current Profiler, was developed that could be used to measure velocities in shallow waters (as shallow as 1,0 m) with a high degree of vertical resolution (0,10 m).

Throughout the 1990s, acoustic Doppler profilers were continually developed and enhanced by several manufacturers. The instruments have been refined from very cumbersome and heavy units that were 1 m in length and weighing as much as 50 kg to compact and light units as small as 14 cm long and weighing 7 kg. The acoustic Doppler profilers now include advanced acoustic instrumentation designed specifically for use in rivers and software for real-time and post-processing of river velocity and discharge measurements. Acoustic Doppler profilers (3.3) are routinely used to measure discharge in estuaries, rivers, and canals where conventional discharge-measurement techniques are either very expensive or impossible due to stratification of the flow. They are also routinely used to measure discharge in large rivers, in part because of cost savings and reduced uncertainties due to smaller changes in discharge during the measurement.

5 Principles of operation

In moving vessel deployments, the acoustic Doppler instrument is mounted to a vessel (usually a motorized boat) that moves across the water body perpendicular to the current being measured. Water velocities are measured by the acoustic Doppler instrument, which transmits acoustic pulses along three or four beams at a constant frequency between 75 kHz to 3 000 kHz. The beams are positioned at precise horizontal angles from each other (120° for 3-beam instruments and 90° for 4-beam instruments (see Figure 1). The beams are directed at a known angle from vertical, typically 20° or 30°. The instrument detects and processes echoes throughout the water column along each beam.

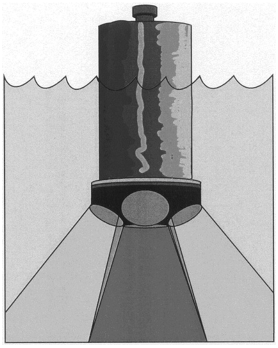


Figure 1 — Schematic diagram of an acoustic Doppler instrument with a 4-beam configuration

The difference in frequency (shift) between successive echoes is proportional to the relative velocity between the acoustic Doppler instrument and suspended material in the water that reflects the pulses back to the instrument. This frequency shift is known as the Doppler effect. The acoustic Doppler instrument uses the Doppler effect to compute a water-velocity component along each beam, and the system software computes water velocity in three directions using trigonometric relations. Velocities are determined at preset intervals called bins along the acoustic path. The instrument setup parameters can be adjusted to optimize the system for the river cross section being measured. These parameters include the depth cell size, the number of depth cells, the number of pings, and velocity reference commands.

The water-velocity measurements incorporate both the true water velocity and the boat velocity. The boat velocity can be measured by using the Doppler shift of separate acoustic pulses reflected from the river bottom. This technique, referred to as bottom tracking, is commonly used; it was first used with early sonar to measure the speed of a moving vessel. In addition to measuring boat velocity, the depth of the river is estimated from the amplitude of the bottom-track echoes (echoes returned from the bottom). Real-time differential global-positioning systems (DGPS) provide an alternative technique for measuring the boat velocity.

When the acoustic Doppler instrument is being used to measure discharge, it transmits a series of acoustic pulses known as pings (3.5). Pings for measuring water velocities are known as water pings, and pings for measuring the boat velocity are known as bottom-tracking pings. Normally, water pings and bottom-tracking pings are interleaved during transmission. A group of these interleaved water and bottom-tracking pings are referred to as an ensemble (3.6). The user sets the number of water and bottom-tracking pings per ensemble. An ensemble is analogous to one vertical in a conventional discharge measurement. For example, a typical ensemble is composed of a combination of water pings and bottom-tracking pings. The velocities and depths measured for each ping are averaged to yield a single velocity profile and depth for each ensemble. In a conventional discharge measurement, velocity is measured at one point in the vertical when the depth is less than 0,8 m and two, three or five points in the vertical when the depth is greater than 0,8 m. Depending on its characteristics, an acoustic Doppler profiler can measure velocities every 0,25 m in the vertical, so that one ensemble for a vertical 10 m deep may contain as many as 34 velocity measurements.

6 Application of acoustic Doppler profilers to measurement of river discharge

6.1 Instrumentation and equipment requirements

Making discharge measurements with acoustic Doppler profilers requires three main pieces of equipment: the acoustic instrument/transducer assembly, a vessel for mounting the instrument, and a portable computer. The instrument includes a pressure case that contains most of the electronics and a transducer assembly (see Figure 1). The transducer assembly may have a convex or concave assembly. The instruments come in a variety of sizes, beam configurations, and frequencies depending on the size and characteristics of rivers to be measured and the type of deployment. The small units are less than 30 cm tall and weigh about 7 kg; large units are 1 m tall and weigh 50 kg.

The type of acoustic Doppler profiler deployed depends on the river being measured. For small rivers, the system can be mounted in the bottom of a small boat, raft or catamaran. A remote-control motor can power the boat or a tether can be used to pull the boat and system across the river. Attaching a line from each bank or traversing the river with a single line from a bridge or cableway can be used for a tethered deployment. Measurements in large rivers require that the acoustic Doppler profiler be suspended in the water column from a mounting bracket on a boat powered with a gas or diesel engine. Examples of these two types of deployment are shown in Figure 2.

The system software processes and displays a large amount of data so a laptop computer with a minimum of 200 MHz processor and > 64 MB of RAM memory is recommended. The computer screen display should be visible in direct and diffuse sunlight.

Figure 2 — Photographs showing acoustic Doppler profilers deployed on a small, tethered boat (A) and a power boat (B)

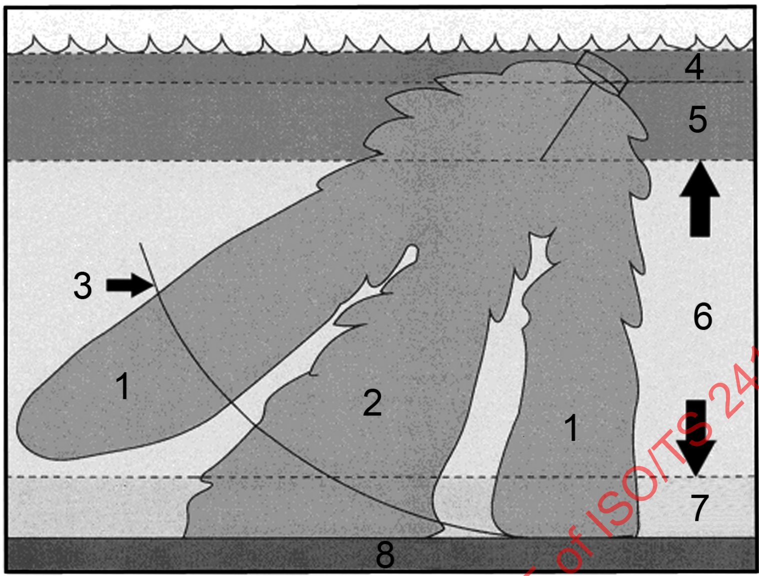
6.2 Making the measurement

A discharge measurement is made with an acoustic Doppler profiler by traversing the river cross section with the boat or tethered boat. A single traverse, called a transect (3.7), consists of a collection of ensembles. A typical transect will contain 300 to 1 000 ensembles, whereas a conventional discharge measurement will typically consist of 25 to 30 verticals. When measuring under relatively steady flow, four transects are made at each measuring location. Pairs of transects on reciprocal headings are used to minimize any directional bias that may be present. If the discharge measured on any given transect varies by more than 5 % of the mean discharge for all the transects, a second set of four transects is made. The mean of the discharges of all transects is used as the measured discharge. The time required to make four transects with an acoustic Doppler profiler is typically less than 30 min whereas a conventional discharge measurement may take 1 h to 2 h or more.

With rapidly-changing stage and unsteady flow conditions, a single transect may be used as a discharge measurement. However, two to four single-transect measurements should be made to help define and verify the stage-discharge rating at a streamgaging station.

6.3 Computing the measurement

Acoustic Doppler profilers have some limitations for measuring discharge in a river cross section. They cannot measure water velocities near the surface and near the bed. Water velocities near the surface are not measured because of the draft of the transducer (depth of the transducer face below the water surface) and the blanking distance of the instrument. The blanking distance is equal to the distance travelled by the signal when the vibration of transducer during transmission prevents the transducer from receiving echoes or return signals. The draft of a transducer can range from 0,2 m to 1 m and the typical blanking distance is 0,3 m. Velocity near the riverbed cannot be measured because of interference from side lobes of acoustic energy at 30° to 40° angles from the main beams. The reflections of the side-lobe energy from the riverbed overwhelm the echoes of the main beam from particles near the bottom of the water column. The effect of draft, blanking distance, and side lobe interference are shown in Figure 3.



Key

1 side lobe
2 main beam
3 maximum slant range
4 draft
5 blanking distance
6 area of measured discharge
7 side lobe interference
8 streambed

Figure 3 — Schematic diagram of areas where velocity is not measured near the water surface and near the streambed [12]

In order to accurately measure discharge, the near-surface and near-bed velocities must be estimated. The constant method or the power-law method is most commonly used for estimating the water velocities near the surface or near the bottom.

With the constant method, the velocity at the surface or the bottom is assumed to equal the velocity of the first or last measured depth cell, respectively. This method is not considered appropriate for estimating the velocities near the bottom because it does not accurately represent typical vertical-velocity distributions for open-channel flow. In open-channel flow, the velocity approaches zero as the bottom is approached.

The power-law method is based on a power-law velocity distribution. In this method, a least-squares fit of the measured water velocities is obtained using the power-law velocity distribution. The user can select the exponent of the function, which typically is set to 1/6 [2]. The function is then used to estimate velocities in the unmeasured part of the water column. Conceptually, the power-law method is better for estimating the unmeasured part of the water column near the bottom.

Acoustic Doppler profilers also cannot measure water velocities near either edge of the river cross section being measured. If the unmeasured discharge area is assumed to be triangular, the velocity for the unmeasured section v_e, is estimated by the equation of Reference [13]:

$$v_e = 0{,}707\ v_m \tag{1}$$

where v_m is the mean velocity at the first or last ensemble.

The assumption that the unmeasured flow area is triangular is reasonable for many river cross-sections where the bottom gradually slopes upwards towards the shore. However, sometimes the edge of water is a vertical wall, such as a sea wall. As the acoustic Doppler instrument approaches a vertical wall, the acoustic beams impinge the wall and cause a false bottom return. The distance at which the acoustic beam impinges the wall depends on the depth of water near the wall and the orientation of the transducers on the instrument relative to the wall. This distance is typically equal to the depth of the stream. Velocities for the unmeasured edge sections could then be estimated by setting $v_e = v_m$. However, this is not entirely accurate because the velocity does decrease to zero as the wall is approached. Therefore, for the measurements described in this Technical Specification, velocities near vertical walls were estimated by the following equation:

$$v_e = 0{,}91\ v_m \tag{2}$$

The coefficient of 0,91 was estimated from data presented in Reference [9] showing the relation of the distance from a smooth wall expressed as a ratio of the depth and mean vertical velocity. The estimated edge discharge, q_e, may then be estimated using the equation:

$$q_e = (C \cdot v_m \cdot L \cdot d_m) \tag{3}$$

where

- C is the coefficient equal to 0,707 or 0,91, depending on channel shape;
- v_m is the mean velocity at the first or last ensemble;
- L is the distance to the shore from the first or last ADP measured subsection; and
- d_m is the depth at the first or last ADP measured subsection.

d_m is measured by the ADP.

L is measured with a tagline or a similar measuring device.

The software packages developed for acoustic Doppler profilers provide procedures to estimate the unmeasured discharge; they typically include optional algorithms for estimating unmeasured discharge near the ends of the cross section, the unmeasured discharge due to side-lobe interference, and the unmeasured discharge due to blanking distance and transducer draft. The software display typically provides a comparison of the measured discharge and the estimated discharge for each of the unmeasured areas.

7 Factors affecting operation and accuracy

The factors affecting the performance of acoustic Doppler profilers for measuring river velocity and discharge can be divided into characteristics of the instrument and accompanying software, the characteristics of the river being measured, and the training and experience of the system operators.

7.1 Characteristics of the acoustic Doppler profiler

7.1.1 Transducers or beams

Acoustic Doppler instruments are available in 3-beam and 4-beam configurations. The computation of velocity in three dimensions requires at least three acoustic beams. The fourth beam of the Janus configuration provides a redundant beam that is used to compute an error velocity. The error velocity is used to check whether the flow is homogeneous within the footprint of the four beams. A significant velocity error could indicate extremely turbulent flow or a bad or corrupt beam velocity.

The angle of the beams from vertical (typically 20° or 30°) affects the performance of the system. The larger angle increases the cone of the beam and the amount of the water column being measured; however, it also increases the side lobe interference. The loss of vertical profiling range because of side-lobe interference is 15 % with a 30° angle and 6 % with a 20° angle.

7.1.2 Size and frequency

The size and frequency of the acoustic Doppler profiler to be used depends on the characteristics of the river being measured and the platform used for deployment. In deep rivers, a large unit mounted on a powerboat is used. The depth of the river determines the frequency of the system to be used because the higher the frequency of the transmitted signal, the greater the attenuation of the acoustic signal and thus the shorter the usable range. A 300 kHz unit can be used to a depth of 130 m while a 1 200 kHz unit can be used to a depth of about 20 m. A 300 kHz profiler typically has minimum bin sizes of 0,20 m to 1,0 m. A 1 200 kHz profiler uses minimum bin sizes of 0,05 m to 0,25 m.

Small rivers with tranquil flow can be measured with acoustic Doppler profiler installed in small powerboats or tethered boats or catamarans. New models of 1 200 kHz and 1 500 kHz systems are capable of measuring rivers with depths as shallow as 0,3 m.

7.2 River and channel characteristics

The river and channel characteristics will affect the performance and operation of acoustic Doppler profilers for making velocity and discharge measurements. A river with a very deep centre channel and shallow side channels or shoals may pose problems for measuring with a single system because the optimum frequency and configuration of the internal parameters of the system will be different for the deep and shallow parts of the channel. This may add a degree of uncertainty to the measurements. The uncertainty of the measured discharge also is affected by the degree of turbulent fluctuations present in the river reach. These fluctuations in velocity and flow are not uncommon and can be measured by the profiler. Fluctuations usually are not discernible in discharge measurements made with conventional velocity-area techniques.

The number of suspended particles in the water can affect the uncertainty of the velocity measurement. Too few particles may result in a limited number of return signals from each cell depth of the ensembles, although too few particles is rare. Too many suspended particles is the more common occurrence, especially during flood flows. The penetration of the acoustic pulses to the lower depths is reduced as the suspended sediment concentration increases.

Rivers with a large part of the sediment load transported as bedload, or having high sediment concentrations near the bed, pose other problems [8]. In such cases, bottom-track measurements are contaminated with returns from near-bed sediments. As a result, bottom-track measurements of the boat location will be located upstream of the true location and velocity measurements will be biased low because the acoustic profiler measures not only the boat speed, but also the speed of the moving sediments near the bed. The changing pattern of the moving bed prevents the bottom-tracking mode of the acoustic Doppler profiler from accurately measuring the traverse of the measuring platform and the width of the river. A DGPS can be used to measure the boat position and velocity; however, using an external reference velocity introduces additional potential errors into the water velocity and discharge measurements.

7.3 Operator training and experience

As with any velocity and discharge measuring equipment, the accuracy of velocity and discharge measurements made with an acoustic Doppler profiler depends on the training and experience of the operators. This includes both the boat operator and the system operator when a powerboat is used in larger rivers. The boat operator must have sufficient experience to maintain a true course while operating the boat at a speed slower than the measured current. The operator also should operate the boat so as to minimize pitching and rolling that may otherwise reduce measurement accuracy.

An experienced operator is needed to set the acoustic Doppler profiler to optimize the measurements to the river conditions. This includes setting the measurement mode of the instrument and the programmable sampling parameters, including the depth cell size, number of depth cells, sampling time, and velocity reference.

8 Verification

A limitation of acoustic Doppler profilers is the lack of an independent calibration and verification system. Calibration is limited to those specifications provided by vendors. Verification is accomplished by several methods. Acoustic Doppler profiler discharge measurements are verified by making comparison measurements using traditional velocity-area measurement techniques (see ISO 748). On most rivers, this consists of several crews making depth soundings and velocity measurements with vertical or horizontal axis current meters along a measured cross section while the acoustic Doppler profiler measurement is being made. This technique provides a comparison of the discharge measured by the acoustic Doppler profiler, but it does not provide an independent measurement of the velocity profile. The Bureau of Hydrology in China did some comparative tests of both fixed and boat-mounted acoustic Doppler profilers with conventional current meters. They evaluated velocities at different points in the vertical as well as the overall velocity distribution, and they found a good correlation between velocities obtained by acoustic Doppler profilers and conventional meters [1].

The velocity measurements of acoustic Doppler profiler are verified to some extent in the tow tanks that are used for calibrating horizontal- and vertical-axis current meters and for designing naval vessels. The profilers are mounted on a tow cart and towed through the tank at a constant speed. However, a relatively wide and deep (> 4 m) tow tank is required to avoid bottom and side wall interference. Variation in backscatter from material introduced into the tow tank for the tests causes some uncertainty. Some verification of acoustic Doppler profilers have been performed by the U.S. Geological Survey and the National Ocean Services [11] at the David Taylor Model Basin in Carderock, Maryland. The model basin is 15,5 m wide and 6,7 m deep.

The U.S. Geological Survey is also investigating a field method for verifying acoustic Doppler profilers [6]. The method uses a DGPS with sub-meter horizontal accuracy to check the distance and velocity of an acoustic Doppler profiler being traversed 400 m to 800 m on a lake or other water body with minimal currents.

9 Construction

In general, acoustic Doppler profilers consist of a transducer assembly and an electronics package. The transducers must be immersed in water in order for the acoustic Doppler profilers to function. For this reason, the electronics are usually housed in a pressure case made of either aluminium or plastic. The electronics inside an acoustic Doppler profiler include such things as a CPU and firmware, a flux-gate compass, and a pitch-roll sensor.

The transducer assembly is often directly attached to the pressure case, and may also be made of either aluminium or plastic. The transducer assembly is bolted to the pressure case. O-rings are used to provide a watertight seal between the transducer assembly and the pressure case.

Most acoustic Doppler profilers also have an end-cap located at the opposite end of the pressure case. Removal of this cap allows access to the electronics for servicing. O-rings are also used to provide a watertight seal between the end-cap and the pressure case. A communication cable is connected to the pressure case via a watertight connector located on the end-cap. The communication cable enables users to

