ACOUSTIC MEASUREMENT OF RIVER DISCHARGE

Rawya Monir Kansoh
Hydraulics and Irrigation Engineering Dept, Faculty of Engineering,
Alexandria University, Alexandria Egypt.

ABSTRACT

The method uses Acoutic Doppler Current Profiler (ADCP) to measure current profiles and boat velocity along transects across a river. An ADCP measures profiles of current velocity relative to the boat and the velocity of the boat relative to the bottom. The discharge calculation depends only on these data, and it is necessary to know either compass heading or the actual location of the boat. Furthermore, the transect can be an arbitrary curve as long as it starts near one side of the river and ends near the other. Uncertainty in discharge from random errors, biases, and missed data near the surface, bottom and sides of the river are investigated. Missed data near the surface and bottom are the largest source of error unless the data is corrected by assuming model profiles. With correction, the error in estimatior of total discharge is dominated by flow in the shallow water at the sides of the river.

Keywords: Measurements characteristics, Acoustic, River disccharge.

INTRODUCTION

A relatively new current-measurement technology, is the acoustic doppler current profilers (ADCPs), for measurement of river discharge. For a boat moving across a river, the following are possible: factors

1. Boat velocity is being measured in the same coordinate system as the current velocity, and it can be directly subtracted from the measured current velocities. This means that the ADCF can produce measured currents relative to the earth rather than relative to the boat.
2. It is possible to directly measure the distance traveled along the path taken over the bottom.
3. The current velocity component prependicular to the path traveled can be directly calculated.

As a result of these factors, it is possible to compute the discharge directly with an ADCP, without requiring data from any additional instrumentation. ADCPs miss data near the river surface and bottom. Therefore, they cannot obtain data when the total depth becomes too shallow.

Thus, computation of total discharge depends on extrapolating the measured data to the surface, bottom, and sides of the river.

Estimating discharge with ADCP

Discharge is the total volume of water flowing through a river cross section per unit time. If L = position along an arbitrary line across a river (see Figure (1)), then the discharge Q is

$$Q = \int\int n(L) \, . \, U(z.L) \, dzdL \qquad (1)$$

where:
n =the horizontal unit vector normal to the line at L:
U = the velocity vector:
z = depth:

and the integrals are taken from surface to bottom and from one side of the river to the other.

When using ADCP data to measure discharge, the integral in Eq. 1 is replaced by a summation, and the elements dz and dL, are replaced by Δz and ΔL, the depth and horizontal resolution of the ADCP measurements. The depth resolution Δz corresponds to the range intervals or "depth cells" into which the measured current profile is broken. Horizontal resolution ΔL depends on the boat speed. It is equal to the distance travelled by the boat during the time interval over which measurements emsembles are averaged. The distance travelled during an ensemble is obtained by integrating the bottom tracking velocity.

In the integral, Eq. 1, it is only necessary to know the current component normal to the path, n.U. and the distance travelled along the path ΔL. Therefore, it is unecessary to know either the distance or the location of the path of the transect.

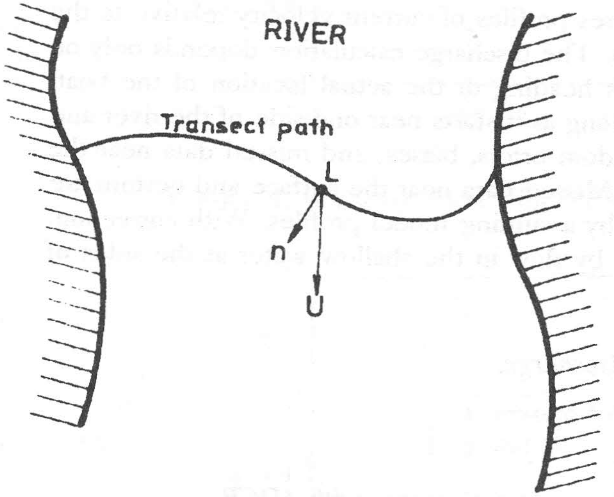

Figure 1. Schematic of transect or path L across river; U=horizontal current velocity vector; and n = unit vector normal to direction of path.

ADCP MEASUREMENT CHARACTERISTICS

ADCPs transmit short acoustic pulses along narrow beams at a known, fixed frequency (from 75-1,200 kHz, depending on the transducer). The ADCP listens to and processes the echoes from successive volumes along the beams to determine how much the frequency has changed. The difference in frequency between transmitted and reflected sound is proportional to the relative velocity between the ADCP and the scatterers in the water that causes the reflection.

Sound is scattered primarily by zooplankton and/or small particles of suspended sediment. At 1,200 kHz, the dominant scaterrer size is about 0.2 mm (about 1/6 of a wavelength). Particles this small tend to move with the water, thus providing an estimate of the water velocity. Reflections from fish are relatively infrequent and rarely affect the measurements.

Figure (2) shows the beam geometry; four beams were oriented at an angle of 30° relative to the vertical and in 90° azimuth increments.

Multiple beams are required because ADCPs measure only the velocity component parallel to the beam. Through range gating, it is possible to compute the velocity in a series of contiguous, discrete ranges along each beam. These ranges are called depth cells. The depth cell size is determined by the durations of both the range gate and the transmit pulse. The range gate and transmit pulse are normally set equal to one another; there durations are equal to twice the spacing between depth cells (using the speed of sound to convert between length and time co-ordinates). The first ADCP depth cell is defined as the one closest to the ADCP, and successive bins are contiguous and partially overlapping. The vertical spacing of the depth cells can be 1,2,4,8,16 or 32 m. Figure (2) shows one depth cell for four beams at a given depth.

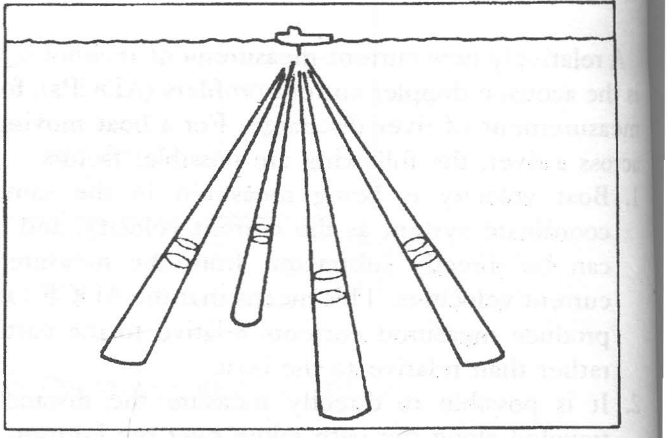

Figure 2. ASCP beam geometry and location of one depth cell.

If one assumes that the current at this depth is the same through all four beams (the homogeneous velocity assumption), then the three dimensional velocies may be computed using trigonometry. Note that any three of the four beams are sufficient to make the calculation and that the fourth beam is thus redundant. The redundant information is valuable because it allows one to evaluate whether the homogenous velocity assumption is reasonable and also permits the detection of other possible problems with data quality.

Measurement Errors

ADCP measurements have both random errors and biases. Random errors can be approximated by:

$$\sigma \frac{1.6\times 10^5}{F.D.(N^1/2)} \qquad (2)$$

where

σ = the standard deviation (m/s);
F = the frequency (Hz):
D = the depth cell size (m); and
K = the number of pings averaged together to obtain the velocity estimate.

The constant 1.6×10^5 has dimensions m^2/s^2.

Random error in single pings is much greater than the bias, but as averaging reduces the measurement uncertainty towards [illegible]o, bias can become significant. After random errors have been reduced through averaging to the aproximate level of the biases, little further improvement may be obtained with more averaging. ADCP measurement bias is on the order of 0.5-1.0 cm/s. This bias is called the long-term accuracy of the ADCP, as opposed to short-term accuracy, which depends on the random error and the amount of averaging used.

In choosing the acoustic frequency for a particular application, one must trade profiling range for short-term accuracy. According to Eq. 2, increasing frequency reduces velocity uncertainty, but this comes at the cost of an approximately proportional loss of profiling range. The ADCP measurement profile misses data at the surface of the river and near the bottom. Data is lost at the surface because the ADCP must be deployed at the approximate keel depth of the boat to prevent the acoustic beams from interfering with the hull. Additional range is lost because the ADCP delays processing for a short period after the acoustic transmission to allow transducer ringing to die down.

Data is lost near the bottom as a result of contamination by echoes from the riverbed directly below the ADCP. While most of the energy in the beam is directed through the main lobes (at 30° relative to vertical), some energy leaks into side lobes, and some of this side-lobe energy will travel downward, directly to the bottom. Even though the side-lobe energy is weak, the bottom is much stronger reflector of sound than are the scatterers in the water. Thus the direct bottom echo can be comparable in strength to the main lobe echo at the same range. Figure (3) shows the range at which side-lobe echoes begin to contaminate the data. Given the 30° beam angles, data beyond 83 % of the distance to the bottom could be contaminated. The ratio 85 % is equal to cos (angle) where the angle is relative to vertical (cos 30° is actually 0.866). The data processing software automatically rejects data beyond about 85 % of the distance to the bottom.

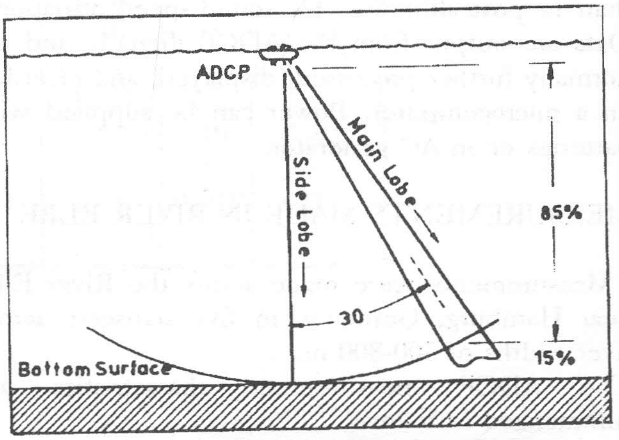

Figure 3. Side-Lobe contamination at ranges strongly reflecting boundaries (e.g., river bottom).

Pitch and roll of the boat can cause the depth cells to move up or down and can affect the trigonometry used to compute the horizontal velocity. Kosro (1985) studied this in detail for ocean data and concluded that random error increases as a result of pitch and roll, but that bias increases by only about one centimeter per second. Given a riverine environment, the pitch and roll will normally be small compared to an ocean-going boat and thus negligible in its effect on data.

Bottom tracking is performed by transmitting much longer acoustic pulses than are used for water profiling. Bottom tracking is not constrained by the need to have small depth cell size, and therefore longer pulses may be used. The longer pulse, combined with the fact that the bottom is a strong, localized scatterer, enables bottom-tracking measurements to be made with substantially more accuracy than water velocity. The amplitude of the returned echo is used to estimate the depth (accurate to about one meter). Because the velocity measurement depends on Doppler shift & not on change in depth, bottom irregularities have no adverse effect on the bottom-track measurement, ADCP calibration depends primarily on stability of the transducer beam geometry and of the frequency generation and processing circuitry. By constructing the transducers to be mechanically rigid and by designing the circuity to minimize drift and temperature effects, the need for calibration is reduced or eliminated. In fact, users cannot adjust, or otherwise affect measurement, calibration other than in postcalibration for sound-speed variations. Data are output from the ADCP digitally and are normally further processed, displayed, and recorded on a microcomputer. Power can be supplied with batteries or an AC generator.

MEASUREMENTS MADE IN RIVER ELBE

Measurements were made across the River Elbe near Hamburg, Germany, in five transects across river widths of 500-800 m.

The ADCP measurement charactristics are summarized as follows:

* ADCP Model: RD-DR1200 direct reading ADCP
* Frequency: 1,200 kHz
* Depth cell size : 1 m
* Measurement ensemble size: 28 pings (± 3 pings)
* Measurement ensemble duration: 30 sec.
* Single-ping measurement error: 13 cm/s
* Measurement bias: [illegible] - 1.0 cm/s
* Ensemble measurement error: 2.5 cm/s
* ADCP transducer depth : 1.5 m
* ADCP beam width: 2°
* Transducer sidelobe level : -55 dB

Figure (4) shows the flow velocity perpendicular to each of the five transects. The gray-scale shade corresponds to current velocity normal to the transect (n.U). The measured depth is shown at the bottom as a solid line. The distance shown are computed along the transect.

The total discharge estimated for the River Elbe is 4,559 m^3/s. The standard deviation of the estimates is about 1 %, and the total estimated error is on the order of 5 % (Table 1).

Errors in calculation of discharge arise primarily from random error, blas, and loss of data at the river surface, bottom, or sides. Errors from lost data are evaluated in the following using simple model profiles extrapolated in two different ways from the River Elbe data (Figure (5)). The first extrapolation assumed that the velocity gradient was constant at the top and bottom of the profile. For the top layer, the gradient was set equal to the average gradient observed at the top of the profiles. For the bottom layer, the gradient was set by forcing the velocity to zero at the river bottom.

The second extrapolation assumed that the velocity was constant in the top and bottom layers and equal to the velocities measured at the ends of the observed profiles. In each case, one method overestimates and the other underestimates the discharge. Discharge is estimated by averaging the two estimates as follows:

$$Q = \frac{(Q_H + Q_L)}{2} \tag{3}$$

where:

Q = the estimated discharge: and
Q_H and Q_L = the higher and lower discharge estimates, respectively.

An upper bound for the uncertainty in the dischare estimate can be obtained with:

$$\Delta Q = \frac{(Q_H - Q_L)}{2} \tag{4}$$

where:
ΔQ = the upper bound uncertainty.

Each source of error in the discharge estimate is addressed in the following.

Random Error

Random errors are cumulatively smaller than bias errors and may be neglected. The measurement uncertainty for each depth cell was about 2.5 cm/s. During each transect across the river, typically 150 depth cells of data were measured (10 depth cells per profile times 15 profiles). The Random uncertainty for each complete transect will be approximately $2.5/(150^{1/2}) = 0.2$ cm/s, which is much smaller than the ADCP bias of 0.3-1.0 cm/s.

The cumulative error on estimated discharge over the cross-sectional area of the river would be about 20 m^2/s, or about 0.4 % of the total.

Table 1.Discharge [m^3/s] in Top, Middle, and Botton Layers of River

Transed number (1)	Discharge				Discharge Uncertainty	
	Middle (2)	Top (3)	Bottom (4)	Total (5)	Top (6)	Bottom (7)
1	3.142	1.045	401	4.588	29	1.34
2	1.152	1.013	411	4.576	31	1.37
3	3.188	1.043	400	4.631	25	1.33
4	3.037	1.058	422	4.517	39	1.41
5	3.063	1.058	362	4.485	38	1.21
Mean	3.117	1.043	390	4.559	32	1.33
Mean/total	0.68	0.23	0.09	1.00	0.01	0.03
or/total	57	16	20	52	5	7
	0.01	0.004	0.004	0.01	0.001	0.001

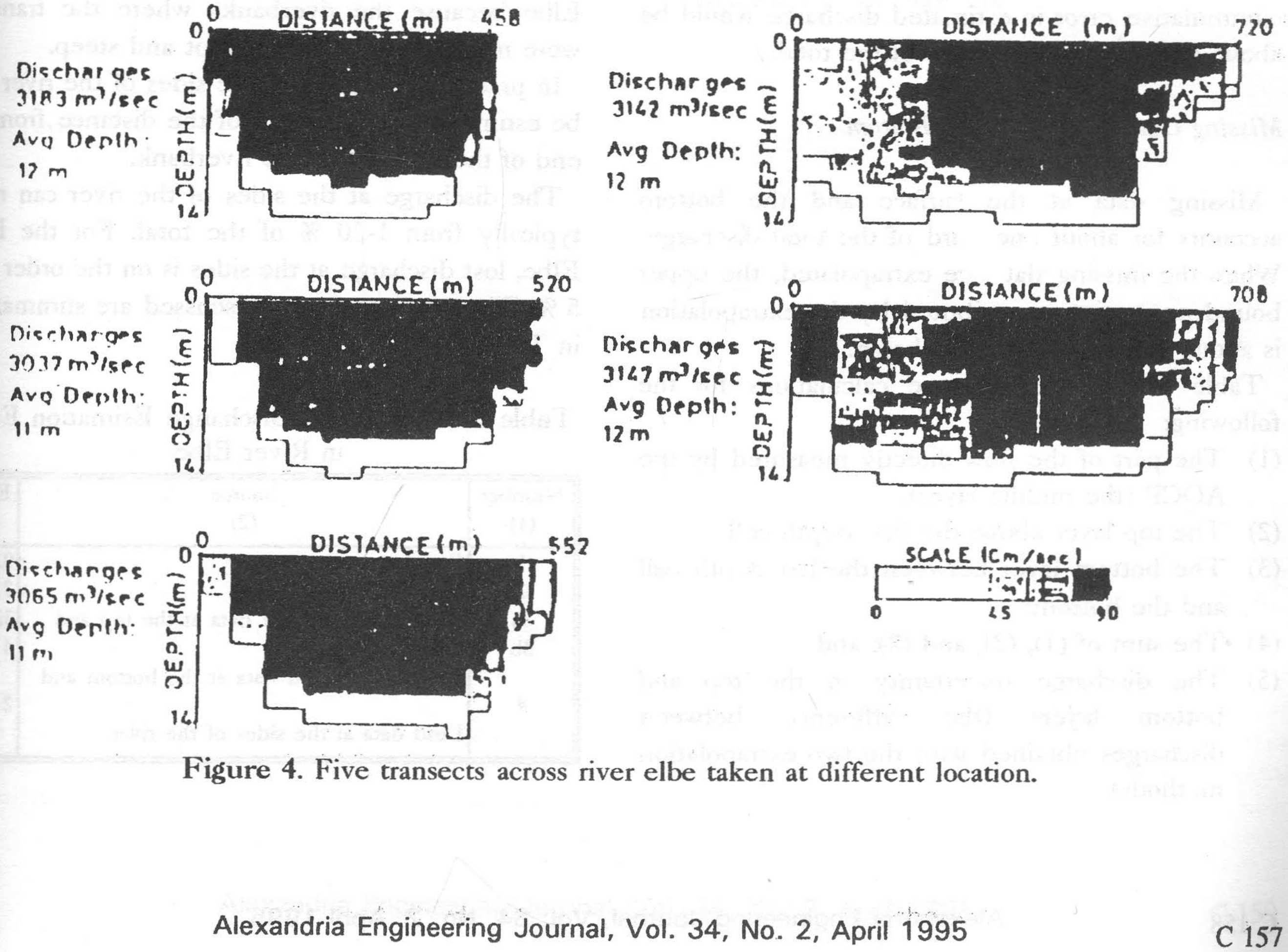

Figure 4. Five transects across river elbe taken at different location.

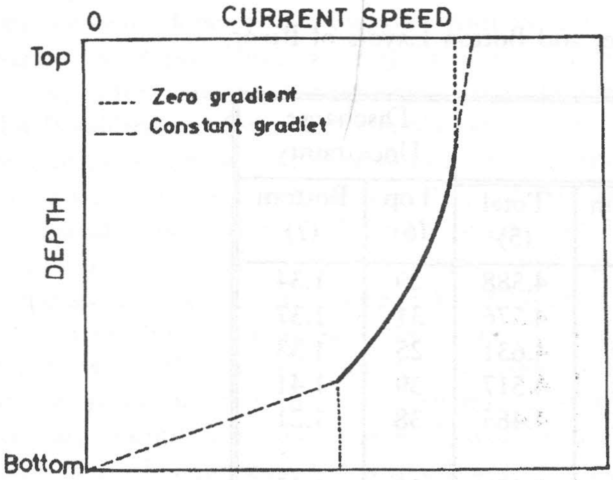

Figure 5. Two different extrapolation methods.

Bias

Bias should be less than one centimeter per second. If there were a uniform measurement bias of one centimeter per second across the river, the cummulative error in estimated discharge would be about 100 m^3/s or about 2 % of the total.

Missing Data at Surface and Bottom

Missing data at the surface and the bottom accounts for about one third of the total discharge. When the missing data are extrapolated, the upper bound uncertainty contributed by the extrapolation is about 4 % of the total discharge.

Table 1 presents discharge calculations for the following:

(1) The part of the flow directly measured by the ADCP (the middle layer):
(2) The top layer above the first depth cell:
(3) The bottom layer between the last depth cell and the bottom;
(4) The sum of (1), (2), and (3): and
(5) The discharge uncertainty in the top and bottom layers (the difference between discharges obtained with the two extrapolation methods).

Discharge is estimated independently in the top, middle, and bottom layers for each transect, "Mean" is the average of the values for all five transects, and σ is the standard deviation. "Mean/total" and "σ/total" expresses the values as fractions of the total estimated discharge, 4.559 m^3/s.

The top and bottom discharges are computed using (3), and the discharge uncertainty is computed using (4).

The total discharge estimates vary from one another by only 1 % standard deviation.

Missing Data at Sides of River

Missing data at the sides of the river amount to a possible loss of a few percent of the total discharge. Lost discharge may be estimated by assuming that the boat missed the last 50 m on either side of the river and that the river depth and current speed fall to zero linearly from each end of the transect. This assumption is probably conservative in the River Elbe because the riverbanks where the transects were made are relatively abrupt and steep.

In practice, discharge at the sides of the river may be estimated as a function of the distance from the end of the transect to the riverbank.

The discharge at the sides of the river can range typically from 1-20 % of the total. For the River Elbe, lost discharge at the sides is on the order of 2-5 %. The sources of error discussed are summarized in Table (2).

Table 2. Summary of Dischange Esimation Errors in River Elbe

Number (1)	Source (2)	Error (3)
1	Ramdown error	0.4
2	Hios	2
3a	Uncorrected missed data at the top and	32
3b	bottom	4
	Corrected missed data at the bottom and	
4		2-5
	Losd data at the sides of the river.	

CONCLUSIONS

A method is presented for estimating total river discharge with the use of an ADCP temporarily mounted on a boat. The method relies only upon measurements made by the ADCP and does not depend on having simultaneous data from the boat (e.g., heading or location).

The distance travelled over the transect is obtained with ADCP bottom-track data. At the same time, the ADCP provides current velocity normal to the transect over a profile from near the surface to near the bottom.

Discharge is calculated as the integrated flow normal to the transect.Missing data at the top and bottom of the profiles represent the largest potential error. This error may be corrected by extrapolating the measured current profiles into the top and bottom layers.

For the River Elbe, the uncertainty introduced by extrapolation appears to be less than about 4 %. The standard deviation in the total discharge calculations was only 1 %.

The instrument used in this study was well-suited for use in the River Elbe, given the relatively large depth of the river. The same instrument could also be used in shallower rivers, but as the river becomes shallower, larger fractions of the total discharge estimate will be based on extrapolations. The minimum average river depth in which useful discharge measurements can be made is around 5-6 m.

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